Where, When, and Why Did It Rain during PECAN?

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ABSTRACT

The overarching goal of the Plains Elevated Convection At Night (PECAN) field campaign was to improve understanding of the processes contributing to the nocturnal precipitation maximum in the U.S. Great Plains. This study presents the precipitation pattern surrounding PECAN and addresses the origin, timing, duration, and potential causes contributing to that pattern. It is shown that the precipitation occurs most frequently at night, as expected. The maximum in the precipitation pattern occurred in the northeastern portion of the PECAN radar domain. The source of the rainfall was attributed to mountain-initiated precipitation, plains-initiated precipitation, precipitation advecting over the border of the radar domain, and episodes in which different initiation categories merged together. Through the combination of mountain-initiated, border, and merged episodes, 70% of the Great Plains precipitation was caused by episodes that formed outside of the PECAN domain and propagated into the region. The remaining 30% of the precipitation was attributed to plains-initiated storms. The mountain-initiated storms formed primarily in the afternoon and typically dissipated near the mountains. For those that survived, they propagated eastward, grew upscale, and contributed 27% of the precipitation in the plains. The plains-initiated precipitation fell mostly during the afternoon but also contributed to overnight rainfall and those locally triggered systems tended to be relatively smaller and shorter lived. For the top 10% rain-producing events, composite reanalysis fields showed that synoptic-scale features influenced the precipitation pattern and timing: an approaching trough established southwesterly moist flow throughout the region and a nocturnal low-level jet transported moisture to its terminus in the northeast corner of the PECAN domain.

1. Introduction

One of the primary motivators for the Plains Elevated Convection At Night (PECAN) field campaign, which took place in and around Kansas during summer 2015, was to improve understanding of the U.S. Great Plains nocturnal precipitation maximum (Geerts et al. 2017). PECAN was designed to bring together multiple instruments and numerical models to study the mechanisms responsible for the initiation and maintenance of the mesoscale convective systems (MCSs) leading to the nocturnal precipitation. This paper uses radar-derived quantitative precipitation estimates (QPEs) to illustrate where and when the precipitation during PECAN occurred and uses North American Regional Reanalysis (NARR) composites to assess why the PECAN precipitation patterns and timing occurred.

It has been known for more than a century that the diurnal pattern of summertime precipitation in the U.S. Great Plains has a strong nocturnal maximum (e.g., Kincer 1916; Bleeker and Andre 1951; Wallace 1975; Easterling and Robinson 1985; Heideman and Fritsch 1988; Colman 1990; Carbone et al. 2002; Fabry et al. 2017). Maddox (1980) used satellite imagery to show that this nocturnal precipitation was largely attributed to long-lived (>12 h) and large (>100 000 km²) systems, termed mesoscale convective complexes (MCCs). Nocturnal systems include isolated convection, squall lines, and MCSs, which are smaller systems than MCCs (e.g., Maddox et al. 1982; Wetzel et al. 1983; Rodgers et al. 1985; Fritsch et al. 1986; Rutledge and MacGorman 1988; Augustine and Howard 1988; Trier and Parsons 1993; Loehr and Johnson 1995; Gallus and Johnson 1995; Braun and Houze 1997; Higgins et al. 1997).

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Carbone et al. (2002) noted that the longevity of convective episodes ranged up to 60 h, significantly exceeding the lifetime of individual convective events. Many mechanisms have been studied to explain the longevity of such convective systems that contribute to the nocturnal precipitation maximum in the central United States. These include, but are not limited to, deep tropospheric gravity waves generated by the Rocky Mountains elevated heat source (e.g., Tripoli and Cotton 1989a,b; Mapes et al. 2003a,b; Warner et al. 2003), potential vorticity anomalies (e.g., Raymond and Jiang 1990; Li and Smith 2010), gravity waves generated by convection (e.g., Fovell et al. 2006), influence by the low-level jet (LLJ; Trier and Parsons 1993; Fritsch and Forbes 2001; Keene and Schumacher 2013) and bores and density currents (e.g., Parker 2008; French and Parker 2010; Marsham and Braham 1949; Ulanski and Garstang 1978; Watson et al. 2011). Some of the complex and interactive factors affecting nocturnal CI and MCS maintenance include a surface-based stable layer (e.g., Crook 1996; Weckwerth et al. 1996; Ziegler and Rasmussen 1998) and wind shear (e.g., Moncrieff and Miller 1976; Rotunno et al. 1988; Lee et al. 1991; Wilson and Megenhardt 1997).

Using a 12-yr climatology, Carbone and Tuttle (2008) found that propagating episodes contributed ~60% of the summer rainfall to the central United States. The remainder of the central U.S. rainfall was found to be due to local initiation episodes. Local initiation episodes in the U.S. Great Plains occur throughout the diurnal cycle. Daytime convection initiation (CI) events are often caused by boundary layer convergence zones that are detectable via surface station data (e.g., Byers and Braham 1949; Ulanski and Garstang 1978; Watson and Blanchard 1984), visible satellite imagery (e.g., Purdom 1982; Wilson and Mueller 1993; Hane et al. 1987; May 1999; Roberts and Rutledge 2003), and radar data (e.g., Wilson and Schreiber 1986; Weckwerth and Parsons 2006). The factors controlling CI associated with daytime boundaries include the combination of environmental stability (e.g., Crook 1996; Weckwerth et al. 1996; Ziegler and Rasmussen 1998) and wind shear (e.g., Moncrieff and Miller 1976; Rotunno et al. 1988; Lee et al. 1991; Wilson and Megenhardt 1997).

Nighttime CI episodes in the U.S. Great Plains account for ~50% of the CI events (Wilson and Roberts 2006). They are more difficult to forecast than daytime CI partly because the most unstable layer is typically elevated and is not as readily observed (e.g., Weckwerth et al. 2019). Some of the complex and interacting factors affecting nocturnal CI and MCS maintenance include a surface-based stable layer (e.g., Carbone et al. 2002; Billings and Parker 2012), the LLJ (e.g., Trier et al. 2006; Tuttle and Davis 2006; French and Parker 2010; Shapiro et al. 2016; Trier et al. 2017; Gebauer et al. 2018; Reif and Bluestein 2018), frontal boundaries (e.g., Maddox et al. 1979; Trier and Parsons 1993; Horgan et al. 2007; Reif and Bluestein 2017), gravity waves (e.g., Wilson et al. 2018; Reif and Bluestein 2018), and nocturnal bores (e.g., Koch et al. 2008a,b; Marsham et al. 2011; Coleman and Knupp 2011; Parsons et al. 2019). In contrast to relatively high skill in warm season quantitative precipitation forecasts (QPFs) under strong synoptic-scale forcing (e.g., Jankov and Gallus 2004; Squitieri and Gallus 2016), the forecasting skill is relatively low for weakly synoptically forced systems in the central United States (e.g., Fritsch and Carbone 2004). This is partially due to the poor forecast skill of nocturnal CI (e.g., Davis et al. 2003; Clark et al. 2007; Surcel et al. 2010; Pinto et al. 2015; Stelten and Gallus 2017).

Section 2 describes the data and methodology used to calculate QPE, define the features, and make the composites to analyze the NARR fields. Section 3 illustrates the distribution and timing of the precipitation pattern. Section 4 uses the NARR fields to investigate why the PECAN QPE pattern occurred. A summary and conclusions are presented in section 5.

2. Data and methodology

a. QPE

This study used mosaic radar data collected during the extended PECAN period of 12 May to 22 July 2015 (UCAR/NCAR–Earth Observing Laboratory 2019). The mosaic included QPE data calculated with 0.01° × 0.01° (~1 km × 1 km) spatial and 1-hourly temporal resolution from a composite of 21 WSR-88Ds and the NCAR S-Pol radar (Hubbert et al. 2018) located near Hays, Kansas. The area covered by this network of 22 radars was termed the radar domain, which encompassed the U.S. Great Plains and extended west to the Rocky Mountains. The radar domain was the entire area shown in Fig. 1, whereas the core PECAN domain is denoted by the black rectangle. QPE was derived using a hydrometeor classification algorithm to determine which rain-rate relationship was appropriate at each location (Giangrande and Ryzhkov 2008; Berkowitz et al. 2013; Dixon et al. 2015). The NCAR particle identification (PID) algorithm was used to distinguish between hydrometeor types at each radar gate (Vivekanandan et al. 1999). A beam blockage algorithm was used to account for the propagation effects and the convolution of the beam pattern with the terrain features. Prior validation with rain gauges showed a high correlation coefficient of 0.834, providing confidence in this enhanced QPE algorithm (Dixon et al. 2015).

Precipitation features were defined as contiguous areas in the hourly QPE data, shown as numbered regions in Fig. 1. Their precipitation amount was calculated in mm using the hourly accumulation rate and their precipitation volume was obtained by multiplying
the precipitation amount by the areal coverage of the precipitation feature. The precipitation features were then sorted according to their precipitation amount and the least productive features, which accounted for 5% of the total precipitation, were excluded to remove noise and nonproductive systems. The remaining 95% of the precipitation came from 1026 precipitation features with precipitation amounts ranging from $5.6 \times 10^6$ to $1.3 \times 10^9$ m$^3$. These features were manually tracked through time, and combined into storms. The numbered contiguous precipitation features with colored outlines were the only ones that remained in the example shown in Fig. 1 because the other small radar echoes produced too little precipitation output.

A CI event was defined as the first precipitation feature of a storm detected within the radar domain, as shown by labels 6 and 7 in Fig. 1c. To investigate the origin of the precipitation falling in the Great Plains, we classified the precipitation from a storm according to the location of its respective CI event: Precipitation was classified as mountain- (plains-) initiated if the CI event first appeared with its centroid located west (east) of the western PECAN longitude of 102.5°W. The western PECAN longitude was chosen for simplicity as other classifications based on different longitudes or terrain altitude led to similar results. We will refer to the radar domain east of this longitude as the Great Plains. Examples of mountain-initiated precipitation are labeled 1 and 2 in Fig. 1a. Examples of plains-initiated precipitation are labeled as 3, 4, and 5 in Fig. 1a. A “border” precipitation classification was used for storms that first appeared with $>10\%$ of their outlines coinciding with the outer border of the radar domain. No border events occurred within the four hours of examples in Fig. 1. If a storm was initiated in close proximity ($<100\text{ km}$) to an existing storm, the CI event and subsequently the storm was considered dependent unless the size of the new storm was $>25\%$ of the size of the existing storm. Precipitation from these dependent storms was given the same class as the precipitation from the storm in close proximity, as illustrated with CI event labeled as 6 in Fig. 1c. Its centroid was west of 102.5°W, giving it a mountain classification. However, because it was $<100\text{ km}$ from storm 1, 2, 3, 4, it

![Fig. 1. Precipitation (mm) shown for 11 Jun 2015 at (a) 0000, (b) 0100, (c) 0200, and (d) 0300 UTC illustrating an example of the classification and evolution of precipitation features. Precipitation features are labeled to track storms in time and are outlined in the color according to their classification of mountain-initiated (light blue), plains-initiated (red), and merged (yellow) episodes, as defined in section 2a. The PECAN domain is shown as the thick black rectangle.](http://journals.ametsoc.org/mwr/article-pdf/147/10/3557/4847898/mwr-d-18-0458_1.pdf)
was considered a dependent feature and therefore we classified it as merged, like the storms it depended upon.

As storms evolved in time they often merged with other storms, forming precipitation episodes. A precipitation episode was defined to include all branches from initiation, through mergers and splits, and ending with dissipation, typically having several CI locations and producing precipitation from different initiation classes. Precipitation classification of merged episodes was defined in the following way: When storms of the same class merged, the precipitation retained the original classification, as shown by mountain- (plains-) initiated storms 1 and 2 (3 and 4) merging together from Fig. 1a to Fig. 1b. When storms of different classes but similar sizes merged, the precipitation was placed into a new classification of “merged” starting at the time of the merger. This is illustrated in Fig. 1c when mountain-initiated storms 1 and 2 merged with plains-initiated storms 3 and 4, becoming merged episode labeled 1,2,3,4. When two storms of different classes merged, if one storm was more than twice the size of the other storm, the postmerger precipitation was then classified in the same category as that of the larger storm. Precipitation from episodes that split retained the precipitation class from before the split. Dissipation was defined to occur when an episode no longer produced enough precipitation to be included in the top 95% of analyzed features. A dissipation example is shown as episode 5 in Fig. 1d. Its dissipation location was defined as its centroid position in Fig. 1c when it was still producing enough precipitation to be included in the analysis.

The top-producing precipitation episodes were identified to determine whether just a few episodes contributed most substantially to the total rainfall observed throughout the entire PECAN period analyzed or whether all episodes contributed more equally to the rainfall. Precipitation episodes were ranked according to their precipitation output over the episode’s entire life cycle. The top 10% rain-producing episodes were selected for further analysis in sections 3c and 4.

b. North American Regional Reanalysis (NARR)

The National Centers for Environmental Prediction (NCEP) NARR was used to assess the influence of synoptic-scale forces on the formation, maintenance and growth of PECAN precipitation episodes (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce 2005). The NARR data, which have an ~32 km horizontal grid spacing, were used to calculate composites for specific time periods (section 4).

Fig. 2. Total accumulated precipitation (mm) within the radar domain from 12 May to 22 Jul 2015. The PECAN domain is shown as the white rectangle.

3. PECAN rainfall statistics

a. Where did it rain during PECAN?

1) RAINFALL

The radar-derived accumulated precipitation for 12 May–22 Jul 2015 illustrates that the most prominent rainfall maximum was observed in the Great Plains just to the northeast of the PECAN domain with a broad maximum extending along the eastern edge of the radar domain (Fig. 2). There were scattered regions of enhanced precipitation in west-central Kansas and southwestern Nebraska. A minimum in precipitation was located in western Kansas and north-central Oklahoma. This PECAN 2015 QPE pattern was similar to the 15-yr climatological precipitation record presented in Fabry et al. (2017).

2) CONVECTION INITIATION (CI)

The CI centroid locations were densely concentrated in the foothills of the Rocky Mountains and were more evenly distributed across the Great Plains (Fig. 3). There were 160 dependent storms that initiated <100 km from other precipitation and 759 independent storms that initiated >100 km from other precipitation. There were 107 border events that most likely initiated outside of the radar domain but were first observed along the radar border and subsequently advected into the radar domain.

3) PRECIPITATION EPISODE DISSIPATION

There was a high concentration of mountain-initiated episodes that dissipated west of 102.5°W, illustrating that the majority of mountain-initiated episodes dissipated before reaching the plains (Fig. 4). Dissipation implies either that the episode dissipated or
that the episode moved out of the domain. J. W. Wilson (2018, personal communication) used multiyear radar data to determine that 91% of mountain CI events dissipate before reaching the plains. The dissipation episodes that occurred east of 102.5°W represent the larger of the mountain-initiated episodes that grew upscale as they propagated eastward, precipitated, and dissipated in the plains later that day or over subsequent day(s).

Figure 5 shows that thirty percent of the overall precipitation was locally initiated in the plains. Most of the mountain-initiated episodes dissipated in or near the mountains but the episodes that survived contributed 27% to the overall plains precipitation. The mountains, portions of the merged, and border categories all represent propagating episodes and together accounted for 70% of the precipitation in the Great Plains. This result is consistent with the ~60% attributed to propagating systems in Carbone and Tuttle (2008).

The fact that most of the rain fell in the eastern portion of the radar domain (Fig. 2) while the most dense concentration of CI events occurred in the western portion of the radar domain along the foothills (Fig. 3) underlines the transitory nature of the precipitation in the U.S. Great Plains. Further analyses about the initiation locations and timing that led to this precipitation pattern during PECAN will be shown.

b. When did it rain during PECAN?

1) RAINFALL

The precipitation time series for the full radar domain shows substantial variability with multiday periods of precipitation interspersed with dry periods (Fig. 6). The total precipitation line (black line) is typically not visible, indicating that a single classification often dominated the overall precipitation. Time periods dominated by mountain-initiated precipitation appear to exhibit greater magnitude rainfall but occurred less frequently than time periods dominated by plains-initiated precipitation.

The 1300–0100 UTC (local time is 5 h earlier than UTC) daytime (Fig. 7a) and 0100–1300 UTC nighttime (Fig. 7b) accumulated precipitation fields show that most of the PECAN precipitation fell over the nighttime hours, consistent with previous long-term studies (e.g., Kincer 1916; Ahijevych et al. 2004; Fabry et al. 2017). The nighttime precipitation was most prevalent in the northeast of the radar domain, similar to the total rainfall distribution of Fig. 2. The daytime precipitation also showed a maximum in the northeast of the radar domain; however, the maximum was less pronounced and rainfall was more spatially distributed across the domain than during the night. The nighttime precipitation dominated the overall PECAN precipitation pattern.

This nocturnal dominance for Great Plains precipitation is further shown in the diurnal histogram showing the percentage of total precipitation that fell east of 102.5°W (Fig. 8). There was a pronounced nocturnal peak in precipitation, occurring at 0500–0700 UTC. The nighttime (daytime) precipitation contributed 65% (35%) to the total Great Plains precipitation. This is consistent with Higgins et al. (1997) 30-yr rain gauge climatology showing that nocturnal precipitation exceeded daytime precipitation by 25%–45% over a large portion of the Great Plains.
Figure 8 shows that in the afternoon through evening (1900–0200 UTC) the precipitation was predominantly derived from locally initiated storms in the plains. Later in the evening the percentage of mountain- and plains-initiated precipitation was nearly equal (0300–0500 UTC). Starting at the time of the overall precipitation maximum (i.e., 0600 UTC), the merged precipitation dominated and continued to dominate throughout the night and into the morning until 1400 UTC. Because all storm types were mostly initiated in the afternoon [section 3b(2) below], this sequence of dominant precipitation classes is likely caused by the distance the storms advected before they reached the Great Plains. While the plains-initiated precipitation was generated locally and therefore started to fall out immediately, the mountain-initiated precipitation advected into the region before it contributed larger precipitation amounts at a later time. Because of the increased likelihood of system mergers with time, merged precipitation dominated even later in the diurnal cycle. Similar to the statistics for overall precipitation, the plains-initiated precipitation accounted for slightly more (27.5%) of the Great Plains nocturnal precipitation compared with the mountain-initiated precipitation (24.8%). Merged precipitation contributed 31% to the nocturnal precipitation in the Great Plains.

2) CONVECTION INITIATION

The daytime CI events (Fig. 9a) occurred throughout the radar domain with a heavy concentration along
the Rocky Mountain foothills west of the PECAN domain. The nighttime CI events were evenly distributed throughout the radar domain with a large portion of them initiating in the plains (Fig. 9b). There appeared to be nearly equal CI episodes at night in the mountains and plains.

Figure 10 shows that the broad peak of CI events occurred during 1900–2200 UTC in the afternoon through early evening, likely as a result of solar heating. The mountain CI events had the same broad maximum during 1900–2200 UTC while the plains CI events had a slightly later maximum, occurring 2000–2200 UTC. The somewhat earlier maximum of mountain CI events was likely the result of additional triggering of convection by terrain-induced ascent caused by differential heating over the sloping terrain (e.g., Banta 1984; Crook and Tucker 2005; Kirshbaum et al. 2018). The border events are not plotted because they first appeared on the edge of the radar domain and therefore the actual time of CI was unknown. Nocturnal CI events (0100–1300 UTC) in the plains maximized around sunset (∼0200 UTC) and then reached a secondary broad maximum 0400–0800 UTC, generally consistent with the 20-yr climatological study of nocturnal convection initiation (Reif and Bluestein 2018), as well as the study focusing on PECAN nocturnal CI (Stelten and Gallus 2017). Nocturnal CI events occurred nearly twice as often in the plains (144) than in the mountains (76). This highlights the importance for improved understanding of nocturnal CI processes (e.g., Weckwerth et al. 2019).

3) PRECIPITATION EPISODE DISSIPATION

The high concentration of mountain-initiated storm dissipation west of 102.5°W was apparent both day and night (Fig. 11). Most of the daytime mountain CI events (Fig. 9a) dissipated in the mountains at night (Fig. 11b). The few mountain-initiated episodes that did reach the plains dissipated predominantly at night. These represented the larger storms that initiated in the mountains, grew upscale and rained that night or subsequent nights in the plains.

The analysis of both the diurnal CI histogram (Fig. 10) and diurnal precipitation histogram (Fig. 8) showed that mountain-initiated precipitation was most often triggered in the afternoon (1900–2200 UTC). For the episodes that did not dissipate in the mountains, they propagated into the Great Plains and contributed substantially to the evening plains precipitation (0300–0600 UTC). The plains-initiated precipitation was primarily triggered in the afternoon (2000–2200 UTC) and contributed the highest percentage to the afternoon through evening precipitation (1900–0200 UTC) in the Great Plains. The merged episodes advected into the radar domain and contributed substantially to Great Plains precipitation overnight 0600–1300 UTC. The precipitation from the border systems also required advection of episodes and contributed consistently to the Great Plains precipitation with a maximum at 1100 UTC.

c. What types of episodes caused the most rainfall during PECAN?

An effort was made to further examine the type of episodes that produced the PECAN rainfall. Figure 12 shows that the top 10% rain-producing episodes (67 episodes) caused 91% of the total PECAN precipitation and therefore the accumulated precipitation map of these episodes (not shown) looks nearly identical to the total accumulated precipitation of Fig. 2. It is quite remarkable that the three most extreme episodes (i.e., the top 0.5% rain-producing episodes) caused 20% of
the total rainfall. Note that the episodes at the top percentiles were dominated by mountain-initiated precipitation while the percentage of plains-initiated precipitation increased in the percentiles that included more episodes. This observation confirms the earlier impression that episodes with predominantly mountain-initiated precipitation were less frequent but yielded larger precipitation amounts. In the following we will focus our analysis on the 67 top 10% rain-producing episodes.

As explained in section 2a, many precipitation episodes had contributions from different initiation classifications. For our further analysis of the top 10% episodes it was desirable to assign only one precipitation class to each of the episodes. This was done by assigning the class with the highest precipitation contribution throughout the life cycle of each individual episode. The results shown in Figs. 13 and 14 follow this new convention. Because most of the precipitation episodes already had 90%–100% of their precipitation coming from only one precipitation class (Fig. 6), only a small portion of the precipitation was actually reclassified.

After assigning only one precipitation class to each of the top 10% rain-producing episodes, there were 17 mountain- and 24 plains-initiated precipitation episodes (Fig. 13). The merged class accounted for 14 episodes and the border class for 12 (not shown). Thus 64% of the top 10% rain-producing episodes (including mountain-initiated, merged and border-initiated precipitation) consisted at least partly of storms that grew upscale and propagated into the region. The locally initiated precipitation accounted for 36% of the top 10% rain-producing episodes.

To analyze the initiation of the top 10% rain-producing episodes we assigned only the first CI event to each episode. In contrast to the total population diurnal cycle of CI events (Fig. 10), the top 10% rain-producing episodes primarily exhibited a dual peak at 2000 and 0000 UTC (Fig. 13). Nine of the top 10% rain-producing episodes initiated at night with six of them as plains-initiated and three as mountain-initiated episodes. As in Fig. 10, the border events and mergers are not plotted.

The plains-initiated top 10% rain-producing episodes were smaller and shorter lived than the other classifications (Fig. 14). The storms that initiated in the mountains and the merged episodes had a mean duration longer than two days and the average duration of the border systems was 21 h (Fig. 14b). Five of the mountain-initiated episodes but only one of the plains-initiated episodes lived longer than 36 h (not shown). The longevity of the mountain-initiated episodes supports the finding that the mountain-initiated precipitation that fell in the Great Plains was attributed to episodes that propagated into the region in contrast to the locally initiated convection. This is consistent with the finding that the mountain-initiated, border and merged episodes grew upscale as they advected into the Great Plains and contributed to the nocturnal precipitation maximum as propagating episodes (e.g., Carbone et al. 2002; Carbone and Tuttle 2008). This current study did not illustrate longevity up to 60 h as they observed in Carbone et al. (2002) but their domain size was larger, which would explain why the durations in their study were longer.

4. Why did it rain at night during PECAN?

From the fact that the top 10% rain-producing episodes contributed 91% of the total precipitation one can
conclude that a main question that needs to be answered is which factors allow the convection to be sustained for extended time periods and grow upscale. The NARR fields were used to investigate potential differences between the environmental conditions leading to the upscale growth and maintenance of convection and ultimately to the PECAN nocturnal precipitation maximum. The time series of the precipitation from the top 10% rain-producing episodes (not shown) was nearly identical to the overall precipitation time series shown in Fig. 6. This similarity is not surprising given the large precipitation contribution coming from these top rain-producing episodes; however, analyses of individual episodes showed that the high precipitation events shown in different colors in Fig. 6 can be attributed to mostly single, long-lived episodes (e.g., the plains precipitation around 14 May came from one single plains-initiated episode, etc.). We divided the PECAN time frame into “active” and “break” days based on whether significant precipitation coming from a top 10% rain-producing episode was observed or not (shown by colored background shadings in Fig. 6). Because the upscale growth of systems typically occurred during the night, we made NARR composites combining 0600 and 0900 UTC times to compare active (Figs. 15a,b and 16a,b) and break days (Figs. 15c,d and 16c,d).

During break days an upper-level ridge was observed west and northwest of the radar domain (Fig. 15d), resulting in northwesterly flow that transported dry continental air to the PECAN domain and manifested as low specific humidity (Fig. 15c). In contrast, during active days, the ridge was east of the PECAN domain (Fig. 15b). With a trough approaching from the west (Fig. 15b), the wind direction was from the southwest (Fig. 15a). A strong LLJ was apparent on the active days with its terminus region located in the northeastern and eastern regions of the radar domain, leading to low-level convergence which extended over the eastern part of the radar domain (Fig. 16a). Examination of Figs. 15a and 16a suggests that the 850-mb (1 mb = 1 hPa) LLJ terminus was coupled with the 300-mb jet streak to provide deep-layer vertical ascent (Figs. 15b and 16b), leading to long periods of sustained convection (e.g., Uccellini and Johnson 1979; Uccellini 1980). This jet coupling likely contributed to the precipitation maximum in that region (Fig. 2). The compositing process used in our analyses smoothed out the jet streak structure so the jet coupling is not as prominent as that shown in Squitieri and Gallus (2016). Significant low-level moisture
associated with the LLJ was observed in the region (Fig. 16a). The enhanced moisture at 300 mb (Fig. 15a) was likely caused by a combination of advection from the southwest and upward moisture transport by the sustained deep convection in the region. Break days also showed 850-mb southerly flow from the Gulf of Mexico but it was much weaker, resulting in substantially lower moisture in the radar domain (Fig. 16c), which was also dominated by subsidence (Figs. 15d and 16d).

To further investigate the reasons for the location of the precipitation maximum shown in Fig. 2, a time series similar to Fig. 6 was constructed (not shown) for precipitation within a longitude (98°–93°W) by latitude (39°–41°N) box centered around the maximum precipitation area. This time series revealed that the precipitation in that region was not associated with one or two precipitation episodes nor one or two active days but mostly followed the overall time series shown in Fig. 6. Nighttime composites for active days for that specific region (which included mostly the same days as the overall active day composites) showed similar results to Figs. 15a,b and 16a,b (and are therefore not shown). However, even higher moisture values at all levels at the location of the precipitation maximum were observed in these composites.

While Figs. 15 and 16 clearly show the synoptic-scale influence and significant role of the LLJ in upscale growth and maintenance of convection, they do not address possible large-scale triggering at the CI stage. To investigate this aspect we made daytime composites when maximum CI occurred (Fig. 10) using 1800 and 2100 UTC NARR fields. We contrasted composites for break days (blue shading in Fig. 6) with composites of the days just before the onset of time periods featuring top 10% rain-producing episodes that we call “episode CI days” (yellow shading in Fig. 6). At the 300 mb level, daytime break day composites (Fig. 17b) showed similar characteristics to nighttime break day composites (Fig. 15c) but with a more westerly wind component. On episode CI days upper-level southwesterly wind was observed (Fig. 17a) similar to the active days nighttime period (Fig. 15a). Moisture in the radar domain (Figs. 17a,c) was less than during the active days nighttime period (Figs. 15a and 16a) but there was more moisture when compared to the daytime break period (Figs. 17b,d). This enhanced moisture on episode CI days was likely the result of advection from the southwest as upward transport of moisture by convection had yet to begin, again underlining the importance of the synoptic-scale conditions in triggering long-lived convection. At the 850 mb level on...
episode CI days, transport of moisture into the radar domain was already occurring during the day prior to the upscale growth of convection (Fig. 17c). During the daytime the low-level southerly flow was not as strong as during the nighttime when the LLJ was at its maximum and significantly contributing to the maintenance of the convection (Fig. 16a). On break days on the other hand, the low-level southerly flow from the Gulf of Mexico was weak and merged with synoptic-scale northwesterly flow over the PECAN domain combining into westerly flow over the eastern part of the radar domain which prevented further northward transport of moisture (Fig. 17d). This cutting off of the moisture source in combination with the strengthening of the westerly flow to the east, which led to divergence (Fig. 17d), limited the CI and upscale growth of convection on break days.

5. Summary and conclusions

Radar data from the PECAN field campaign were used to confirm the existence of a nocturnal precipitation maximum over the U.S. Great Plains shown in numerous previous studies (e.g., Kincer 1916; Carbone et al. 2002; Fabry et al. 2017) and to provide insights into the mechanisms that led to its occurrence. The time of maximum rainfall observed during the PECAN extended time frame of 12 May to 22 July 2015 was 0500–0700 UTC (0000–0200 LT). The precipitation pattern illustrated a maximum in the northeast portion of the radar domain. Seventy percent of the observed Great Plains precipitation came from episodes that were at least partly initiated outside of the PECAN domain, particularly over the foothills of the Rocky Mountains, grew upscale, and propagated into the PECAN domain, consistent with previous studies (e.g., Carbone and Tuttle 2008) while 30% of the precipitation was initiated locally over the Great Plains. Convection initiation peaked in the late afternoon from 1900–2200 UTC in both mountain and plains regions. The majority of the mountain-initiated episodes dissipated in the mountains and never reached the plains. Precipitation over the Great Plains was dominated by locally produced storms in the afternoon/early evening (1900–0300 UTC) while later in the evening, after the largest of the mountain-initiated episodes had time to grow, merge and propagate eastward, the precipitation over the Great Plains was equally derived from plains- and mountain-initiated episodes (0300–0500 UTC). During the late night hours and through morning (0600–1400 UTC), the dominant precipitation type was from merged episodes as mountain- and plains-initiated systems combined, grew upscale and precipitated over the Great Plains.

The largest 10% rain-producing storms produced 91% of the PECAN precipitation, which underlines the importance of investigations into the factors that lead to maintenance and upscale growth of
convection. Analysis of these largest storms showed that the mountain-initiated episodes were larger and longer lived (>2 days duration) than the plains-initiated episodes (<2 days duration). The longevity of the mountain-initiated, merged and border episodes explains the significant portion of precipitation from propagating episodes that were observed in the PECAN domain at all times of the day.

The maintenance and upscale growth of precipitation episodes appeared to be influenced by synoptic-scale factors. Break periods between precipitation events occurred on nights with a ridge to the west of the radar domain, leading to northwesterly flow and decreased moisture in the region. Nights with precipitation generally showed an 850 mb southerly LLJ transporting moist air from the Gulf of Mexico to the

Fig. 15. Nighttime (0600 and 0900 UTC) composites of NARR (a),(c) wind direction (arrows) and speed (contours; m s⁻¹) and specific humidity (shading; g kg⁻¹), and (b),(d) pressure vertical velocity ω (shading; Pa s⁻¹) and geopotential height (contours; gpm) at the 300 mb level. (top) Active composites (time periods shaded pink in Fig. 6) and (bottom) break composites (time periods shaded gray in Fig. 6). PECAN and radar domains are shown as black rectangles.
Great Plains, which likely helped sustain prolonged precipitation episodes there. There was some evidence of coupling between the LLJ and 300-mb jet streaks during active periods that led to the precipitation maximum in the northeast portion of the PECAN domain. Daytime CI episodes were associated with deep moisture from low-level southerly and upper-level southwesterly flow.

This study highlights that both local initiation and upscale growth contributed substantially to the nocturnal precipitation maximum in the U.S. Great Plains and further research is required to better understand these separate and distinct mechanisms influencing the nocturnal precipitation maximum. Case study analyses of the top rain-producing events may shed further light on detailed characteristics and precursors to the precipitation pattern.
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