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ON THE EPISODIC NATURE OF DERECHO-PRODUCING CONVECTIVE SYSTEMS IN THE UNITED STATES

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ABSTRACT

Convectively generated windstorms occur over broad temporal and spatial scales; however, one of the larger-scale and most intense of these windstorms has been given the name 'derecho'. This study illustrates the tendency for derecho-producing mesoscale convective systems to group together across the United States – forming a derecho series. The derecho series is recognized as any succession of derechos that develop within a similar synoptic environment with no more than 72 h separating individual events. A derecho dataset for the period 1994–2003 was assembled to investigate the groupings of these extremely damaging convective wind events. Results indicate that over 62% of the derechos in the dataset were members of a derecho series. On average, nearly six series affected the United States annually. Most derecho series consisted of two or three events; though, 14 series during the period of record contained four or more events. Two separate series involved nine derechos within a period of nine days. Analyses reveal that derecho series largely frequent regions of the Midwest, Ohio Valley, and the south–central Great Plains during May, June, and July. Results suggest that once a derecho occurred during May, June, or July, there was a 58% chance that this event was the first of a series of two or more, and about a 46% chance that this was the first of a derecho series consisting of three or more events. The derecho series climatology reveals that forecasters in regions frequented by derechos should be prepared for the probable regeneration of a derecho-producing convective system after an initial event occurs.

KEY WORDS: derecho; windstorm; climatology; convective systems

1. INTRODUCTION

Studies by Miller (1972); Johns (1982); and Schneider *et al.* (2004) observed that severe weather outbreaks are likely to repeat on several successive days across the conterminous United States. Johns (1982) found that 71% of all US northwest flow (NWF) outbreaks during 1962–1977 were associated with a 'series' of severe weather events (defined as any combination of two or more outbreaks that occurs with no more than two calendar days between any outbreaks in the series). Most of the NWF outbreak series consisted of two or three severe weather outbreaks, but could contain as many as eight or more separate outbreaks within a series. Johns and Hirt (1987) suggested that warm season derechos, or widespread convectively induced windstorms, are often associated with meteorological environments similar to those found in NWF outbreaks. They found that more than one-quarter of all 1980–1983 warm season derechos qualified as NWF outbreak series.

A more recent study by Carbone *et al.* (2002) discovered coherent warm season precipitation patterns that are continental in scale and exhibit durations well in excess of normal mesoscale convective system (MCS) life cycles. Carbone *et al.* (2002) labeled these coherent patterns as 'episodes'. These episodes, lasting up

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to 60 h each, dominate synoptically benign, midsummer patterns in the central and eastern United States. Previous studies (e.g. Johns and Hirt, 1987; Bentley and Mote, 1998) have shown that derechos often occur in these 'weakly forced' synoptic-scale environments. Tuttle and Carbone (2004) examined a long-lived convective episode that included the development of a derecho-producing convective system (DMCS) that formed along the cold pool boundary generated by a dissipating MCS. In this case, the convective episode owed its longevity to a coherent regeneration process facilitated by favorable mesoscale cold pool-wind shear dynamics and synoptic-scale forcing that optimized favorable shear and low-level moisture conditions. Hence, there may be a linkage between successions of warm season derecho events and the episodic nature of the convection identified by Carbone *et al*. (2002).

Several additional case studies in the literature have examined the environments of convective system series, some of which contained derechos. Bartels *et al*. (2002) illustrate such an example during the period 6–10 July 2001, where two derecho events occurred within an episode of convection in a NWF scenario, while Keighton *et al*. (2001) describe a pair of consecutive Appalachian-crossing derechos in August 2000. In another case, Bosart *et al*. (1998) examined a sequence of derechos that occurred across the northern tier of the United States during 13–15 July 1995. Their results suggest that a sequence of mesoscale, upper-level potential vorticity (PV) anomalies migrating atop a large-scale, stagnant ridge produced a favorable environment for the development of a succession of strong derechos. Unfortunately, this derecho grouping was responsible for 12 fatalities, 41 injuries, and over $100 million in insured property losses in the United States (NOAA, 1995; Ashley and Mote, 2004). Many forests across the region were devastated by the derechos with one estimate of lost timber in the Adirondack State Park of New York reaching $234 million (adjusted to 2003 dollars; NOAA, 1995). In another illustration of the tendency of convective systems to replicate, Tollerud *et al*. (2000) described a group of MCSs and mesoscale convective complexes (MCCs) that formed over the central United States during 27 June 1999 to 2 July 1999. This convective group included two derechos and several flooding MCCs that appeared to be spawned by a PV streamer that persisted across the region.

In a larger climatological study, Bentley and Sparks (2003) established the tendency for derechos to 'train' or group over similar regions. They found a high propensity for summer, northern-tier US derechos (a corridor reminiscent of Johns (1982) NWF scenario) and northeast-moving Great Plains derechos to occur in groups. However, their criteria for derecho groups were relatively liberal, with up to a 7–8 day period between events.

The aforementioned studies have documented and examined several cases of derechos occurring in a series; yet, no study has examined thoroughly the climatology of these groupings. As illustrated by Weiss *et al*. (2002), improvements in operational forecasts and warnings of severe convection are often the result of improved analysis/forecasting techniques and new scientific understanding that develops from basic and applied research such as descriptive climatologies. Hence, it is important not only for forecasters to continue to improve pattern recognition and meteorological parameter assessment of severe convection but they must also recognize and understand the climatology of the events they are forecasting. This study seeks to improve forecaster 'situational awareness' of derechos by constructing a climatology illustrating the tendency for these widespread, convectively induced windstorms to group.

The study utilizes a much larger dataset compiled from several different sources to reveal the characteristics of these series and a more conservative approach to delineate derecho groupings than have been utilized in the past (i.e. Bentley and Sparks, 2003). The investigation reviews 10 years of derecho data in order to detail the tendency for these convective events to form in succession. Two or more derecho events occurring within several days and within a similar environment are labeled a derecho 'series'. Corridors that are most frequented by these derecho series, as well as the overall temporal and spatial features of derecho series in the central and eastern United States are revealed.

2. METHODOLOGY

2.1. Derecho dataset

The conterminous US derecho dataset utilized in this study was compiled through several sources including two recently completed long-term climatologies. Initially, the dataset presented by Bentley and Mote (1998) and Bentley and Sparks (2003) was employed to establish 230 derecho occurrences for the period 1986–2000. The derecho dataset in the Bentley and Mote (1998) and Bentley and Sparks (2003) studies was derived from the US Storm Prediction Center's (SPC's) on-line database of severe convective wind gusts and the SPC's *SeverePlot* software (Hart, 1993). Bentley and Mote (1998) and Bentley and Sparks (2003) modified existing derecho identification criteria proposed by Johns and Hirt (1987) to facilitate analysis of the large dataset (*cf* Table I in Bentley and Sparks (2003) or Table I in Coniglio and Stensrud (2004)).

Recently, Michael Coniglio of the National Severe Storms Laboratory compiled a derecho database consisting of 244 events for the period 1986–2001. This dataset is employed in both Coniglio *et al*. (2004) and Coniglio and Stensrud (2004). Coniglio constructed the database (hereafter Coniglio and Stensrud (2004) dataset) utilizing the SPC's severe convective wind database, *SeverePlot* software, and available radar data. Coniglio and Stensrud (2004) utilized a similar derecho identification method as that proposed by Bentley and Sparks (2003), but also included varying degrees of intensity on the basis of wind gust speed and damage reports in order to document cases that met the more stringent Johns and Hirt (1987) criteria and particularly intense events as illustrated by Miller and Johns (2000). Furthermore, Coniglio and Stensrud (2004) examined radar imagery to confirm that the derecho was produced by an MCS. The Coniglio and Stensrud (2004) dataset was acquired via the Internet. (This dataset is available at http://www.nssl.noaa.gov/users/mcon/public_html/derlist.htm)

These two primary datasets were compiled and checked for coherence. Interestingly, the two datasets had a large number of inconsistencies. Of the 285 events identified in at least one of the two datasets during the overlapping periods of study (i.e. 1986–2000), only 152 (53%) of the events were documented in *both* studies. This discrepancy in the database is likely due to differences in the way the events were screened in each of the climatologies and the fact that the individual datasets *did not* identify all events. Differences in methodologies developed to determine derecho status is beyond the scope of this paper. The reader is asked to consult Bentley and Mote (2000a); Johns and Evans (2000); Coniglio and Stensrud (2004) for discussions regarding derecho identification criteria.

In order to be consistent with the derecho identification methodology defined by Coniglio and Stensrud (2004), all derechos that were previously not identified utilizing radar data (namely, those events identified by Bentley and Mote (1998); Bentley and Sparks (2003)) were verified using available radar resources from the US National Climatic Data Center, SPC, and US National Aeronautics and Space Administration's Global Hydrology Resource Center. All events in the database were scrutinized utilizing the radar data to make sure that multiple swaths of damage were a part of the same MCS. Events that did not verify this criterion were removed from the dataset.

Table I. Criteria used to identify derechos for this study

Minimum length	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 (unless a land constraint necessitates using a shorter distance).
Chronological progression	The wind reports must have chronological progression, either as a singular swath (progressive) or as a series of swaths (serial), and nonrandom pattern of occurrence by temporally mapping the wind reports of each event.
Temporal and spatial restriction	No more than 2.5 h can elapse between successive wind reports with no more than 2° of latitude and longitude separating successive wind reports.
Origin of wind swath	Multiple swaths of damage must be part of the same MCS as indicated by examining available radar data.
MCS continuity	The associated MCS, as indicated by available surface pressure and wind fields and/or radar data, must have temporal and spatial continuity.

In addition to the Bentley and Sparks (2003) and Coniglio and Stensrud (2004) climatologies, the authors examined all derecho literature and documented any missing derecho events not revealed by the aforementioned climatological investigations. Finally, several additional events were added where the Johns and Hirt (1987) length criteria were not met, but were indeed derecho events (e.g. serial derecho crossing Florida peninsula on 13 March 1993). Eight such cases were included in the dataset. Finally, we documented derechos from 2002 and 2003 by examining the SPC's daily on-line severe storm reports, SPC's severe thunderstorm event database, *Storm Data, SeverePlot*, and available radar data.

All derechos that were identified or compiled for this study met a set of consistent criteria (Table I). This set of criteria is analogous to that proposed and utilized by Bentley and Mote (1998); Bentley and Sparks (2003); Evans and Doswell (2001); Coniglio and Stensrud (2004); and Coniglio *et al.* (2004). The unified derecho dataset, consisting of 377 events for the period 1986–2003, is used to improve the record of derechos by combining several sources of data into a single dataset. Ultimately, with the unified database developed in this study, we intend to diminish the chance of unidentified events and to reduce the biases associated with the derecho identification methods utilized by the previously mentioned authors (e.g. failure to use radar data to screen events that led to slight overestimation of derecho events by Bentley and Mote (1998) and Bentley and Sparks (2003)).

Although the derecho dataset contains 18 years of documented derecho events, only the 10-year period from 1994 to 2003 is utilized for this study. The basis for this restriction is due to the large increase in the annual number of events evident after 1993 (Figure 1). For example, the 10-year period between 1994 and 2003 consists of over 85% of the derechos associated with series in the 18-year dataset, while the 9-year period between 1985 and 1993 consists of *only* 15% of the events. This bias is likely a result of a number of human-related factors associated with an increase in the severe wind reports contained within the severe thunderstorm wind event database, including: (1) population growth and urban sprawl, (2) an increase in weather awareness by the general population, (3) improved communications (e.g. cell phones), (4) the development of spotter networks, (5) the deployment of WSR-88Ds, and (6) the implementation of the national warning verification program that has resulted in increased accountability of NWS warning products (Schaefer *et al.*, 2003). Hence, for the years prior to the NWS modernization (Friday, 1994), many derecho events may be unidentified, resulting in an underestimate of the actual number of events during this early period of the dataset (Coniglio and Stensrud, 2004). Therefore, this data restriction allows for an examination of the most *consistent* portion of the derecho database, which is a desirable condition when examining time-series data.

2.2. Derecho series identification

Numerous synoptic environments and mesoscale mechanisms can promote the formation of successive MCSs, including those producing derechos, such as traveling baroclinic waves and their associated extratropical cyclones and fronts; a persistent low-level jet (LLJ) oriented perpendicular to a zonal-oriented front (Trier and Parsons, 1993); a sequence of shortwaves propagating through persistent NWF aloft (Johns, 1984); convectively generated propagation mechanisms such as residual outflow/cold pools (Keighton *et al.*, 2001; Tuttle and Carbone, 2004), gravity waves (Schmidt and Cotton, 1989; 1990), mesoscale convective vortices (MCVs; Fritsch *et al.*, 1994; Trier *et al.*, 2000); a succession of upper-level PV anomalies migrating atop a large-scale, stagnant ridge (Bosart *et al.*, 1998), among others. Moreover, Stensrud (1996) has found that the cumulative effects of multiple MCSs developing in succession over the same region can promote more convection by increasing baroclinicity and the influx of warm, moist air into the region. Although this study does not specifically classify the derecho series into their formative environments or mechanisms, we do use a temporal restriction and a subjective assessment of the large-scale environment and distance between systems to define the series. A subsequent study investigates the environments of some of the more unique series and illustrates environments that typify series across the eastern two-thirds of the United States.

Undoubtedly, the longer the interlude between two successive derechos, the greater the probability that the environment that generated the events has undergone change or the mechanism that produced the sequence of events has dissipated. Hence, the first requirement in constructing a derecho series classification is to develop

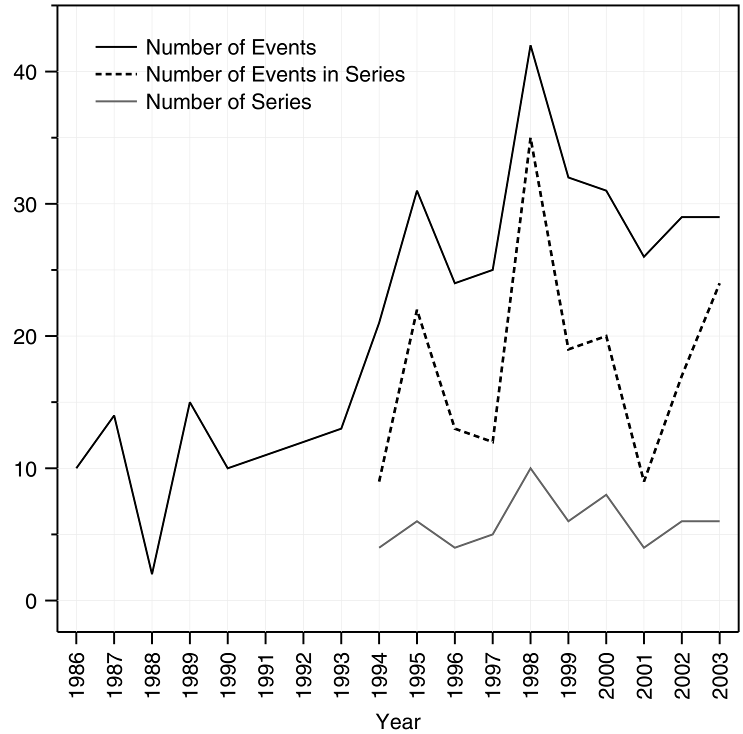

Figure 1. The number of derechos annually for 1986–2003 and the number of derecho series and derecho series members for 1994–2003

a temporal restriction that will limit the time interval between subsequent storms. Initially, in order to establish derecho series from the dataset, we determined the amount of time (in hours) that occurred between the *last* wind report from the previous derecho and the *first* wind report of the next derecho. Interestingly, the dataset reveals a strong clustering of derechos around the low end of the reoccurrence interval distribution (Figure 2). This supports the hypothesis that derechos have a tendency to form in succession.

We subjectively determined on the basis of Figure 2 and prior research (Johns, 1982) that any events that were within three days of each other had the *possibility* of forming in similar tropospheric environments or by the same mechanism. Thus, all events less than 72 h apart were selected as initial derecho series members. This approach is much more restrictive than the 7–8 day temporal restriction put forth by Bentley and Sparks (2003), but fairly consistent with the method that Johns (1982) utilized to identify 'NWF outbreak series' – i.e. any combination of two or more NWF outbreaks that occur with no more than two calendar days between any of the outbreaks of the series. Of the 377 derechos occurring between 1986 and 2003, 225 (60%) derechos met the initial derecho series criteria.

After these preliminary events were selected, 500 hPa and surface analyses from the *Daily Weather Map Series* (NOAA, 1994–2003) were examined for all days within each derecho series temporal window. Events that were environmentally disparate (e.g. associated with significantly differing mid-level tropospheric patterns or surface boundaries) were discarded from the derecho series dataset. In two cases, a large grouping of derechos that met the temporal criterion of a single series was separated into two discrete series since the derechos comprising the initial series were associated with two distinctive synoptic environments. Hence, this method created consistent series for each distinguishing environment.

Other temporal restrictions for identifying derecho families were tested, but the 72-h threshold was determined to be the optimum time constraint. For example, a 36-h threshold unnecessarily split and/or removed derecho cases that formed within a similar synoptic pattern. In effect, this shorter temporal constraint led to an inflation of short reoccurrence families that formed in the same environment. The 72-h time constraint included events that were generated by both synoptic-scale features (with short-to-long reoccurrence

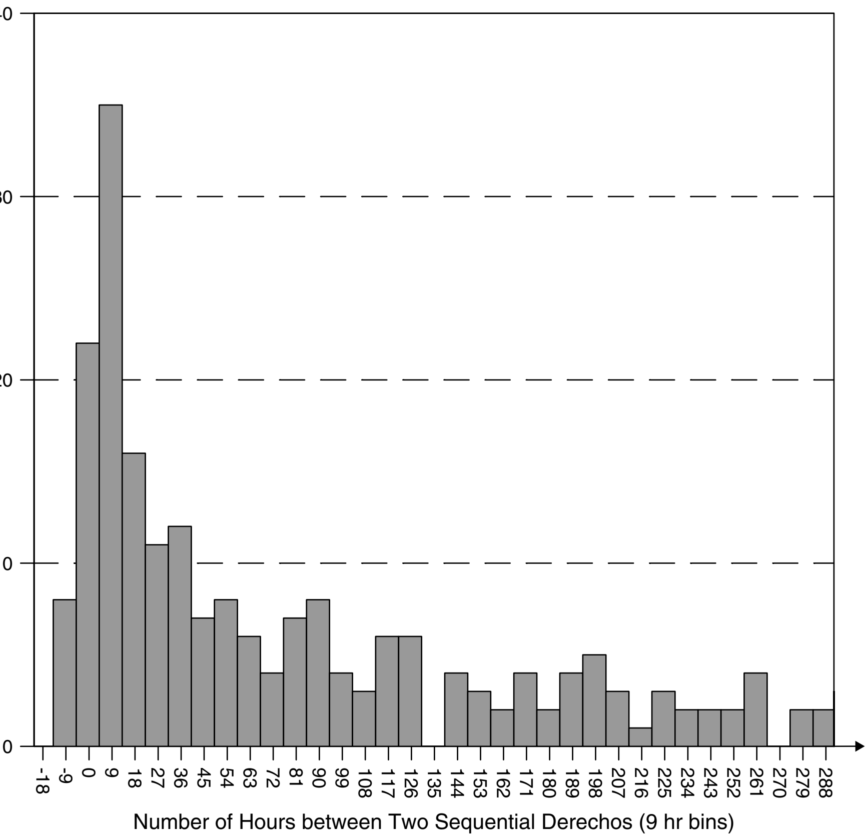

Figure 2. A frequency histogram showing the number of hours (9-h bins) between two sequential derecho events in the 1994–2003 derecho database. Negative values occur when two derechos overlap temporally in the time series

intervals) and those triggered directly by mesoscale features from a prior derecho (short reoccurrence intervals).

Figure 3 illustrates three derecho series that were identified utilizing the procedure described above. In the first case, the temporal component of the derecho series definition employed was certainly satisfied as all the events tended to overlap one another. A subsequent examination of the *Daily Weather Map Series* (not shown) for the potential series' temporal window indicated that all three derechos formed in the same fast, mid-level flow ahead of a migratory mid-level trough. The surface analyses indicated that the individual events in the series developed near a synoptic-scale cold front and/or along convectively induced outflow boundaries equatorward of the cold front. Hence, the examination of the charts indicated that the three derechos formed in a similar environment, confirming that the events comprised a derecho series. Regrettably, the events in this series were responsible for 3 fatalities and over 65 injuries across the southern tier of the United States (NOAA, 1998; Ashley and Mote, 2004).

The second case (Figure 3(b)) illustrates a series that consists of two derechos that produced over a quarter billion dollars in insured damage losses, six fatalities, and numerous injuries across northeast United States – including the New York City metropolitan area (NOAA, 1998; Ashley and Mote, 2004). Again, the temporal component of the derecho series definition was met as the two events were separated by only a few hours. The synoptic environment (not shown) for this series was characterized by abnormally moist (>21 °C surface dewpoints) and unstable (≤−6 °C Lifted Index) conditions across the region with relatively fast and dry mid-level flow aloft. A mid-level low and strong jet streak poleward of the derecho genesis region combined with low-level convergence along a synoptic-scale cold front traversing the region to promote the lift required for overcoming a strongly capped environment that had overspread the area. The juxtaposition of

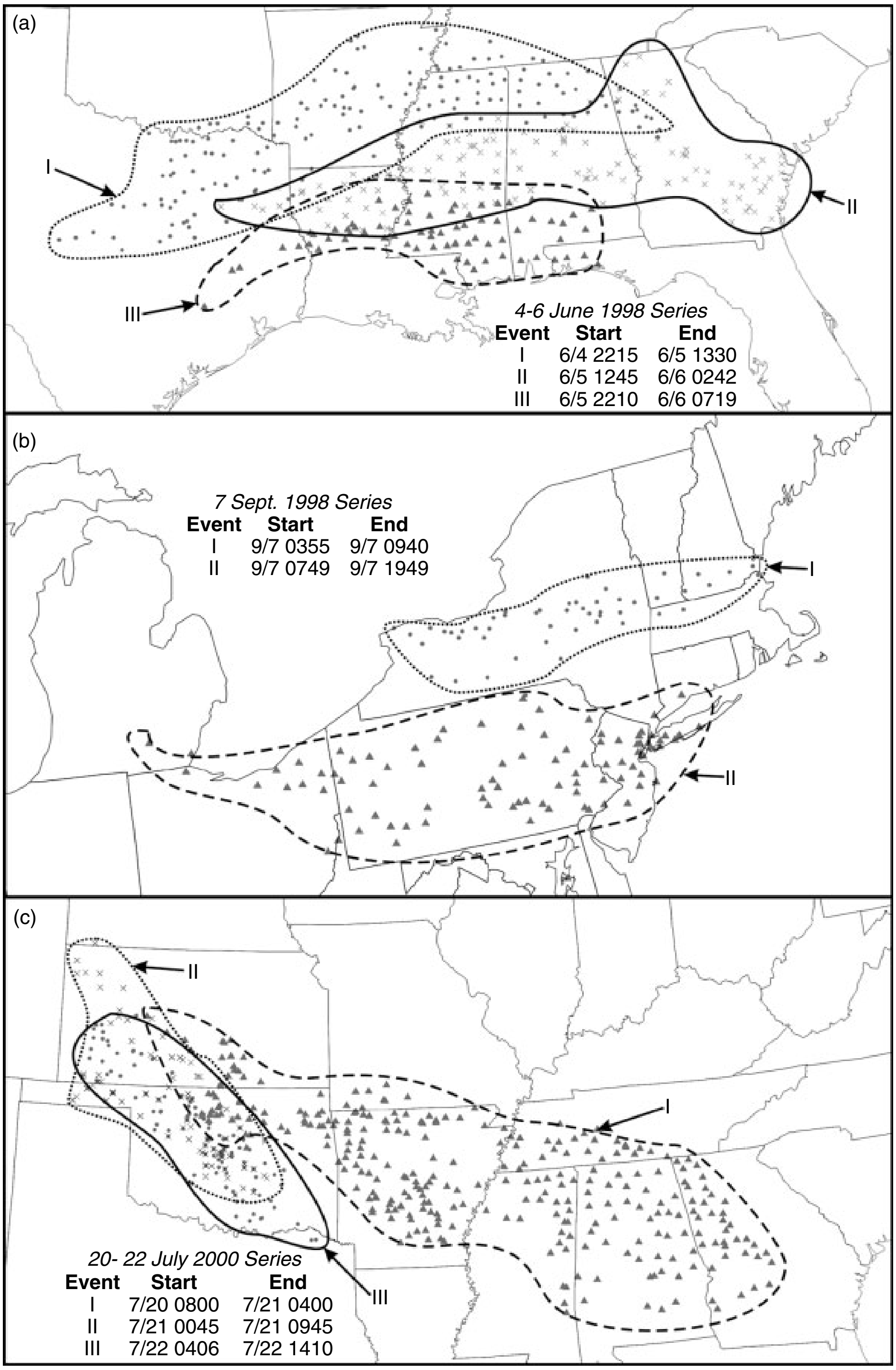

Figure 3. Illustration of three derecho series identified in this study utilizing the procedure outlined in Section 2.2. Series include events that occurred on (a) 4–6 June 1998, (b) 7 September 1998, and (c) 20–22 July 2000. Derechos in each series case have a unique symbol associated with damaging wind or gust reports inside a corresponding isobront

unseasonable moist and unstable conditions, very strong unidirectional shear, and cold front moving across the region promoted an environment conducive to the successive formation of derechos.

The final case of three derechos over the southern Great Plains (Figure 3(c)) is illustrative of rather benign synoptic situations that often typify summer derecho events. This series formed in a highly amplified mid and upper-level pattern (not shown) reminiscent of the NWF environments described by Johns (1984). A quasi-stationary surface boundary, paralleling the WNW-to-ESE oriented upper-level flow and continually reinforced by convective complexes, provided the focus for diurnally initiated convection across this region. In addition, moderate-to-strong northwesterly flow with embedded low-amplitude shortwave troughs supplied the necessary ingredients for convective system organization. The temporal component of the derecho series definition was met as the events were separated by less than the 72-h limit.

These cases demonstrate a few select environments conducive to derecho series formation and are in no way exhaustive of all of the situations that produce series. It is also important to distinguish that, in many of the series scenarios, derechos are not formed by a prior derecho event. Although there are some cases where one DMCS triggers another event, the persistent arrangement of synoptic-scale features (i.e. instability, capping inversion, shortwaves) appears to be the most important element in the development of sequentially occurring derechos.

3. RESULTS

3.1. Temporal frequency

Of the 290 events in the derecho dataset from 1994 to 2003, 180 (62% of the 10-year dataset) met the series criteria discussed in the previous section. The 180 events consisted of 59 series with a mean of 3.1 derechos per series. On average, there were 5.9 series and 18 series members annually. Most series involved only two or three derecho events (Figure 4); however, 14 series contained four or more events. Two separate series – one in June 1998 and one in July 2003 – involved nine derechos within a period of nine days.

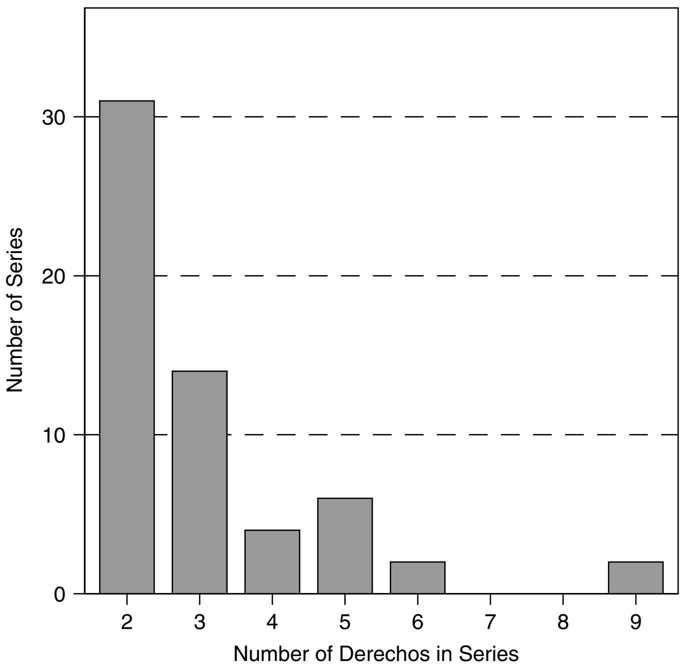

Figure 4. The frequency of series by the number of derechos in a grouping for 1994–2003

Derecho series typically began between 16 and 03 UTC, with more than 72% of the series initiating during this period. The series tended to end around the late afternoon and evening period, with more than 61% of the series ending between 23 and 06 UTC. Thus, there does appear to be some association between derecho series initiation and the diurnal heating cycle. However, the linkage becomes complex when one considers that derecho series tend to dissipate before local midnight – well before typical ending times found for derechos and MCSs identified in other studies (e.g. Augustine and Caracena, 1994; Gale *et al*., 2002). This discrepancy in ending times may be due in part to the consideration of derechos across all seasons including both dynamic and warm season synoptic patterns, while those in other studies tend to focus on nocturnal, warm season events with dissipation near noon local time (e.g. Gale *et al*., 2002). However, examining dissipation times for derecho series from May–September indicates that nearly 50% of warm season series dissipate between 00 and 06 UTC. Hence, it appears that derecho series dissipation is not linked to the diurnal heating cycle and it is probable that different mechanisms other than the dissipation of nocturnal LLJs appear to influence the derecho series cycle.

Derecho series durations range from just over 6 h to nearly 11 days with a mean duration of almost 65 h. The shortest series was associated with two temporally overlapping derechos that developed along the same quasi-stationary boundary.

Examining derecho series frequency by month (Figure 5) indicates that derecho series occurred predominantly during the warm season months of May, June, and July. In fact, 75% of the series and 82% of derecho events in the series occurred during this 3-month period. This is not surprising considering that 62% of derechos from 1994 to 2003 occurred during these months. Similar to the results of Coniglio *et al*. (2004), May was the leading month of DMCSs in the United States. The late-spring peak was likely due to a combination of both serial and progressive type events that tended to frequent the eastern two-thirds of the United States during this transition season month. May was also the peak month for derecho series and the number of events constituting those series. The large occurrence of NWF outbreaks during July (Johns, 1982) was the likely cause of the secondary maximum in derechos and derecho series experienced this month. Interestingly, August had roughly one-third the number of derechos as the three preceding warm season months. This diminishing frequency during late summer was likely caused by an increasingly capped environment in the region (i.e. northern tier of the United States) favorable for derecho development (Farrell and Carlson, 1989), a decrease in the thermodynamic instability of the atmosphere (Johns, 1982), and a general weakening of the mid-tropospheric westerlies leading to an overall decrease in the deep-layer shear needed to facilitate the growth of DMCSs (Johns, 1982; Coniglio and Stensrud, 2001; Coniglio *et al*., 2004).

Of the 290 events documented during this 10-year period, 110 were 'loner' derecho events and 180 events were associated with one of the 59 series. These numbers indicate that once a derecho event occurred, there was a 35% chance that this event was the first of a series of two or more and a 20% chance that this was the first of a derecho series consisting of three or more events. Upon examining the months with the highest frequencies of derecho events for this same period, considerably higher percentages were obtained. For example, during May, June, and July for the 1994–2003 period, there were 32 'loner' events and 148 events associated with one of 44 series. These data suggest that *once a derecho occurred during the warm season months, there was a 58% chance that this event was the first of a series of two or more and about a 46% chance that this was the first of a derecho series consisting of three or more events*.

When examining the percentages on an annual basis, the chance that an event was the initial member of a series was highly variable (Table II). This variability was likely caused by a shift in annual, and even monthly or weekly, synoptic patterns favorable to producing derechos, particularly during the warm season (Bentley and Mote, 1998; Bentley and Sparks, 2003; Coniglio and Stensrud, 2004). In terms of 1998 derecho series, there was a 59% chance that an event was the first of two or more and a 46% that it was the first of a series with three or more events. These numbers are considerably larger when the analysis is restricted to the warm season months during this year. Conversely, during two other years (1994 and 2001), the chance that an event was the first of two or more remained at or below 25%, suggesting that the environment was not as favorable for derecho series formation during these years as other more active years.

The importance of the synoptic pattern on the frequency and concentration of DMCSs and derecho series can be illustrated by comparing the 'active' 15 May–30 June 1998 period with the 'inactive' late spring–early

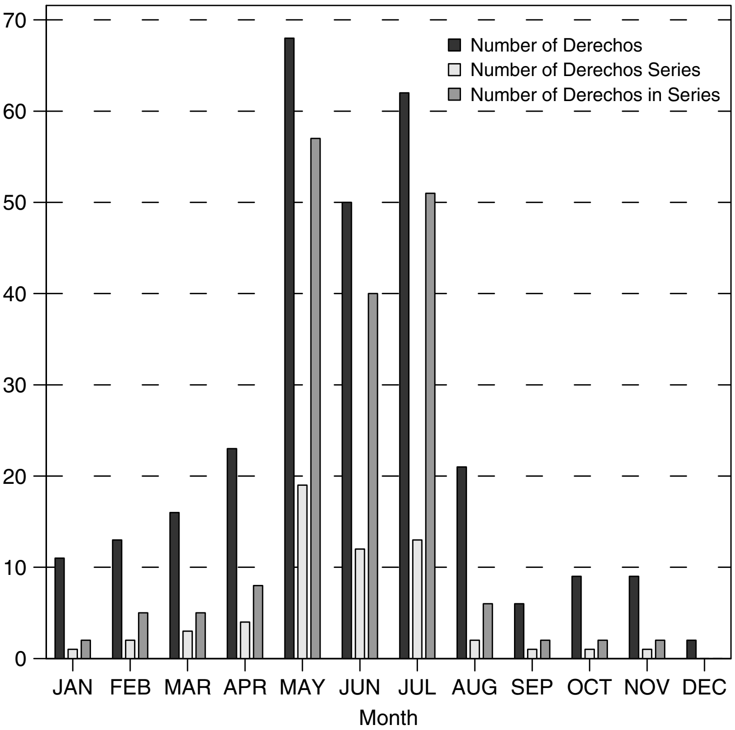

Figure 5. The number of derechos, derecho series, and events in series by month for 1994–2003

Table II. Chance that an event was in a series

	Chance that event was:					
Time period	First of two or more (%)	First of two or more during May, June, or July (%)	First of three or more (%)	First of three or more during May, June, or July (%)	In a series (%)	In a series during May, June, or July (%)
Annual	34.9	57.9	20.3	45.8	62.1	82.2
May	61.3	–	45.5	–	82.4	–
June	57.1	–	43.8	–	82.0	–
July	54.2	–	47.6	–	82.3	–
1994	25.0	57.1	7.7	25.0	42.9	75.0
1995	40.0	40.0	30.8	30.8	71.0	95.7
1996	26.7	40.0	15.4	40.0	54.2	75.0
1997	27.8	22.2	7.1	12.5	48.0	46.2
1998	58.8	80.0	46.2	75.0	83.3	94.0
1999	31.6	55.6	23.5	50.0	59.4	81.0
2000	27.6	75.0	16.1	60.0	64.5	88.2
2001	19.1	42.9	5.6	20.0	34.6	63.6
2002	33.3	42.9	14.3	33.3	58.6	71.4
2003	54.6	71.4	37.5	60.0	82.8	91.7

summer period in 2003. The 1998 pattern featured abnormally strong polar and subtropical jet streams spanning the conterminous United States with extreme thermodynamic instability situated beneath and along the margins of an anomalously strong subtropical ridge positioned across the southern tier of the United States (Figure 6(a) and (c)). This synoptic situation was particularly favorable for the formation of a large number of derechos. From 15 May 1998 to 30 June 1998, 29 derechos occurred across the United States – i.e., new derecho development occurring every 39 h during this extremely active episode. Of the 29 derechos, 28 were members of one of seven series with one series consisting of nine events. Unfortunately, several of these events were 'high-end' derechos (Coniglio and Stensrud, 2004) that ultimately produced hundreds of millions of dollars in insured property losses (Ashley and Mote, 2004). Collectively, the 29 derechos were responsible for a reported 12 deaths and over 440 injuries in the United States (NOAA, 1998). DMCSs tended to form and migrate around the periphery of the subtropical ridge, indicating that the large anticyclone was an important feature in establishing the environment conducive to a large number of derechos occurring successively, while also assisting in focusing (or anchoring) their tracks in the Midwest, Ohio Valley, and lower Great Lakes (not shown). The region beneath the stagnant ridge was characterized by an environment of high convective instability, yet it typically remained capped and free of convection. However, as mid-level shortwaves migrated atop the ridge, they induced a region of low pressure at the surface. In response to the isallobaric minimum, a low-level ageostrophic flow developed and circulated a portion of this convectively unstable air from beneath the lid edge, promoting deep, moist convection and, in many cases, DMCSs. This process – known as 'underrunning' (Lanicci and Warner 1991; Bentley *et al*. 2000) – was instrumental in producing an environment conducive to derechos through focusing low-level instability around the periphery of the anticyclone.

Conversely, from 15 May 2003 to 30 June 2003, only three derechos and one series were documented across the United States. This period was associated with an anomalous deep trough situated across the eastern third of the United States with an upstream anomalously strong ridge positioned in the intermountain

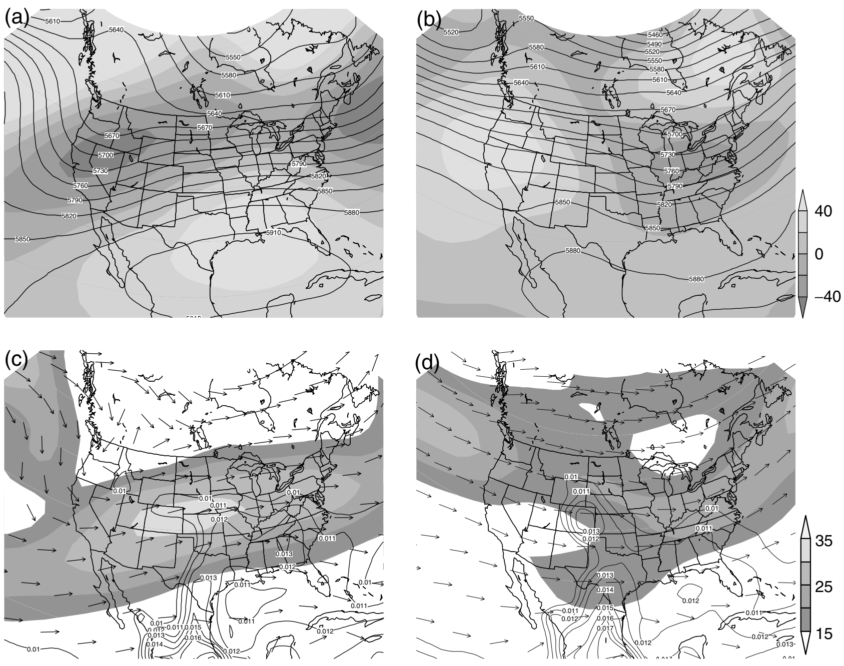

Figure 6. Mean 500 hPa geopotential heights (solid lines) and anomalies (shaded) for (a) 15 May 1998–30 June 1998 and (b) 15 May 2003–30 June 2003. Mean 250 hPa winds (directional arrows and speeds shaded greater than 15 m s^{-1}) and 925 hPa specific humidity (g kg^{-1}; dotted lines) for (c) 15 May 1998–30 June 1998 and (d) 15 May 2003–30 June 2003. Composites created utilizing the NCEP/NCAR Reanalysis dataset (Kalnay *et al*. 1996) available via the NOAA-CIRES climate diagnostic Center. Total means are based on 1968–1996 data

west (Figure 6(b)). The rather benign, stagnant ridge/trough configuration allowed for successive disturbances and unseasonably strong cold fronts to move southward toward the Gulf of Mexico. Although the pattern featured NWF aloft across the typical derecho formative regions, DMCSs were limited across the area because the cold fronts continually scoured low-level moisture (Figure 6(d)), reduced thermodynamic instability, and produced an environment unfavorable for deep moist convection. Johns (1982) suggests that NWF severe weather outbreaks are not common during the early part of the warm season since low-level moisture in areas of NWF aloft is usually insufficient for the production of the severe weather outbreaks. Indeed, as the 2003 warm season continued, moisture and instability returned to the east–central United States, with 14 derechos, including a series of 9 derechos, occurring during the month of July.

Through this brief comparison, it is apparent that the position, strength, and persistence of large-scale, anomalous ridge/trough patterns appear to be very important in restraining or establishing groupings and in the placement of activity corridors of warm season derechos. Although not all derechos are directly influenced by the synoptic environment, evidence suggests it is important in 'priming' mesoscale environments by promoting instability and shear conducive to DMCS formation (Bentley and Mote, 1998; Bentley and Sparks, 2003; Coniglio *et al*., 2004). Nevertheless, the near-storm environment and internal storm dynamics (e.g. cold pool/shear relationships, rear-inflow jets) appear to be the primary features that aid in convective system maintenance and sustenance in a majority of bow-echo events (Weisman 1992, 1993), similar to those that may produce derechos.

3.2. Areal frequency

In order to reveal spatial distributions of derechos and derecho series in the United States, wind damage and gust reports from derechos for the period 1994–2003 were mapped onto 1° latitude × 1° longitude grid. The distributions were determined by identifying grid cells with at least one wind report for a given event and then summing the number of events affecting each grid cell. Contour maps were created using inverse-distance interpolation (Davis 1986). The smoothing technique was employed to leave only the moderate-to-strong signals. This smoothing leads to an underestimate of the original gridded values; therefore, the locations of maximum grid cells prior to the smoothing, and their values, are indicated on the maps.

Examining the derecho frequency for the 10-year period utilized in this study reveals that derechos predominately occurred throughout the eastern two-thirds of the United States (Figure 7(a)). In general, the distribution is similar to the results of Bentley and Sparks (2003) and Coniglio *et al*. (2004). However, there are some minor differences in the strength and placement of the maximum frequency corridors as suggested by the previous research. Similar to Bentley and Sparks (2003) and Coniglio *et al*. (2004), two maximum frequency axes exist within the analysis – one in the south–central Plains, and the other, larger corridor, in the Ohio Valley. However, in comparison to previous studies (*cf* Bentley and Sparks (2003), Figure 14 and Coniglio *et al*.'s (2004), Figure 3(a)), the southern Plains corridor is more subdued and the region including western Kentucky and northwestern Tennessee is more substantial. Our analyses, which contain only the latter more consistent 10 years of the available 18-year dataset, indicate that the Ohio Valley region has the highest derecho frequency, with one grid cell in this region affected by 36 events during the 10-year period (i.e. on average, 3.6 events per year).

The comparatively smaller frequency maximum in the southern Plains could be due to the exclusion of late 1980s and early 1990s data, which evidence suggests was a period of favorable synoptic conditions for southern Plains events (Bentley and Sparks, 2003; Coniglio and Stensrud, 2004). Derechos for the period 1986–1993 occurred primarily within a distinct, high-frequency southern Plains maximum (not shown), with two 1° × 1° grid cells in Oklahoma affected by more than 15 events and an area stretching from north–central Oklahoma through northern Louisiana affected by more than 9 events. This supports the hypothesis presented by Bentley and Sparks (2003) that the southern Plains region was the primary derecho corridor during the late 1980s and early 1990s. Thus, there does appear to be interannual variability in the primary derecho corridor; however, further analysis of these trends is limited by the number of years of consistent derecho data available for analysis. As suggested by Bentley and Sparks (2003), the examination of many more years of derecho activity will be needed to capture accurately the genuine character and long-term variation of derechos.

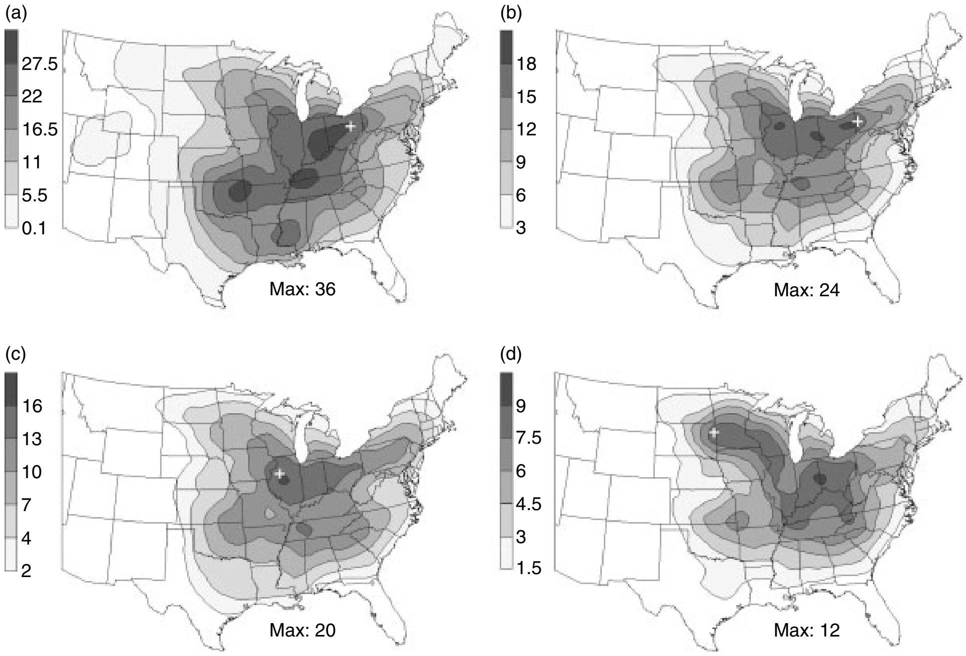

Figure 7. Total number of (a) derechos, (b) derechos associated with series, (c) derecho series, and (d) derecho series with three or more members occurring for 1994–2003. Symbols indicate the location of maximum values before interpolation

Restricting the analysis to only those events that were members of derecho series (Figure 7(b)) illustrates that derechos associated with series were more likely to occur in a region from the upper Midwest through the Ohio Valley. This primary high-frequency axis indicates that northern-tier events have a larger derecho series association than their southern-tier counterparts. Nevertheless, there remains a high occurrence of derecho events associated with series in the northeast Oklahoma–southwest Missouri region. This region is frequented by both springtime-northeastward and summertime-southeastward moving (i.e. 'southward-burst' type) derechos (Bentley and Mote, 1998). The central Mississippi and lower Ohio Valleys may experience derecho series during any season because of their proximity to a number of seasonal derecho corridors.

Derecho series (Figure 7(c)) occur throughout the eastern two-thirds of the United States, but are confined generally to the southern Plains, the southern Great Lakes, and the Mississippi, Ohio, and Tennessee River Valleys. Series with three or more members (Figure 7(d)) were more likely to occur in a region from southern Minnesota to the Ohio Valley. Derecho series with four or more members (not shown) occurred generally in either southern Minnesota or in the region near southwest Ohio/northern Kentucky, while series with five or more members (not shown) were restricted to the Ohio River valley. These analyses illustrate that the area from the upper Midwest through the Ohio Valley was the area most likely to be affected by derecho series. As illustrated by Johns (1982) (*cf* his Figure 4) this region is also the primary high-frequency axis of the NWF outbreak series.

Examining the months with the highest derechos and derecho series – May, June, and July – illustrates that peak-season series events (Figure 8(a)) occurred primarily in the northern tier in an axis from the northern Plains, through the Midwest, eastward to the lower Great Lakes region. During May, derechos associated with series occurred largely in the central Mississippi Valley and lower Ohio Valley, with a secondary frequency maximum located in the northeast (Figure 8(b)). Derechos associated with June series took place predominantly in the Midwest, Ohio Valley, and lower Great Lakes region, but the southeast was also affected by several events. July series derechos occurred in a well-defined primary high-frequency axis from the northern Plains through the lower Great Lakes region that is reminiscent of Johns (1982) primary NWF outbreak high-frequency axis (*cf* his Figure 4). A secondary high-frequency axis existed in Kansas and

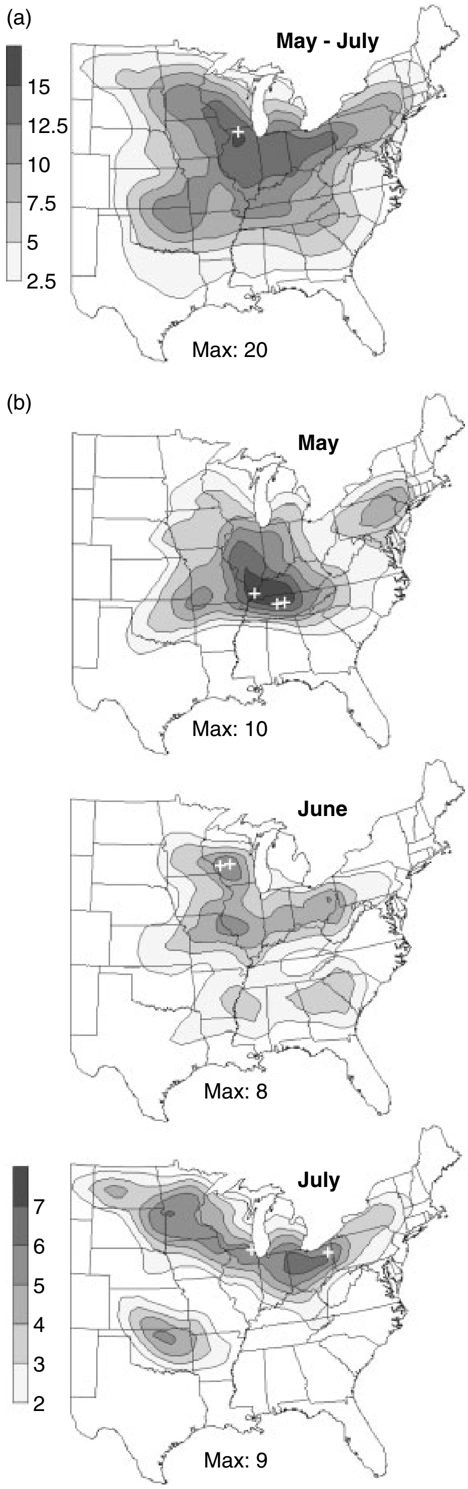

Figure 8. Number of derechos for 1994–2003 associated with series for (a) May–July and (b) for the individual months of May, June, and July. Symbols indicate the location of maximum values before interpolation

Oklahoma and was an artifact of two separate derecho series that were made up of sequentially occurring, 'southward-burst' type derecho events embedded within NWF aloft.

Vector analysis indicates that the propagation of derechos in series varies from the north–northeast to south–southeast, with a mean storm direction of 278° for all series derechos. However, nearly 75% of all series derechos during June, July, and August, the 3 months with the most NWF outbreaks (Johns, 1982), had a storm motion between 270° and 360°, with a mean storm motion of 287°. Since summertime, progressive derechos tend to move along and slightly to the right of the mean wind (Johns and Hirt, 1987), the mean propagation of derechos in series during the summer months indicates that a large number of the events likely occurred within west-to-northwest flow.

Research by Bentley and Mote (1998) and Bentley and Sparks (2003) have identified the tendency for derechos to dominate specific corridors in the eastern two-thirds of the United States. These two studies defined a corridor as four or more events with similar spatial and temporal characteristics that occur in a season. Fourteen US corridors distributed over three separate seasons (i.e. spring season – March–May; summer season – June–August; and cool season – September–February) have been identified by Bentley and Mote (1998) and Bentley and Sparks (2003). Readers are asked to consult the numerous figures presented in Bentley and Mote (1998) and Bentley and Sparks (2003) depicting the various corridors.

During the cool season, series derechos typically occurred within the southeast US corridor with 54% of events occurring in this southern corridor. This is likely a reflection of the relatively higher convective potential energy available for storm formation in the lower latitudes during this season and the large number of strongly forced, dynamic synoptic systems that frequent this region and can produce serial-type derechos (Bentley and Mote, 2000b; Burke and Schultz, 2004).

During the spring season, events in series typified the more eastward and northward locales in the United States – in particular, the southeast (consisting of 26% of events in series during this season), northeast-moving Ohio Valley (17%), and northeast corridors (12%). Another spring season corridor not revealed by previous research appeared in our analyses – the northeastward moving, northern-tier corridor – which consisted of 16% of events during this transition season. This corridor was made up of events that migrated across the northern Plains and upper Midwest primarily during the month of May. Hence, despite the fact that the southern and central Great Plains have the highest incidence of severe weather occurrences in the United States during this period, derechos in spring season derecho series are more likely to occur *outside* of the corridors traversing the south–central Great Plains.

The summer season was dominated by the southeastward-moving, northern-tier corridor. More than 57% of all series derechos that occurred during this 3-month season formed within this corridor. Derechos within this corridor often developed in synoptic situations similar to the NWF scenarios observed by Johns (1984). Consequently, there appears to be a direct association between NWF series and derecho series during the summer season.

4. SUMMARY AND CONCLUSION

This study has outlined the tendency for US DMCSs to group together – forming derecho series. The derecho series was established as any succession of derechos occurring within a similar synoptic environment with no more than 72 h separating the individual events constituting the series.

The results of this study indicate that groupings of derechos are more common than previously thought, with more than 62% (82%) of annual (May, June, and July) derecho events affiliated with a derecho series. However, derecho groupings were highly variable on annual and seasonal bases, with their numbers appearing to be dependent upon the existence of a favorable synoptic-scale environment that promotes the formation of successive DMCSs. Analyses of one of the most and least active warm season derecho periods illustrate that the synoptic environment is an important control on the spatial and temporal distributions of derechos and their groupings.

Derecho series frequented the Midwest, Ohio and Tennessee River Valleys, and the south–central Plains during the year, but were most frequent during May, June, and July across the Midwest, lower Great Lakes, and Ohio Valley region. Once a derecho occurred during the warm season months, there was a 58% chance that the event was the first of a series of two or more derechos and a 47% chance that it was the first of a series with three or more events. Hence, it is essential for forecasters within regions affected by derechos to remain alert following an event for the likely reoccurrence of derechos thereafter.

The sequential development of convective systems, including those producing derechos as illustrated in this study, suggests a causal relationship between the environments of successive systems and, consequently, an intrinsic predictability. For this reason, a future study should examine the large-scale environments that produce these derecho series. In particular, the study should consider the environments and mechanisms that produced some of the largest derecho series. Moreover, the climatological record of derechos should be extended to allow for an examination of the important climatological shifts in derecho corridors that appear to occur across a multitude of timescales – i.e. from weekly or monthly 'high-activity' corridors that emerge frequently during a specific season (e.g. the 15 May 1998–30 June 1998 pattern described in Section 3.1) to large-scale shifts in the overall derecho climatology due to shifts in the favorable synoptic-scale patterns on a semiannual basis (e.g. the climatological shifts described by Bentley and Sparks, 2003).

Ashley and Mote (2004) illustrate that derechos can have a substantial effect on humans and the environment, both built and natural. In fact, Ashley and Mote (2004) suggests that derechos can be as hazardous and are comparable in magnitude to most US tornadoes and hurricanes. Further, derechos continue to be forecasted poorly by operational numerical guidance utilized by forecasters, and often, they cannot be simulated, even after the event, using contemporary mesoscale models and superior data assimilation methods (e.g. Gallus *et al*., 2004). Hence, it is important to continue to increase our understanding of these inadequately forecasted, often devastating, windstorms through applied research such as this climatology. By integrating the results of this climatology with continually improving pattern recognition and meteorological parameter assessment techniques, the ability for forecasters to predict these damaging events will improve significantly.

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