Characteristics and Variations of Low-Level Jets and Environmental Factors Associated with Summer Precipitation Extremes over the Great Plains

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ABSTRACT

Low-level jets (LLJs) are associated with 10%–45% of the summer precipitation in the U.S. Great Plains region (GPR). This study uses the NCEP North American Regional Reanalysis data product (1979–2017) to characterize the association between LLJs and precipitation extremes (anomalously wet versus dry) during the summer months (June–August) over the GPR. It is found that the number, distribution, and direction of LLJs are not clearly associated with the precipitation anomalies. The characteristics and structural variations of the LLJs and their large-scale and mesoscale environment are then examined to identify the links between LLJs and precipitation extremes. Results show that dry and wet summers vary by synoptic anomaly patterns. During dry summers the anomalous ridging results in a warmer and drier environment, primarily through subsidence, which inhibits precipitation near LLJs. In contrast, during wet summers, a reduction in subsidence occurs, resulting in stronger lift and a cooler and moister environment, which leads to enhanced precipitation near LLJs. The LLJ speed, orientation, and spatial properties vary according to the synoptic anomaly patterns. LLJs do not drive precipitation extremes, but instead, they respond to them. Specifically, the LLJ exit region is characterized by stronger baroclinity and higher moisture content during the wet years. The higher moisture content allows for ascending air parcels to reach saturation more quickly, while the stronger baroclinity increases the warm advection associated with the LLJ. This, in turn, leads to faster rising motion and is therefore closely associated with the location and intensity of the LLJ associated precipitation.

1. Introduction

The low-level jet (LLJ) is a narrow region of anomalously strong winds that blows in the lower troposphere (Wexler 1961; Stensrud 1996; and others). Over the Great Plains region (GPR) of the United States, the LLJ is an important feature of the climate with a strong nocturnal preference (Bonner 1968; Whiteman et al. 1997; Song et al. 2005). Climatologically, the LLJ occurs throughout the year over the GPR, where southerly LLJs are a regular feature during the summer months and especially at night (Whiteman et al. 1997).

The continental United States receives up to one-third of its total water vapor from the Great Plains LLJ (Helfand and Schubert 1995), and the GPR region obtains up to 25% more precipitation at night than during

the day (Higgins et al. 1997; Reif and Bluestein 2017). When the LLJ has a path over the Gulf of Mexico it enhances moisture transport as well (Higgins et al. 1997). As a result of this moisture transport, the LLJ is known to be associated with precipitation. Specifically, it has been shown that the LLJ affects precipitation through increasing its frequency, altering its distribution, and locally increasing its intensity (Pitchford and London 1962; Mo et al. 1995; Walters and Winkler 2001; Schumacher and Johnson 2009; Squitieri and Gallus 2016a,b). In addition to moisture advection, the LLJ is also responsible for warm air advection, which can enhance precipitation as well (Maddox and Doswell 1982).

Previous studies have indicated that the LLJ affects precipitation through rising motion in its exit region caused, at least in part, by low-level convergence. Bonner (1966) found that this region of rising motion is frequently collocated with a precipitation maximum. In addition to the exit region, rising motion is also common along the LLJs western axis (Beebe and Bates 1955; Walters and Winkler 2001; Hodges and Pu 2019). Rising motion occurs from ageostrophic wind convergence,

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which is often located near peak mesoscale convective system (MCS) formation (Arritt et al. 1997). MCSs in the vicinity of the LLJ are responsible for many instances of flooding, high winds, and severe weather in the GPR (e.g., Raymond 1978; Maddox 1983; Augustine and Caracena 1994; Stensrud 1996; French and Parker 2010; Pu and Dickinson 2014). One other way that the LLJ can affect precipitation is through increased wind shear. The LLJ increases wind shear by definition, which can enhance convection as well (Bonner 1968; Stensrud 1996; French and Parker 2010). Therefore, an accurate forecast of the LLJ can be important for local forecasts of MCSs.

Precipitation can also affect the LLJ. It has been observed that in cases with MCS, the convection can increase the LLJ speed upstream of the convection by inducing stronger ageostrophic winds (Chen et al. 1998; Saulo and Ruiz 2007).

Despite the fact that the LLJ and precipitation affect each other, there are also case studies (e.g., Walters 2001) that have indicated that the effectiveness of the LLJ at producing precipitation is affected by the type of LLJ present. Namely, the interactions between LLJ and precipitation depend on the LLJ structure and its environmental conditions. In reality, the LLJ can be influenced by various factors with complicated environmental conditions. For instance, the LLJ is known to be susceptible to large-scale influences such as the ENSO state and remote sea surface temperature forcings (Song et al. 2005; Weaver et al. 2009). It can also be influenced by large-scale synoptic pressure systems (Weaver and Nigam 2008, 2011), jet streaks (Uccellini and Johnson 1979), frontal systems (Igau and Nielsen-Gammon 1998; Browning and Pardoe 1973), MCSs (Chen et al. 1998; Saulo and Ruiz 2007), inertial oscillations (Blackadar 1957; Van de Wiel et al. 2010; Shapiro et al. 2016), thermal imbalances on sloped terrain (Holton 1967; Parish and Oolman 2010), and isallobaric acceleration from developing cyclones (Uccellini and Johnson 1979; Chen and Kpaeyeh 1993). As a result of these many influences, the LLJ has been noted to have diversity in its structure with a large number of typical shapes, locations, and intensities (Walters and Winkler 2001; Chen and Kpaeyeh 1993; Djurić and Damiani 1980; Walters 2001).

Although previous case studies are devoted to the interactions between LLJs and precipitation over the GPR, as well as the large-scale environmental influences to both of them, there have been limited studies focused on characterizing the mesoscale structure and variations of GPR LLJs during precipitation extremes (e.g., drought and flood, or dry and wet periods) on a statistical basis. In particular, the common characteristics and variations of LLJs and their associated precipitation patterns during anomalous summer precipitation extremes are not well

FIG. 1. Map of domains used in study. Inner domain (red box; 30°–42°N, 103°–95°W) is the region where LLJs must have occurred in order to be used in this study. Outer domain (yellow box; 25°–47°N, 108°–90°W) is area of potential reach of the moving composite domain (around the daily LLJ spot). The background color fill is the composite wind speed at 850 hPa at 0900 UTC for the June–August period from 1979 to 2017. Units: m s^{-1} .

understood. Given the diversity of LLJ types and forcing mechanisms, it is reasonable that LLJs in dry or wet periods may see significant structural differences. A previous study by Dong et al. (2011) emphasized aspects of the LLJ during the contrasting dry and wet hydrological years (HYs) of 2006 and 2007. They compared the energy budget, radiation feedbacks, soil properties, and cloud properties between the HYs 2006 and 2007 and found that LLJ and precipitation interactions can vary during hydrologic extremes. In the most recent study, Hodges and Pu (2019, hereafter HP19) used the same case (HYs 2006 and 2007) to examine how the structure of the LLJ and its associated environment varied during the dry warm season of 2006 and the wet warm season of 2007, which was defined to be May–July in that study to maximize the precipitation differences between 2006 and 2007. They found numerous differences in the structure and properties of the GPR LLJ that apparently affected its precipitation production. Specifically, in 2006, relative to 2007, the LLJ was found to be on average faster, more frequent, closer to the ground, had a greater westerly component and a stronger inertial oscillation. The environment was also found to be warmer and drier. The LLJ associated precipitation was displaced farther northeast of the jet core and was weaker. Results from HP19 indicated that there are important discrepancies about the mesoscale structures and environment of LLJs during drought and flood periods in the warm season over the GPR.

FIG. 2. Standardized precipitation anomalies for the United States during the June–August period during 1979–2007, based on NARR precipitation data. Anomalies are based on 1980–2010 average. The anomalies are categorized for (a) dry-north years, (b) dry-south years, (c) wet-north years, and (d) wet-south years. Quantity is dimensionless.

As a natural extension of HP19 (a case study), in this study we further examine the characteristics and discrepancies of the mesoscale structure and variations of LLJs during the wet and dry years over the GPR based on the statistics obtained from 1979 to 2017 period. This is accomplished using the NCEP North American Regional Reanalysis (NARR; Mesinger et al. 2006) data products to establish a more general climatology of the LLJ and its variations during wet and dry conditions. The LLJs and their environment during wet and dry periods are compared to explore the answers to the following questions: What are the significant synoptic-scale and mesoscale environmental deviations that occur during wet and dry extremes, and how were these extremes related to variations in the LLJ structure and its environment? How did the LLJ affect precipitation extremes during wet and dry periods?

Section 2 describes the datasets and the definition of LLJs. Section 3 explains the criteria to identify wet and dry years, details about the wet and dry periods, and demonstrates the importance of LLJs to precipitation. Section 4 examines in detail the differences in the large-scale patterns that lead to wet and dry conditions, as well as the nature of those differences. Some discussion is also made about how these conditions are relevant to LLJs and associated deviations. Section 5

compares the mesoscale structure of the LLJs between the dry and wet periods. Section 6 contains additional discussion on dry versus wet LLJs considering just the very wet or dry days within a general dry or wet period. Section 7 offers the conclusions.

2. Data and methodology

a. Data

The NARR is employed as a primary data source in this study. The NARR is a 3-hourly analysis, available at a 32-km horizontal resolution with 45 vertical layers. It also has successful precipitation data assimilation (Bukovsky and Karoly 2007). In this study, the NARR is used over its period of record for every summer (June–August) from 1979 to 2017 to characterize LLJ structures and to classify these years as either wet, dry, or average. Other higher-resolution data sources, such as the NCEP Stage-IV precipitation data (Lin and Mitchell 2005), are used in HP19 but not used in this study because of the shortness of their temporal record.

b. LLJ definition

Bonner (1968) classified LLJs from radiosondes according to maximum daily wind speed and the wind

FIG. 3. As in Fig. 2, but averaged over each category, namely, (a) dry-north, (b) dry-south, (c) wet-north, and (d) wet-south. The domains from Fig. 1 (red boxes) are marked for reference.

speed decrease with height based on sounding observations. In his definition, LLJs had a minimum speed of 12 m s^{-1} and the speed fell to at least half of the LLJ peak wind speed value by 3000 m in altitude. However, several previous studies have found that the criteria of the required speed drop off with height (wind shear) could affect the number of LLJs identified (e.g., Walters et al. 2014). Ruchith and Raj (2015) only required that the wind speed fall off by 1 m s^{-1} above and below the LLJ core.

The suitability of using NARR reanalysis data to study LLJs has previously been documented by Walters et al. (2014) and Berg et al. (2015). They noted that the number of LLJs identified were similar between radiosonde observations and NARR reanalysis, but with an

underestimation of NARR for these strong LLJs with wind speeds greater than 20 m s^{-1} . In light of these issues, especially in regards to the LLJ definition, HP19 defined a LLJ to occur in NARR data products with daily wind speed maximum of 12 m s^{-1} or greater at or below 800 hPa, and when the wind speed dropped by at least 1 m s^{-1} between the level of the LLJ core and 775 hPa. We follow this same definition of LLJ, as in HP19. In addition, previous studies (Whiteman et al. 1997; HP19) have shown that the majority of warm season LLJs have a south to southwest wind direction. In HP19, and in this study, the few LLJs that did not have a southerly component were excluded.

The location used in this study has been shown in previous studies to be well correlated with LLJ activity

FIG. 4. Distribution of LLJs (identified according to location of max speed on a daily basis) during the summer (June–August) over GPR for dry-north (blue dots, 507 days, 9 yr, 61%), dry-south (green, 425 days, 7 yr, 66%), wet-north (black, 494 days, 8 yr, 67%), and wet-south (red, 459 days, 8 yr, 62%). Percentage is calculated by taking number of days with LLJs and dividing it by possible days with LLJs, which is the number of years in the bin times the number of days (92) in each summer period.

(Weaver and Nigam 2008; Helfand and Schubert 1995; Doubler et al. 2015). Figure 1 illustrates the average 850-hPa wind speed and direction at 0900 UTC during the months of June–August and the years 1979–2017 with NARR. All LLJs used in this study are found within the inner red box, which encompasses the climatological LLJ signal (the area with the highest average wind speed) based on the color fill in Fig. 1. Therefore, most plots that relate to the LLJ will cover this domain.

c. Precipitation anomalies

Wet and dry years are identified according to the standardized precipitation anomalies for summer months (June–August), based on the NARR precipitation data from 1979 to 2017. Standardized precipitation anomalies are calculated by taking the anomaly from the seasonal mean of precipitation during the summer and dividing it by the standard deviation of that precipitation over the summer period.

To rank the magnitude of the relative wet or dryness of a year, the standardized anomalies were weighted with a cubic function that decreased the weight with increasing distance from the center of the domain, such that values in the inner domain (red box) were weighted

at 98%–100% of their value, while outside of the red box the weight decreased to near 0% at the outer boundary. Therefore, the weighting function heavily favors the region near the average location of the LLJ and lessens the impact of precipitation away from it. The equation used is as follows:

$$\begin{aligned} \text{lat}_{\text{dist}} &= |36^\circ - \text{lat}| \\ \text{lon}_{\text{dist}} &= |-99^\circ - \text{lon}| \\ \text{dist} &= (\text{lat}_{\text{dist}} \times \text{lat}_{\text{dist}} + \text{lon}_{\text{dist}} \times \text{lon}_{\text{dist}}) \\ \text{wgt} &= 1 - \left(\frac{\text{dist}}{202} \right)^3. \end{aligned}$$

Here, 36° and -99° are the latitude and longitude of the center of the domain, and the denominator 202 was chosen based on the size of the domain, and as mentioned previously it leads to zero weight at the corners of the outer domain. The average standardized anomaly is then modified according to this weight when the domain average is calculated and ranked. The top wet and dry years were then manually analyzed to make sure that the anomaly type was continuous across much of the domain, particularly near the LLJ region. We note that the results of this study have been completed using different choices for the threshold of classifying a year as wet or dry, and they are not sensitive to the threshold chosen.

d. Significance

To obtain confidence regarding the representativeness of comparisons in this study, statistical significance tests are conducted with the Student's *t* method, which determines if two samples are from the same population. It is used to compare the populations of, for instance, samples of wet and dry days for various atmospheric variables. Results are deemed significant at the 95% confidence interval. As each composite contains several hundred days (or LLJs for later comparisons), the sample size is fairly large. This is manifested on composite plots by stipple when applicable or noted as significant in the text.

3. Characteristics of precipitation anomalies and LLJ distribution in wet and dry years

Standardized precipitation anomalies are plotted for all wet and dry years as shown in Fig. 2. According to the anomaly maps, during the wet and dry years, areas of precipitation anomalies usually do not cover the entirety of the GPR. Instead, they focus more on either the northern or the southern part of the GPR. In light of this fact, we further divided the precipitation anomalies into north or south focused. For north focused, this would simply mean the precipitation anomalies in the northern half of the

FIG. 5. The percentages (%) of total LLJ associated precipitation relative to the overall precipitation in the area over the summer season for (a) dry-north, (b) dry-south, (c) wet-north, and (d) wet-south. The LLJ associated precipitation is precipitation in the domain within -6 to $+3$ h relative to the maximum LLJ wind speed. The total precipitation is all precipitation in the grid box for the entire June–August period for all years included in the respective bin.

outer domain in Fig. 1 (north of 36°N), while south focused would mean the southern half. This makes four main categories of precipitation extremes for comparison, including wet-north, wet-south, dry-north, and dry-south.

Figure 2 shows that there are 9 dry-north, 7 dry-south, 8 wet-north, and 8 wet-south years, making for a total of 32 summer wet/dry events for 1979–2017 used

during this study (note that a few years were qualified for more than one category so 26 total years are used). The remaining 13 years did not neatly fit into any of dry or wet categories. Although the number of years in each category varies somewhat, the difference is not large, with a large sample of LLJs within each. Figure 3 shows the average standardized precipitation anomalies for

FIG. 6. NARR composite 500-hPa geopotential height anomaly (units: m) charts for (a) dry-north, (b) dry-south, (c) wet-north, and (d) wet-south. Anomalies based on 1980–2010 averages for the June–August months. Values that are significant at the 0.05 level or greater are stippled.

all years in each category. The unique distributions of precipitation anomalies for each category, as well as the discrepancies among different categories, are apparent. In this study we emphasize the region including northern Texas, Oklahoma, and Kansas (small red box). This region has the most frequent occurrence of LLJs (Bonner 1968; Helfand and Schubert 1995; Doubler et al. 2015) in the GPR during summer. As can be seen in Fig. 3, this area (although it is a subdomain of the total Great Plains) represents all four precipitation categories well.

The LLJ frequency, distribution, and its contribution to precipitation are examined according to the precipitation categories. Figure 4 (uses inner domain from Fig. 1) shows the distribution of total LLJs over the GPR during the identified wet and dry summers for each of the four categories. The spatial distribution of LLJs (identified by the location of the maximum wind speed, or jet core, on a daily basis) indicates the majority of LLJs cluster near Kansas. There are a total of 507, 425, 494, and 459 LLJs in the dry-north, dry-south, wet-north, and wet-south cases, respectively. This corresponds to frequencies of 61%, 66%, 67%, and 62% during the summer season over the 9, 7, 8, and 8

years, respectively, in each case. Therefore, a correlation between the dry and wet conditions and LLJ frequency does not seem to exist. In general, there is a slightly greater number of LLJs over Oklahoma and Texas in the wet years compared to dry years. However, there are not clear discrepancies among these different categories regarding number and the distribution of LLJs. In addition, the statistics of LLJ directions at the jet core are also compared among four categories, similar to HP19, where the dry summer 2006 had a stronger westerly component (HP19, Fig. 6). Unlike in HP19, the correspondence between the dry and wet conditions and LLJ direction is not apparent (not shown).

Figure 5 illustrates the percentages of total LLJ associated precipitation relative to the overall precipitation over the summer season for years in each wet/dry category using the NARR data. Following HP19, the LLJ associated precipitation is defined as the total precipitation from 6 h before to 3 h after the LLJ peak time (time of maximum winds; note NARR is available every 3 h), which roughly covers the lifetime of the LLJ. In HP19, it was noted that the average peak LLJ speed is observed around 0900 UTC on NARR (not shown), so the period of 6 h before this to 3 h after is approximately

FIG. 7. As in Fig. 6, but for wind anomaly (vectors, units: m s^{-1}) and height anomaly (color fill, m) at 850 hPa. Statistical significance is met across the entire domain, but no stipple is plotted for readability.

equivalent to 0300–1200 UTC on average. Both the precipitation associated with the LLJ and the total precipitation are calculated within the boundaries of the domain in Fig. 5. The total precipitation is all precipitation during the June–August period for all years included in the respective category; while the LLJ associated precipitation is only counted on the days that the LLJ is present and during the hours outlined above. Results from Fig. 5 suggest that the LLJ contributes to the precipitation in the GPR, especially north of its core, which is the center of the image. On average, the total precipitation over the region that occurs while the LLJ is present varies from 10% to 45%. Specifically, over Kansas it is relatively more important with a higher percentage of precipitation occurring when the LLJ is present, ranging from 20% to 45%. The overall average ranges from 32% in wet-north years to 27% in dry north years. In all years the LLJ associated precipitation is greater in the exit region than elsewhere, but the percentage also appears to be fairly stable among the different precipitation regimes.

Figures 4 and 5 indicate that LLJs are essential mesoscale events that contribute to the precipitation extremes over the GPR. However, although there are discrepancies in the frequencies, direction, and distribution of

LLJs among the four categories we have presented, there is no obvious association between these LLJ properties with precipitation. Therefore, in order to explore why precipitation distribution and amount are different in each of the four categories, and to uncover their association with LLJs, it is worthwhile to investigate the characteristics of LLJs regarding their environment and mesoscale structures. In light of this, as well as the findings from HP19, we hypothesize that the synoptic patterns and the characteristics of LLJs mesoscale structure must be control factors in precipitation extremes. Therefore, further diagnoses have been conducted.

4. The anomalies in synoptic patterns

The climatology (seasonal mean over 1979–2017) of NARR geopotential heights over the GPR during the summer months is characterized by a synoptic-scale ridge centered over the Rocky Mountains and a trough over the eastern states at 500 hPa (not shown). At 850 hPa a thermal trough is typically present over the Rocky Mountains (HP19; Adams and Comrie 1997) and an extension of the Bermuda high (Davis et al. 1997) is evident over the eastern United States (not shown, but compare to Fig. 4 from HP19, which shows the mean

FIG. 8. As in Fig. 6, but for composite 850-hPa temperature anomalies (color fill) and 850-hPa specific humidity anomalies (contour). Units are $^{\circ}\text{C}$ for temperature and g m^{-3} for specific humidity. Statistical significance is met across the entire domain, but no stipple is plotted for readability.

850-hPa heights during May–July 2006 and 2007). On average, there is a pressure gradient over the central United States with higher pressure to the east. This pressure gradient is conducive for a LLJ with southerly flow over the GPR, indicating that LLJs are the typical features over GPR from the synoptic background. More importantly, when these LLJs pass over the Gulf of Mexico they can induce strong moisture transport to parts of the GPR, especially when they couple with atmospheric rivers (Debbage et al. 2017). As a consequence, precipitation tends to increase near the path of the LLJ and points east.

Figure 6 reveals averaged 500-hPa geopotential height anomaly for each category (dry-north, or in other words, all years in that category, etc). The anomalous stagnant ridges at 500 hPa typify dry conditions (Hoerling et al. 2014; Trenberth et al. 1988). In contrast, deep troughs are common in wet conditions (Bell and Janowiak 1995; Coleman and Budikova 2010). The dry-north case shows a broad region of positive height anomalies across most of the United States and Canada with a focus on the northern GPR. Neutral to slightly negative height anomalies are

present across the far south. For most of the continental United States, and especially the northern GPR, the wet-north is nearly a mirror image of the dry-north with a very large negative height anomaly region focused on the northern GPR and a slight positive anomaly across the far southeastern United States. These differences in the height anomalies between wet and dry years are consistent with previous studies, which were cited earlier. The dry-south and wet-south also share this distinction of having generally opposite height anomalies to each other, but the nature of the anomalies is different than the north-focused composites. For these years a wave-like pattern is evident with above normal heights being flanked by below normal heights in the dry-south years, and the reverse in the wet-south years. These anomalies are also not as strong or spatially broad as the north-focused anomalies and are significant over the entirety of the domain.

Moreover, during the dry years, due to the anomalously strong upper-level high pressure, subsidence should be enhanced. If so, it would result in both warmer and drier conditions. In contrast, during wet years there

FIG. 9. NARR composite peak nightly LLJ wind speed (units: m s^{-1}) over the June–August months for (a) dry-north, (b) dry-south, (c) wet-north, and (d) wet-south. Vector length corresponds to wind speed. Composite map moves with LLJ each day present and plotted location is average location of LLJ. Values that are significant at the 0.05 level or greater are stippled.

should be a weakening of subsidence from the anomalous low pressure, with cooler and moister conditions present. To verify if the subsidence was enhanced during the dry years compared to wet years, a $\mathbf{Q}$ -vector analysis is conducted at 700 hPa (not shown). The $\mathbf{Q}$ -vector analysis identifies regions that would be expected to see rising or sinking motion, and is based on QG theory (Lackmann 2011) and given by

$$\mathbf{Q} = -\frac{R}{\sigma p} \begin{bmatrix} \frac{\partial \mathbf{V}_g}{\partial x} \nabla \theta \\ \frac{\partial \mathbf{V}_g}{\partial y} \nabla \theta \end{bmatrix} = \begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix}.$$

The parameter R is the atmospheric ideal gas constant, σ the static stability parameter, $\mathbf{V}_g$ the geostrophic wind, p the pressure, and θ the potential temperature (theta). One would expect that areas of $\mathbf{Q}$ -vector convergence should be correlated with areas under the anomalous troughs from Fig. 6, while $\mathbf{Q}$ -vector divergence should be correlated with the anomalous

ridges. It was found that near the LLJ exit region there is $\mathbf{Q}$ -vector divergence in the dry-north years and convergence in the wet-north years, and this difference is significant. Similar differences exist between the dry and wet south years, but the results do not reach significance. Therefore, subsidence was likely less over the GPR in the wet-north years than the dry-north years. This difference in subsidence may extend to the southern comparison as well, but not at the 95% confidence level.

In addition to affecting subsidence, the previously identified anomaly cores at 500 hPa are related to the low-level pressure anomalies and their related wind direction, strength, and location. Figure 7 shows the 850-hPa height anomalies as well as the corresponding wind anomalies. This level was chosen because it was found to be the average altitude of the LLJ in HP19. The 850-hPa height anomalies are similar to the 500-hPa anomalies, just spatially shifted somewhat. The wind anomalies are consistent with the synoptic geopotential height anomaly present. The differences are significant across the

FIG. 10. As in Fig. 9, but for vertical velocity. Rising motion is red. Units: hPa s^{-1} .

entire domain, although no stipple is included in the figure for readability (Fig. 7).

In dry-north years, the dominant, strong height anomaly over the northern GPR leads to an enhanced easterly flow anomaly where LLJs typically form, and northerly flow over the Gulf of Mexico (Fig. 7a). Importantly, the less-southerly flow over Texas limits inland moisture transport and weakens the LLJ there. The location of the high pressure also leads to enhanced southerly flow over the central to north GPR, but without the moisture tap to the south (Fig. 8a). In this way the LLJ is less effective at moisture transport. Temperatures are also higher under the ridge (Fig. 8a). In wet north years a southerly wind anomaly is noted over a broad region east of the anomalously low heights over the GPR (Fig. 7c). A northwesterly wind anomaly is observed over the northern GPR, representing cool and dry air. This is also seen with temperature and moisture gradients in the area of interest (Fig. 8c). The height anomaly pattern, shifting wind, as well as the temperature and moisture gradients, suggest the presence of frequent cold fronts in the vicinity. This apparent enhancement of cold front activity (compared to the dry composite) likely helped to enhanced precipitation near

the LLJ. In fact, the wet north composites resemble the corridors of precipitation indicated in Tuttle and Davis (2006) where persistent synoptic anomalies focus heavy mesoscale precipitation over a certain area for an extended period of time. The dry-south case had anomalously high 850-hPa heights southeast of the LLJ and low heights northwest (NW) of the LLJ. This acts to tighten the geostrophic height gradient relative to climatology and make for a stronger LLJ (Fig. 7b). However, in spite of the stronger LLJ over the GPR there were limiting factors that reduced precipitation, the most important being the close proximity of the ridge, which leads to subsidence over the area and both warms the atmosphere and dries it (Fig. 8b). The opposite height configuration is observed in the wet-south years, and the corresponding LLJ is weaker than average (Fig. 7d). In this case, the LLJ does not extend into the GPR as far as normal, so moisture tends to move into the southern GPR but less effectively into points north of there (Fig. 8d). Cooler upper-level temperatures were also present (Fig. 8d), which likely reduced static stability in the area. Synoptically, a mean cutoff low over the southern GPR interacts with this moisture to produce enhanced rainfall. Previous (less extensive) studies have shown similar

FIG. 11. As in Fig. 9, but for (a)–(d) potential temperature and (e)–(h) potential temperature advection. Units are K for temperature and $\text{K km}^{-1} \text{s}^{-1} \times 10^3$ for advection.

low-level height and wind patterns are common during wet (Bell and Janowiak 1995) or dry events (Namias 1991).

5. Characteristics of LLJ structures

a. Description of the composite

To characterize the structure of LLJs and their mesoscale environment, composite maps are produced over the GPR. This is done by first identifying the time, pressure level, and core region of the LLJ (if present) occurrence on each day, for each LLJ within the inner box in Fig. 1. The daily LLJ region is defined as a box of 5° in each direction from the LLJ core on that date, same as in HP19, and is always contained within the outer box on Fig. 1. In practice this means that, for example, if the LLJ core is at 30°N , 100°W the box will span from 25° to 35°N and 95° to 105°W . If the LLJ moves to 35°N , 95°W the next day, the box will span from 30° to 40°N and 100° to 90°W , and so forth. Then, for each category (e.g., dry-north, etc.) the relevant variables are averaged for all LLJ days throughout the June to August time period over the years binned in that category.

This type of average allows for each daily map that is incorporated into the composite to move with the LLJ core each day, and thus only information that is pertinent to the LLJ will be retained on the composite maps; everything else will be averaged out. In this study the LLJ-related composite plots will be shown on the average location of the LLJ for each bin, which is 37.5°N , 98.9°W for dry-north, 37.2°N , 98.6°W for dry-south, 36.6°N , 98.9°W for wet-north, and 36.5°N , 99.1°W for wet-south.

To be sure that the composite is not being diluted with too dissimilar of LLJs the LLJs are restricted in terms of location, time, altitude, and seasonality. Only LLJ cores that are centered between 30° and 42°N , 103° and 95°W (Fig. 1 inner box), and that occur at night (0300–1500 UTC) are counted. LLJs must also occur between 950 and 800 hPa. As mentioned previously, LLJs must contain a southerly component to be counted. This is also done to match HP19 for a nearly direct comparison of the findings in that study. In general, we do not expect a loss of many LLJs this way because very few tend to peak during

FIG. 11. (Continued)

the daytime (HP19). Seasonality is considered because we have restricted the time to the summer months only. It is noted that in light of the fact that not all LLJs occur at the same altitude that we do not refer to specific altitudes on future LLJ plots. However, the majority of LLJs maximize near 850 hPa, so this level should be considered as a representative level of the LLJ, similar to HP19. To obtain confidence regarding the representativeness of these composite maps, a statistical significance test is conducted with the Student's t method, as was outlined in section 2d, except here only days with LLJs are compared.

b. Dynamic structure and characteristics of LLJs during wet and dry periods

Wind speed composite plots (Fig. 9) show that wet-north years have a stronger LLJ, a more southerly wind direction south of the LLJ core, and curves to westerly flow downwind of the LLJ core sooner than dry-north years do (Figs. 9a,c). Wet-south years have a slightly slower LLJ than dry-south, are overall more southerly south of the LLJ core, and cover a slightly smaller spatial

area (Figs. 9b,d). The differences in speed between wet and dry north are significant across most of the domain, with limited significant differences between wet and dry south. The results are consistent with HP19, which compared 2006 (dry-north) to 2007 (wet-south).

Vertical velocity (ω) shows that the wet-north years have stronger maximum upward ω than dry-north in the LLJ exit region, and this result is significant (Fig. 10). The wet and dry-south categories are not significantly different in the LLJ exit region. However, for both north and south, the wet years have stronger rising motion along the western axis of the LLJ than the dry years do, and this is significant. In all cases a pattern of sinking motion upwind and to the east of the LLJ axis, and rising motion downwind of the LLJ core is observed. These results are also consistent with HP19 (dry-north versus wet-south).

c. Thermodynamic structure

The temperature distribution in all cases shows higher potential temperature (θ) values to the southwest (SW) and lower values to the northeast (NE) (Figs. 11a–d). Relatively higher potential

FIG. 12. As in Fig. 9, but for relative humidity (units: %).

temperature is present along the path of the LLJ as well, allowing for the inference of warm air advection from the LLJ in its exit region, which is confirmed by the potential temperature advection plots in Figs. 11e–h. As seen on the larger composites from earlier in this study, the temperature is higher in the dry years than the wet ones. In all cases the temperatures tend to decrease to the north of the LLJ core, but rate is quicker in the wet years, and especially wet-north, and slowest in dry-north. Overall the wet-north has the coolest temperatures and dry-south the warmest near the LLJ core. These results are significant north of the LLJ core in the north-focused years and across most of the area near and southeast of the LLJ in the south-focused years. The spatial extent of potential temperature advection (Figs. 11e–h) appears to be overall similar, with a maximum in the LLJ exit region in all cases. The potential temperature advection is significantly stronger in the wet-north compared to the dry-north, but the dry and wet south are not significantly different.

The mesoscale moisture distribution is also consistent with the larger composites shown previously (Fig. 8).

Specific humidity (not shown) is higher in the wet years than the dry years and matches the distribution of relative humidity (RH), which is shown in Fig. 12. RH is lower along the path of the LLJ axis and into its jet core than the domain average, and especially lower than the LLJ exit region, where RH increases quickly. Importantly, this relative depression in RH near the LLJ core and upwind of it is greater in dry years, whereas it tends to be only lightly depressed from the domain average in wet years. RH increases downwind of the LLJ core in all years and reaches its maximum in this location, but the rate of increase is slightly less during dry years. This means in wet years that not only is the background RH higher, but the LLJ increases the RH from the background at a higher rate during the wet years. RH differences are statistically significant across nearly the entire domain in all years. Vertical advection of water vapor in the LLJ exit region is relevant, but appears to vary wildly from case to case and so results were not statically significant and are not shown. Still, we note that its magnitude (without considering condensation removal) appears to be on average about the same

FIG. 13. As in Fig. 9, but for precipitation [units: mm (9 h)^{-1}] from -6 to $+3$ h (9 h total) relative to the peak LLJ speed.

magnitude as horizontal advection, but over a spatially smaller area. Also, it is roughly twice as strong in the wet years. Since the spatial pattern of RH does not change between wet and dry years, and the background RH matches what would be expected from the large-scale synoptic anomalies, this suggests that the LLJ is not driving the environmental RH. However, it is always responsible for increasing the RH from the background state in its exit region, with a greater increase in the exit region RH during the wet years as previously noted.

d. LLJ associated precipitation distribution

Precipitation composite plots show the average nightly precipitation that falls when a LLJ is present (Fig. 13). In all cases it is heavily concentrated in the exit region of the LLJ, which is consistent with the best forcing as has been outlined in this section, and implies that the LLJ is responsible for much of the precipitation in the area. The wet years show much greater precipitation than the dry years. This result is statistically significant in the exit region in all years, and is consistent with HP19. In fact, this pattern of precipitation very closely matches the warm advection seen previously

(Figs. 11e–h). As warm advection is known to cause rising motion based on QG theory, it suggests that a critical component to the way that the LLJ forces precipitation is through warm advection. This agrees with previous studies as well (Maddox and Doswell 1982).

Previously it was noted that the percentage of LLJ associated precipitation of the total precipitation did not change much between the wet and dry years, but here we note significant differences in the magnitude of total precipitation. Therefore, it is likely that the increased precipitation in the LLJ exit region in the wet years is proportional to the increase of total precipitation from a more favorable synoptic set up in the wet years. This lends credence to the idea that the LLJ is more effective at precipitation due to a more favorable background state.

6. Dry LLJs versus wet LLJs

a. Description of subcategory comparisons

The results presented so far show that on average, different characteristics are observed for many variables

FIG. 14. As in Fig. 9, NARR composite peak nightly LLJ wind speed (units: m s^{-1}), but with datasets split into anomalously wet or dry days for each data subset [i.e., dry-north is now dry-north (wet) and dry-north (dry) and so forth]. Approximately the 10% of driest days with LLJs go into the dry categories, and 10% of wettest days with LLJs into the wet categories.

related to the LLJ in wet and dry years. To determine if these differences were simply a product of different kinds of LLJs being more common, or if otherwise similar LLJs (frontal, synoptically benign, etc.) had structural differences relating to the precipitation anomaly present, additional tests were conducted. The methodology from the previous section is used, but here we look at two subsets of each dataset. To be specific, we take days from each dataset (e.g., dry-north) where the total regional precipitation around the LLJ core exceeds a threshold for minimum and maximum amounts of precipitation. The choice of the threshold was designed to include approximately the top 10% wettest and driest days for their respective bins. This leaves the dry-north (dry) and dry-north (wet) subsets for the dry-north dataset. Similar dry and wet bins are made for the dry-south, wet-north, and wet-south categories from the previous section, creating eight categories. The sample size for each bin ranges from about 40–70 days. Statistical significance is tested at the 95% confidence level for results in this section. Since two types of significance are discussed [i.e., dry-north (dry) to wet-north (dry) or dry-north (dry) to dry-north (wet)], the significance of results will be discussed when applicable but not shown in plots.

b. Dynamic structure and characteristics of dry and wet LLJs

Overall, when comparing the wind speed and direction of the LLJs (Fig. 14), the structure generally resembles what was seen previously in Fig. 9. Still, some differences are found. Wet-north LLJs are faster than dry-north LLJs for either dry or wet conditions, and this is significant everywhere (Figs. 14a,b). This is also observed, with dry-south LLJs being faster than wet-south LLJs for dry days, but the speed is similar for wet days (Figs. 14c,d).

Strong differences in LLJ speed and structure are found within an anomaly type (i.e., dry-north) for wet and dry days and are statistically significant across the entire domain for all comparisons. Dry-north (dry) days show a very different structure than dry-north (wet) reflecting a typical synoptically benign pattern versus a likely active frontal pattern (a strong wind shift is noted NW of the jet core on these maps and a circulation is evident). The same holds for wet-north (dry) versus wet-north (wet) and other comparisons. An additional difference is that the LLJ extends farther north in the dry day composites in all cases compared to the wet day composites, where it shears off quickly north of the jet core.

FIG. 15. As in Fig. 14, but for vertical velocity (units: hPa s^{-1}).

These comparisons show that wet periods contain LLJs with different structure than dry periods. This implies that the differences in the composites between the general wet and dry periods are primarily because of different types of LLJs being favored to occur based on the anomalous synoptic set up in each precipitation regime. As noted for the general wet-north composites earlier, here the wet day composites resemble the patterns associated with persistent precipitation corridors (Tuttle and Davis 2006; Fritsch et al. 1986).

Vertical velocity comparisons, similar to the LLJ speed comparisons, show that there are minor differences among anomaly types [dry-north (dry) versus wet-north (dry), etc.], and they are not significant (Fig. 15). They also show that there are dramatically different and significant signals during wet and dry days within anomaly types for all comparisons [dry-north (dry) versus dry-north (wet), etc.]. During the dry days in all cases there is very little rising motion in the exit region of the LLJ, with sinking motion dominating elsewhere. This intriguing observation appears to be related to the lack of convergence in the LLJ exit region on these days (not shown). In wet days it is observed, again in all cases, that there is strong rising motion in the LLJ exit region. This strong rising motion matches a region of strong convergence in the LLJ exit region (not shown) where the LLJ (Figs. 14b,d) shears

strongly from the south to a southwest direction. The wet days during the dry-north and especially dry-south have stronger upward ω than wet-north (wet) days or wet-south (wet) days do, but that this result does not reach significance.

c. Thermodynamic structure and characteristics of dry and wet LLJ environment

The results for the temperature comparisons also yield a number of interesting conclusions (Fig. 16). Dry days have higher temperatures at jet level than wet days. General dry periods are warmer [i.e., dry-north (dry) versus wet-north (dry)] as well. Unlike for wind speed and vertical velocity, this intra-anomaly comparison is significant, and across most of the domain. This shows that background conditions of long-term wet or dry conditions can affect the LLJ environment even on individual days that do not match the background state. During dry days for both general wet and dry periods, the maximum temperatures are observed west to northwest of the LLJ core, whereas on wet days for general wet or dry periods they are located WSW of the LLJ core. Further, on wet days the temperatures in the LLJ exit region are dramatically different than dry days, with a strong baroclinic horizontal temperature gradient. These differences are also significant domain-wide. This temperature gradient is important because of the increased

FIG. 16. As in Fig. 14, but for potential temperature (units: K).

warm air advection (not shown, but present) and associated lift (Fig. 15). This combination of the circulation, wind shift, and temperature gradient suggest that fronts are frequently present in these wet subsets.

The relative humidity distribution is shown in Fig. 17. Previously, a downstream RH maximum in the exit region of the LLJ was observed in all subsets. In fact, this feature is only marginally present during dry days, and is very strong during wet days. The RH still generally increases in the LLJ exit region on the dry days, but its gradual and a small magnitude. Spatially, there is little difference between the dry-north (dry) and wet-north (dry) as well as other comparisons except that RH is significantly higher in the wet years. This difference is relevant, because it makes condensation and precipitation more likely.

7. Summary and conclusions

The LLJ of the GPR of the United States is an important and regularly occurring phenomenon. It transports both energy and water into the region and is important for warm season precipitation production. In this study the processes by which wet and dry regimes modify the environment in which the LLJ forms were examined. Additionally, how the LLJ responds to these environmental changes in the form of structural

differences, how it modifies the environment around it, and the corresponding precipitation differences were explored.

Consistent with findings from the case study in HP19, the LLJ does not drive climate extremes leading to wet or dry conditions, rather it responds to persistent large-scale pressure anomalies that are themselves consistent with wet or dry regimes. This means that the LLJ can amplify or diminish these extremes but it does not cause them. Anomalous high pressure enhances subsidence, which both warms and dries the atmosphere. It also deflects storm systems from moving into the area. The warmer and drier air makes saturation, and thus precipitation, harder to achieve. This quiescent pattern also favors the more classical LLJ model of an inertial oscillation and slope baroclinity. Anomalous low pressure does the opposite in every sense. It reduces subsidence, which promotes upward vertical motion. This can help the air cool and saturate it more efficiently. The presence of stronger baroclinity as well as specific placement and orientation of height anomalies also infers the existence of more frontal LLJs, especially in wet-north years.

The exact placement of the height anomalies in each precipitation regime affects the LLJ position, speed, and other properties in predictable ways. The wet-north height configuration amplifies the climatological height

FIG. 17. As in Fig. 14, but for relative humidity (units: %).

gradient for the strongest LLJ and deep inland penetration, while the dry-north weakens and displaces the LLJ to the north. The wet-south weakens the climatological gradient resulting in a slower LLJ, with small spatial coverage as well. The dry-south enhances the gradient (and thus the LLJ) somewhat near its climatological position while not allowing for deep moisture transport due to limited access to the Gulf of Mexico; the dry-north limits deep moisture transport as well.

As the LLJ is modified according to its corresponding precipitation regime, it can also influence its own environment. The nature of these differences was realized by producing composite maps for subsets of wet and dry periods: dry-north, wet-north, dry-south, and wet-south. These comparisons were further broken down into the driest and wettest days within each bin for some comparisons. A summary of some of the key findings is as follows.

It was found that the LLJ has significant speed and structure differences during the north-focused wet and dry periods, with more limited differences in the south-focused wet and dry periods. The wet-north LLJs were the fastest while the dry-north were the slowest. The LLJ speed drops very quickly in its exit region and the wind direction changes sharply on the wettest days, while on the driest days the speed drop off and wind direction change are gradual, with the LLJ extending farther north.

There were also important differences found in the dynamic and thermodynamic fields between the precipitation regime types. In particular, the LLJ is associated

with a local maximum of relative humidity in its exit region. This signal is on average present in all years, but is significantly stronger during wet periods, and nearly absent on the very dry days. RH is always higher across the region (not just exit region) during wet years than dry years, even when comparing dry days within general wet and dry years or wet days within those years. The maximum of RH that occurs in the exit region is likely associated with several factors, including horizontal moisture advection, vertical moisture advection through rising motion in the exit region, and lessened subsidence (less drying in wet years).

The RH distribution can be better understood in the context of the potential temperature distribution, which varies in a similar way. Lessened subsidence in the wet years results in significantly lower potential temperature across the region during wet years compared to dry years. Further, comparing the very wet and dry days the potential temperature is dramatically different north of the LLJ core. On wet days a baroclinic structure is present with a strong temperature gradient. This gradient is absent on the dry days. This temperature gradient does not appear to be caused by the LLJ, but it changes the effects of the LLJ. The stronger temperature contrast, beyond adding instability, also makes the warm advection in the LLJ exit region stronger, all else being equal. Warm advection can cause rising motion according to QG theory. The precipitation that occurs in the LLJ exit region matches the locations of strong warm advection, with the precipitation magnitude proportional to the warm advection magnitude.

The LLJ exit region is also subject to strong upward vertical motion, which is stronger in wet years compared to dry years. Rising motion along the western axis of the LLJ is greater in wet years than dry years. Comparison of the wettest and driest days revealed that LLJs only have very gentle rising motion in their exit region during the very dry days but explosive rising motion on the wet days, implying that the rising motion found in the exit region may not be intrinsic to itself, but possibly from other factors such as convective initiation in the LLJ exit region, or perhaps other mesoscale features that increase convergence.

The factors thus presented indicted that the LLJ, and especially in its exit region, are associated with precipitation development. The relative favorability of precipitation production varies according to the precipitation regime. The wet years have LLJs that are associated with more precipitation in terms of magnitude, with a slight difference in the percentage of LLJ associated precipitation between the wet and dry north years.

In summary, this study has made significant progress at understanding differences in the LLJ between wet and dry regimes. During wet years, anomalous upper-level troughs resulted in decreased subsidence which led to higher moisture content and cooler temperatures aloft compared to dry years. The synoptic anomalies during wet (dry) years also led to patterns conducive to enhanced (reduced) baroclinity near the LLJ. The LLJ acts upon the baroclinity through enhanced warm air advection and causes stronger rising motion and increased wind shear. RH also increases more quickly in the LLJ exit region in wet years. Together, these factors result in higher LLJ associated precipitation amounts in the wet years. Future work should emphasize on numerical simulations with sensitivity studies to obtain additional insights about these processes.

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