Rainfall Occurrence in the U.S. Warm Season: The Diurnal Cycle*

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ABSTRACT

The diurnal occurrence of warm-season rainfall over the U.S. mainland is examined, particularly in light of forcings at multiple scales. The analysis is based on a radar dataset of 12-seasons duration covering the U.S. mainland from the Continental Divide eastward. The dataset resolves 2-km features at 15-min intervals, thus providing a detailed view of both large- and regional-scale diurnal patterns, as well as the statistics of events underlying these patterns. The results confirm recent findings with respect to the role of propagating rainfall systems and the high frequency at which these are excited by sensible heating over elevated terrain. Between the Rockies and the Appalachians, ~60% of midsummer rainfall occurs in this manner.

Most rainfall in the central United States is nocturnal and may be attributed to the following three main forcings: 1) the passage of eastward-propagating rainfall systems with origins near the Continental Divide at 105°W; 2) a nocturnal reversal of the mountain–plains solenoid, which is associated with widespread ascent over the plains; and 3) the transport of energetic air and moisture convergence by the Great Plains low-level jet.

Other features of interest include effects of the Appalachians, semidiurnal signals of regional significance, and the impact of breezes along the Gulf of Mexico. A modest effort was put forth to discern signals associated with El Niño and the Southern Oscillation. While tendencies in precipitation patterns are observed, the record is too short to draw conclusions of general significance.

1. Introduction

Many aspects of the earth’s water cycle are not well understood and precipitation is not well simulated by climate system models. Convective precipitation is especially problematic, including convection organized at the large mesoscale. Numerous studies have employed diurnal variability as a framework from which to improve the understanding of water cycle forcings and to serve as a benchmark for new representations in models. This study examines the diurnal cycle of warm-season precipitation, which may result either from local cumulus convection or remote forcing and the delayed-phase arrival of propagating rainfall systems.

Carbone et al. (2002, hereafter CAR02) examined the statistics of warm-season precipitation events over the conterminous United States. They clarified the nature of events underlying a well-known statistical maximum of nocturnal precipitation between the Rockies and Appalachian Mountains. As with many who had preceded them, they observed the diurnal excitation of ordinary thunderstorms and a tendency for these storms to scale upward over time. Pioneering studies by Maddox (1980, 1983) led to the discovery of mesoscale convective complexes (MCCs), which were organized to scales previously unrecognized at midlatitudes. Subsequently, Velasco and Fritsch (1987) and Laing and Fritsch (1997, 2000), among many others, diagnosed the structures and forcings associated with MCCs, both in the United States and on several other continents.

CAR02 discovered yet a larger scale of dynamical organization marked by the coherent regeneration of rainfall systems and their systematic propagation eastward over distances of 500–2000 km and durations of 10–60 h. They referred to these events as “episodes” to connote a coherent sequence of mesoscale systems. In the warm season this phenomenon was shown to occur 11 times daily over the United States, thereby influenc-
ing the phase and amplitude of the diurnal cycle eastward of the Continental Divide. This knowledge has paved the way for improved representation of summertime rainfall in global models because the population of underlying events is now recognized and many of the relevant dynamical principles are understood.

The main objective of this study is to extend and to clarify the findings of CAR02, which were based on a short period of record (4 yr). The period of record is now 12 yr, thus permitting us to reduce uncertainty and to place the results on firmer ground for climate science applications. We report new results at the continental scale and we delve into some regional aspects of diurnal variability that were not previously examined. Finally, we search for evidence of diurnal anomalies that might occur during phases of El Niño–Southern Oscillation (ENSO; Madden and Julian 1972).

Pioneering work by Tripoli and Cotton (1989a,b) established a causal relationship between propagating mesoscale convective systems over the Great Plains and diurnal forcing over the Rockies, which acts as an elevated heat source. They showed that convection scaled upward from simple cumulonimbus over the mountains to meso-β- and meso-α-scale systems over the plains, propagating eastward for hours. Gravity wave modes constrained by background slope flow circulations were shown to be central to the underlying dynamics. More recently, various global and regional studies (e.g., Davis et al. 2003; Wang et al. 2004, 2005; Ahijevych et al. 2004; Tuttle and Davis 2006; Parker and Ahijevych 2007; Levizzani et al. 2006; Jiang at al. 2006; Janowiak et al. 2007; Keenan and Carbone 2008; Laing et al. 2008) have extended our understanding of phenomena that underlie the diurnal cycle of warm-season rainfall. Among recent findings, it has been determined that several continents and countries (e.g., China, Africa, South America, Europe, Australia, and India) are frequented by the diurnal excitation of propagating convection. With few exceptions these regions are located in the lee of mountain ranges with an equatorward source of potentially warm, moist air (Laing and Fritsch 1997). The resulting episodes of rainfall produce a sizeable fraction of seasonal precipitation in most of these regions. The ensemble of climate system model projections (Solomon et al. 2007, p. 859) highlights nearly all of these regions as having uncertain precipitation trends in the twenty-first century. This uncertainty is partly the consequence of inadequate convective representations in models (Dai and Trenberth 2004; Fritsch and Carbone 2004).

This study employs radar observations at a continental scale as its primary dataset. Our emphasis is on the time and place of rainfall occurrence, not rainfall amount. While there is information concerning mean rainfall rate inherent to the dataset, it is prudent to view such rates as relative to other times and locations. The observations, methodologies, and domains of computation are briefly described in section 2.

2. Observations, methodologies, and computational domains


a. Observations and data conditioning

The radar data for this study were provided by the WSI Corporation’s national composite NOWrad product. This product is derived from the Weather Surveillance Radar-1988 Doppler (WSR-88D) level II data, and undergoes several levels of quality control. It consists of an ~2-km latitude–longitude grid averaged over 15-min intervals. There are 16 levels of radar reflectivity factor [10 log $Z_e$ (mm$^6$ m$^{-3}$)] at 5-dB$Z_e$ intervals, which is considered too coarse for quantitative rainfall estimates. At each grid point the dB$Z_e$ maximum among all of the samples in the vertical column is the value of record.

Data conditioning procedures herein are identical to those of CAR02. Equivalent instantaneous rainfall rates are calculated from the expression $Z_e = 300R^{1.5}$, which is a typical relationship for convective rainfall at midlatitudes. The actual instantaneous rainfall rate may differ by more than a factor of 2 from this relationship and, if left unconstrained by rain gauge data, averages over regions and seasons may be biased by 20%–30% or more.

These potential biases are of little consequence to this study. What is of concern is the time and location of rainfall, and whether that rainfall is relatively light, moderate, or heavy. For these applications the dataset is highly satisfactory from the continental divide eastward. Our principle variable is the percent of time within a given UTC hour for which rain is present at a grid point. When radar-estimated “equivalent rainfall rate” is exhibited, it is done so only to convey a relative measure of spatial or temporal variability.

The CAR02 pattern of diurnal variability has been verified by several studies employing the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) North American Regional Reanalysis (NARR; e.g., Jiang et al. 2006; Janowiak et al. 2007). NARR is a 3-hourly analysis (cf. 15 min herein) achieved by means of data assimilation on an ~32-km grid (cf. ~2 km herein). NARR-based analyses reveal a low-pass-filtered portrayal of the
CAR02 diurnal pattern. Wind and thermodynamic data used in this study were obtained from the National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory Web site, including the NCEP–NCAR reanalysis products, the NARR, and the Rapid Update Cycle (RUC). Among these sources, only the RUC data were able to adequately resolve mean regional-scale circulations on scales of the order of 500-km dimension. Had the RUC dataset not been available, some erroneous forcings could have been inferred.

b. Computational domains

We define “warm season” as May through August and “midsummer” as June–August (JJA). Use of the CAR02 computational domain (Fig. 1, top) facilitates a direct comparison between the 4- and 12-yr time series (30°–48°N, 115°–78°W). Several smaller domains are introduced (Fig. 1, bottom), principally either to illustrate or to isolate regional phenomena, for example, sea and land breezes. These domains include the northern and central zonal corridors (NC and CC, respectively), the Mississippi Valley and Gulf Coast (MV), and the Southeast (SE). As in CAR02, much of the analysis is performed in a “reduced dimension.” That is, we statistically analyze the properties of rainfall events in one spatial dimension (e.g., longitude) versus time, this is often referred to as a Hovmöller diagram.\(^1\) In a reduced dimension, rainfall “events” are defined as coherent

\(^1\) Details of the computational procedures are described in CAR02, which also references a technical report from which the full set of calculations may be reproduced.
patterns of rainfall occurrence in time–space, which appear as elongated streaks when propagating. The smallest events are of mesoscale convective system size and O[100–200 km, 3–6 h] duration.

Our major focus is midsummer, the period of maximum thermal forcing and minimum occurrence of transient synoptic disturbances. We rely on reduced dimension analyses, mainly to facilitate the detection of major dynamical and thermal signals. Two-dimensional horizontal depictions are then restored to clarify the spatial extent of certain features and forcings. Animations are provided (supplemental information related to this paper is available online at http://dx.doi.org/10.1175.2008JCLI2275.s1) to better convey a sense of the (rainfall) diurnal cycle dynamics, which in some sense is the hydrometeorological heartbeat of a continent.

3. Continental-scale diurnal cycle

a. Major features

Relatively few major features present themselves on the continental scale (Fig. 2). From the Continental Divide eastward, local excitation of afternoon rainfall (Fig. 2a) occurs most frequently over the Florida Peninsula and the Gulf of Mexico (GoM) coastline, the Front Range of the Rockies, and the Appalachian Mountains. As the cycle progresses through the evening hours (Fig. 2b), rainfall occurrence becomes more widespread owing to the delayed local excitation of rainfall in less favored (flatland) areas. The nocturnal hours (Fig. 2c) exhibit a rainfall frequency maximum in the central states, decreased frequency in the lee of mountains and over the landward side of coastlines, and an increase in rainfall frequency offshore. The morning hours (Fig. 2d) show increased rainfall frequency offshore and continued eastward progression of a diminished central states maximum. Subsequent discussion will examine each of these features and forcings, with emphasis on the wavelike eastward progression of rainfall, breeze effects, and other signals associated with a semidiurnal harmonic. In reference to the wavelike eastward progression of rainfall, this is best visualized by means of an animation of the 12-season (JJA) average diurnal cycle (the P12 diurnal animation is available online at http://dx.doi.org/10.1175/2008JCLI2275.s1).

One measure of diurnal variation is standard deviation (h) of the diurnal maximum (Figs. 3 and 4). Figure 3 provides local illustrations of the diurnal maximum standard deviation, and Fig. 4 illustrates the continental variation. Where the diurnal period is of large amplitude, and in the absence of other harmonics, the standard deviation is small (2–3 h), as evidenced, for example, over the Colorado Front Range (Fig. 4c) and the Florida Peninsula (Fig. 4d). Conversely, where the diurnal amplitude is small and other harmonics are present, the standard deviation is large (~7 h), as evidenced, for example, over central Illinois (Fig. 4b). Intermediate values are observed at other locations, for example, western Montana (Fig. 4a). To first approximation, in reference to Figs. 2 and 4, a large standard deviation is associated with the dissipation region just east of the late-stage nocturnal maximum. In addition, a large standard deviation occurs along the track of transient synoptic disturbances (northern tier), the Great Lakes, and oceanic breeze zones.
b. Comparison of the 4- and 12-yr records in reduced dimension

As illustrated in Fig. 5, the continental pattern of diurnal variation is largely unchanged from that of CAR02. As a function of longitude, and as expressed in percent time of occurrence, major features in the diurnal pattern differ only in detail between the 4- (P4; see Fig. 5a) and 12- (P12; see Fig. 5b) yr periods of record. Among other features are the following:

- Hot spots within the diurnal maximum occur at similar locations and times.
- The amplitude of diurnal variation is greatest in the west and is highly correlated with an elevated surface sensible heat source.
- The principal origin of propagating convection (~105°W) is similarly positioned and timed on the east slope of the Continental Divide.
- The local diurnal maximum surrounding 98°W is suppressed, owing to the descending branch of the mountain–plains solenoid.
- Evidence of semidiurnal forcing is apparent at ~1000 UTC, 85°–90°W.
- Owing to data-void regions (Canada and the Atlantic) east of 83°W, occurrence values are biased low near the eastern edge of our continental domain.

A significant difference between P4 and P12 is the ~4% increase in P12 occurrence values over the eastern half of the domain, whereas the west remains essentially unchanged. While the P12 local diurnal maximum remains greatly suppressed at 98°W, it is ~5% stronger than P4. Overall, the principal conclusions drawn from P4 are reaffirmed by P12.

c. Breeze influences and monthly variability

The semidiurnal maximum east of 92°W may be the result of one or more influences, including Gulf of Mexico breezes. To isolate these breeze effects, we repositioned the domain’s southern boundary northward from 30° to 33°N (Fig. 6). This domain change reduces both the diurnal and semidiurnal amplitudes resulting from the exclusion of the Gulf Coast region. A weak semidiurnal signal is still apparent in approximately one-half of the 36-monthly averages. It was most prevalent in 1997 and 2000, and largely absent in 1999 and

Fig. 3. Examples of the standard deviation of the diurnal rainfall maximum. This calculation is performed using averaged radar-estimated rainfall rate in (a) Florida, and (b) the north-central and (c) southern plains.
2005. Breezes and other regional factors associated with semidiurnal forcing are examined further in section 4.

The delayed-phase diurnal maximum (DDM) from 105° to 92°W exhibits considerable variability in the monthly averages. The DDM, while always present, can be a relatively diffuse feature (i.e., excitation is not as focused at 105°W) in a significant minority of months. In such conditions, the DDM subtends a broader longitudinal swath, and it is relatively weak (diminished maximum frequency) in roughly one-third of the months observed. Diffuseness and weakness, while intersecting sets, are not coincident, because August is more often weaker than June or July but is not especially diffuse. The weakest and most diffuse DDM year is 2002, especially in July (Fig. 7), which is a month of widespread drought and wildfires in the west. Meridional focus and strength in the DDM is somewhat more likely in June, when shortwave sensible heating is strongest and ambient-free troposphere temperatures have

![Diagram showing standard deviation of the diurnal maximum frequency of occurrence (h; center image). Average rainfall rate over the diurnal cycle in (a) central Kansas, (b) central Illinois, (c) Colorado's Front Range, and (d) Florida Peninsula.](image-url)
yet to reach their seasonal peak. Seasons exhibiting the greatest focus and strength of the DDM were 2004 and 2005.

d. Fraction of rainfall resulting from propagating systems

More than 12,000 propagating rainfall events were observed in JJA over the period of record, \( \sim 11 \text{ day}^{-1} \).

Fig. 5. Diurnal radar echo frequency of occurrence in the continental domain, JJA: (a) 1997–2000 (after CAR02) and (b) 1996–2007. A longer period of record yields a substantially similar diurnal pattern.

To assess the significance of propagating systems, radar-equivalent cumulative rainfall resulting from these was calculated as a fraction of total rainfall versus longitude (Fig. 8). An ambiguity arises at the local diurnal maximum, where one may attribute either all, some, or none of the rainfall to a coincident propagating system, owing to the superposition with locally forced convection. We account for this ambiguity by exhibiting the
extremes, that is, 0% and 100% attribution to the propagating component (shaded) and the 50% partition line.

A characteristic fraction of total precipitation that results from propagating systems of 6-h duration or longer is $\frac{1}{2}$ between the Rockies and the Appalachian Mountains (Fig. 8a). This fraction decreases for propagating systems that are longer than 12- and 24-h duration to $\frac{1}{2}$ and $\frac{1}{3}$, respectively (Figs. 8b and 6c). While the precise fraction of total precipitation is uncertain, it is evident that propagating rainfall systems weigh heavily in the diurnal cycle over the central United States.

e. Nocturnal rainfall distribution

As illustrated in Fig. 2, nocturnal rainfall is both frequent and widespread in the central United States. There are multiple factors underlying the diurnal cycle in this region, among these are the mountain–plains solenoidal circulation (MPS; Wolyn and McKee 1994) and the Great Plains low-level jet (GPLLJ; Bonner 1968). According to RUC summertime climatology, the MPS is characterized by an afternoon ascent of the order of 4–8 cm s$^{-1}$ near the Continental Divide and descent of the order of 1–2 cm s$^{-1}$ over a broad area centered at $\sim$90°–100°W (Fig. 9a; 60 kPa). Anomaly winds (i.e., the climatological departure from the seasonal daily average) indicate transport consistent with a closed solenoid circulation, the eastward branch of which is apparent at 60 kPa. At night, vertical motion reverses sign, exhibiting an ascent of 1–2 cm s$^{-1}$ over the lowlands and a descent of 3–6 cm s$^{-1}$ over the mountains (Fig. 9b; 65 kPa). The anomaly winds clearly illustrate both directional and horizontal divergence patterns associated with a thermally direct circulation in westerly flow. Differential cooling rates between mountains and plains is the most straightforward explanation for a thermally direct reversal of flow. The MPS is favored east of the Rockies where the prevalent condition includes the westerly shear of the zonal wind.

We note that weak and sometimes complicated patterns of vertical air motion are present over the central Appalachians, often opposite in sign to those over Illinois, Indiana, and Ohio. At 2100 UTC, 70-kPa weak afternoon ascent (1–2 cm s$^{-1}$) is routinely diagnosed near the central Appalachians, together with $\sim$1 cm s$^{-1}$
descent in the Illinois–Indiana region (not shown). Anomaly winds are inconsistent with the notion of a solenoid circulation in this region; however, regional mass compensation is suggested. Surprisingly, any direct effects of the Great Lakes themselves are not especially prominent or evident in the average RUC analysis (Fig. 9).

Other nocturnal maxima of note include rainfall over the coastal Atlantic and the GoM, and rainfall resulting from the passage of fronts and cyclones across Montana and the northern plains, both of which are discussed in section 4.

4. Regional-scale diurnal variation

It is instructive to examine these data in greater detail over limited regions, once again in reduced dimension. First, we clarify the diurnal pattern in the CC of propagating convection, between 36° and 42°N. This is compared to activity across the NC. Next, we examine the MV region, from the GoM to the western Great Lakes. Subsequently, we focus on the SE region more generally.

a. The central and northern corridors

Coherent sequences of propagating convective systems are frequent and well developed near the 40th parallel (CC), as described in CAR02. While similar to the broader domain, a closer look at diurnal variation in the 36°–42°N zone is useful to clarify the significance of the propagating component in the continental system of warm-season rainfall (Fig. 10b). The following main features are familiar:

- The principal origin of convective systems is at the Continental Divide with a peak frequency of ~65% circa 2100 UTC. That is to say, for 65% of the days during 2100 UTC, rainfall is present between 36° and 42°N at 105°W.
- Day-1 propagation extends to 92°W with a phase speed of ~17 m s⁻¹.
- Evidence of day-2 and day-3 propagation is not evident in the P12 average. However, multiday propagation is prominent in monthly averages of the diurnal cycle of rainfall occurrence, particularly in June and July (CAR02). Varying phase speeds that occur over the whole P12 period obscure this feature.
The suppressed local diurnal maximum, circa 98°W at 0100 UTC, peaks at \( \frac{23}{100} \% \) while the nocturnal (delayed phase) diurnal maximum is \( \frac{35}{100} \% \). The strong eastern diurnal maximum peaks at \( \frac{50}{100} \% \). An independent semidiurnal maximum, located 85°–90°W, peaks at \( \frac{25}{100} \% \). The diurnal minimum in the mountain west is \( \frac{5}{100} \% \). The diurnal minimum east of the plains states is \( \frac{21}{100} \% \).

The local diurnal maximum near 98°W is only slightly elevated from the diurnal minimum east of the Rockies in the CC. The nocturnal maximum (85°–90°W) is \( \sim 4\% \) higher than the minimum (90°–95°W).

Immediately to the north (NC), a markedly different pattern prevails (Fig. 10a). The amplitude of the diurnal cycle is small, with maxima of \( \sim 25\% \) and minima of \( \sim 15\%–20\% \) east of the Rockies. Evidence of propagation is minimal, though events of this type often frequent the region in midsummer. Most of the summertime precipitation, while convective and often well organized, is associated with forcing from transient synoptic systems, the passages of which are asynchronous with the diurnal cycle. For example, Fig. 2c illustrates evidence of this pattern across the northern tier of western states, where substantial precipitation occurs but is out of phase with local diurnal heating.

In the NC, the strength of the nocturnal maximum is considerable over the high plains (\( \sim 90°–100° \)) and is comparable in magnitude to the diurnal maximum. Reference to Fig. 9b at 45°N reveals that the NC is frequented alternately by afternoon subsidence and regions of nocturnal ascent over the plains, seemingly as part of the broader MPS. Largely absent from this picture is a focused point of convective triggering in the mountains to the west; however, positive correlation with terrain height is evident.

b. Mississippi Valley and Gulf Coast

The western half of the Mississippi Valley is a dissipation zone for many propagating rainfall systems. A minority of events survives in a dissipated state and regenerates in the next cycle (CAR02). At the Gulf Coast (Fig. 11; 30°N) copious rainfall occurs in association with breezes. Both sea and land breezes produce rainfall that is locally diurnal both on- and offshore. Direct and indirect effects of sea-breeze forcing penetrate \( \sim 300 \) km inland to 34°N (Fig. 11) where some of the heaviest rainfall on the continent occurs. The occurrence statistics in summer reach 80% at the coast and approach 60% offshore. Precipitation systems propagate inland over a 5-h period (1700–2200 UTC) at a mean rate of 14 m s\(^{-1}\). Because there are no meridional steering winds of this magnitude, it is speculated that mesoscale cold pool dynamics drive this propagation in a manner similar to that observed under breeze conditions elsewhere in the tropics (e.g., Carbone et al. 2000).

The remaining feature of note in Fig. 11 is the nocturnal maximum from 35° to 45°N. The small maximum frequency between 37° and 39°N and between 1200 and 1400 UTC is most likely related to the dissipation of propagating systems because both the time of arrival and the latitude band coincide with the CC. The larger maximum between 40° and 44°N and between 0800 and 1400 UTC may be of a different origin. In reference to
an earlier discussion of diurnal vertical motion reversal in the central Appalachian Mountains, the southwest Great Lakes region may be part of a mass-compensating circulation with the Blue Ridge Range. An argument to counter this speculation is that ambient flow and shear are mainly westerly, and the anomaly winds (Fig. 9) fail to support the existence of a solenoid connecting these regions. Furthermore, the RUC analysis fails to show kinematic evidence of diurnal forcing by Lakes Michigan and Erie, as we had originally anticipated.

c. Southeast and Atlantic coast

The southeast is marked by a combination of sea breeze and “air mass” convection (Figs. 2a and 12). Some of these systems propagate; however, this component of the eastern diurnal cycle is relatively weak (Parker and Ahijevych 2007). The southeastern region has the strongest local diurnal maximum on the continent, exceeding 80% in the upper Florida Peninsula. Figures 2d and 12 also show land-breeze convection along the Gulf Coast. Some of the land-breeze convection is a modest regeneration of the previous day’s sea-breeze storms, which slowly move seaward at ~3.5 m s⁻¹, likely in association with the land-breeze front (Figs. 11 and 12; 83°–90°W).

Nocturnal rainfall is quite frequent and extensive off of the Carolina coasts (Figs. 2c,d and 12; 76°–79°W). Because of its frequency, persistence, and relatively distant offshore maximum, the bulk of this rainfall occurrence is likely associated with lower boundary forcing from warmer Gulf Stream waters.

In summary, there are regional influences involving the MPS circulation, the GPLJ, the passage of troughs and fronts across the northern tier, the Appalachian elevated heat source, and breezes and oceanic forcing along the Gulf of Mexico and Atlantic coasts, respec-

![Average vertical air motion and horizontal anomaly winds](image-url)

**Fig. 9.** Average vertical air motion and horizontal anomaly winds from the RUC, 1998–2007. Vertical motion contoured and horizontal anomaly winds are vectors: (a) 0000 UTC, 60 kPa, and (b) 0900 UTC, 65 kPa.
tively. Relatively low-amplitude semidiurnal forcings appear to be associated with the reversal of the MPS, which becomes stronger where in concert with moisture convergence provided by the GPLLJ. Finally, we speculate that a weak circulation of the thermally direct type may exist between the southwest Great Lakes area and the central Appalachian Mountains, possibly contributing to a nocturnal maximum over Illinois and Indiana.

5. Interannual variability

We examined the monthly average of radar-estimated precipitation amount in search of signals that were possibly linked with remote oceanic forcings. The NOAA Multivariate ENSO Index (MEI; Wolter and Timlin 1993, 1998) is based on six observed variables over the tropical Pacific (surface observations of $P$, $u$, $v$, SST, $T$, and total cloudiness fraction of the sky). The
Fig. 11. JJA diurnal echo frequency of occurrence in the Mississippi Valley and Gulf coast region (depicted graphically in Fig. 1). Dashed line is the characteristic coastline latitude.

Fig. 12. JJA diurnal echo frequency of occurrence in the SE (region depicted graphically in Fig. 1). Diurnal maximum at 80°W is dominated by sea-breeze-related convection over Florida, not the high terrain, though it also contributes substantially.
1997 El Niño was the only strong event during our period of record (MEI = +3). A weak El Niño in the summer of 2002 (MEI = +1) and a moderate La Niña in the summer of 1999 (MEI = −1) are the only other events that lend themselves to examination.

The correlation between the MEI and radar-equivalent precipitation amount were calculated for JJA as a percent precipitation anomaly from the 12-yr mean. Statistically significant (95% confidence) positive correlations appear across the northern tier of the states, especially the northwest (not shown); however, our period of record is too short to draw any conclusions of general significance.

6. Discussion and conclusions

a. Diurnal component

The results of this study over a 12-yr period of record serve to confirm the statistical findings of CAR02 and to provide additional insights into some related causes and effects. The daily occurrence of propagating episodes has a high impact on the continental diurnal cycle. A disproportionate fraction of these events is triggered by sensible heating over high terrain. As reported in CAR02, this leads to a phase-locked pattern that thoroughly dominates the diurnal cycle between 105° and 95°W, which is a distance equivalent to ~18 h of propagation. Propagating episodes account for approximately 60% of seasonal (JJA) rainfall in the central United States. The superposition of this delayed-phase diurnal maximum onto the local diurnal maximum leads to a strong semi-diurnal signal centered at 95°W (CAR02); however, this signal should not be equated with semi-diurnal forcing. In the eastern United States both this analysis and that of Parker and Ahijevych (2007) have shown that the local diurnal maximum is the dominant rainfall occurrence.

b. Semidiurnal forcing

Semidiurnal signals traditionally have been associated with tides, which we believe either to be less relevant or irrelevant to this region. However, we find clear evidence of semi-diurnal forcing resulting from a nocturnal reversal of the MPS. The MPS reversal results in widespread vertical ascent circa 98°W, approximately in phase with the arrival of propagating events (Fig. 7a,c). The amplitude of this circulation is ±3–8 cm s
-1 over the continental divide and ±1–2 cm s
-1 over the plains. This circulation works in concert with the GPLLJ, which is dynamically related and is especially prominent over the southern plains. Strong moisture transport from the Gulf of Mexico and moisture convergence is widely attributed to the GPLLJ (e.g., Bonner 1968). Tuttle and Davis (2006) have shown that “corridors” of propagating convection are associated with this convergence near the terminus of the jet (~40°N). The threefold circumstance of self-sustaining organized convection, MPS ascent, and the GPLLJ conspire to produce the observed nocturnal rainfall maximum where its amplitude is largest. Farther north, the GPLLJ either plays a lesser role or no direct role.

The Gulf of Mexico breeze circulations are vigorous and associated with the most frequent occurrence of warm-season rainfall in the United States. While breeze systems are inherently semi-diurnal, rainfall both on- and offshore is locally diurnal. Perhaps the only surprise associated with this breeze system is the rapidity of rainfall propagation inland during the sea-breeze phase. The 14 m s
-1 phase speed takes rainfall more than 250 km inland from the coast over a 5-h period. Mesoscale cold pool dynamics and associated gravity waves are a likely mechanism to achieve this (e.g., Tripoli and Cotton 1989b). During the nocturnal phase, which is dissipative for many hours, rainfall moves slowly out to sea at 3.5 m s
-1.

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