A Synoptic Climatology of Spring Dryline Convection in the Southern Great Plains

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ABSTRACT

A dataset of drylines within a region of the southern Great Plains was constructed to investigate the large-scale environments associated with the initiation of deep moist convection. Drylines were identified using NOAA/NWS Weather Prediction Center surface analyses for all April, May, and June days 2006–15. Doppler radar and visible and infrared satellite imagery were used to identify convective drylines, where deep, moist convection was deemed to have been associated with the dryline circulation. Approximately 60% of drylines were convective, with initiation most frequently occurring between 2000 and 2100 UTC. Composite synoptic analyses were created of 179 convective and 104 nonconvective dryline days. The composites featured an upper-level long-wave trough to the west of the Rockies and a ridge extending across the northern and eastern United States. At the surface, the composites featured a broad surface cyclone over western Texas and southerly flow over the south-central states. Convective drylines featured more amplified upper-level flow, associated with a deeper trough in the western United States and a stronger downstream ridge than nonconvective drylines up to 5 days preceding a dryline event. By the day of a dryline event, the convective composite features greater low-level specific humidity and higher CAPE than the nonconvective composite. These results demonstrate that synoptic-scale processes over several days help create conditions conducive to deep, moist convection along the dryline.

SIGNIFICANCE STATEMENT

The southern Great Plains dryline separates moist air from the Gulf of Mexico from drier air farther west. Drylines sometimes initiate convective storms, that is, storms that produce lightning, tornadoes, and other extreme weather. We wanted to know if we could tell the difference between days when such storms occur and days when they do not. We found that there were distinctive weather patterns in the middle and upper troposphere that distinguished these two sets of days. These differences were apparent 3–5 days ahead of time, suggesting an opportunity for more lead time in forecasting such storms.

1. Introduction

The southern Great Plains dryline is a boundary that separates moist air originating over the Gulf of Mexico from drier air originating from the desert southwest (e.g., Rhea 1966; Schaefer 1973, 1974; McCarthy and Koch 1982; Schaefer 1986; Hane 2004; Hoch and Markowski 2005). The dryline is often associated with a

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zone of convergence beneath the ascending portion of a thermally direct circulation (e.g., [Sun and Ogura 1979](#); [Ziegler et al. 1995](#)). This convergence zone is a preferred region for convection initiation (e.g., [Fujita 1958](#); [Beebe 1958](#); [Miller 1959](#); [McGuire 1962](#); [Rhea 1966](#)). However, low-level moist air east of the dryline is typically capped by warmer, drier air. The environment east of the dryline can also be hostile to deep convection because dry-air entrainment can reduce the buoyancy of ascending air parcels. For deep convection to occur, moist air parcels need to be lifted to their level of free convection before leaving the mesoscale updraft region ([Ziegler and Rasmussen 1998](#)). As incipient convection moves away from the dryline, it requires sufficient instability for deep convection to develop. Moisture, instability and lift are necessary ingredients for deep, moist convection to occur ([Doswell 1987](#)), and the dryline is often a region where these ingredients overlap. However, despite the apparent presence of these ingredients, sometimes deep, moist convection does not develop along or near the dryline ([Ziegler et al. 1997](#)).

Uncertainty over whether deep convection will occur is not limited to drylines. Convection initiation in general is sensitive to small changes in conditions, such as changes in temperature and moisture within the planetary boundary layer ([Mueller et al. 1993](#); [Crook 1996](#)) and changes in lapse rate above the level of free convection ([Houston and Niyogi 2007](#)). Improving understanding of convection initiation has been a motivation of research projects such as the International H₂O Project (IHOP_2002; [Weckwerth and Parsons 2006](#)) and the Spring Forecast Experiment of 2011 ([Kain et al. 2013](#)). Although not focused on dryline convection specifically, some cases of convection initiation during those projects occurred along the dryline. However, robust conclusions regarding dryline convection initiation are hard to draw due to the small number of dryline events. For instance, the Spring Forecast Experiment of 2011 included only five cases of dryline convection initiation. Despite this limitation, the literature on dryline convection contains several examinations of the causes of convection initiation failure along the dryline, particularly during IHOP.

One such example of initiation failure during IHOP was examined by [Demos et al. \(2006\)](#). They speculated that a relatively dry near-surface layer, a strong capping inversion, and moisture detrainment in a dry layer between the LCL and the LFC were detrimental to initiation. The presence of a dry layer between the LCL and LFC was also thought to have contributed to initiation failure during the Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX;

[Weiss and Bluestein 2002](#)) and in an IHOP case examined by [Cai et al. \(2006\)](#). [Cai et al. \(2006\)](#) also found that midlevel subsidence contributed to a strong capping inversion over the dryline. Midlevel subsidence and warming were also blamed for initiation failure in a case from VORTEX studied by [Richter and Bosart \(2002\)](#) as a short-wave ridge migrated over the Texas Panhandle region. The importance of migratory mesoscale features for convection initiation was also demonstrated by [Hill et al. \(2016\)](#). In a simulation of two dryline events, they found that convection initiation was sensitive to the location of a 700-hPa short-wave trough.

Although the passage of features such as short-wave ridges and troughs are primarily mesoscale processes, variables such as the strength of a capping inversion, the vertical distribution of moisture, and the magnitude of moisture detrainment can also be affected by large-scale processes. [Schultz et al. \(2007\)](#) showed that synoptic-scale processes are important in regulating the strength of the dryline. Stronger drylines were associated with passage of a short-wave trough in the ambient westerlies, favoring surface cyclogenesis, increased confluence, and tighter moisture gradients. Short-wave troughing may also increase the likelihood of convection given the presence of a dryline. [Rhea \(1966\)](#) found that 71% of cases of storm formation within 100 n mi (185 km) of the dryline were associated with a discrete feature at 500 hPa in the temperature or wind field at 1200 UTC. The most frequent of these features was an upstream trough. However, Rhea did not examine the synoptic environment for drylines that did not produce convection. Questions remain as to the role of large-scale processes in dryline convection initiation. Does short-wave troughing west of the dryline increase the chances of convection? More generally, are there large-scale differences between drylines that produce deep, moist convection and those that do not? Or is dryline convection initiation determined only by smaller-scale processes that are harder to predict at short time scales? These questions suggest the need for a climatology of dryline convection initiation.

Although there have been several studies of the mechanisms by which dryline convection occurs, there has only been one previous climatology of dryline convection specifically. [Rhea \(1966\)](#) identified thunderstorm formation along drylines on April, May, and June days for 1959–62. The dryline location was estimated using 3-h surface charts, and thunderstorms were identified by examining hourly radar summaries for new echoes within 200 n mi (370 km) of the dryline. However, Rhea's work was somewhat limited by the lack of meteorological data available. Present-day observation networks such as the state mesonets in Texas and Oklahoma make it easier to determine dryline

location and subsequent convection today. Furthermore, the availability of atmospheric reanalyses provides more options for examining dryline conditions, including the potential for automated detection (Clark et al. 2015).

To address the question of whether there are large-scale differences between convective and nonconvective drylines, we present a climatology of dryline convection initiation in the southern Great Plains by separating days with drylines into those that produced deep, moist convection and those that did not. In section 2, dryline days are identified using NOAA/NWS Weather Prediction Center surface analyses, then days with or without convection are identified using NEXRAD radar mosaics and visible and infrared satellite imagery. Section 3 presents a climatology of convection at the dryline. In section 4, the differences between convective and nonconvective drylines are discussed by examining composite dryline environments constructed from North American Regional Reanalysis (NARR) data. Section 5 examines composite dryline environments in the days preceding a dryline event. Finally, section 6 summarizes the main results of this article.

2. Data and methods

a. Dryline selection

Drylines have commonly been identified using gradients in moisture obtained from surface station data (e.g., Rhea 1966; Schaefer 1973; Peterson 1983). Dewpoint temperature has often been used as a measure of surface moisture because it is easily obtained from NWS observations (Schaefer 1986). However, the dryline is not always identified by exclusively considering moisture gradients. In addition to requiring a 10°F (5.6°C) dewpoint discontinuity between neighboring stations, Rhea (1966) also required an organized line of veering surface wind. Schaefer (1973) expanded these criteria to include a diurnal reversal of the direction of the temperature gradient across the dryline. More recently, in their climatology of drylines, Hoch and Markowski (2005) excluded the necessity for a wind shift or diurnal reversal of temperature gradient. They also considered specific humidity rather than dewpoint, because specific humidity is conserved when gradients in pressure are present due to sloping terrain. Finding a reliable method to identify drylines is an ongoing problem (e.g., Coffey et al. 2013; Clark et al. 2015), with no widely used method to automate dryline identification. Because the focus of the present study was to identify dryline convection rather than develop a method to identify

drylines, we therefore used an existing dataset that includes previously identified drylines by an independent organization.

The Weather Prediction Center (WPC) combines analyses from the Hydrological Prediction Center, Ocean Prediction Center, National Hurricane Center, and the Honolulu Weather Forecast Office to form the Unified Surface Analysis, available at 3-h intervals (Berg et al. 2007). These analyses are created by experienced surface analysts using a library of conceptual models with the aid of data from surface observations, satellite data, and model analyses, and the analyses depict synoptic and mesoscale features such as fronts, troughs, outflow boundaries, and drylines (NOAA 2013). According to the Unified Surface Analysis Manual, “A tight 14°C (25°F), or a broader 17°C (30°F), dewpoint gradient is used to help determine the existence of a dryline. The dryline does not have to be the leading edge of all the change in the dewpoint, merely where the best gradient/leading edge of foehn winds exists.” Dryline data were obtained from an online archive of surface analyses produced by the WPC, with analyses available from May 2005 onward. The choice of the WPC analysis for our dryline provided an independent analysis of dryline occurrence and location, minimizing any bias on our analysis. It also avoided us having to develop, verify, and implement criteria for dryline occurrence from gridded model output. Thus, in this instance, a manual method of detection was deemed superior to an automated method (Schultz 2009, 210–212).

WPC analyses were obtained for all April, May, and June days for 2006–15. These months were chosen for two reasons: 1) consistency with the months examined in previous dryline climatologies (e.g., Rhea 1966; Schaefer 1973; Peterson 1983; Hoch and Markowski 2005) and 2) convective storms most often initiate along the dryline during these months (Hoch and Markowski 2005).

Although most dryline studies have focused on late spring and early summer, previous climatologies differ in the size and location of the region in which drylines were considered. Schaefer (1974) only selected drylines in the south-central United States. Peterson (1983) was even more restrictive than Schaefer, only studying drylines in the West Texas region. However, Hoch and Markowski (2005) chose a broader region, identifying drylines within the Great Plains. The domain chosen for the present study (Fig. 1) was guided by the work of Hoch and Markowski (2005) who found that drylines were most frequent around 101°W, with approximately 98% of drylines located between 97° and 104°W. Thus, to limit the domain to be considered, we studied drylines

FIG. 1. The domain chosen for the dryline study is enclosed by the red box.

within a domain with a western boundary imposed along a line at 104°W , and an eastern boundary imposed at 97°W . The western boundary was chosen to incorporate dryline convection in western Texas and eastern New Mexico while avoiding convection initiation associated with upslope flow. Although dryline formation is dependent on the sloping terrain, topographic features can lead to localized regions of enhanced convergence, increasing the likelihood of convection (e.g., Banta 1984). The effects of local features on dryline convection are beyond the scope of this study. For similar reasons, the southern boundary was restricted to 31.5°N to avoid including the higher terrain in the Trans Pecos region (e.g., Nielsen et al. 2016). The northern boundary was imposed at 40°N , coincident with the Kansas–Nebraska state line. Although drylines can be observed north of this boundary, drylines are more frequently observed in Texas, Oklahoma, and Kansas (Schaefer 1986).

A day was classified as having a dryline if at least 100 km of a WPC-analyzed dryline was present within the domain in any analysis between 1500 and 0300 UTC the following day. Although drylines can occur outside of this time frame (e.g., see Fig. 5b in Hane 2004), drylines typically have a diurnal cycle with a peak in intensity in the late afternoon and early evening. Convection associated with the dryline also has a diurnal cycle. Rhea (1966) found that the first occurrence of convective echoes in the vicinity of the dryline was most common between 1900 and 2100 UTC, with no occurrences before 1500 UTC or after 0200 UTC. Therefore, the use of analyses between 1500 and 0300 UTC seems appropriate to capture most events.

Most dryline days featured drylines being present in more than one of the WPC analyses produced.

However, occasionally there were inconsistencies between consecutive analyses. An example of one such inconsistency is a feature analyzed as a cold front in the morning, but identified as a dryline in a subsequent analysis. We believe that these cases represent the same feature. Overnight, dry air west of the dryline often cools more quickly than the moist air to the east overnight, resulting in a west–east temperature gradient by morning. This temperature gradient may be misidentified as a cold front, before the gradient reduces or even reverses during the day. Because a dryline is only required to be present on one analysis on a given day, these instances were included, despite the duration of the dryline being in question.

Drylines were identified on 33 days per season on average, corresponding to approximately 36% of all days analyzed. This frequency of dryline occurrence is greater than that obtained by Hoch and Markowski (2005), who found drylines on 32% of the days they analyzed over a 30-yr period. They identified drylines using gradients of specific humidity obtained from surface observations, requiring a horizontal gradient of $3\text{ g kg}^{-1} (100\text{ km})^{-1}$. The most likely explanation why Hoch and Markowski identified a lower proportion of drylines is the use of a more restrictive time constraint. They required a dryline to be present at 0000 UTC, whereas the criteria used in this study allowed for a dryline at any time between 1500 and 0300 UTC. Sometimes a dryline can be present in the late morning or early afternoon, but may no longer exist by 0000 UTC. One such example is when a cold front moves east faster than the dryline, and they eventually merge.

b. Identifying dryline convection

The Iowa Environmental Mesonet generates and archives national radar mosaics, which are derived from base reflectivity output from the Next Generation Weather Radar (NEXRAD) network. The mosaics are available at 5-min intervals and can be viewed using the NCEI/NOAA Interactive Radar Map Tool (NCEI 2016). Potential dryline convection was identified using the radar tool, with a minimum radar reflectivity factor of 40 dBZ required for a continuous period of at least one hour. Echoes that satisfied these criteria were most likely indicative of deep, moist convection.

Echoes were not considered if they were deemed to have been caused by a feature other than a dryline. Preexisting convection such as a mesoscale convective system was excluded. Cases of convection that could be identified as being initiated along an outflow boundary were also excluded, as well as that associated with

frontal boundaries. However, convection that occurred at the intersection of a dryline and convective outflow or a front was considered. On occasion, a dryline was present during the afternoon, but was later overtaken by a cold front. Echoes were rejected if convection was not determined to have initiated along the dryline before it was overtaken by a cold front, even if subsequent echoes fulfilled the reflectivity criterion.

Visible and infrared satellite imagery were used to help distinguish convection initiating along the dryline from convection initiating along outflow boundaries or fronts. The dryline can often be spotted in visible imagery as a thin line of cumulus or the western edge of a cumulus field. When it was not possible to confidently identify the dryline using visible satellite imagery, infrared images were used. Infrared satellite images were useful in distinguishing drylines from fronts, particularly when the frontal temperature gradient was strong.

When a combination of visible and infrared satellite images failed to distinguish dryline convection, Doppler radar imagery was sourced for the nearest radar site with the aim of identifying radar fine lines. Radar fine lines are lines of low reflectivity returns that are not associated with precipitation. The returns are associated with scattering by insects and typically occur in areas of low-level convergence (Russell and Wilson 1997). The presence of fine lines is helpful in detecting boundaries such as drylines, fronts, and outflow (e.g., Geerts and Miao 2005).

On 41 occasions, the use of satellite and radar imagery failed to distinguish dryline convection from other types of convection. In these cases, Storm Prediction Center mesoscale discussions and National Weather Service (NWS) area forecast discussions were used as a supplement to the WPC analyses. Mesoscale discussions are usually issued in advance of severe weather and contain a forecaster's thoughts about a mesoscale event within the forecast area. The product is often a combination of a text forecast plus a mesoscale analysis, which can sometimes offer greater detail than the WPC surface analyses. However, mesoscale discussions are issued on an ad hoc basis and are not available every day, as opposed to area forecast discussions, which are issued by NWS offices several times a day. Area forecast discussions usually give a detailed breakdown of the forecast for a NWS forecast area and often include a summary of the challenges and general thoughts of the forecaster when making their forecast for the area (NOAA 2016).

Once dryline convection had been established, echoes were also required to have initiated no farther than 100 km from the dryline in a perpendicular distance to

the dryline orientation. The 100 km is consistent with Fig. 4 in Rhea (1966) who found first new radar echoes formed within 50 n mi (93 km) of 69 non-consecutive dryline days. More recently, Ziegler and Rasmussen (1998) used special mesoscale observations from three drylines studied during separate field projects. One of the cases they examined featured high-based cumulus 55 km east of the dryline. They found a peak cumulus frequency approximately 15 km east of the dryline, but urged caution when interpreting the results of such a small sample. Given the time it takes for initial cumuli to develop to 40-dBZ echoes, movement of the convective storms of the order of tens of minutes and tens of kilometers could have placed the storms farther east, as much as 100 km eastward.

Initiation was deemed to occur at the first occurrence of a 40-dBZ echo that maintained or exceeded that intensity for a continuous period of at least one hour. This threshold is consistent with previous literature on convection initiation (e.g., Parker and Johnson 2000; Fowle and Roebber 2003; James et al. 2005; Trapp et al. 2005; Hocker and Basara 2008; Grams et al. 2012). Because radar scans are available at 5-min intervals, the recorded time of initiation was at worst a late estimate by four minutes, but never early. At the time of initiation, the location of initiation was defined as the center of a local maximum in reflectivity.

3. Climatology of dryline convection

Three-hourly WPC surface analyses were analyzed between 1500 and 0300 UTC for all April, May, and June days 2006–15. Of the 329 drylines identified, 199 (60%) were associated with convective storms as defined in section 2b. The other 130 days did not fulfill the criteria of deep, moist convection defined in section 2b. The proportion of dryline days that produced deep, moist convection was less than that found by Rhea (1966) in his study of thunderstorm formation along drylines. He found new radar-echo development within 200 nautical miles (370 km) of the dryline for 70% of drylines identified. The most likely explanation for the lower frequency of dryline convection found in this study is the more restrictive criteria used. Echoes were required to be within 100 km of the dryline, rather than 370 km used by Rhea. The lower frequency may also be explained by the different durations examined. Rhea's study spanned only 4 years and may have sampled a period where dryline convection was more frequent than the long-term average.

The importance of the dryline sampling period is demonstrated when assessing the interannual variability

FIG. 2. The number of convective (purple) and nonconvective (orange) dryline days that occurred in a given year.

FIG. 3. The number of convective (purple) and nonconvective (orange) dryline days (2006–15) separated by the month in which they occurred.

of dryline convection (Fig. 2). Dryline frequency shows large year-to-year variation with as few as 16 dryline days in 2007 to as many as 50 in 2011. As with dryline frequency, there appears to be large interannual variability in dryline convection. The number of convective dryline days ranged from as few as 10 in 2007 to as many as 27 in 2013.

In addition to the variability in dryline frequency between years, the frequency of both drylines and dryline convection also varied within a season. Both dryline days and convective dryline days were most frequent in May, followed by April then June (Fig. 3). These results are similar to that of Hoch and Markowski (2005) who found that peak dryline frequency occurred in mid- to late May. When broken down by week (Fig. 4), dryline frequency appears to reduce toward the end of June. Hoch and Markowski also found a reduction in dryline frequency at the end of June. They hypothesized that the onset of the North American monsoon season moistening air over the elevated mixed-layer source regions such as the desert southwest may be responsible for the reduction in dryline occurrence. The moistening of these regions would likely reduce the moisture gradient between the tropical continental air and moist air from the Gulf of Mexico.

a. Convection initiation

The first occurrence of dryline convection initiation most commonly occurred in the midafternoon to early evening (Fig. 5a). In total, 71% of convective drylines had first initiation between 1900 and 2300 UTC, with a peak in frequency between 2000 and 2100 UTC. This result is not unexpected, as the conditions for dryline convection are often optimal around the time of maximum heating. Convergence

at the dryline is often at a maximum in the mid- to late afternoon (Ziegler et al. 1995). Furthermore, instability generally increases with surface temperature while surface heating can help reduce convective inhibition.

A midafternoon peak in convection initiation is consistent with previous studies of both drylines and surface-based convection more generally. Rhea (1966) found 45% of first echoes associated with the dryline occurred between 1900 and 2100 UTC. More recently, the International H₂O Project studied convection initiation and evolution in the southern Great Plains. During the field campaign, surface-based initiation most commonly occurred between 1800 and 2100 UTC (Wilson and Roberts 2006). However, only 6 out of 55 initiation episodes featured a dryline.

In the present study, the first occurrence of convection initiation was generally most common in the Texas Panhandle, but much less common farther

FIG. 4. The number of convective (purple) and nonconvective (orange) dryline days (2006–15) separated by the week in which they occurred.

FIG. 5. (a) The frequency of convection initiation separated by the time at which it occurred. (b) The location of first occurrence of convection initiation for all convective dryline days (2006–15). Each blue circle represents an initiation location for a dryline day. Background shading represents topography.

north (Fig. 5b). Eastern Colorado and far western Kansas were rarely locations where storms first initiated. Overall, the first occurrence of initiation was more common in the southern half of the domain. Convection often initiated west of 100°W in Texas. Initiation in that region is consistent with Hoch and Markowski (2005) who found that the 0000 UTC dryline position had a peak frequency around 101°W. This longitude approximately coincides with the Caprock escarpment, which extends southward for around 200 miles from the eastern Texas panhandle. Across the escarpment, elevation changes by as much as 300 m. The elevation change may be a contributing factor as to why there is a peak in dryline frequency at that longitude. The dryline can be considered as the location where the western edge of the moist air mass intersects with the sloping terrain (Jones and Bannon 2002). Fewer initiations occur in Colorado and Kansas, consistent with synoptic experience that the dryline is more common in Texas than farther north (e.g., Schaefer 1986).

There are many questions that remain unanswered with regard to orography. For instance, do storms initiate earlier in certain locations than surrounding areas? Does convection preferentially occur in some locations,

but not others? However, answering these questions is beyond the scope of this study.

b. Temporal clustering

Drylines often occurred in multiday sequences. The frequency of consecutive dryline days is shown in Fig. 6.

FIG. 6. The proportions of the total (gray) drylines and convective (purple) drylines that occurred for a given number of consecutive days (2006–15).

FIG. 7. 500-hPa geopotential height for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Stippling indicates significant points controlled for a false discovery rate of 0.1.

Over 66% of drylines occurred over two or more consecutive days, and drylines were identified as many as nine days in succession. Consecutive dryline days were typically due to a dryline persisting overnight, rather than

FIG. 8. Mean sea level pressure for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

regeneration of a new dryline each day. The occurrence of dryline days in temporal sequences has previously been studied by Schaefer (1974). He found that 22 distinct dryline events over 3 years resulted in 114 dryline days.

FIG. 9. (left) 850- and (right) 700-hPa specific humidity composite fields. (a),(b) The convective composites; (c),(d) the null; and (e),(f) the difference between the two. Stippling indicates significant points controlled for a false discovery rate of 0.1.

These results suggest that conditions conducive to dryline development often exist for more than one day in the Great Plains.

Convective drylines were less likely to occur in multiday sequences. Only 34% of convective drylines occurred in sequences of two or more consecutive days. On 52 of the 199 convective dryline days (26%), a convective dryline occurred on the second day of a dryline sequence or later. However, even if conditions were conducive to deep, moist convection on one day,

it does not mean that subsequent dryline days would produce deep, moist convection. On 43 occasions (22%), a convective dryline day was followed by a dryline day with no convection. Thus, the ingredients for deep, moist convection are either not consistently present following a convective dryline day, or present in insufficient quantity or magnitude. Are any ingredients missing on days that do not produce deep, moist convection? The following section will explore synoptic composites on days with and without

FIG. 10. Surface-based CAPE for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Stippling indicates significant points controlled for a false discovery rate of 0.1.

dryline convection to identify any differences in these ingredients.

4. Synoptic composites of days with and without dryline convection

To examine differences between drylines that produce deep, moist convection and those that do not, synoptic composites were created using NCEP North American Regional Reanalysis (NARR) data. The NARR is available from 1979 and consists of 45 vertical levels of data at a 32-km horizontal grid spacing (Mesinger et al. 2006). Composites of hourly mean conditions were created from 2100 UTC data, chosen because dryline convection most commonly initiates between 2000 and 2100 UTC. Days where a dryline was not present at 2100 UTC were excluded. Two composites were created: convective and null. The convective composite consisted of drylines that satisfied the criteria for convective storms defined in section 2, whereas the null composite was created from all the remaining dryline cases. The convective composite contained 179 days, and the null composite contained 104.

Composite differences were calculated by subtracting the null composite from the convective composite. Statistical significance of the differences was initially calculated using a two-tailed t test applied to each grid point. Field significance was tested by applying the false discovery rate (FDR) method recommended by Wilks (2016). The FDR method accounts for random rejections

of local null hypotheses that occur when performing multiple hypothesis tests and is robust to spatial autocorrelation of underlying data. An acceptable proportion of incorrect rejections of local null hypotheses was chosen by controlling the FDR using the Benjamini–Hochberg procedure (Benjamini and Hochberg 1995). The procedure calculates a local threshold p value for each grid point. Unless otherwise stated, field significance presented in this section is calculated using an FDR of 0.1. The remainder of this section will present a comparison of the synoptic-scale conditions in the convective and null composites, before focusing on the ingredients necessary for deep, moist convection.

a. Synoptic overview

At 500 hPa, both the convective and null composites show a long-wave trough with an axis extending from north to south, west of the Rockies (Figs. 7a,b), while there is long-wave ridging in the eastern United States. However, the convective composite shows a more amplified pattern than the null. Figure 7c shows the difference between the two composite height fields, calculated by subtracting the null from the convective. The heights in the convective composite are lower over Arizona, New Mexico, and southern Colorado, but higher in the northeastern United States, suggestive of both a deeper trough and stronger ridge in the convective composite.

At the surface, there is a high over southern Florida and low pressure in the lee of the Rockies (Figs. 8a,b). In both composites, the low pressure area extends

FIG. 11. 700–400-hPa lapse rate for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Regions where the convective composite has steeper lapse rates are shown in red. Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

through the Texas and Oklahoma panhandles, southwest Kansas, southeast Colorado, and eastern New Mexico. However, in the null composite, troughing extends farther north into Wyoming. This northward extension may be explained by the greater zonal component to winds aloft over the northern Rockies (Fig. 7), which would induce stronger lee troughing. Figure 8c shows

the effect of this troughing, with higher surface pressure in northern Wyoming and southern Montana in the convective composite.

b. Moisture

The synoptic-scale conditions in the composites provide a favorable environment for dryline development

FIG. 12. Surface-based convective inhibition for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

FIG. 13. As in Fig. 12, but for 700-hPa temperature.

and deep, moist convection. Lee troughing east of the Rockies results in large-scale confluence that facilitates the development of a dryline. The average dryline position can be approximated as the location of strongest west–east moisture gradient at 850 hPa (Figs. 9a,b). The strongest gradient is at the western edge of a tongue of moisture that extends northward from the Gulf of Mexico. In the convective composite, the moist air east of the dryline extends farther

north and is more moist than in the null composite. Differences of over 1 g kg^{-1} extend from northern Texas into the Midwest (Fig. 9c). These differences in moisture are not restricted to east of the dryline, however. In fact, the convective composite is more moist almost everywhere east of the Rockies.

At 700 hPa, the poleward-extending moist tongue is not as well defined, especially in the null composite (Figs. 9d,e). The highest specific humidity values in the

FIG. 14. Vertical velocity at 850 hPa for (a) convective and (b) null days at 2100 UTC. (c) The difference between the two fields, calculated by subtracting the null from convective. Regions where the convective composite has more ascent are shown in red. Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

FIG. 15. 500-hPa geopotential height for (left) 120, (center) 72, and (right) 24 h before a dryline event. (a)–(c) The convective composite, (d)–(f) the null, and (g)–(i) the difference between the two. Stippling indicates significant points controlled for a false discovery rate of 0.1.

convective composite are observed in the central states, but the null composite is drier in this region and lacks an obvious region of higher values. As at 850 hPa, the 700-hPa convective composite is more moist than the null over a large swath extending from Texas into the Midwest (Fig. 9f). However, the region of significant difference between the composites extends farther south and west than at 850 hPa, and overspreads some of the surface dryline. All other things being equal, incipient convection would be less affected by the detrimental effects of dry-air entrainment.

c. Convective instability

As with the 850-hPa specific humidity field, the location of the dryline in both composites can be identified by the west–east gradient in surface-based CAPE (Figs. 10a,b). A region of high CAPE exists east of the dryline, extending north and east from the Gulf of Mexico. There is a maximum in CAPE in eastern

Oklahoma, where values exceed 2600 J kg^{-1} in the convective composite and 2000 J kg^{-1} in the null composite. Overall, the convective composite has higher CAPE values than the null composite over Texas, Oklahoma, Kansas, Nebraska, and all locations farther east (Fig. 10c). The differences in CAPE are most pronounced east of the dryline, where values differ by as much as 700 J kg^{-1} . The regions of largest difference in CAPE are somewhat collocated with the regions of largest difference in specific humidity, suggesting that the CAPE differences are caused by differences in low-level moisture.

The argument that the CAPE differences between the composites are driven by low-level moisture is supported by the 700–400-hPa lapse-rate difference shown in Fig. 11. The steepest lapse rates occur over southern Colorado, northern New Mexico and northwest Texas. However, areas where the convective composite has steeper lapse rates than the null are separated from the

FIG. 16. As in Fig. 15, but for 850-hPa geopotential height.

region of higher CAPE values, implying that the differences in CAPE are primarily driven by moisture differences.

d. Convective inhibition

The presence of moisture and instability are necessary, but not sufficient, ingredients to initiate deep, moist convection as enough lift must be provided to overcome any existing convective inhibition. In both composites, inhibition is weak near the dryline and increases in an easterly direction toward central Texas and Oklahoma (Figs. 12a,b). The strongest inhibition is found over the Gulf of Mexico near the Texas coastline. The convective composite has inhibition values that rarely exceed 80 J kg^{-1} , with most of the dryline region exhibiting less than 60 J kg^{-1} , and has weaker inhibition than the null composite over a large area east of the dryline. The largest differences in inhibition occur in eastern Oklahoma where the difference widely exceeds 30 J kg^{-1} .

What effect do midlevel temperatures have on the magnitude of inhibition? At 700 hPa, temperatures are lower in the convective composite over Arizona, New Mexico, Colorado, and western regions of Kansas, Oklahoma, and Texas (Fig. 13). In fact, the convective composite is colder over almost all of the domain defined in section 2. However, as with convective inhibition, there are no areas where the differences are significant. Furthermore, the regions of weaker inhibition are somewhat separated from regions of lower 700-hPa temperatures. This separation is evident in the Midwest where the convective composite is warmer than the null (Fig. 13c), but inhibition is weaker (Fig. 12c). The differences in inhibition are primarily controlled by low-level moisture rather than midlevel temperature. Examination of 850-hPa specific humidity (Fig. 9e) reveals that regions of higher moisture are roughly collocated with regions of lower CIN (Fig. 12c), suggesting that moisture is

FIG. 17. As in Fig. 15, but for mean sea level pressure.

the primary factor driving differences in inhibition as well as CAPE.

e. Lift

Weak inhibition will not always result in deep, moist convection along the dryline. The inhibition must be overcome by low-level convergence and ascent through the inversion, weakened by large-scale ascent and cooling, or a combination of the two. Even before the smoothing effect of compositing, the dryline circulation cannot be resolved by the NARR, which has a horizontal grid spacing of 32 km. However, vertical motion over larger spatial scales can be analyzed.

Ascent is observed in both the convective and null composite 850-hPa vertical velocity fields over a large area of the Great Plains (Figs. 14a,b). The strongest ascent over the Plains is located through central regions of Texas, Oklahoma, and Kansas. Larger ascent is observed in the convective composite than the null to the

immediate east of the dryline, with the difference widely exceeding 0.1 Pa s^{-1} . However, these differences are not significant.

A similar pattern is also observed at higher altitudes (not shown), but the magnitude of the ascent over the Great Plains generally weakens with increasing altitude. The ascent in both the convective and null composites is likely associated with warm-air advection. However, there may be some contribution from ongoing convection given that the composites are created from 2100 UTC data.

5. Synoptic composites of days preceding a dryline

Many differences are observed between convective and nonconvective composites of 2100 UTC NARR data on the day of a dryline, but is it possible to distinguish between convective and nonconvective drylines at longer lead times? Applying the same criteria as in section 4, composites were created of

FIG. 18. As in Fig. 15, but for 850-hPa specific humidity.

conditions at 2100 UTC for 120, 72, and 24 h before a dryline day.

a. Synoptic overview

Figure 15 shows the difference in 500-hPa geopotential height, for 120, 72, and 24 h before a dryline day (T). In both the convective and null composites, heights rise in the upper Midwest and Great Lakes region as the lead time reduces, while heights fall over the west coast between T-72 and T-24. At T-72, significant differences can be observed between the composites. The convective composite features a more amplified west coast trough and higher heights in the east than the null. By T-24, the convective composite features a prominent trough west of the Rockies and a ridge in the Midwest. However, the null composite has a less amplified pattern. The trough over the west coast is more shallow, and the ridge is weaker and located slightly farther west than in the convective composite.

The building of a ridge in the east in combination with stronger troughing in the west is also seen at lower altitudes (Fig. 16). At T-120, both 850-hPa composites have a height minimum in Colorado and higher heights in the southeast (Figs. 16a,d). At T-96 (not shown) and T-72, the null composite also features a height minimum over Colorado, but the convective composite has significantly lower heights over the central Rockies in addition to higher heights in the northeastern United States than the null. By T-24, the convective composite has higher heights over the entire eastern United States, with the largest differences occurring over the upper Midwest. However, the differences in the strength of the western trough have all but disappeared by T-24.

A similar trend is observed in mean sea level pressure as the differences between the composites are maximized at T-72 and reduced by T-24 (Fig. 17). At T-120, both composites feature lower pressure in New Mexico and southern Colorado, and higher pressure in the

FIG. 19. As in Fig. 15, but for surface-based CAPE.

southeast with southerly flow into the Great Plains. By T-72, the convective composite has a deeper low pressure region than at T-120, but the low pressure region in the null composite is relatively unchanged. As a result, the mean sea level pressure in the convective composite is over 3 hPa lower over Colorado and parts of adjacent states. At T-24, both composites have a deeper low pressure area than at T-72; however, the differences between the composites have all but disappeared.

b. Moisture

The presence of significant differences in mean sea level pressure at T-72, but none on the day of a dryline, suggests that the large-scale pattern in the three or four days before a dryline event can help create the differences observed on a dryline day. The composites at T-72 feature a large-scale pattern that is conducive to moisture advection into the Great Plains from the Gulf of Mexico. The convective composites feature a stronger trough, likely associated with greater moisture advection than the null.

Composites of 850-hPa specific humidity (Fig. 18) confirm that convective cases are more moist in the days preceding a dryline event. For all the times shown, the highest specific humidity values are found in the south and southeastern United States, with drier air in the southwest. At T-120 h, the convective composite is more moist over the western Plains. By T-72, a tongue of moisture extends farther north in the convective composite and the convective composite is more moist over the entire Great Plains region. This difference is significant over much of Oklahoma and Kansas, and significant differences extend as far north as North Dakota. By T-24, the convective composite has specific humidity values over 1.6 g kg^{-1} higher than the null composite in eastern Oklahoma.

c. Convective instability

A result of this difference in specific humidity is that the convective composite has greater surface-based CAPE values in the Plains from T-72 onward (Fig. 19).

FIG. 20. 700–400-hPa lapse rate for (left) 120, (center) 72, and (right) 24 h before a dryline event. (a)–(c) The convective composite, (d)–(f) the null, and (g)–(i) the difference between the two. Regions where the convective composite has steeper lapse rates are shown in red. Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

At T-72, the convective composite has CAPE values over 300 J kg^{-1} greater than the null over most of Oklahoma and Kansas. By T-24, the convective composite has larger CAPE values over a large swath extending from Texas into the Midwest. The differences in CAPE are greatest over eastern Oklahoma and Kansas, and western Missouri.

The steepest lapse rates (exceeding $7.5^\circ \text{C km}^{-1}$) exist over Colorado and New Mexico (Fig. 20), appearing to be collocated with the 850-hPa trough (Fig. 16), while the 7°C km^{-1} isopleth extends eastward to central Oklahoma. By T-24, the region of lapse rates greater than 7°C km^{-1} extends farther east, reaching the Kansas–Missouri border. The steepening lapse rates are likely explained by the arrival of cool air aloft due to the approaching trough. However, the increase in lapse rates farther east as the lead time shortens may be also be an indicator of advected elevated mixed-layer air.

The argument that the increase in lapse rates is associated with the elevated mixed layer is supported by an increase in convective inhibition (not shown) between T-72 and T-24. Convective inhibition increases over almost all of Texas, Oklahoma, and Kansas between those times. However, even if the elevated mixed layer is responsible for the increase in convective inhibition, the characteristics of the elevated mixed layer do not appear to be important in distinguishing between convective and nonconvective drylines. No significant differences are observed between the convective and null composites of 700–400-hPa lapse rate (Figs. 20g–i).

d. Lift

There are also no significant differences between the convective and null composites of vertical velocity in the days preceding a dryline event (Fig. 21). Composites of

FIG. 21. 850-hPa vertical velocity for (left) 120, (center) 72, and (right) 24 h before a dryline event. (a)–(c) The convective composite, (d)–(f) the null, and (g)–(i) the difference between the two. Regions where the convective composite has more ascent are shown in red. Note the different scale used in (g)–(i). Lack of stippling indicates that no differences were significant using a false discovery rate of 0.1.

850-hPa vertical velocity feature weak ascent ($\sim 0.1 \text{ Pa s}^{-1}$) over most of the southern Great Plains. The magnitude of this ascent is greatest at T-24 with values exceeding 0.1 Pa s^{-1} over much of Oklahoma and Kansas. Although the magnitude of ascent is slightly greater ($< 0.1 \text{ Pa s}^{-1}$) in the convective composite at T-24, this difference is not significant.

Ascent is also present over much of the southern Plains at higher altitudes (not shown), but the magnitude of ascent weakens with height. The strongest ascent is at low levels, and the southerly winds over the southern Plains in the mean sea level pressure composites (Fig. 17) suggest the ascent in both composites is associated with warm-air advection. In the midlevels (not shown), there is no clear signal for vertical motion in the Plains, even at short lead-times. Although it appears that the large-scale pattern is conducive to warm-air advection and ascent in the low-levels, the

large-scale influence of vertical motion at higher altitudes is unclear.

6. Summary

A dataset of drylines within a region of the southern Great Plains was constructed to investigate the importance of large-scale processes in the initiation of deep moist convection. Drylines were identified using WPC surface analyses, then radar and satellite imagery were used to establish whether deep, moist convection initiated along the dryline. Over the 10 years examined in this study, approximately 60% of drylines produced deep, moist convection, with convection most frequently initiating between 2000 and 2100 UTC. Convective drylines were most common in May.

Synoptic composites were created in an attempt to identify differences between convective and nonconvective

drylines. Analysis of the composites reveals that the large-scale environment appears to not only facilitate the development of a dryline, but also create conditions conducive to deep, moist convection. Three days before a dryline event, convective drylines feature a stronger 500-hPa ridge in the eastern United States and a deeper west coast trough. Meanwhile, convective drylines feature a deeper surface low over the central Rockies. As a result of greater poleward advection of low-level moisture into the Great Plains, the convective composite is more moist over large areas east of the Rockies.

On the day of a dryline, the synoptic composites feature a long-wave trough over the western Rockies and a ridge in the east. However, convective drylines have more amplified flow, a deeper trough, and a stronger downstream ridge. At the surface, both composites feature low pressure over the Texas panhandle region with associated poleward moisture advection to the east of the low. However, convective drylines have more abundant low-level moisture over the Plains, which results in greater values of CAPE east of the dryline.

Although CAPE differences appear to be primarily caused by differences in low-level moisture, the influence of the elevated mixed layer in creating greater CAPE values in convective cases is unclear. No significant differences were found in 700–400-hPa lapse rates or midlevel temperatures between the composites. Although convective inhibition was weaker in the convective composite east of the dryline, this result was also insignificant. It is possible that convection initiation is affected by variations in convective inhibition on a smaller spatial scale than the NARR can resolve.

Of course, composites cannot help answer all of the questions regarding dryline convection initiation. Whether or not the magnitude of convergence, and hence ascent, along the dryline can help distinguish between convective and nonconvective drylines remains unclear. Drylines vary in location and orientation within the Plains, and convergence is often confined to a narrow band along or ahead of the dryline. Future work could benefit from accounting for dryline location, orientation, and strength to help establish the importance of both convergence, any frontal circulation, and the strength of the moisture gradient in determining whether convection will initiate.

Despite these unanswered questions about finescale dryline variations, we have shown that the large-scale pattern is not only important in creating conditions conducive to dryline development, but may also help determine whether or not deep, moist convection initiates along the dryline. Convective drylines are associated with greater low-level moisture and higher values of surface-based CAPE than nonconvective drylines, a

result of greater moisture advection into the Plains in the preceding days. Our results indicate that synoptic-scale processes may be important in determining whether dryline convection will occur.

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Data availability statement. The WPC and NARR datasets are publicly available (https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php and <https://psl.noaa.gov/data/gridded/data.narr.html>, respectively).

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