Analysis of a Progressive Derecho Climatology and Associated Formation Environments

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ABSTRACT

A 1996–2013 May–August U.S. progressive derecho climatology existing entirely within the modern radar era is constructed identifying 256 derecho events over the 18-yr span. A corridor of enhanced derecho activity in agreement with previous derecho studies stretches from southern Minnesota to the border of Ohio and West Virginia with a marked decrease east of the Appalachian Mountains. A secondary maximum in progressive derecho activity exists in Kansas and Oklahoma. Analyses of derecho frequency by month of the warm season indicate a northward shift in frequency through July and an increase in derecho frequency through the first half of the warm season followed by a large decrease in August.

The 256 identified derecho events are divided subjectively into seven distinct categories based on the synoptic environments in which they form. While the prevailing ''northwest flow'' conceptual model is upheld as the dominant progressive derecho synoptic category, the common occurrence of warm-season progressive derechos ahead of well-defined upper-level troughs is presented. This connection between upper-level troughs and progressive derecho formation expands on the relationship between upper-level troughs and serial derecho formation that has been the focus of past studies. In addition, a link between progressive derecho formation and easterly low-level flow to the north of a Rocky Mountain lee cyclone is bolstered. Consistent with previous derecho studies, all composite categories are characterized by large low-level moisture and the presence of an upper-level jet at derecho initiation.

1. Introduction

a. Derecho climatologies

Derechos are a class of mesoscale convective system (MCS) characterized by considerable severity and longevity. Hinrichs (1888) defined the term derecho to refer to swaths of straight-line wind damage, but the first limited climatology of derechos was not performed until Johns and Hirt (1987, hereafter JH87). The JH87 climatology included four years of warm-season (May–August) data that led to the identification of 70 derechos. After identification, the derechos were classified as either serial or progressive. JH87 described serial derechos as dynamic, cold-frontal MCSs characterized by a line-echo wave pattern appearance on radar and progressive derechos as weakly forced MCSs characterized by a single bow. A radar continuity map and associated severe wind reports for a particularly severe progressive derecho occurring on 29 June 2012 are shown in Figs. 1a and 1b. The signature progressive derecho bowing presentation is immediately evident on radar (Fig. 1a). JH87 noted the weakly forced nature of progressive derechos ''frequently presents a difficult forecast problem for the operational meteorologist'' (p. 32). The day-1 Storm Prediction Center (SPC) convective outlook for 29 June 2012 issued at 0600 UTC on that day (Fig. 2a) illustrates the forecast difficulty progressive derechos pose as only a portion of the eventual severe wind reports that verified were captured by the slight risk contour (Fig. 2b). This forecast difficulty has motivated derecho research since the JH87 publication and serves as motivation for the current study.

Of the 70 warm-season derechos identified in JH87, 76% were classified as progressive and the remaining 24% as serial. All derechos included in JH87 met six

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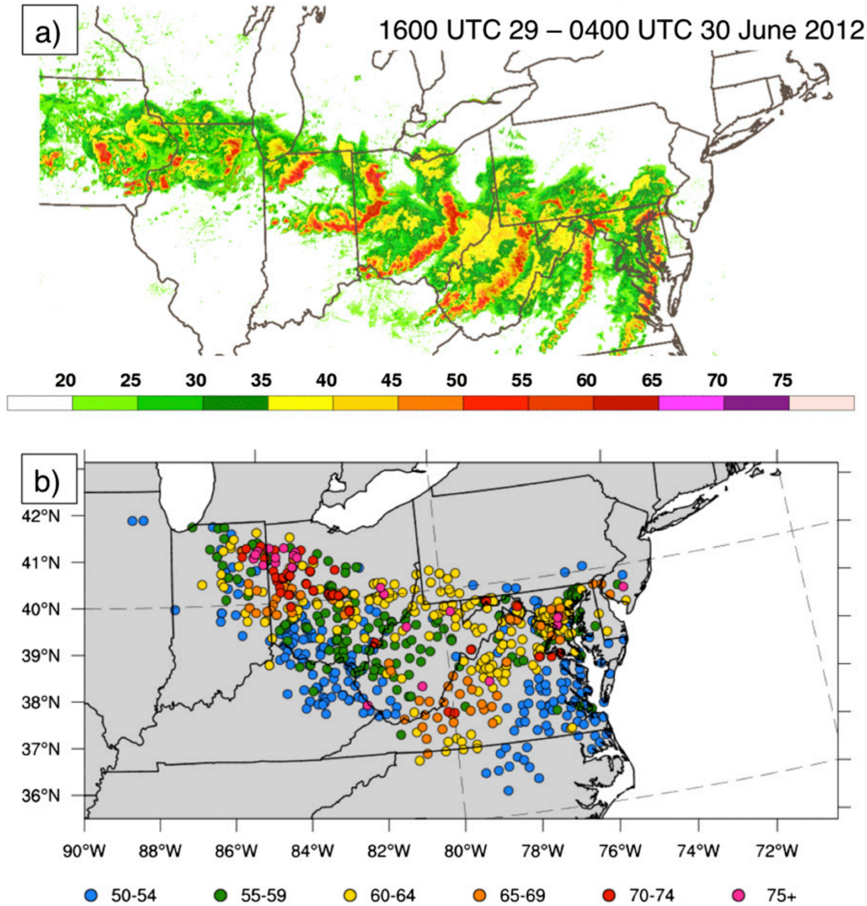

FIG. 1. (a) Radar continuity map every 2 h from 1600 UTC 29 Jun to 0400 UTC 30 Jun 2012. (b) Storm Prediction Center severe wind reports colored by wind speed (kt) for the 29–30 Jun 2012 progressive derecho. It is noted that many of the wind speeds contained in the Storm Prediction Center data are estimated.

criteria (Table 1) concerning convective mode and wind swath characteristics. When mapped, JH87 derecho activity marked a well-defined corridor across the Midwest with the highest concentration of activity stretching from southern Minnesota to central Ohio (Fig. 3a).

Bentley and Mote (1998, hereafter BM98) performed the second warm-season derecho climatology, which spanned the years 1986–95. Instead of a dominant Midwest corridor of derecho activity, BM98 found a large concentration of derechos centered on Oklahoma (Fig. 3b). The BM98 climatology notably forwent two JH87 derecho criteria (Table 1)—the consultation of radar data to ensure the wind reports were caused by MCSs as well as the requirement of three reports of F1 damage and/or gusts in excess of 33 m s^{-1} (65 kt). Studies have discussed the implications of inconsistent derecho criteria among published climatologies and have found that a given derecho climatology may differ considerably when the criteria are altered [Johns and Evans 2000; Bentley and Mote 2000; Coniglio and Stensrud (2004, hereafter CS04)]. Additionally, a derecho climatology may be shaped substantially by the dominant synoptic patterns of the selected time period. For example, Bentley and Sparks (2003) extended the BM98 climatology to 2000 and found a reemergence of a Midwest corridor similar to that depicted in JH87 (not shown).

The most recent climatology published is CS04 spanning 1986–2001. The climatology was constructed three times: once using the JH87 wind gust criteria, a second time using the BM98 wind gust criteria (Fig. 3c), and a third time using wind gust criteria more stringent than JH87. The three resulting maps differed in areas, especially the Southeast and southern plains, but all showed a combination of derecho activity corridors with one relative maximum in the vicinity of Oklahoma as in BM98 and another across the Midwest as in JH87 and the latter years of Bentley and Sparks (2003). While

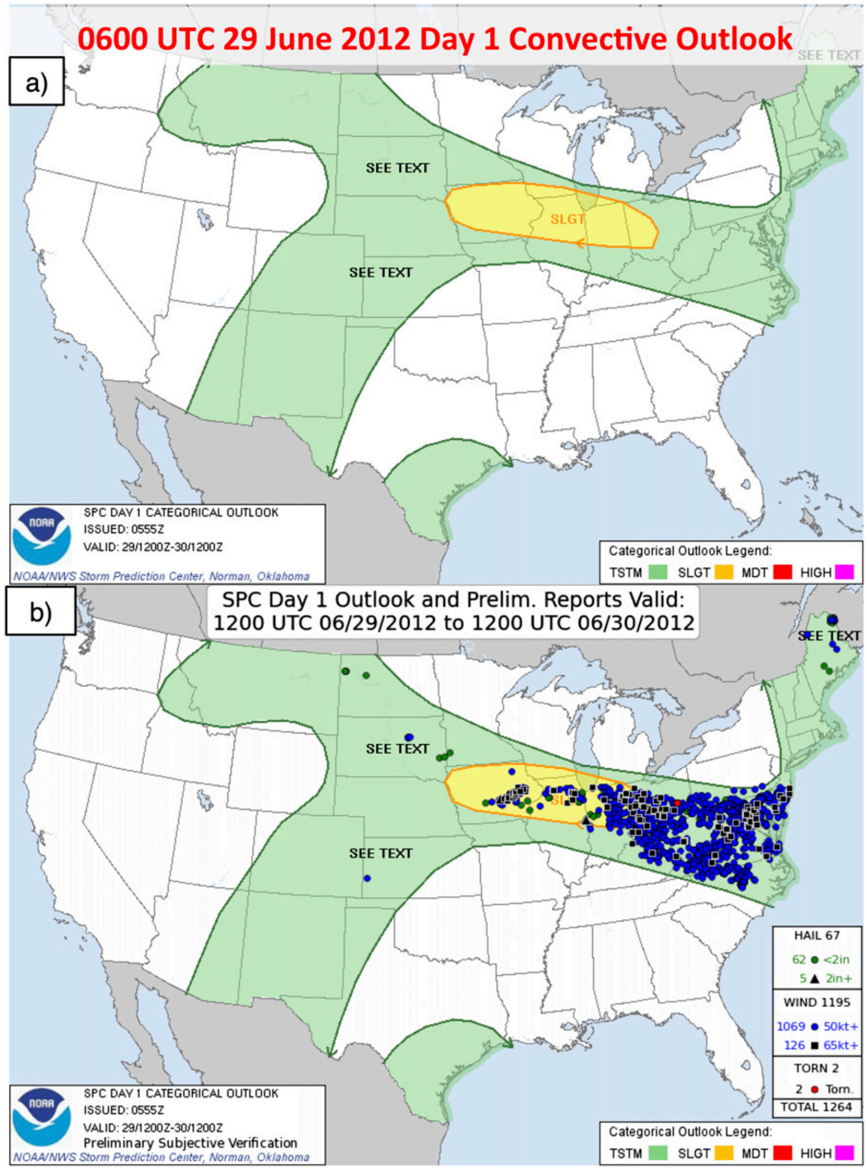

FIG. 2. (a) Storm Prediction Center day-1 convective outlook issued at 0600 UTC 29 Jun 2012 and (b) verification.

choice of criteria influenced the resulting climatology maps, CS04 suggested criteria choice is not as important to a resulting climatology as the examination of radar data to ensure wind reports were the result of MCSs and not other convective phenomena. CS04 concluded with the assertion that confidence in the derecho climatology will require many years of WSR-88D Doppler radar data. Accordingly, the current study aims to enhance confidence by presenting an 18-yr (1996–2013), warm-season, progressive derecho climatology existing entirely within the modern radar era. In its effort to investigate progressive derechos, the current study attempts to distinguish systematically between the progressive derecho phenomenon and the serial derecho phenomenon. This distinction is subjective and motivated by the tendency for progressive derechos to be weakly forced and consequently difficult to predict.

b. *Derecho initiation environments*

JH87 describes progressive derecho environments as characterized by mean west/northwest flow in the troposphere and an east–west-oriented, quasi-stationary boundary at the surface. The extensive convergence of preexisting low-level moisture along an antecedent boundary and associated low-level frontogenesis creates a region of large surface-based instability near the boundary

TABLE 1. Criteria used to identify the progressive derechos. JH87 refers to Johns and Hirt (1987), BM98 refers to Bentley and Mote (1998), and CS04 refers to Coniglio and Stensrud (2004). (Adapted from CS04, their Table 1.)

No.	JH87 criteria	BM98 criteria	CS04 criteria	Our criteria
1	There must be a concentrated area of convectively induced wind gusts greater than 26 m s^{-1} that has a major axis length of 400 km or more	As in JH87	As in JH87	As in JH87
2	The wind reports must have chronological progression	As in JH87	As in JH87	As in JH87
3	No more than 3 h can elapse between successive wind reports	No more than 2 h can elapse between successive wind reports	No more than 2.5 h can elapse between successive wind reports	As in CS04
4	There must be at least three reports of either F1 damage or wind gusts greater than 33 m s^{-1} separated by at least 64 km during the MCS stage of the event	Not used	Low end, not used; moderate, as in JH87; high end, there must be at least three reports of either wind gusts greater than 38 m s^{-1} or comparable damage, at least two of which must occur during the MCS stage of the event	Not used
5	The associated MCS must have spatial and temporal continuity	The associated MCS must have spatial and temporal continuity with no more than 2° of latitude and longitude separating successive wind reports	The associated MCS must have spatial and temporal continuity and each report must be within 200 km of the other reports within a wind gust swath	As in CS04
6	Multiple swaths of damage must be part of the same MCS as indicated by the available radar data	Multiple swaths of damage must be part of the same MCS as seen by temporally mapping the wind reports of each event	As in JH87	As in JH87

and elevated instability poleward of the boundary. Convection forms on the cool side of the boundary in conjunction with low-level warm air advection, grows upscale into a bowing MCS, and produces a swath of severe surface winds as it follows the instability corridor. Johns and Doswell (1992) expanded upon this synoptic setup describing steep midlevel lapse rates coincident with the extensive low-level moisture. Together with the large low-level moisture, the steep midlevel lapse rates create extreme instability. The base of the layer of steep midlevel lapse rates also acts to form a cap south of the quasi-stationary boundary, which restricts the bowing MCS's southward development. Indeed, the JH87 and Johns and Doswell (1992) progressive derecho setup is common, but case studies in the literature have shown synoptic environments supporting progressive derecho development to be more varied (e.g., Rockwood and Maddox 1988; Duke and Rogash 1992; Bentley and Cooper 1997; Gallus et al. 2005; Metz and Bosart 2010) and to include the influence of the Rocky Mountains, upslope flow, and well-defined upper-level troughs.

Bentley et al. (2000) and Bentley and Sparks (2003) attempted to account for some of the variation in derecho formation environments by geographically clustering derecho events. For example, their "northeastward-moving Great Plains" composite category depicts derecho initiation in easterly surface flow to the north of a Rocky Mountain lee cyclone, but only four events were included in this composite. A much larger sample size must be utilized to establish robustness in the lee cyclone setup. Coniglio et al. (2004) presented a robust examination of large-scale environmental flow patterns associated with 270 derecho-producing MCSs through the objective clustering of 500-hPa geopotential height fields. A total of 72% of the derecho events fell into a ridge, trough, or zonal 500-hPa pattern. Composite analyses of each pattern demonstrated that derecho initiation frequently occurs in an area of enhanced 850-hPa moisture, low-level warm air advection, and upper-level divergence associated with the equatorward entrance region of an upper-level jet. While illuminating and supportive of claims made in prior derecho publications, the composite analyses in Coniglio et al. (2004) lacked easterly low-level flow to the north of a surface cyclone, an environmental characteristic common to severe convection initiating in the proximity of the Rocky Mountains (Doswell 1980), due to clustering without regard to geographic location of the derechos. The current study aims to present a comprehensive picture of the derecho formation spectrum through the subjective analysis of progressive derecho environments over the continental United States east of the Rockies.

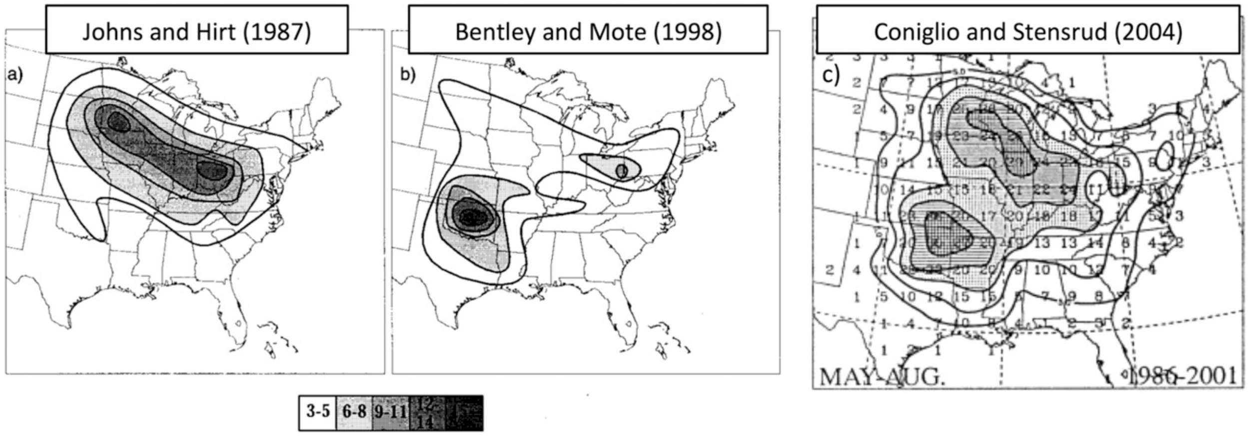

FIG. 3. The three notable derecho climatologies published to date for the warm season (May–August): (a) JH87 (spanning the years 1980–83), (b) BM98 (1986–95), and (c) CS04 (1986–2001). The CS04 climatology depicts a combination of the maximum activity corridors shown in JH87 and BM98. [(a) and (b) are from BM98 (their Fig. 1) and (c) is from CS04 (their Fig. 3a).]

The progressive derecho climatology presented herein was constructed for May–August of 1996–2013 through the examination of SPC severe wind reports and WSR-88D Doppler radar data to ensure the fulfillment of the required derecho criteria. The full methodology used in the construction of the progressive derecho climatology and in the development of a classification scheme to divide the derecho events into distinct synoptic categories is presented in section 2. The results of the progressive derecho climatology are presented in section 3. Analysis of the classified derechos is presented in section 4. A discussion and synthesis is presented in section 5.

2. Methodology

Though there is not always a clear demarcation between progressive and serial derechos, multiple articles in the literature have described the appearance of progressive derechos on radar as short (generally 100–400 km) squall lines in either a bow echo or line-echo wave pattern form (JH87; Coniglio and Stensrud 2001) as opposed to the extensive lines, at times upward of 1000 km, which characterize serial derechos (JH87; Johns and Doswell 1992). This radar description was used when making the progressive derecho distinction in the current study.

Progressive derechos were identified for the warm season (May–August) of 1996–2013. The climatology was restricted to the warm season because the original JH87 climatology was for the warm season and subsequent climatologies have identified a prominent peak in derecho activity during the warm season (BM98; Evans and Doswell 2001).

The specific criteria used for derecho identification in this study are identical to the low-end classification in CS04 and are shown in Table 1. Radar imagery from the NCDC (available online at http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=radar&theme=radar&display=nexrad) was used to ensure the identified wind swaths were associated with bowing MCSs and to ensure that, to the best of the coauthors' ability, the included derechos were progressive and not serial. Once a progressive derecho was identified, the wind reports associated with the derecho were isolated objectively using the CS04 low-end derecho criteria. The first wind report for a given derecho need not occur when the derecho is bowing, it may be a result of discrete cells that later merge into a bowing MCS.

The climatology contains 256 progressive derecho events over the 18-yr span and has the distinction of existing completely within the modern radar era. This radar distinction helps to create the more consistent climatology described at the conclusion of CS04. After the identification of the derecho events, the continental United States was divided into 100 km × 100 km grid boxes. If a wind report associated with a given derecho fell within a box, the count was incremented for that box. After all 256 derecho events were tallied, the grid was contoured objectively to create frequency maps for the entire warm season as well as for individual warm-season months.

For each identified progressive derecho event, various atmospheric fields were plotted at atmospheric levels ranging from the surface to 250 hPa using the 0.5° Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) analyses closest to the initiation time of the derecho, defined as the time and location of the first severe wind report associated with the derecho. CFSR analyses are every 6 h; therefore, no analysis used to evaluate the derecho-initiation synoptic environment was more than 3 h removed from the true derecho initiation time.

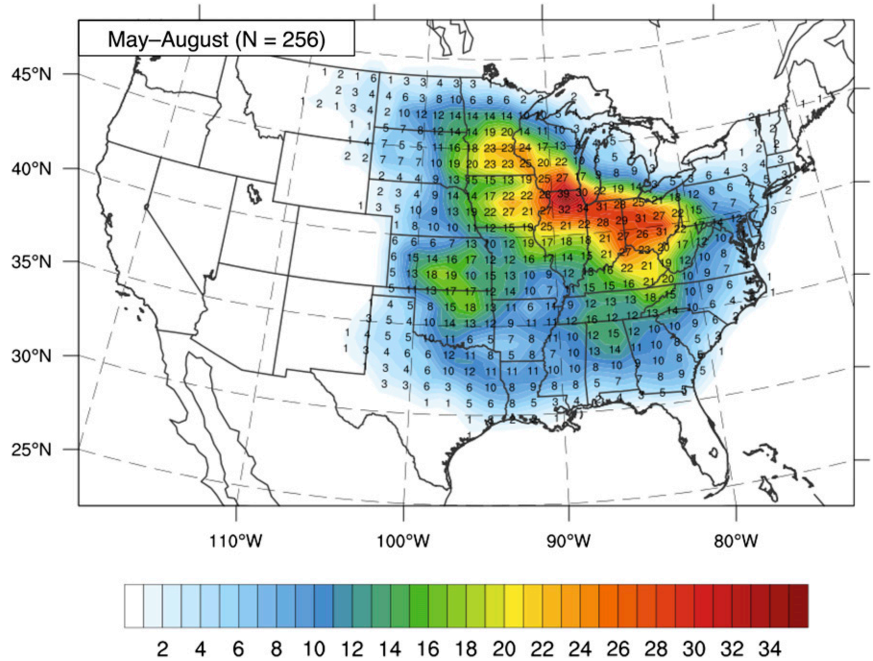

FIG. 4. Climatology of progressive derecho events for the warm season (May–August) of 1996–2013. The number of progressive derechos passing through a given 100 km × 100 km grid box over the 18-yr span is located at the center of the grid box and is plotted for those boxes containing at least one progressive derecho.

Division of the 256 progressive derechos into distinct synoptic categories commenced with the coauthors independently examining the CFSR-derived synoptic maps and formulating individual classification schemes. Once the coauthors felt they had reached a satisfactory classification scheme, they met and discussed the strengths and weaknesses of their schemes. Individual classification then recommenced followed by another joint meeting. This process continued until a relatively simple, seven-group classification scheme was converged upon. Derecho initiation-relative composites were constructed using the CFSR data by shifting the derecho initiation point of each event in a given category to the average initiation location of that category and then averaging the grids. The consistency of the CFSR configuration enables greater confidence in the results compared to those derived from other modeling systems that change configurations frequently.

Composite soundings were constructed by averaging derecho proximity soundings using the method of Trier et al. (2000) whereby each proximity sounding was interpolated to common levels in a normalized $\sigma = p/p_s$ vertical coordinate, where p_s is surface pressure, before averaging. To be considered viable, each proximity sounding must have occurred within 3 h and 200 km of derecho initiation, had data to 100 hPa, and been free of convective contamination. A total of 61 proximity soundings were identified as viable for compositing.

3. Climatology results

The distribution of the 256 progressive derechos identified during the warm season (May–August) of 1996–2013 is shown in Fig. 4 and reflects features of the three existing derecho climatologies presented in Fig. 3. A prominent corridor of derecho activity similar to that in JH87 (Fig. 3a) extends through the Midwest from southern Minnesota to the Ohio–West Virginia border with a maximum in derecho activity (39 derechos or approximately 2 yr^{-1}) over northern Illinois (Fig. 4). A secondary concentration of derecho activity similar to that in BM98 (Fig. 3b) is present in the southern plains, primarily Kansas and Oklahoma.

The CS04 climatology (Fig. 3c) shows a remarkable spatial similarity to the current climatology, but a difference emerges through the comparison of the Midwest and southern plains derecho magnitudes. The Midwest and southern plains corridors are equal in magnitude in CS04, but the southern plains magnitude in the current study is almost half the magnitude of the Midwest corridor (Fig. 4). This discrepancy in relative frequencies between the southern plains and Midwest reflects either a less frequent setup of synoptic conditions

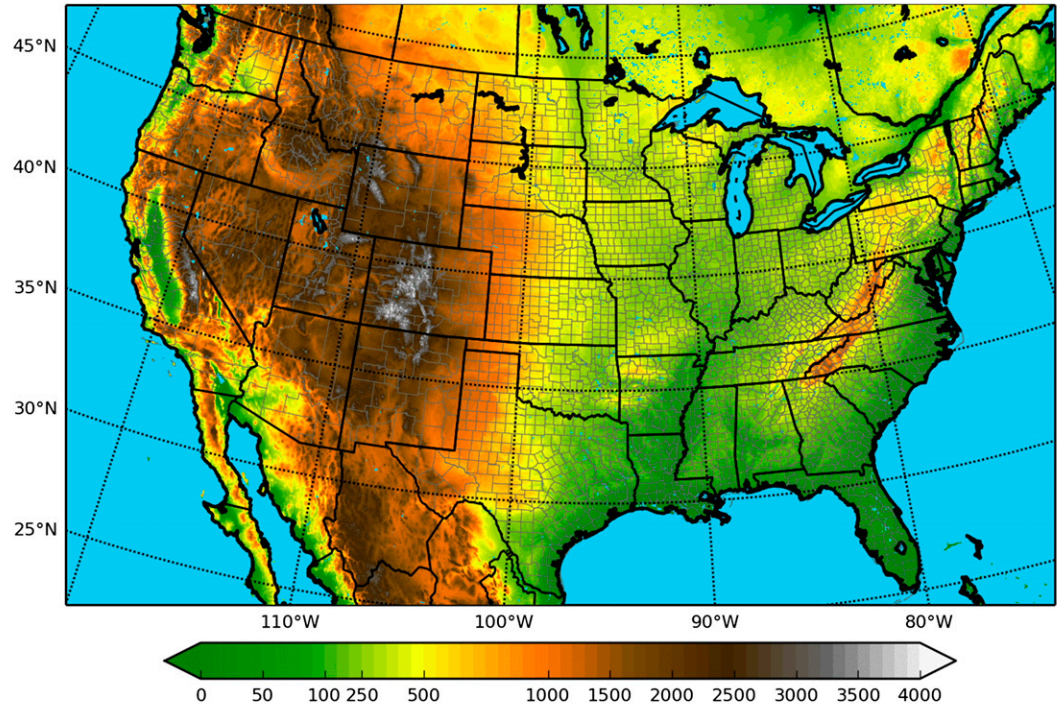

FIG. 5. Topographic map of the United States (terrain height in m).

favoring southern plains progressive derechos over the years covered in the current study compared to the years covered in CS04 (1986–2001) and/or a tendency for southern plains derechos to occur as serial instead of progressive MCSs. Figure 4a of Coniglio et al. (2004) shows the frequency of trough-induced derechos over the United States for the years 1980–2001. Since serial derechos are predominantly trough induced, most serial derechos identified in that time span should be included in the figure. A comparison of the number of trough-induced derechos occurring over the southern plains in Fig. 4a of Coniglio et al. (2004; less than 10) and the number of all derechos occurring over the southern plains in CS04 (Fig. 3c; greater than 25) suggests the vast majority of derechos occurring over the southern plains are not serial. Therefore, the smaller magnitude of southern plains derecho frequency in the current study is likely not a result of omitting serial derechos but rather reflects less favorable synoptic conditions supporting progressive derechos over the southern plains in 1996–2013 compared to 1986–2001. The dominant synoptic patterns of the years included in a given derecho climatology are unquestionably important to the resulting maps of derecho frequency (BM98; Johns and Evans 2000).

The current derecho climatology shown in Fig. 4 reflects topographic features of the United States (Fig. 5). No derechos were identified over and west of the Rockies, and there is a sharp decrease in derecho occurrence east of the Appalachian Mountains. Previous studies have addressed squall lines crossing the Appalachians and have demonstrated that the Appalachians have an impact on MCS structure and dynamics, at times preventing MCSs from crossing into the lee (e.g., Frame and Markowski 2006; Letkewicz and Parker 2010, 2011). The line that marks the western extent of derecho activity has a northwest–southeast slope from eastern Montana to the Colorado–Kansas border. This slope parallels the contour of the spine of the Rocky Mountains (Fig. 5), which marks the westward extent of severe convection initiated by upslope flow. In addition, progressive derechos were rare across much of New York and New England in the period of this study.

When each derecho initiation location is shaded according to the number of significant SPC wind reports [defined as $33+ \mathrm{m\,s^{-1}}$ (65+ kt)] contained within the entire derecho swath, the Southeast emerges as the region with the least severe warm-season derechos (Fig. 6), which is consistent with the findings of CS04. Multiple $33+ \mathrm{m\,s^{-1}}$ (65+ kt) wind reports within a given derecho event are most common in those derechos that initiate over the central and northern plains.

The progressive derecho climatology broken down by month depicts variation in the number and location of derechos throughout the warm season. A total of 40 events (15.6% of the total) occurred in May, and

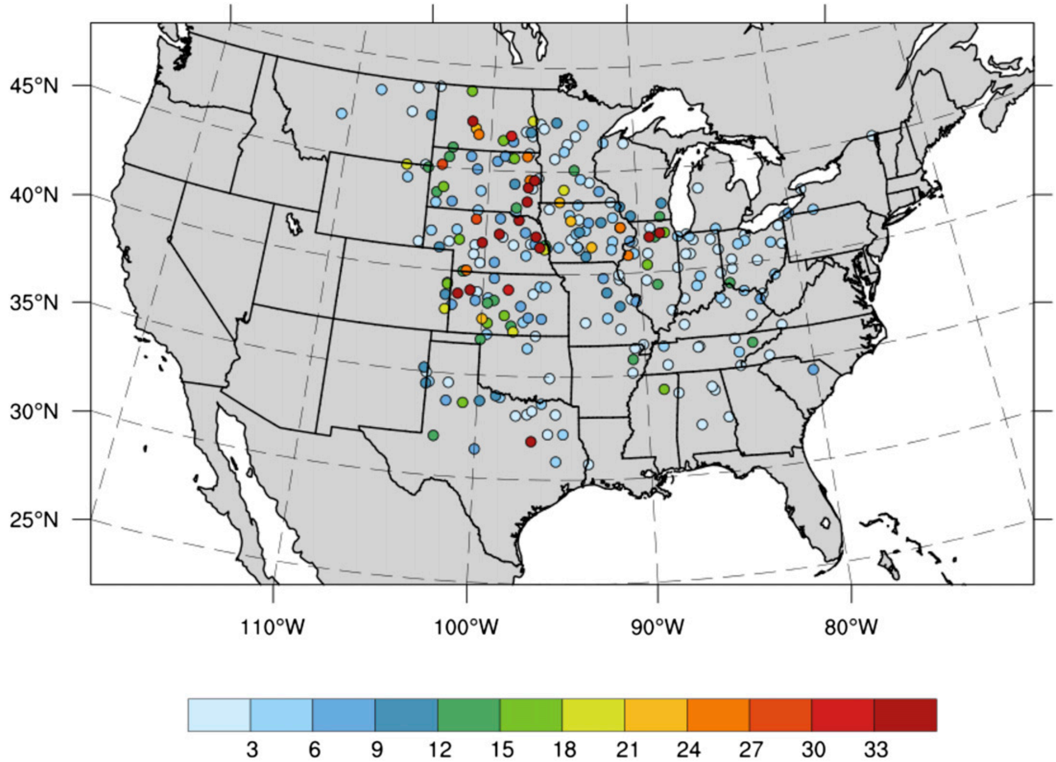

FIG. 6. Derecho initiation locations colored by number of significant [33+ m s^{-1} (65+ kt)] severe wind reports in a given derecho wind swath.

derecho activity in that month has no clear geographical preference except for a relative maximum in the south-central plains (Fig. 7). It is notable that the northward extent into Minnesota and the northern plains present in the full warm-season climatology is absent in the May climatology. In June, the number of derecho events substantially increases to 84 (32.8% of the total), and multiple maxima exist from the Gulf States northward to Minnesota (Fig. 8). The June climatology exhibits a transition between the more southern activity of May (Fig. 7) and the predominantly northern activity of July (Fig. 9). July contains 86 derecho events (33.6% of the total) with a distinct northward shift in activity characterized by a maximum extending from eastern South Dakota eastward through Minnesota and turning southeastward toward northern Illinois. This northward shift is consistent with the climatological northward building of upper-level ridges (e.g., Bell and Bosart 1989; Parker et al. 1989; Galarneau et al. 2008), the northward retreat of the polar jet stream (Koch et al. 2006; Manney et al. 2014), and the disappearance of the subtropical jet stream (STJ) over the United States as the warm season progresses.

In August, as the severe thunderstorm season wanes in the United States (Doswell et al. 2005), the number of progressive derechos declines to 46 (18.0% of the total) with a corridor of maximum derecho activity shifting slightly farther south and east stretching from northern Illinois through central Ohio (Fig. 10). Activity in Kansas and Oklahoma is present in all months of the warm season but decreases in August.

4. Composite category characteristics

A subjective examination of derecho synoptic environments by the coauthors resulted in seven distinct categories as well as an eighth unclassifiable category. The seven categories can be split broadly into ''western'' and ''eastern'' groups, where western refers to those synoptic environments occurring in the vicinity of the Rocky Mountains over the western half of the continental United States, and eastern refers to those synoptic environments favoring the eastern half of the continental United States. All western categories share the presence of a Rocky Mountain lee trough/cyclone and 850-hPa flow containing an easterly component at the derecho-initiation location. The remaining characteristics of the three western categories used for identification are as follows:

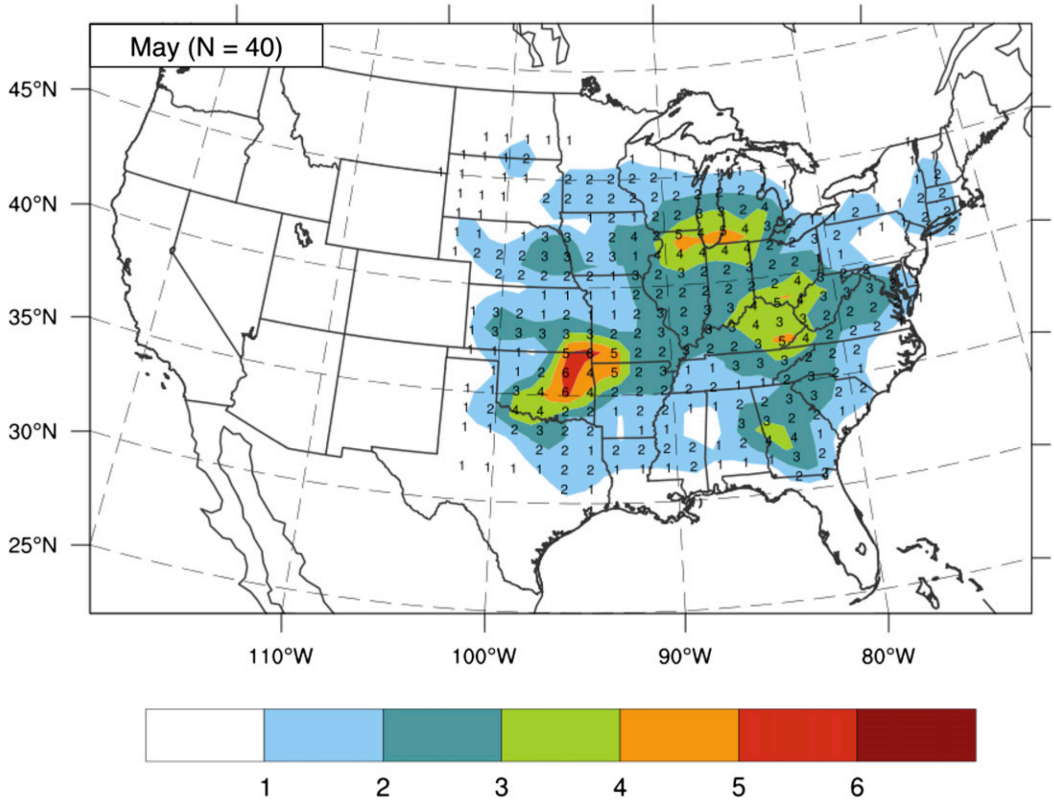

FIG. 7. As in Fig. 4, but for the month of May.

- Southwest flow across the Rockies: (N = 35; 13.7%) a trough is approaching the Rocky Mountains causing mid- and upper-level southwest flow across the spine of the Rocky Mountains.
- Northwest flow across the Rockies: (N = 22; 8.6%) ridging west of the Rocky Mountains and a trough downstream of the Rocky Mountains causes mid- and upper-level northwest flow across the spine of the Rockies.
- Zonal flow across the Rockies: (N = 14; 5.5%) mid- and upper-level flow is almost entirely zonal across the spine of the Rocky Mountains due to the location of a broad trough directly to the north of a broad ridge.

The four eastern categories were defined for identification as follows:

- Upper-level trough: (N = 51; 19.9%) the derecho initiation location is in southwesterly mid- and upper-level flow ahead of an approaching trough. A surface cyclone is present. At 850 hPa, there is an equivalent potential temperature (θ_e) gradient and wind shift associated with a cold front to the west of the initiation location.
- Ridge environment: (N = 20; 7.8%) the derecho initiation location is in southwesterly mid- and upper-level flow on the northwestern periphery of a ridge. The upper-level jet is curved anticyclonically to the north of the ridge.
- Northwest flow: (N = 64; 25.0%) a broad trough downstream of a ridge causes northwesterly mid- and upper-level flow at the derecho initiation location. This category is qualitatively similar to the JH87 progressive derecho conceptual model.
- Zonal flow: (N = 36; 14.1%) a broad trough to the north of a broad ridge causes an anomalously strong zonal jet and an extensive corridor of zonal mid- and upper-level flow at the derecho initiation location.

The unclassifiable category is defined as such:

- Unclassifiable: (N = 14; 5.5%) the synoptic pattern is either a hybrid between two categories making a single classification impossible or the synoptic pattern happens too infrequently to be its own category, such as derechos propagating from east to west on the southeastern side of a ridge.

Initiation-centered composite analyses, where initiation of each derecho is defined as the time and location of the first wind report associated with the derecho, are presented in Figs. 11–17. The composite analyses of the eastern categories (Figs. 11–14) support the derecho synoptic environments identified in Coniglio et al. (2004) as well as those proposed in JH87. Though mean

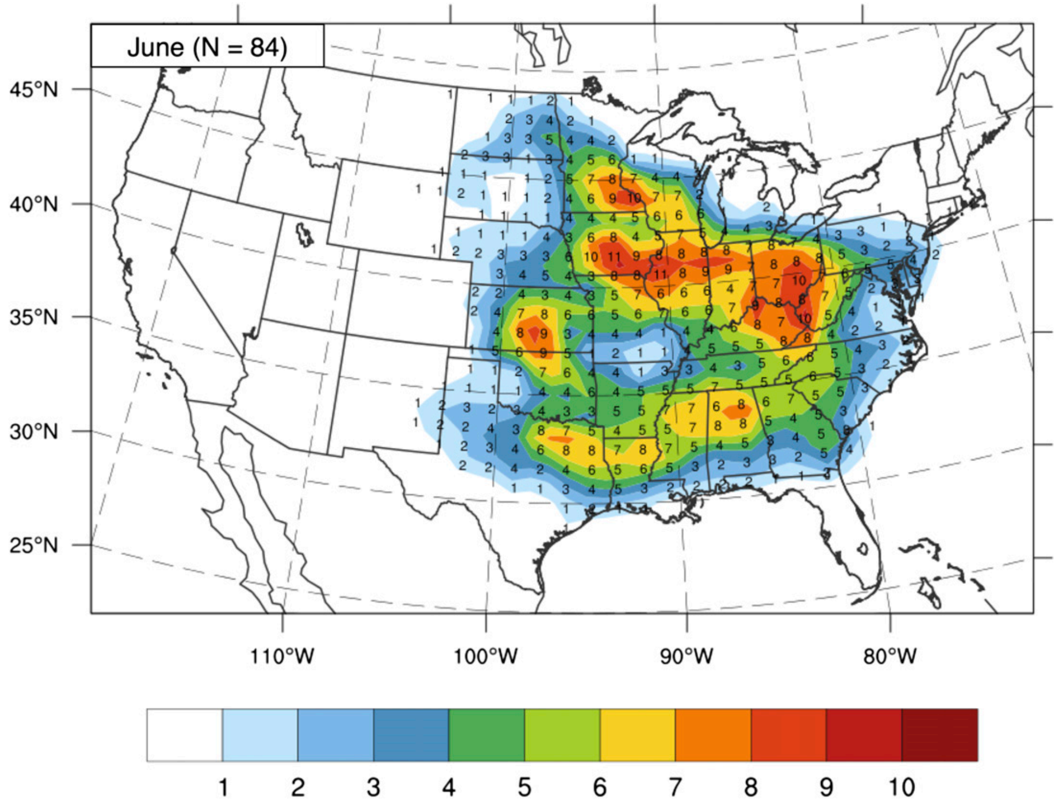

FIG. 8. As in Fig. 4, but for the month of June.

tropospheric wind direction varies from southwest to northwest among the ridge, zonal, and northwest flow categories, respectively, they all depict derecho initiation located along an east–west-oriented low-level boundary, indicated by a meridional gradient in 850-hPa θ_e (Figs. 11a, 12a, and 13a), coincident with a surface trough axis (Figs. 11b, 12b, and 13b). A zonally oriented moisture corridor marked by relatively high precipitable water values in excess of 35 mm is also located along and to the south of the boundary (Figs. 11b, 12b, and 13b). Furthermore, derecho initiation in each of the ridge, zonal, and northwest flow categories occurs within the equatorward entrance region of an upper-level jet (Figs. 11b, 12b, and 13b). The upper-level trough category differs from the other three eastern categories in that the high-θ_e moisture corridor crucial to creating large instability is oriented meridionally in southwesterly flow ahead of an 850-hPa trough (Fig. 14a). Derecho initiation occurs in the warm sector of a surface low ahead of a southwesterly upper-level jet (Fig. 14b). The prevalence of upper-level troughs in the identified progressive derechos initiation environments (~20% of the total) is notable. While Coniglio et al. (2004) included instances in which a progressive derecho occurred ahead of an upper-level trough, it, and other derecho studies (e.g., JH87; Burke and Schultz 2004), have focused on the connection between upper-level troughs and serial derechos rather than the role of upper-level troughs in the production of progressive derechos. The current study thus reinforces the link between upper-level troughs and progressive derecho formation.

The derecho tracks corresponding to each eastern category are consistent with the direction of flow used in defining the category. This consistency is an expected result as prevailing methods of forecasting MCS motion rely heavily on the direction of the mean tropospheric wind (Corfidi 2003). Zonal flow tracks tend to lie west to east (Fig. 13c) while northwest flow tracks lie northwest–southeast (Fig. 12c). Ridge category tracks also tend to lie northwest–southeast (Fig. 11c) due to the preferred clockwise propagation of the derechos around the northern periphery of an amplified ridge. Upper-level trough category derechos show the most variation in track (Fig. 14c), which likely results from largely varying mean wind directions among member derechos as they propagate away from the trough.

Composite analyses of the three western category derechos (Figs. 15–17) all contain a surface cyclone with derecho initiation located at the apex of a low-level moisture corridor (Figs. 15a, 16a, and 17a) in easterly

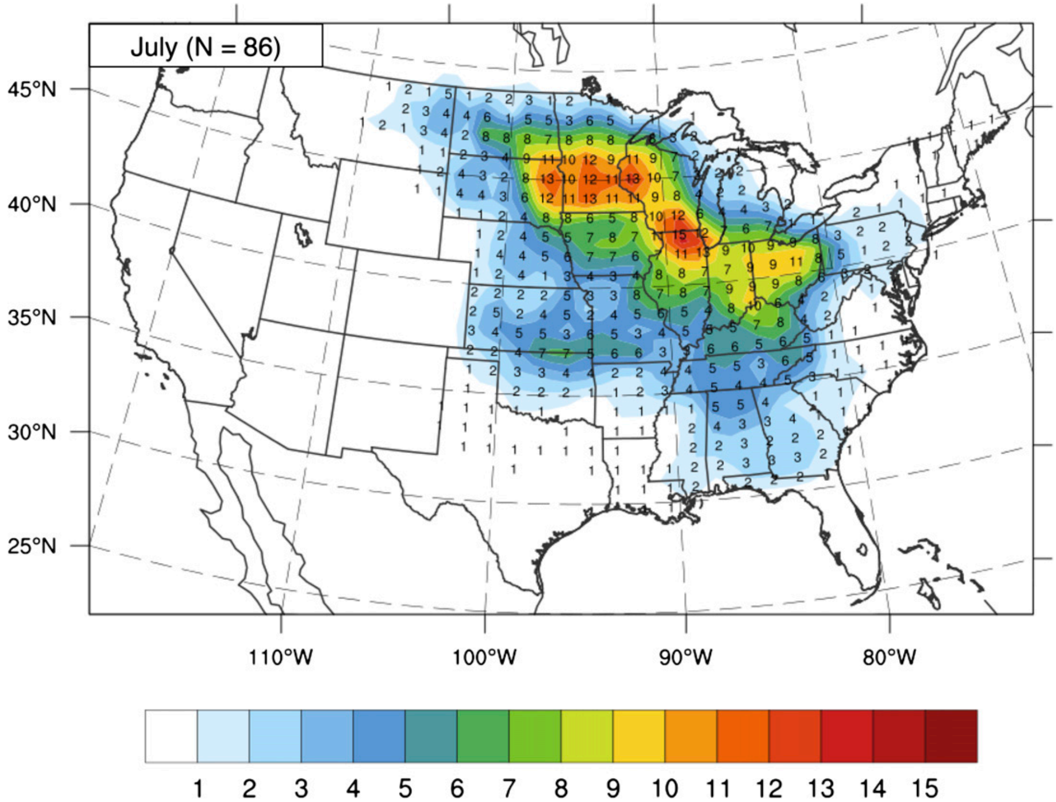

FIG. 9. As in Fig. 4, but for the month of July.

surface flow to the north of the cyclone (Figs. 15b, 16b, and 17b). The composite cyclone pressure is lowest in the southwest flow across the Rockies category at 1004 hPa and highest in the northwest flow across the Rockies category at 1010 hPa with the zonal flow across the Rockies category in-between. Similar to the trough category, the moisture corridors in the three western categories are oriented meridionally in flow containing a large southerly component ahead of the surface low (Figs. 15a, 16a, and 17a). The derecho tracks in the western categories are again consistent with the expected mean tropospheric wind varying from southwesterly to northwesterly (Figs. 15c, 16c, and 17c), and it is evident from examining the northwest flow across the Rockies tracks (Fig. 16c) that those derechos are primarily responsible for the southern plains maximum in the full warm-season progressive derecho climatology (Fig. 4).

The southwest flow across the Rockies, northwest flow across the Rockies, and zonal flow across the Rockies categories are analogous to the trough, northwest flow, and zonal flow categories, respectively, with differences in corresponding low-level synoptic details at derecho initiation (i.e., easterly surface flow to the north of a surface low and, in the northwest flow across the Rockies and zonal flow across the Rockies categories, a meridionally oriented moisture corridor) predominately attributed to the interaction of the synoptic flow with the complex terrain of the Rocky Mountains. This attribution necessitates the consideration of geography in constructing a spectrum of progressive derecho formation environments and delineation between "eastern" and "western" progressive derechos.

To further reveal details of the differences between derecho initiation environments in the western half of the country and those in the eastern half of the country, two composite soundings were constructed, one using sounding sites west of 95°W and another using sounding sites east of 95°W. All soundings occurring within 3 h and 200 km of a given derecho initiation were candidates for compositing. After filtering out candidate soundings that were convectively contaminated, had incomplete data, or were generally unrepresentative (e.g., located on the opposite side of a surface boundary from derecho initiation), 37 proximity soundings remained viable for the western sites and 24 for the eastern sites. All soundings were interpolated to a normalized vertical coordinate system before averaging.

The easterly low-level flow component characteristic of western derecho environments is immediately evident in the western composite sounding (Fig. 18a) and contrasts with the nearly unidirectional flow of the eastern

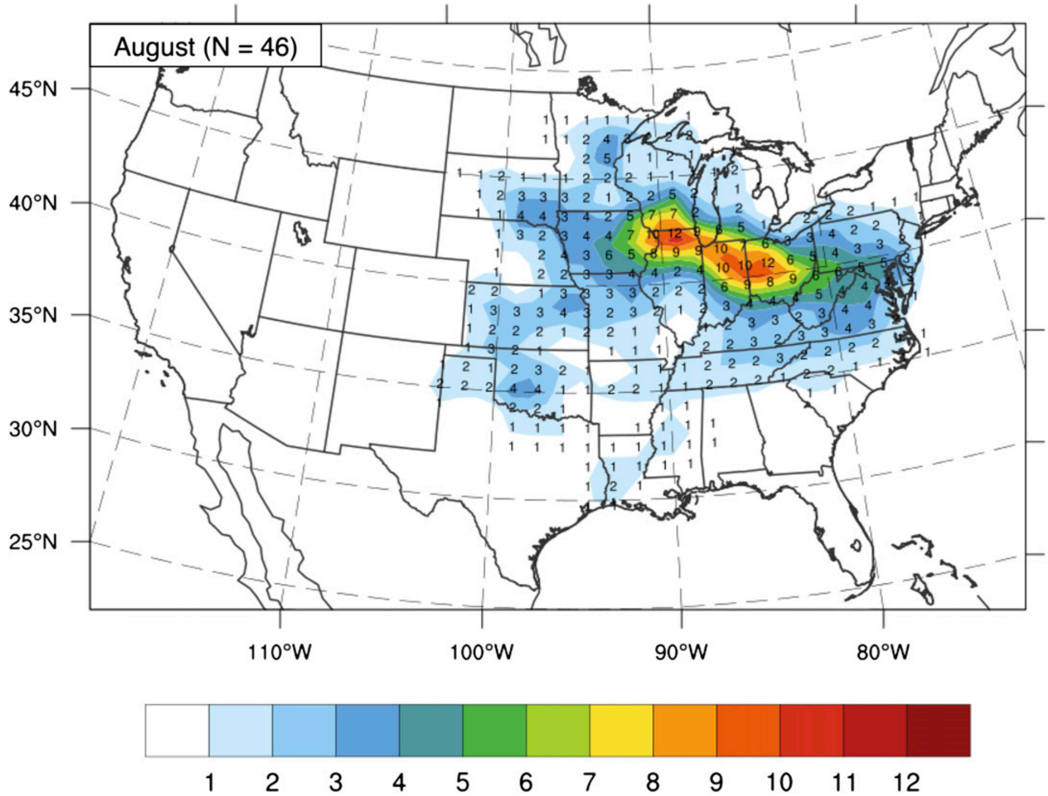

FIG. 10. As in Fig. 4, but for the month of August.

composite sounding (Fig. 18b). The western composite sounding also contains steeper midlevel lapse rates due to the fact that western derechos occur near the origin location of elevated mixed layers that routinely form over the complex terrain of the Intermountain West and become advected in the direction of the mean flow (Carlson and Ludlam 1968; Carlson et al. 1983; Lanicci and Warner 1991; Banacos and Ekster 2010). Though its midlevel lapse rates are steeper, the western sounding contains less low-level moisture and subsequently less precipitable water (34.4 mm west vs 38.5 mm east) and convective available potential energy (2341 J kg^{-1} west vs 3068 J kg^{-1} east) than the eastern sounding. The drier air present in the western sounding compared to the eastern sounding is more conducive to evaporational cooling, the production of negative buoyancy, and the associated development of cold pools that produce severe surface winds (e.g., Johns and Doswell 1992; Evans and Doswell 2001; Wakimoto 2001), which may explain why the most severe progressive derechos initiate in the plains (Fig. 6). Both soundings display warm air advection in the low levels consistent with derecho environments described in JH87, but the clockwise turning of the hodograph is much greater in the western sounding due to the backed winds at the surface. These backed surface winds in the western sounding provide a change in wind direction with height that is crucial for producing sufficient vertical wind shear to support severe convection, as the magnitude of the low-level winds is relatively small in comparison to the eastern sounding. Surface–6-km wind shear is ~18.5 m s^{-1} (36 kt) in the eastern sounding and ~20 m s^{-1} (39 kt) in the western sounding, both well within the range of values observed in previous observational studies of derecho environments (Evans and Doswell 2001; Coniglio et al. 2004). In addition to low-level wind differences, the eastern and western soundings differ in upper-level wind profiles as shear continues above 5 km in the western sounding but drops off steeply above 5 km in the eastern sounding. This upper-level wind difference is indicative of the tendency for eastern derechos to initiate in west/northwest flow downstream of ridge axes in environments more barotropic than those associated with western derechos.

Figure 19 shows derecho initiation longitude plotted as a function of the UTC hour of day. Derecho initiation shifts westward as the hour of the day increases, presumably tied to times of peak diurnal heating. The main cluster of western derechos is centered on 0000 UTC, times when convective initiation facilitated by the Rocky Mountains is favored (e.g., Wallace 1975; Riley

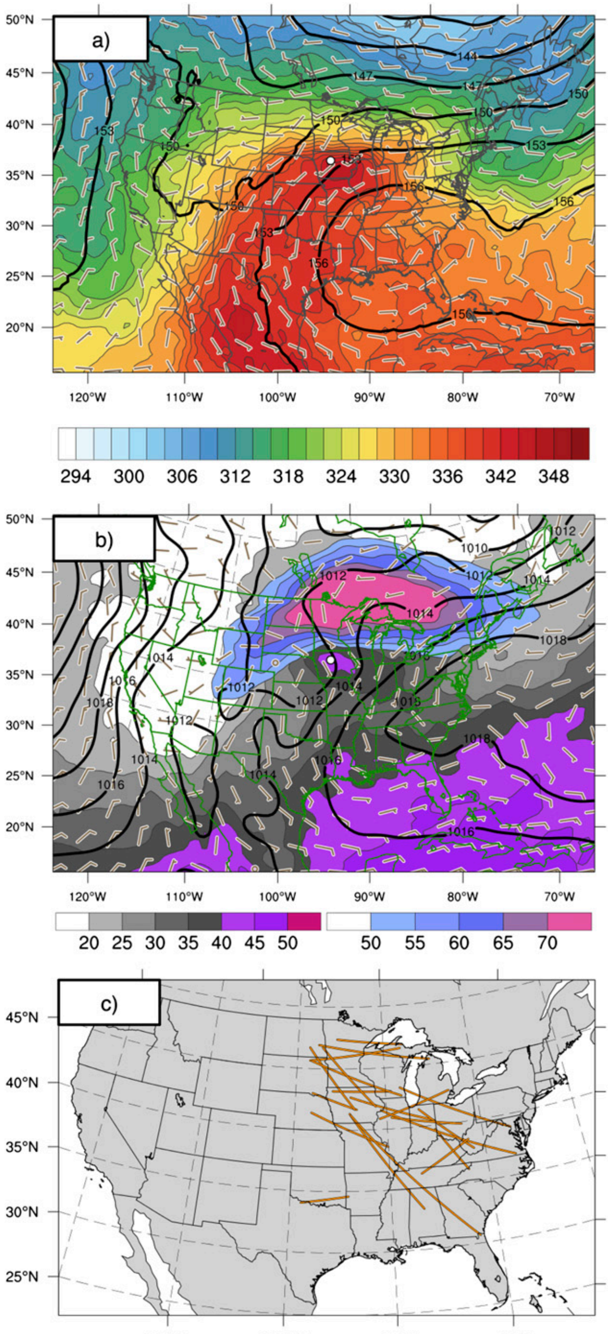

FIG. 11. Ridge environment ($N = 20$; 7.8%) (a) composite 850-hPa geopotential height (contour; dam), 850-hPa winds (barbs; kt), and 850-hPa θ_e (color fill; K); (b) composite mean sea level pressure (contours; hPa), precipitable water (gray fill; mm), 250-hPa wind magnitude (color fill; kt), and 1000-hPa winds (barbs; kt); and (c) lines connecting the starting and ending points of each of the 20 events in the ridge composite category. The white dot in (a) and (b) is located at the composite initiation location to which each member grid was shifted before averaging over all category members.

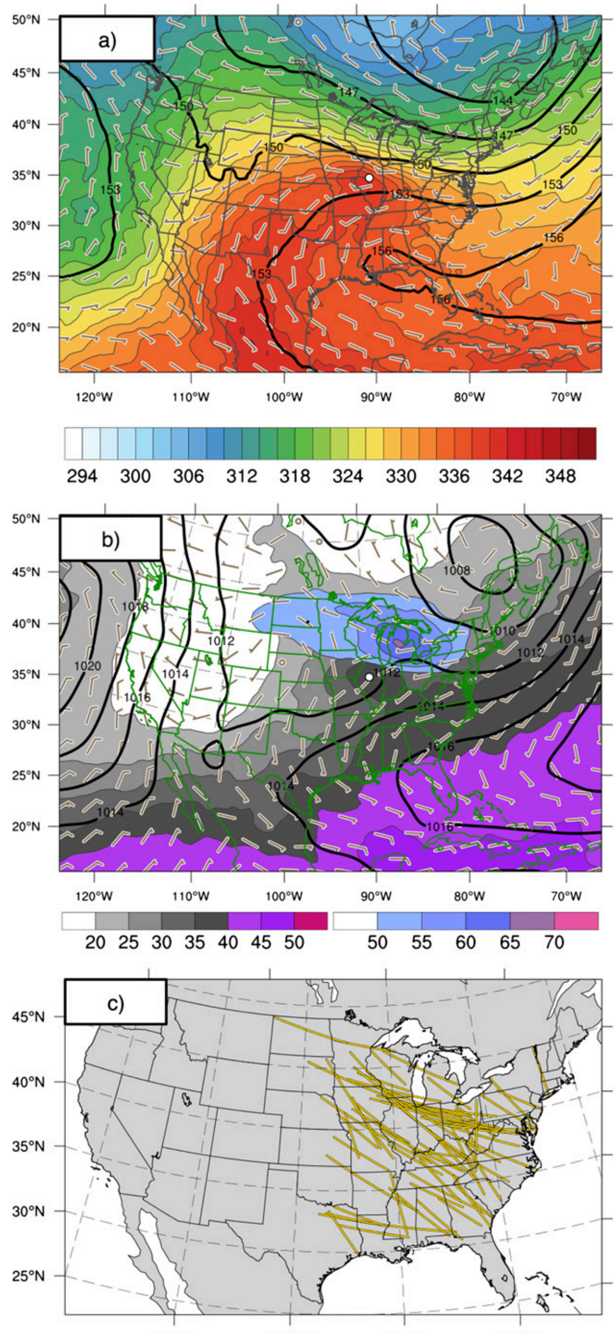

FIG. 12. As in Fig. 11, but for composite category northwest flow ($N = 64$; 25.0%).

et al. 1987; Trier and Parsons 1993; Trier et al. 2010; Dai 2001a,b). Though derecho initiation shows a nocturnal minimum, it is notable that all but one of the derecho events that do initiate between 0300 and 0900 UTC do so west of 90°W (Fig. 19). This central plains preference may be a reflection of the nocturnal low-level jet (LLJ) initiating or enhancing plains convection at these times

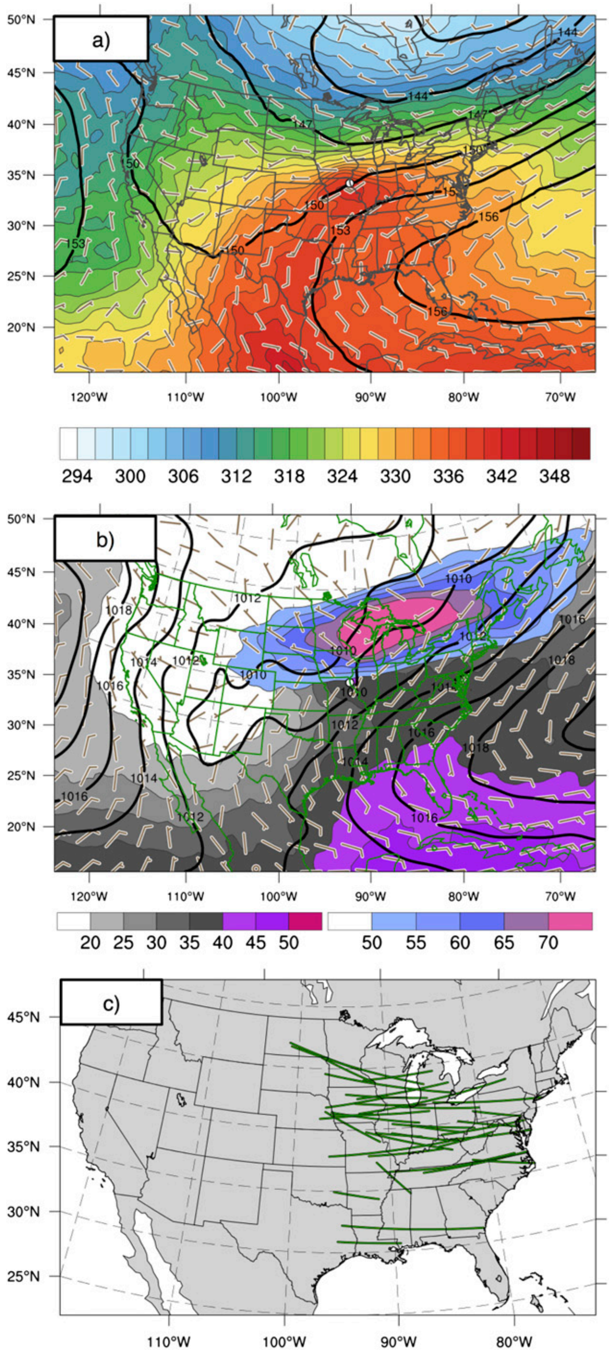

FIG. 13. As in Fig. 11, but for composite category zonal flow ($N = 36$; 14.1%).

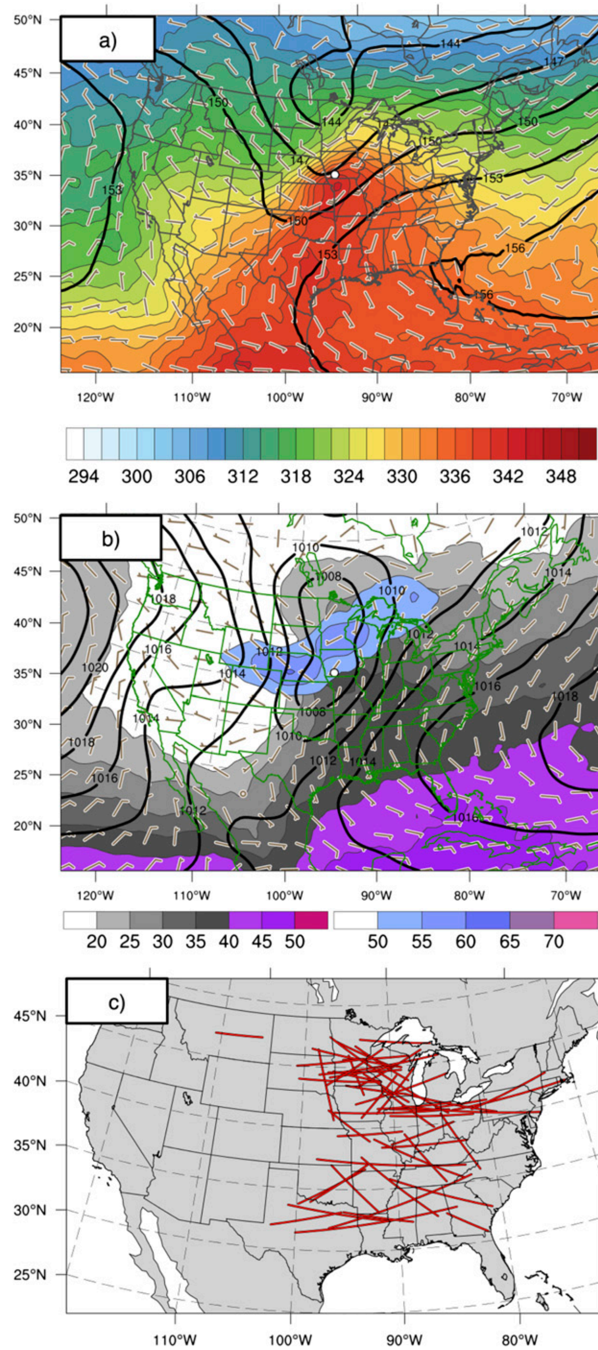

FIG. 14. As in Fig. 11, but for composite category upper-level trough ($N = 51$; 19.9%).

(e.g., Means 1952; Blackadar 1957; Bonner et al. 1968; Stensrud 1996; Monaghan et al. 2010; Rife et al. 2010).

5. Discussion

The 1996–2013 warm-season, progressive derecho climatology presented in Fig. 4 is an extension of the previous derecho climatologies presented in Fig. 3, though it is reiterated that the current study focuses on progressive derechos while previous studies included serial derechos. The prominent northern plains to Midwest corridor present in JH87 (Fig. 3a) is the dominant corridor in Fig. 4, but the Oklahoma and Kansas concentration of events in BM98 (Fig. 3b) is also present

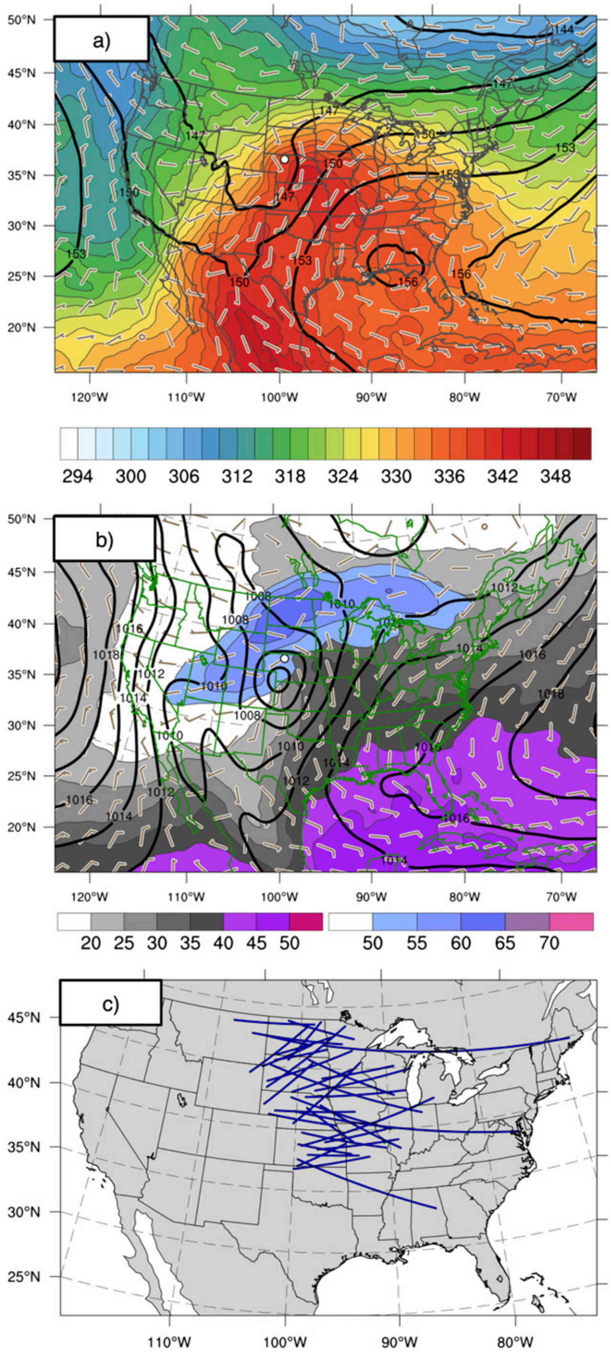

FIG. 15. As in Fig. 11, but for composite category southwest flow across the Rockies (N = 35; 13.7%).

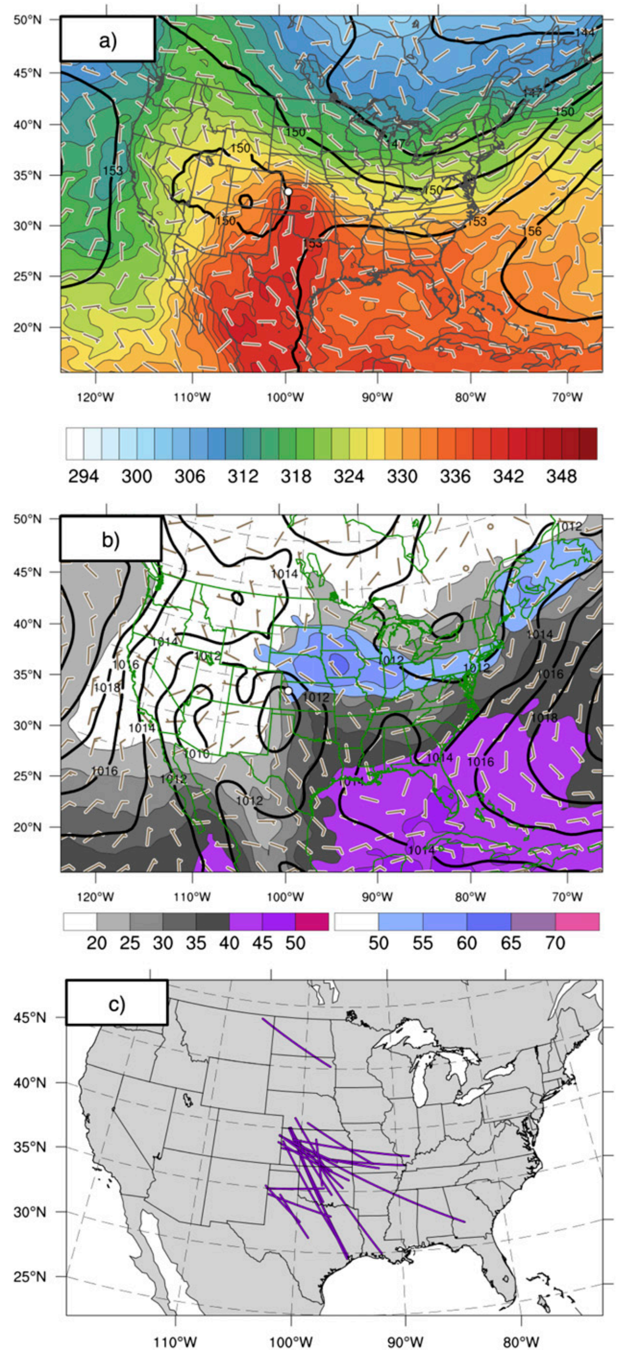

FIG. 16. As in Fig. 11, but for composite category northwest flow across the Rockies (N = 22; 8.6%).

in the current climatology, albeit at a lesser magnitude. The CS04 climatology (Fig. 3c) shows a strong spatial similarity to the current study but differs in the relative frequencies of derechos in the Midwest and southern plains. The higher frequency of southern plains derechos in CS04 compared to the current study is hypothesized to be the result of synoptic environments supporting such derechos occurring more often in 1986–2001 compared to the current period of study (1996–2013), as favorable corridors of derecho activity have been shown to vary with time (BM98; Johns and Evans 2000). In addition to corroborating previously identified corridors of maximum derecho frequency, the current results reinforce the sharp decrease in frequency east of the

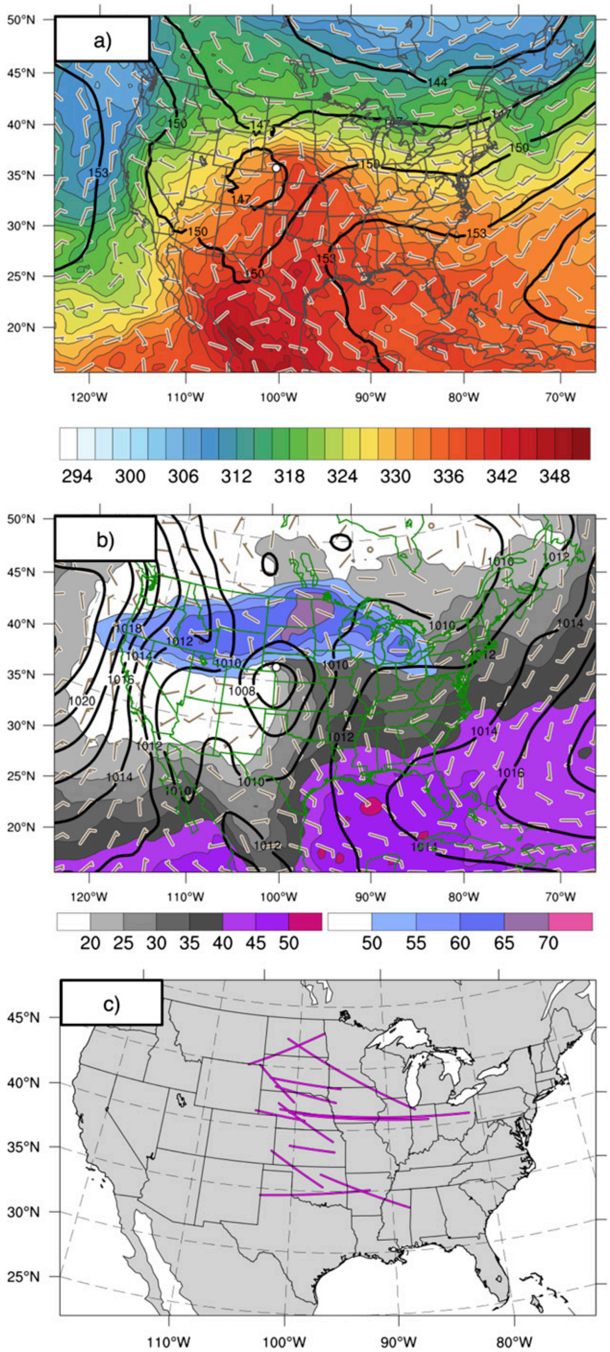

FIG. 17. As in Fig. 11, but for composite category zonal flow across the Rockies (N = 14; 5.5%).

Appalachians shown in both the JH87 (Fig. 3a) and CS04 (Fig. 3c) climatologies that is a reflection of the adverse effect of these mountains on MCS maintenance.

Overall, progressive derecho initiation times reflect hours of peak diurnal heating as evidenced by derechos initiating later in the day toward western longitudes (Fig. 19). The western derechos initiate near 0000 UTC, a favorable time for convective initiation over the Rockies (e.g., Wallace 1975; Riley et al. 1987). Climatologically, a nocturnal maximum in precipitation exists over the plains for a variety of interrelated reasons (Trier et al. 2010) including convection initiated by sensible heating over the Rockies propagating eastward during the night (Carbone and Tuttle 2008), the reversal of the mountain–plains solenoidal circulation causing mean rising motion over the plains at night (Tripoli and Cotton 1989a,b), and the nocturnal LLJ facilitating convective initiation and intensification over the plains (e.g., Blackadar 1957; Bonner et al. 1968; Tuttle and Davis 2006). A nocturnal maximum in plains precipitation is implied in the current study by the preference for derechos to initiate in the vicinity of the Rocky Mountains near 0000 UTC (Fig. 19) and then track eastward onto the plains in the hours that follow (Figs. 15c, 16c, and 17c). Augustine and Caracena (1994) found a comparable temporal evolution of nocturnal MCSs over the central United States. Though derecho-producing MCSs frequently propagate into the plains at night, initiation over the plains during the nighttime hours (between 0300 and 1200 UTC; Fig. 19) is far less common. This lack of nocturnal derecho initiation may be due to a stable nocturnal boundary layer keeping nighttime plains convection elevated (Colman 1990a,b), which restricts downward momentum transport and severe surface winds (Grant 1995; Horgan et al. 2007). An explanation for why derecho-producing MCSs initiating during the day can continue into the plains at night exists in Parker (2008), who found simulated surface-based squall lines to persist as surface based even when they encountered low-level cooling similar to that of a stabilizing nocturnal boundary layer. In effect, a derecho propagating rapidly eastward sees the top of a forming shallow nocturnal stable layer as a minor obstacle above which a deep moist and unstable air mass provides a favorable environment for sustained severe convection.

In addition to a favorable thermal profile, the kinematics provided by the upper-level jet and associated enhanced mean-tropospheric winds and vertical wind shear appear critical to warm-season derecho formation. Progressive derechos show a marked northward shift throughout the warm season as baroclinicity decreases climatologically, upper-level ridges build northward, the polar jet retreats northward, and the STJ disappears. Parker and Ahijevych (2007) argue that, in the east-central U.S. warm season, instability for organized convection often exists while the enhanced vertical wind shear is lacking. It is the presence of the upper-level jet that produces the vertical wind shear that supports organized convection. Consistent with previous derecho research, each composite category presented in the

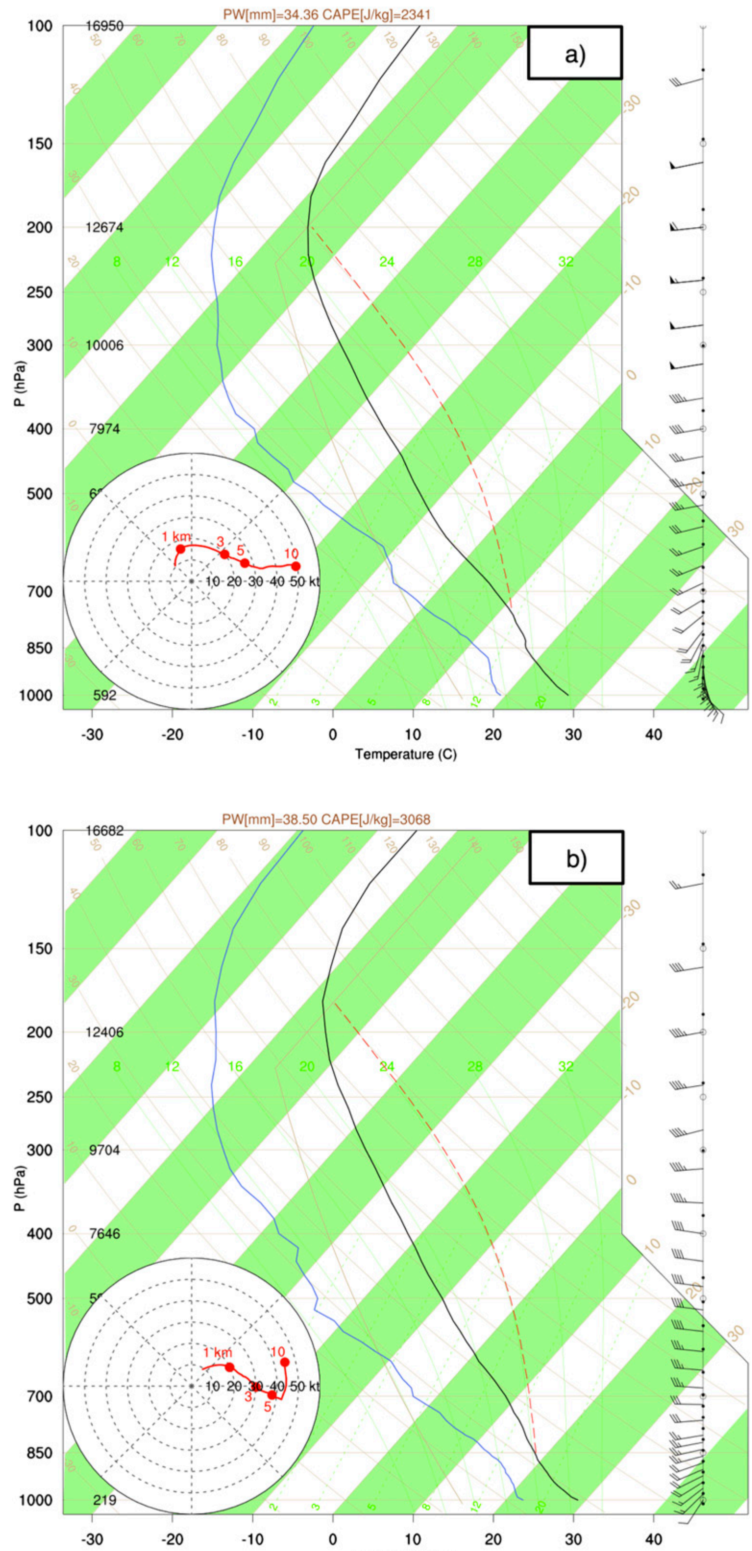

FIG. 18. Composite soundings comprising (a) 37 proximity soundings west of 95°W and (b) 24 proximity soundings east of 95°W.

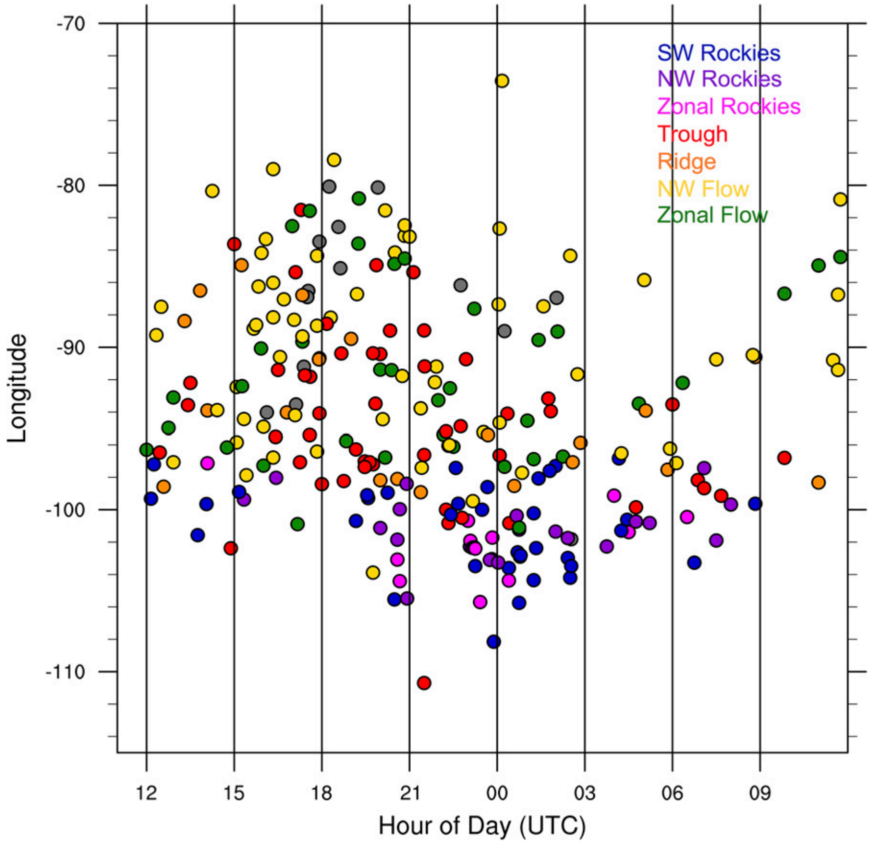

FIG. 19. Derecho initiation longitude as a function of UTC hour of day colored by composite category.

current study contains a well-defined upper-level jet in the vicinity of derecho initiation.

While favorable progressive derecho environmental characteristics established in previous research have largely been confirmed here including large low-level moisture coincident with an east–west-oriented surface boundary beneath mean west/northwest tropospheric winds, the current study bolsters a relationship between upper-level troughs and progressive derechos, namely with the finding that one in five progressive derechos forms ahead of a distinct upper-level trough. In addition, nuance in the environments of derechos initiating near the Rocky Mountains is revealed. Specifically, a common western progressive derecho initiation environment characterized by a Rocky Mountain lee cyclone inducing increased backing of surface winds and a more meridionally oriented moisture corridor is established.

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