The Low-Level Jet over the Southern Great Plains Determined from Observations and Reanalyses and Its Impact on Moisture Transport

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ABSTRACT

This study utilizes six commonly used reanalysis products, including the NCEP–Department of Energy Reanalysis 2 (NCEP2), NCEP Climate Forecast System Reanalysis (CFSR), ECMWF interim reanalysis (ERA-Interim), Japanese 25-year Reanalysis Project (JRA-25), Modern-Era Retrospective Analysis for Research and Applications (MERRA), and North American Regional Reanalysis (NARR), to evaluate features of the southern Great Plains low-level jet (LLJ) above the U.S. Department of Energy’s Atmospheric Radiation Measurement Program (ARM) Climate Research Facility (ACRF) Southern Great Plains site. Two sets of radiosonde data are utilized: the six-week Midlatitude Continental Convective Clouds Experiment (MC3E) and a 10-yr period spanning 2001 through 2010. All six reanalyses are compared to MC3E data, while only the NARR, MERRA, and CFSR are compared to the 10-yr data. The reanalyses are able to represent most aspects of the composite LLJ profile, although there is a tendency for each reanalysis to overestimate the wind speed between the nose of the LLJ (at approximately 900 mb) and a pressure level of 700 mb. There are large discrepancies in the number of LLJs observed and derived from the reanalysis, particularly for strong LLJs, leading to an underestimate of the moisture transport associated with LLJs. When the 10-yr period is considered, the NARR and CFSR overestimate and MERRA underestimates the total moisture transport, but all three underestimate the transport associated with strong LLJs by factors of 1.4, 2.0, and 2.7 for CFSR, NARR, and MERRA, respectively. During MC3E there were differences in the patterns of moisture convergence and divergence, but the patterns are more consistent during the 10-yr period.

1. Introduction and motivation

It is well recognized that the southern Great Plains (SGP) low-level jet (LLJ) plays an important role in the regional-scale moisture transport over the central United States (e.g., Uccellini and Johnson 1979; Helfand and Schubert 1995; Stensrud 1996; Higgins et al. 1997; Schubert et al. 1998; Tollerud et al. 2008; Frye and Mote 2010). A number of different mechanisms have been suggested as the cause of LLJs, as highlighted by Kraus et al. (1985) and Stull (1988). These processes include inertial oscillations associated with changes in the diurnal cycle of surface heating and boundary layer mixing (Blackadar 1957), horizontal temperature gradients associated with heating of elevated topography across the interior of North America (Holton 1967), channeling of the winds by topography (Wexler 1961), and synoptic-scale weather patterns such as fronts or cold-air outbreaks (e.g., Kraus et al. 1985; Bowen 1996; Whitman et al. 1997). It is likely that none of the proposed mechanisms alone are responsible for LLJs found over the southern Great Plains but rather some combination of these physical processes that are dominated by inertial oscillations (e.g., Parish et al. 1988; Zhong et al. 1996; Parish and Oolman 2010).

Regional and global reanalyses have been utilized by the research community to study the hydrological cycle (e.g., Gutowski et al. 1997; Betts et al. 1999; Roads et al. 2002; Mo et al. 2005; Schneider et al. 2006). Other work has linked the LLJ to patterns of the large-scale flow, using the North American Regional Reanalysis (NARR), National Centers for Environmental Prediction (NCEP) reanalysis, and ERA-40 reanalysis (Weaver and Nigam 2008; Weaver 2011), or investigated the impact of atmospheric rivers (Newman et al. 2012). A careful evaluation of reanalyses is needed to document their shortcomings. Trenberth and Guillemot
(1998) compared the NCEP–NCAR reanalysis to a number of different datasets and found that there were significant biases in a number of moisture variables, including evaporation and precipitation. Subsequently, Trenberth et al. (2011) investigated the performance of eight different global reanalyses and found that the lifetime of moisture in the atmosphere was too short.

A number of studies have focused on evaluating the performance of one or two reanalysis products and their representation of the LLJ. Mo and Higgins (1996) reported that differences in the NCEP reanalysis and NASA Data Assimilation Office (DAO) reanalysis moisture flux divergence over North America were attributed to uncertainties in the LLJ. Higgins et al. (1996) compared the NCEP and DAO reanalyses to surface observations of precipitation and radiosonde data. They found that while the reanalyses captured key features of the LLJ, there were significant differences in column-integrated moisture flux. Their research was extended to investigate the diurnal cycle of rainfall and its relation to the LLJ, in which they documented seasonal changes in the nocturnal precipitation (Higgins et al. 1997). Other studies (e.g., Wang and Paegle 1996; Min and Schubert 1997) reported that errors associated with the representation of the LLJ led to a large amount of uncertainty in the moisture transport. Research has shown that the NCEP and ERA-40 reanalyses tend to have fewer intense LLJs than are found using data collected by the NOAA wind profiler network (Anderson and Arritt 2001). Walters et al. (2014) compared the NARR with radiosonde observations from over the central United States and found that the NARR generally had fewer LLJs than were found in the observations.

The motivation of this work is to determine how well the LLJ and moisture transport are represented in a number of reanalysis products, including high-resolution reanalyses that have been developed relatively recently. This work focuses on two distinct time periods, analyzing the performance of the reanalyses with data collected during 1) the short-duration Midlatitude Continental Convective Clouds Experiment (MC3E) that was conducted over the Atmospheric Radiation Measurement Project (ARM) Climate Research Facility (ACRF) Southern Great Plains site during April and May of 2011 and 2) a 10-yr period spanning 2001–10 that builds on other climatologies such as that of Song et al. (2005). The 10-yr period has been divided in two ways. First, composites have been generated using only data from the month of May, allowing for a fair comparison with the MC3E period. Second, composites have been generated for the warm season months (May–August), when LLJs are most common over the southern Great Plains (e.g., Whiteman et al. 1997). The MC3E study includes five additional radiosonde launch sites over an area of approximately 70,000 km², allowing for investigations of the spatial inhomogeneity of the LLJ. This work utilizes six reanalyses for the MC3E period [NCEP–DOE Reanalysis 2 (NCEP2), NCEP Climate Forecast System Reanalysis (CFSR), ECMWF interim reanalysis (ERA-Interim), Japanese 25-year Reanalysis Project (JRA-25), North American Regional Reanalysis (NARR), and Modern-Era Retrospective Analysis for Research and Applications (MERRA)] and three for the 10-yr climatology (NARR, MERRA, and CFSR).

The definition of LLJs applied in this study is presented in section 2, including a methodology for determining the thickness of the LLJ. Section 3 includes a description of both the radiosonde data that forms the basis of the observations and the reanalysis products that are applied. The climatology of LLJs from both the observations and reanalyses is presented in section 4 and includes not only composites of the wind speed profiles but also probability density functions (PDFs) of the LLJ height and LLJ thickness during MC3E and the 10-yr study period. This section also describes the spatial variability of the LLJ during MC3E. The impact of LLJs on the moisture transport over the southern Great Plains is presented in section 5, where differences in transport associated with LLJ and non-LLJ cases are discussed.

2. Definition of the LLJ

Bonner (1968) proposed criteria that can be used to identify LLJs, which have been widely accepted in the research community. To be classified as an LLJ, the wind speed maximum must occur below a pressure level of 700 mb (corresponding to an altitude of approximately 3 km over the ACRF site). The magnitude of the wind speed maximum ($U_{\text{max}}$) and the change in wind speed with height ($\Delta U_z$) between two different altitudes are used to group the jets into four categories based on their intensity. Bonner (1968) originally proposed three different categories, with the minimum value of $U_{\text{max}}$ for an LLJ defined to be 12 m s⁻¹. Based on their analysis of data from the southern Great Plains, Whiteman et al. (1997) added a fourth category for weaker jets with wind speeds less than 10 m s⁻¹. The categories defined by Bonner (1968) will be applied here (Table 1) but with one important caveat. As they were defined, Bonner’s criteria were not exclusive [as pointed out by Whiteman et al. (1997)]. In other words, a category 3 LLJ would also be identified as a category 0, 1, and 2 LLJ. In this work we have made the LLJ categories exclusive, so that only the weakest LLJs are identified as a category 0. While this makes some comparisons with the existing literature
more difficult, it makes it much easier to understand the stronger LLJs and their role in the regional-scale moisture transport. Other researchers, such as Andreas et al. (2000) and Banta et al. (2002), have proposed other modifications, but they have not been adopted here.

In this work the vertical extent, or thickness, of the LLJ is also examined. While previous studies have presented the vertical distribution of the altitude of the peak wind speed, they have not quantified the vertical extent of individual LLJs over the southern Great Plains (e.g., Bonner 1968; Whiteman et al. 1997). The vertical thickness of LLJs over India was presented by Kalapureddy et al. (2007), but the conditions found over India are likely quite different from those over North America. The vertical thickness of the LLJ has been defined as the difference in the pressure levels, above and below the jet maximum, at which the wind speed is 75% of the maximum value. While this definition is arbitrary, it was found that selecting a value smaller than 75% yielded many cases in which the thickness of the LLJ could not be defined because of the relatively small fractional change that may be observed between the nose of the LLJ and the minimum wind speed above the jet.

3. Data and reanalysis products

a. Radiosonde

We utilize radiosonde data collected across the ACRF SGP site, including regular radiosondes launched from the ACRF SGP central facility and additional radiosondes that were included as part of MC3E (Jensen et al. 2015; Holdridge et al. 1994) to provide profiles of wind speed, wind direction, and specific humidity $(q)$. Prior studies have utilized ACRF datasets over relatively short time periods to investigate LLJs (e.g., Stensrud 1996; Whiteman et al. 1997; Song et al. 2005), whereas this work utilizes data collected over a full 10-yr period in addition to that from MC3E. As pointed out by Tollerud et al. (2008), the synoptic radiosonde network is not adequate for studying phenomena like the LLJ owing to the large distances between launch sites and the relatively infrequent launch times. In contrast, the ACRF launches radiosondes nominally four times a day (at 0530, 1130, 1730, and 2330 UTC), providing higher temporal resolution that is adequate for studies of the LLJ (e.g., Whiteman et al. 1997). During MC3E, radiosondes were launched more frequently (at 0230, 0530, 1130, 1730, 2030, and 2330 UTC) at five additional locations within the ACRF SGP site (Fig. 1). The spacing of the MC3E radiosonde network also allows for an analysis of the spatial inhomogeneity of the LLJ over distances on the order of 150 km that is not possible from standard networks. The second period of study consists of the warm season months for a 10-yr period extending from 2001 through 2010 that is designed to provide a long-term perspective. The period also includes relatively dry (2006) and wet (2007) years (e.g., Lamb et al. 2012; Qian et al. 2013) over the central United States. An additional 10-yr dataset, consisting only of data from May, which is more consistent with the MC3E study period, is also derived. In this study, the radiosonde data and reanalysis products have been interpolated to match the vertical resolution of the NARR (which is the same vertical resolution used by the MERRA and CFSR for pressures greater than 300 mb). Each reanalysis product was interpolated in space to match the latitude and longitude of the various radiosonde launch locations. No time interpolation was applied, and the radiosonde launch time was nominally 30 min after the hour for which the reanalysis is valid.

In addition to the radiosonde data collected during MC3E, a number of other instrument systems are deployed at the SGP site, including a scanning Doppler lidar for measuring profiles of wind speed and direction (e.g., Newsom et al. 2013), atmospheric emitted radiance interferometer (AERI)-measured profiles of temperature and $q$ (e.g., Feltz et al. 2003; Turner and Löhnen 2014), and a Raman lidar that can be used to measure the $q$ profile (e.g., Ferrare et al. 2006). In the context of this analysis, however, we will focus only on data collected by the radiosondes, for two reasons. First, radiosondes can reliably measure the wind profile from near the surface through the top of the atmosphere, meaning the entire depth of the LLJ can be measured. Second, at this time there is a much longer historical record of radiosonde data allowing us to better document the climatology of the LLJ.

b. Reanalyses

Six different reanalysis products have been selected for this study: the NCEP2, CFSR, ERA-Interim, JRA-25, NARR, and MERRA. These particular products were selected because they are widely used in the research community, span a range of different horizontal and vertical spatial scales, and utilize a number of different data assimilation systems. Key aspects of each reanalysis are provided in Table 2, and additional

<table>
<thead>
<tr>
<th>LLJ category</th>
<th>$U_{\text{max}}$ (m s$^{-1}$)</th>
<th>$\Delta U_z$ (m s$^{-1}$)</th>
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<tr>
<td>0</td>
<td>$\geq$10</td>
<td>$\geq$5</td>
</tr>
<tr>
<td>1</td>
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<td>$\geq$6</td>
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<tr>
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<td>$\geq$16</td>
<td>$\geq$8</td>
</tr>
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<td>3</td>
<td>$\geq$20</td>
<td>$\geq$10</td>
</tr>
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</table>
descriptions of the various reanalysis products can be found in the references listed in the table.

The 10-yr average precipitation for May from each of the reanalysis products highlights some of the similarities and differences among the group (Fig. 2). In this case the 1/8° Parameter-Elevation Regressions on Independent Slopes Model (PRISM/UW; Daly et al. 2008) precipitation is assumed to represent the true amount of precipitation. Each of the reanalyses have an east–west precipitation gradient, with larger amounts of precipitation occurring over the eastern half of the study area consistent with observed precipitation (Fig. 2). There are, however, some striking differences. The largest values of precipitation in the MERRA reanalysis occur over southern Texas, while the other reanalyses and observations center the maximum value of precipitation much farther north, over Missouri, Kansas, and Oklahoma. There are also clear differences associated with the different horizontal grid spacing used in each of the reanalyses. The coarse-resolution products (the NCEP2 and JRA-25) have larger amounts of precipitation over the northern Great Plains (including Minnesota, as well as North and South Dakota) than is seen in the higher-resolution reanalyses.

4. Analysis of LLJs

The analysis of LLJs has been broken into two sections: one includes a detailed analysis of the MC3E period, while the other investigates the 10-yr averages for both May and May–August.

a. MC3E period

Periods with LLJs during MC3E are identified based on the criteria presented in section 2. During MC3E there are a total of 76 cases of observed LLJs, out of a total of 116 radiosonde profiles available from the ACRF SGP central facility. Time–height cross sections of $q$, wind direction, wind speed, and moisture transport (defined as the product of the wind speed and $q$) derived...
from SGP central facility radiosondes are shown in Fig. 3. Time periods with category 0 or 3 LLJs are indicated by symbols, and the height of the symbol indicates the height of the maximum wind speed associated with the LLJ. As highlighted in Fig. 3, the LLJs are found to occur over the entire MC3E period, although there are some periods (24–28 April and 13–18 May) that were free of LLJs. It is interesting to note that the period 24–27 April includes a large tornado outbreak over the southeastern United States.

As was documented by Whiteman et al. (1997) and Song et al. (2005), the LLJs are not limited to periods with southerly winds, and a small number were found to occur when the winds are from the north during MC3E as well. The two instances of northerly LLJs can be attributed to the synoptic weather pattern. In the case of the LLJ that occurred on 27 April, the northerly winds are associated with the northeastward movement of a region of surface low pressure from south-central Texas to the Oklahoma–Arkansas border. The northerly winds

<table>
<thead>
<tr>
<th>Reanalysis</th>
<th>Horizontal resolution</th>
<th>Number of vertical levels</th>
<th>Global or regional</th>
<th>Reference</th>
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<tr>
<td>NCEP2</td>
<td>280 km × 225 km</td>
<td>28</td>
<td>Global</td>
<td>Kanamitsu et al. (2002)</td>
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<tr>
<td>ERA-Interim</td>
<td>170 km × 135 km</td>
<td>60</td>
<td>Global</td>
<td>Dee et al. (2011)</td>
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<tr>
<td>JRA-25</td>
<td>120 km × 120 km</td>
<td>40</td>
<td>Global</td>
<td>Onogi et al. (2007)</td>
</tr>
<tr>
<td>CFSR</td>
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<td>37</td>
<td>Global</td>
<td>Saha et al. (2010)</td>
</tr>
<tr>
<td>NARR</td>
<td>32 km × 32 km</td>
<td>45</td>
<td>Regional</td>
<td>Mesinger et al. (2006)</td>
</tr>
<tr>
<td>MERRA</td>
<td>56 km × 60 km</td>
<td>42</td>
<td>Global</td>
<td>Rienecker et al. (2011)</td>
</tr>
</tbody>
</table>

FIG. 2. Average total precipitation rate for May 2001–10 for (a) NCEP2, (b) ERA-Interim, (c) MERRA, (d) JRA-25, (e) NARR, (f) CFSR, and (g) PRISM/UW.
observed at the central facility on 2 May occur after the passage of a cold front on 30 April.

Time-height cross sections of wind speed have been generated using each of the reanalysis products, and periods with LLJs have been identified during MC3E (Fig. 4). The lower-resolution reanalyses, including the NCEP2, ERA-Interim, and JRA-25, have smaller peak wind speeds during LLJs than those found for the MERRA, NARR, CFSR, and observations. For example, LLJs are observed between 8 and 12 May that have peak wind speeds larger than 28 m s\(^{-1}\). During this same time period the wind speeds of the LLJs in the MERRA, NARR, and CFSR are between 30 and 24 m s\(^{-1}\). The wind speeds associated with the LLJ in the NCEP2, ERA-Interim, and JRA-25 are weaker than the observations and generally smaller than the MERRA, reaching peak values of 24, 26, and 24 m s\(^{-1}\), respectively.

The MC3E radiosonde network provides the opportunity to examine the horizontal variability of the LLJ over the study domain. The composite wind speed profiles derived using data collected for the LLJs indicate little difference in the average vertical structure of the LLJ at the various sites (not shown). There are, however, several instances when an LLJ is observed at only a subset of the MC3E radiosonde launch locations. For example, during the period from 7 through 12 May, 11 LLJs were observed at the ACRF SGP central facility and 13 LLJs were observed at the S5 site, which was approximately 180 km south of the central facility (Fig. 1). The wind roses shown in Fig. 1 have been generated using the wind speed and direction measured at the jet maxima. They highlight the range of wind directions associated with the LLJ and the variability of the LLJ across the measurement domain, with the strongest LLJs being found in the western half of the MC3E domain. Frequency of occurrence of the LLJ at the S2, S3, and S5 sites is summarized in contingency tables (Tables 3 and 4). Additional tables were

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**FIG. 3.** Time–height cross section of (a) specific humidity, (b) wind direction, (c) wind speed, and (d) moisture transport measured by radiosondes launched at the ACRF central facility during MC3E. Symbols indicate occurrences of LLJs in categories 0 (circles) and 3 (crosses).
constructed for the other sites, but they are similar and are therefore not included here. Focusing on S2 and S3 (which are separated by approximately 375 km), when an LLJ was observed at S2, an LLJ was observed at S3 62% of the time. Conversely, when an LLJ was observed at S3, an LLJ was observed at S2 76% of the time. Similar statistics were found for a comparison between S2 and S5. While LLJs were frequently found to span the radiosonde domain, there is also spatial variability in the strength of the LLJ. For example, when a category 2 LLJ was observed at S2, there are many instances (17 out of 21 cases) when a weaker or stronger LLJ was observed at S3 (Table 3). The MC3E radiosonde data have also been analyzed to determine times when the same category of LLJ or the absence of an LLJ was observed at any two MC3E sites at the same time (Fig. 5). In cases

Fig. 4. Time–height cross section of wind speed derived from the (a) NCEP2, (b) ERA-Interim, (c) JRA-25, (d) MERRA, (e) NARR, (f) CFSR, and (g) observed during MC3E for grid points located near the ARM SGP central facility. Symbols show occurrences of LLJs and indicate their intensity and altitude.
where no LLJs are included, the same category of LLJ is observed at any two stations anywhere from 45% to 65% of the time. Site C1 is located at the center of the domain, and one might expect higher agreement between C1 and the other stations (Fig. 5a). That is not necessarily the case, and the greatest level of agreement is found for stations C1 and S1 along with stations S2 and S3. The level of agreement drops when cases with no LLJs are excluded (Fig. 5b). This result highlights the large number of profiles that do not have LLJs over large parts of the day. The greatest level of agreement is still found for the same pairs, but the same category of LLJ is observed only 50% to 55% of the time. At the other extreme, the same category of LLJ is observed at stations C1 and S4 for only 20% to 25% of the observations. These results highlight the high degree of spatial variability in the LLJ on the spatial scale of the MC3E domain.

One important advantage of the reanalysis products is the ability to examine the spatial distribution of the LLJ over large areas, which is not possible with current observation networks. One such example, for 11 May 2011, highlights the spatial and temporal variability of the LLJ in the NARR and across the MC3E study domain (Fig. 6). The largest wind speeds are found over north-central Texas and south-central Oklahoma at 0300 UTC, while the radiosonde data (Holdridge et al. 1994) show larger wind speeds extending into western Kansas. As the evening progresses, the largest wind speeds increase, and the area of the largest wind speeds moves north of central Oklahoma (0600 UTC) and central Kansas (0900 UTC) in agreement with the radiosonde data, with the exception of the observations made at S2. By 1200 UTC the area of maximum wind speed has moved south to be over central Texas, and by 1800 UTC the LLJ has dissipated.

Composite profiles of observed wind speed for each category of LLJ observed from the ACRF SGP central facility and derived from the six different reanalyses from the MC3E period are shown in Fig. 7. Each reanalysis is subsampled so that only results from periods during which there are valid radiosondes are included in the figure. In addition, the NARR and CFSR, which have time frequencies of 3 and 1 h, respectively, have been subsampled at 6-h intervals to match both the data and coarser time resolution of the other reanalysis products. There is a tendency for the reanalysis to overestimate the wind speed below a pressure level of 800 mb, particularly in the case of stronger (category 2 and 3) jets, although the differences are not significant at the 0.05 level. The LLJs in the reanalysis products also tend to have their maximum velocity higher above the surface and have LLJs that are thicker than those observed. The standard deviation of the observations (error bars) as well as from the NARR and MERRA (shading) are shown in Fig. 7. The magnitudes of the standard deviations of the two reanalyses are in agreement with the observed standard deviation. While there are biases, the mean from each reanalysis falls within the spread of the observations. The relatively poor agreement between the observed and reanalysis-derived winds above 700 mb for the category 2 LLJs is associated with a very small number of cases in which the observed winds were quite large aloft (see, e.g., the period around 2 May in Fig. 4).

In addition to the biases in the wind speed determined from the reanalyses, there are large differences in the number of LLJs during the MC3E period, particularly for the reanalyses with coarser resolution, with only 10 LLJs identified in the NCEP2, 41 in the ERA-Interim, and 46 in the JRA-25 compared to 75 in the observations during MC3E, consistent with the findings of Anderson and Arritt (2001) and Walters et al. (2014). Category 0 and 1 LLJs are the least frequent (15 observed cases for each category), category 2 LLJs were found in 19 radiosonde profiles, while category 3 LLJs were found in 27 profiles. Regardless of the LLJ category, there are more observed LLJs than determined from any reanalysis products, although the agreement is better for
the high-resolution NARR, MERRA, and CFSR. The difference between the number of observed LLJs and LLJs in the reanalysis is greatest for category 3 LLJs. In this case there were 27 LLJs observed, while the NARR had 16, the CFSR had 11, and the MERRA only 10.

These results can be examined further by looking at PDFs of LLJ height (defined as the pressure level of $U_{max}$), although these distributions are noisy because of the relatively small number of LLJs during MC3E (Fig. 8). The median height of observed category 0 and 1
LLJs is near a pressure level of 950 mb, but the results are skewed and some cases are observed to occur at pressures as small as 775 mb. The median pressure level of the category 2 LLJs is 925 mb, and all of the cases are observed to occur between 950 and 825 mb. The observed category 3 LLJs are generally higher, with a median pressure of 875 mb, and all of the observations occur between 950 and 825 mb. The PDFs of pressure

FIG. 7. Composite wind speed profiles for LLJ categories 0 through 3 observed using the ACRF SGP central facility radiosondes during MC3E (black) and reanalysis products (colors) as described in the figure legend. The numbers indicate the number of individual profiles used to construct the composite profile. Error bars show the standard deviation of the observations, and shading indicates the standard deviation of the NARR (pink) and MERRA (light blue). Filled circles on the reanalysis curves indicate pressure levels where the differences between the observations and reanalysis are significant at the 0.05 level.
The level of $U_{\text{max}}$ derived from the reanalyses are also included in Fig. 8. In the case of category 0 and 1 LLJs, each reanalysis had an increased frequency of LLJs relative to the observations at pressures smaller than 950 mb. The differences in the observed and reanalysis-derived LLJs are less pronounced for the category 2 LLJs. The category 3 LLJs obtained from the JRA-25 and ERA-Interim were found to be between 875 and 825 mb, well above many of the observed LLJs, but there was better agreement for the MERRA and NARR.
The PDFs of observed LLJ thicknesses are found to range from 75 to 325 mb (Fig. 9), and the thickest LLJs are found in category 0. Category 3 LLJs have a smaller range of thickness than the other categories. There were no systematic differences in the vertical extent of the LLJ as a function of the location of the radiosonde launch site (not shown). These thickness values found over the southern Great Plains are generally smaller than those reported by Kalapureddy et al. (2007) for LLJs over India. The LLJs from the reanalyses covered

Fig. 9. Similar to Fig. 8, but for LLJ thickness rather than pressure level of the LLJ.
b. Multiyear analysis

MC3E spans a period of approximately 6 weeks. Data from the ACRF SGP central facility, however, can be used to look at the properties of the LLJ over a much longer time interval, and in this case May (to be consistent with the duration of MC3E) and May–August over the 10-yr period from 2001 through 2011 have been selected for a detailed analysis of LLJs. Based on the results from the MC3E period, the NARR, MERRA, and CFSR reanalyses are found to do the best job representing various aspects of the LLJ and represent reanalyses with relatively fine resolution (56 km × 60 km for the MERRA, 32 km × 32 km for the NARR, and 38 km × 38 km for the CFSR at the latitude of the ACRF SGP central facility). Therefore, only these three products are used in the multiyear analysis of the LLJ presented in this section.

Ten-year composite wind speed profiles have been constructed using observations from the ACRF SGP central facility for both May and May–August. While there is generally good agreement between composites generated from the observations and both reanalysis products (Fig. 10) during May, there is a tendency for the MERRA to have a larger wind speed between the nose of the LLJ (near a pressure level of 900 mb) and a pressure level as high as 800 mb for category 0, 1, and 2 LLJs. The agreement is better for category 3 LLJs. The performance of the CFSR is similar, but the overestimate of wind speed extends to a pressure level of approximately 800 mb for all categories of LLJ. The NARR underestimates the wind speed below LLJs in cases with category 1, 2, and 3 LLJs. The NARR overestimates the wind speed for pressure levels ranging from 925 to 825 mb in the case of category 1 LLJs and at a pressure level of 900 mb in the case of category 2 LLJs. When LLJs are present, the wind speeds derived from the reanalyses are smaller than the observed wind speed above a pressure level of 700 mb, but the differences are statistically significant only for the MERRA. This behavior is consistent with the results from the MC3E period, although the differences are smaller for the 10-yr period. This is due in part to the larger number of samples in the 10-yr datasets. The variability in the observations and reanalyses is nearly the same, as demonstrated by the similar standard deviations shown in Fig. 10.

The NARR, MERRA, and CFSR capture the relative frequency of category 0, 1, and 2 LLJs reasonably well (Fig. 10). The NARR overestimates the frequency of category 0 LLJs by 5%, while the MERRA had 15% fewer LLJs than observed. For category 1 LLJs the NARR underestimates the number of LLJs by 9%, compared to 5% for the MERRA and 4% for the CFSR. In the case of category 2 LLJs the NARR overestimates the frequency of occurrence by 8%, while the MERRA underestimates by 11%. The CFSR overestimates the number of category 2 LLJs by 33%. The NARR and MERRA reanalyses do a much poorer job with the category 3 LLJs, with 29% or 55% fewer LLJs than observed, respectively. In contrast, the CFSR underestimates the category 3 LLJs by only 1%. It is interesting to note that there were only small differences in the observed LLJ frequency or intensity between the dry (2006) and wet (2007) years that are included in the 10-yr period.

Ten-year composite wind speed profiles have been constructed for May–August. The MERRA, NARR, and CFSR overestimate the wind speed associated with the LLJ from the nose of the LLJ to pressure levels as high as 700 mb, depending on the intensity of the LLJ (Fig. 11). Similar to the May composite, the NARR wind speed is smaller below the altitude of $U_{\text{max}}$ for all categories of LLJs than the MERRA or the observations. The reanalysis products shown here reproduce the observed variability for each category of LLJ, as indicated by the shading and error bars in Fig. 11. Similar to the analysis of the results from the MC3E period and May 10-yr period, the NARR and MERRA tend to underestimate the frequency of occurrence for the more intense category 2 and 3 LLJs. The frequency in the CFSR, however, is much closer to what is observed. For example, the NARR had 17% and 38% fewer category 2 and 3 LLJs, the MERRA had 15% and 53% fewer category 2 and 3 LLJs, and the CFSR had 15% more category 2 and 9% fewer category 3 LLJs than were observed.

The PDFs of the heights of the peak wind speed for LLJs during the MC3E period are relatively noisy because of the small number of events (Fig. 8). Examining the 10-yr periods, either May or May–August, reduces the amount of noise (Fig. 12 and Fig. 13). The median pressure level of observed LLJs in the May 10-yr average ranges from 950 to 900 mb for the various categories. The PDF of the observed category 0 LLJs ranges from 975 to 725 mb, while the distribution of category 3 LLJs occurs over a much smaller range of pressure levels (975–850 mb), and the range of category 1 and 2 LLJs falls between these two extremes. The PDFs of LLJ heights derived from the NARR, MERRA, and CFSR reanalysis are nearly the same as the observations,
although the category 0 and 1 LLJs are found at slightly higher pressure levels. In the case of category 3 LLJs, the median height in the CFSR is found to be at a slightly higher pressure level than in the NARR or MERRA. When the May–August 10-yr period is considered, the distribution of observed LLJs becomes more peaked, with a median height of 950 mb for category 0 and 1 LLJs and 975 mb for category 2 and 3 LLJs. Similar behavior is seen in both reanalyses but with the median value being 25 mb smaller than the observations.

Similar to the PDFs of the pressure level of the LLJ, the PDF of LLJ thickness derived from the reanalysis products during MC3E were noisy because of the relatively small number of cases. As one would expect, the PDFs of the LLJ thickness are smoother when the analysis is extended to include a 10-yr period (Fig. 14).
During the May period, the thickness of the LLJ was found to range from 50 to 325 mb for category 0 and 1 LLJs. The more intense category 2 and 3 LLJs generally have less vertical extent (ranging from 50 to 225 or 250 mb for category 2 and 3 LLJs, respectively). Similar behavior is found for the NARR, MERRA, and CFSR reanalyses, but the category 2 and 3 jets in the MERRA are thicker than NARR or CFSR jets, while the distributions are nearly the same (and generally in good agreement with the observations) for cases with weaker jets. PDFs of LLJs have been computed for May–August 2001–10, and the results are similar to the May 10-yr period (not shown).

From the results presented here, it is not possible to determine why the NARR and MERRA reanalysis products underestimate the frequency of category 3

FIG. 11. Similar to Fig. 7, but for LLJs during the period May–August 2001–10 rather than MC3E.
LLJs by 38% and 53%, respectively. The behavior of the CFSR is better in this regard, and category 3 LLJs are underestimated by only 9%. The better estimates by the CFSR and to a lesser extent NARR could indicate that increasing the horizontal resolution from the MERRA’s 56 km × 60 km to the CFSR’s 38 km × 38 km and NARR’s 32 km × 32 km, or that the assimilation of precipitation over the continent in the NARR, leads to improved performance, but there are many other differences related to the details of the data assimilation that could have an impact as well. It is worth noting that these three reanalyses utilize the same vertical
resolution for pressures greater than 300 mb so that differences in the vertical resolution are not responsible for the differences seen in this study.

5. Impact of LLJs on moisture transport

Enhanced transport of moisture from south to north is one important climatological impact of the LLJ. There were two periods during MC3E (7–12 and 19–27 May) during which there were large values of $q$ and southerly winds (Fig. 3). These periods have the largest values of observed moisture transport seen during the entire MC3E study period, and nearly 55% of all observed moisture transport over the ACRF SGP central facility during MC3E was associated with LLJs (Fig. 15). The strongest LLJs, those in category 3, contribute nearly

Fig. 13. Similar to Fig. 12, but for May–August 2001–10 rather than May 2001–10.
24% of the observed total observed moisture transport. There are observed differences in the moisture transport across the study domain, with the total moisture transport by LLJs representing 49%–65% of the total moisture transport at the MC3E sites, and category 3 LLJs contribute 17% and 35% of the total transport observed at the MC3E sites. There are large differences between the observed and reanalysis-derived fraction of moisture transport due to LLJs. Each reanalysis attributes too little moisture transport to the cases with LLJs.

FIG. 14. Frequency of occurrence for category 0, 1, 2, and 3 LLJ thicknesses computed from the observations (gray boxes) and NARR (red) and MERRA (blue) reanalysis products for the period of May 2001–10.
compared to the observations (Fig. 15). The reanalyses underestimate the transport because of their inability to represent the transport associated with strongest LLJs, with the smallest differences found for the MERRA and NARR. It is interesting to note that while the CFSR had nearly the correct number of category 3 LLJs, it still underestimated the transport by those jets during MC3E.

The trends in moisture transport change when the analysis period is extended to 10 years. For both May and May–August the NARR and CFSR moisture transports were larger than the observed transport while the MERRA was smaller (Fig. 15). There is also better agreement in the fraction of moisture transport associated with category 0, 1, and 2 LLJs between the NARR, MERRA, and CFSR when compared to the observations. Similar to the findings for MC3E, the MERRA, NARR, and CFSR underestimate the moisture transport associated with the category 3 LLJs, although the CFSR is closest to the observations. Given the reasonable agreement in the composite profiles during conditions with LLJs (Fig. 10 and Fig. 11), the differences in the transport are likely due to the relatively small number of category 3 LLJs in the reanalyses, similar to the results for the MC3E period.

The reanalysis products can be used to provide insight into the regional moisture budget and the relative role of the LLJ in the moisture budget over the central United States. The atmospheric water budget for an arbitrary control volume reaching from the surface to the top of the atmosphere can be expressed as (Trenberth and Guillemot 1998; Trenberth et al. 2011)

$$\frac{\partial w}{\partial t} + \mathbf{V} \cdot \nabla \int_0^P \rho w d\sigma = E - P, \quad (1)$$

where $w$ is the precipitable water, and $E$ and $P$ are the surface evaporation and surface precipitation rate, respectively. The second term on the left side of (1) represents the moisture convergence or divergence within the control volume. The moisture convergence has been calculated from the NARR, MERRA, and CFSR reanalyses for periods with and without LLJs at the ACRF SGP central facility using (1). During MC3E, the moisture transport in the MERRA reanalysis is significantly enhanced for cases with LLJs compared to those without (as shown by the vectors in Fig. 16). In the MERRA there is also a region of moisture divergence over central Texas and central Oklahoma when the LLJs are present that is associated with the acceleration of the winds by the LLJ (as shown by the colors in Fig. 16). There are areas of moisture convergence over western Texas and central Kansas and Nebraska in the MERRA. As expected, the convergence and divergence are weaker for non-LLJ cases, and there is generally weak divergence over central Oklahoma. The moisture convergence pattern associated with the CFSR is similar to the MERRA in some regards. For example, in the CFSR there is an area of moisture divergence over much of Oklahoma and moisture convergence over parts of

![Figure 15](https://example.com/figure15.png)
Kansas and Nebraska. The CFSR also has large areas of moisture convergence over the Texas Gulf Coast, where both the MERRA and NARR have moisture divergence. The pattern is much different in the NARR reanalysis compared to the MERRA and CFSR. In the NARR, the magnitude of the moisture transport does not change much between the LLJ and non-LLJ case. In cases with an LLJ at the ACRF SGP central facility, the moisture transport in the NARR has a much larger westerly component than was seen in either the MERRA or CFSR, indicating that the moisture from the Gulf of Mexico does not make it as far north as in the MERRA or CFSR. When an LLJ is present over the SGP central facility in the NARR there is moisture convergence over Oklahoma and Arkansas as well as over part of central Texas (Fig. 16). This behavior leads to weaker moisture convergence over the northern Great Plains in the NARR compared to the MERRA and CFSR when LLJs are present. When LLJs are not present in the NARR at the ACRF SGP central facility there is still an area of moisture convergence over northern Arkansas and southern Missouri and weak moisture divergence over Oklahoma.

The analysis has also been completed for May–August over the 10-yr period (Fig. 17), and there is generally better agreement between the NARR, MERRA, and CFSR when the longer time period is considered. When LLJs are found over the ACRF SGP central facility in the MERRA there is moisture convergence over eastern Kansas, Missouri, and Iowa, as well as along the Gulf Coast of Texas and northern Mexico (with the largest values of convergence found over northern Mexico). There is moisture divergence over much of Oklahoma, which is likely driven by the acceleration of the LLJ across the state, similar to the conditions during MC3E. The MERRA pattern of moisture transport over much of Oklahoma is similar to that in non-LLJ cases with moisture divergence found over the state. There are differences in the regional distribution of moisture convergence and divergence in the MERRA in the non-LLJ cases. Moisture convergence is found over western Texas, Oklahoma Panhandle, western Kansas, and western Nebraska and moisture divergence over much of Oklahoma, eastern Kansas, and eastern Nebraska. The results from the CFSR are similar in pattern to the MERRA. When an LLJ is present at the ACRF SGP central facility there is a region of moisture divergence over much of Oklahoma, while moisture convergence is found over eastern Kansas, Missouri, Iowa, and the Gulf Coast of Texas (which is the location of the largest moisture convergence in the CFSR). When no LLJs are present, the CFSR has widespread moisture divergence over Oklahoma and the northern Great Plains and an area of moisture convergence along the Gulf Coast of Texas. The results from the NARR are noisier than those from the MERRA and CFSR. In the NARR the area of largest moisture convergence is found over

![Image of moisture convergence and column-integrated moisture transport](http://journals.ametsoc.org/jcli/article-pdf/28/17/6682/4049302/jcli-d-14-00719_1.pdf)
eastern Kansas, eastern Nebraska, Missouri, and Iowa. There is also convergence along the Texas Gulf Coast, but it is more muted than that seen in the CFSR and MERRA. There is moisture divergence over central Oklahoma and Texas, but it is less pronounced than what is found for the MERRA. When no LLJs are present at the ACRF central facility there is very little systematic pattern to the convergence and divergence in the NARR.

The precipitation in all three reanalysis products is quite different for cases with LLJs at the SGP central facility (Fig. 18). While all three products have a peak in precipitation over Iowa, the intensity is much larger and the area more widespread in the NARR than in the MERRA and CFSR. The MERRA also has a much larger amount of precipitation along the Gulf Coast compared to the NARR, with the precipitation in the CFSR being between the other two. Based on the results shown in Fig. 18, it appears that much of the summertime precipitation over Iowa and the adjoining region is associated with periods in which an LLJ is observed over the SGP central facility, but it is important to note that there are many more non-LLJ cases than LLJ cases and that the precipitation rate shown for the instances with LLJ shrinks if averaged over the entire time period (which can be noted by comparing Fig. 18 with Fig. 2, which shows the muted precipitation amounts over Iowa compared to regions to the south). Even with this consideration, it is clear that the LLJ plays an important role in patterns of moisture convergence/divergence and the hydrologic cycle, and the region of precipitation centered over Iowa matches the regions of moisture convergence in each reanalysis.

The NARR, MERRA, and to a lesser extent CFSR underestimate the moisture transport associated with category 3 LLJs. The differences in the $q$ derived from the radiosondes and from the NARR, MERRA, and CFSR are relatively small (not shown), so differences in moisture transport are most likely associated with differences in LLJs. It is interesting that the NARR overestimates the moisture transport in the 10-yr composite even while underestimating the moisture transport associated with the LLJs. This implies that the NARR overestimates the moisture transport during non-LLJ periods. The MERRA underestimates the moisture transport over the full 10-yr period but also underestimates the moisture transport associated with the LLJ. The total moisture transport associated with the CFSR is in good agreement with the observed values over the 10-yr period, although this reanalysis also has too little transport associated with LLJs. Increasing the frequency of category 3 LLJs in the MERRA could increase the moisture transport to be in better agreement with the observations. The differences in the LLJ and moisture convergence in the MERRA, NARR, and CFSR could explain at least some of the differences seen in the precipitation when LLJs are present, but a more detailed explanation would
require a much more in-depth analysis than is possible in the context of this work. For example, the CFSR has a region of moisture convergence reaching through Missouri and into Arkansas when LLJs are present (Fig. 17), but there is very little precipitation found in that area (Fig. 18). Additional research should be directed toward our understanding these discrepancies between the moisture transport derived from the reanalyses and the observations.

6. Summary and conclusions

This study utilized six commonly used reanalysis products, including the NCEP2, ERA-Interim, JRA-25, MERRA, NARR, and CSFR, to study key features of the southern Great Plains LLJ, including the role of the LLJ in moisture transport over the region. The reanalyses were evaluated using radiosonde observations obtained from the ACRF SGP site. This particular location was selected because of the relatively high temporal frequency of radiosonde launches (6 h compared to 12 h in the regular synoptic network) and its application to previous studies such as Whiteman et al. (1997) and Song et al. (2005). Two different observation periods were used: One was the approximately 6-week-long MC3E study that included radiosondes launched from five additional locations within the ACRF SGP site. The second period was a 10-yr period from 2001 to 2010 focused on both May (to correspond with the length of the MC3E study) and May–August.

During MC3E there are biases in the composite wind speed profile compared to the observations. The reanalyses overestimated the wind speed between the nose of the LLJ and a pressure level of 800 mb. The reanalysis products also tend to have the nose of the LLJ at a higher altitude than is observed, regardless of the spatial resolution of the reanalyses. These differences, however, were not statistically significant at all pressure levels. The PDF of LLJ thickness showed generally good agreement between the high-resolution reanalyses and the observations, while the NCEP2 and ERA-Interim reanalyses had LLJs that were much thicker than those observed. There were differences in the frequency of occurrence of the LLJs with many more jets being observed than were found for any of the reanalysis products. The relatively high-resolution NARR, MERRA, and CSFR included many more LLJs than the low-resolution reanalyses.

The radiosonde network deployed during the MC3E period provides the opportunity to investigate the spatial variability of the LLJ on horizontal spatial scales on the order of 150 km. When an LLJ is observed at one remote site, one is found at another selected remote site 62% to 76% of the time. There were, however, a number of cases where LLJs of different strengths were found at the different sites, indicating that there is spatial heterogeneity to the LLJ over the southern Great Plains.
This behavior could be due to the presence of individual jet filaments or instances when one station is located near the core of the LLJ and another station is closer to the edge.

Only the NARR, MERRA, and CFSR are included in the 10-yr analysis. The results were generally consistent with the findings from the MC3E period, and all three overestimate the wind speed between the nose of the LLJ and a pressure level of 800 mb but were able to represent the observed variability. There is generally good agreement between the PDFs of LLJ height and thickness compared to the observations from the 10-yr period. The number of weak and moderate LLJs (category 0, 1, and 2) were nearly the same in the observations and reanalyses, although many more category 3 LLJs were observed than appeared in either the NARR or MERRA, consistent with the findings of Anderson and Arritt (2001) and Walters et al. (2014). There is, however, much better agreement between the number of observed category 3 LLJs and the CFSR.

The moisture transport is computed from both the radiosondes and the reanalyses. During MC3E, the majority of the moisture transport computed from the reanalyses is associated with periods without LLJs, and category 3 LLJs are found to contribute very little to the total moisture transport. In contrast, the observed LLJs contribute more than half of the total moisture transport, and category 3 LLJs contribute more than LLJs in any other category. During the 10-yr study period, the observations show smaller contributions to the moisture transport from LLJs, but it is still larger than the transport by LLJs derived from the MERRA, NARR, or CFSR.

Regional-scale features of the moisture transport and moisture convergence and divergence are determined using the NARR, MERRA, and CFSR for periods with and without LLJs over the ACRF SGP central facility. During MC3E, there are significant differences in the moisture transport derived from the NARR, MERRA, and CFSR. The transport in the MERRA as well as the CFSR has a larger northward component compared to the NARR, and both the MERRA and CFSR have a large area of moisture divergence over central Oklahoma. When 10-yr averages are considered the differences in the moisture transport are smaller, and the areas of moisture convergence/divergence are in better agreement, although there are large differences in the precipitation pattern. Overall the results from this study highlight that while the reanalyses generally do a reasonable job representing the structure of the LLJ, they underestimate the frequency of occurrence of LLJs and thus the contribution of the LLJs to the total moisture transport. The MERRA, NARR, and CFSR have a region of enhanced precipitation centered over Iowa when an LLJ is present, with the most precipitation in NARR and the least in MERRA, consistent with the magnitude of the moisture convergence over this region.

Based on the results of this study, it is difficult to determine why there are the observed biases in the frequency of LLJs. While increasing the vertical and horizontal resolution leads to improved performance (as found by comparing the frequency of intense LLJs between the NARR, MERRA, CFSR, and other reanalyses), other factors might also be important. For this reason, additional studies are needed to help identify the causes of these biases and develop improved reanalysis products.

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