METEOROLOGICAL APPLICATIONS
Meteorol. Appl. **14**: 227–244 (2007)
DOI: 10.1002/met.23

The extensive episode of derecho-producing convective systems in the United States during May and June 1998: A multi-scale analysis and review

Walker S. Ashley,[a]* Thomas L. Mote[b] and Mace L. Bentley[a]
[a] *Meteorology Program, Department of Geography, Northern Illinois University, USA*
[b] *Climatology Research Laboratory, Department of Geography, University of Georgia, USA*

ABSTRACT: A multi-scale analysis is presented on widespread and long-lived convectively generated windstorms, known as derechos. Analyses of the derecho-producing environments during 15 May–30 June 1998 indicate that this exceptional episode of derechos and derecho groupings (or series) was supported by ingredients (i.e. moisture, instability, and wind shear) that were supplied by the large-scale setting. In particular, the semi-stagnant subtropical ridge and associated capping inversion across the southern tier of the U.S. were important in supplying amplified moisture and instability to derecho-genesis regions through an underrunning process. Regions of preferred derecho formation appeared to correspond to shifts in the overall strength and position of the ridge, illustrating the importance of the ridge in focusing successive organized convection. Initiating mechanisms varied widely and were not restricted to warm-air advection regimes along quasi-stationary boundaries that forecasters often associate with warm-season derecho environments. In several cases, derecho-producing convective systems were generated by tropospheric features not consistent with common conceptual models of derecho environments such as closed lows and strong vorticity maxima. Further, three distinct series types were identified and classified based on their initiating mechanisms. Copyright © 2007 Royal Meteorological Society

KEY WORDS derechos; convective systems; windstorms; United States

Received 11 January 2007; Revised 20 April 2007; Accepted 20 April 2007

1. Introduction

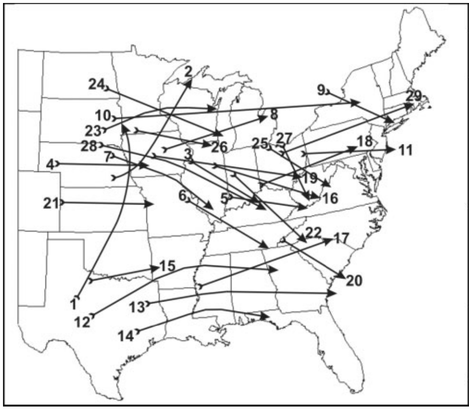
In the late nineteenth century, Iowa physical scientist Hinrichs (1888) defined a derecho as any widespread, straight line windstorm produced by a thunderstorm. It was not until nearly a century later that Johns and Hirt (1987) first developed formal criteria for identifying derecho events utilizing contemporary datasets and the classification of large-scale, convectively induced wind events described by Fujita and Wakimoto (1981). Long-term climatologies by Bentley and Mote (1998), Bentley and Sparks (2003), Coniglio and Stensrud (2004), and Ashley and Mote (2005) demonstrate that derechos are prevalent throughout the eastern two-thirds of the U.S. and can occur during any month of the year. A recent study by Ashley and Mote (2005) illustrates that, although derechos do not account for a majority of non-tornadic casualties in the U.S., individual events can be as hazardous as some of the more notable hurricanes and tornadoes in recent U.S. history. Forecasting derechos remains difficult because of the inadequate observation network, deficient numerical model assimilation methods and parameterizations, insufficient model resolutions (e.g., Gallus *et al.* 2004), and failure of current forecast techniques to include all scenarios in which organized convection produces derechos.

Several observational studies since the mid-1980s have illustrated environments conducive to derecho-producing meso-scale convective systems (DMCSs). The first of these studies, Johns and Hirt (1987), defined two primary derecho types – 'progressive' and 'serial' – after examining 70 warm-season derechos during the 4-year period 1980–1983. More recent studies by Bentley *et al.* (2000), Bentley and Mote (2000), Evans and Doswell (2001), and Coniglio *et al.* (2004) have suggested that the two primary derecho environments – 'warm-season' and 'dynamic' – described by Johns and Hirt (1987) and Johns (1993) do not fully represent the spectrum of environments conducive to DMCS formation and sustenance. Bentley *et al.* (2000) described two warm-season environments associated with the northern-tier DMCSs, while Bentley and Mote (2000) detailed cool-season derecho patterns. Using a proximity sounding method, Evans and Doswell (2001) demonstrated a large range of shear and instability environments associated with derechos compared to those described by observational studies (e.g. Johns and Hirt, 1987; Johns *et al.*, 1990; Johns, 1993) and numerical cloud simulations (Weisman, 1992, 1993; Weisman and Rotunno, 2004).

Coniglio *et al.* (2004) found a wide spectrum of mid-tropospheric flow patterns associated with the DMCSs

---

* Correspondence to: Walker S. Ashley, Department of Geography, Northern Illinois University, Room 118, Davis Hall, DeKalb, IL 60115, USA. E-mail: washley@niu.edu



Fam	Event	Date	Fam	Event	Date
A	1	5/15	E	16	6/12
	2	5/15		17	6/15
B	3	5/19		18	6/16
	4	5/20	F	19	6/18
	5	5/20		20	6/19
	6	5/21	G	21	6/22
	7	5/21		22	6/22
C	8	5/28		23	6/25
	9	5/29		24	6/26
	10	5/31		25	6/27
	11	6/1		26	6/27
D	12	6/4		27	6/28
	13	6/5		28	6/29
	14	6/5		29	6/30
n/a	15	6/9			

Figure 1. Tracks of the 29 derechos that occurred during 15 May–30 June 1998. Events are labeled sequentially on the basis of initiation times and subdivided by series (each identified by a letter).

using a cluster analysis technique on 500 hPa geopotential height fields. The majority of the DMCSs identified in their study fell within three main synoptic flow environments: upstream-trough, ridge, and zonal patterns. Although the upstream-trough and ridge patterns had been identified previously, variations within these patterns were refined in this study. Interestingly, 28% of the events identified by Coniglio *et al.* (2004) did not fit into any of these three primary patterns. These additional synoptic settings determined were either unclassifiable or considered 'hybrid' patterns – i.e. having characteristics of the upstream-trough, ridge, and/or zonal patterns.

The following study utilizes a multi-scale analysis perspective (i.e. from the large-scale synoptic setting to features identified on the meso-scale using radar) to examine environments and characteristics associated with the DMCS events during the most active derecho period identified in the climatological record of these storms. This exceptionally active period included 29 derechos over a period of 47 days from 15 May to 30 June 1998 – that is, new derecho development occurring, on average, every 39 h (Figure 1). The active period also includes numerous derecho groupings, or 'series' (Ashley *et al.*, 2005), in which a number of derecho events occur sequentially and appear to be linked by convective ingredients produced by the large-scale environment. The high-frequency period described provides a unique opportunity to investigate the variety of derecho environments, even across a relatively short window of time, that can occur during the warm season.

2. Data and methodology

Derechos from this active period were identified using a derecho dataset discussed in Ashley and Mote (2005) and Ashley *et al.* (2005). The dataset was constructed primarily from two prior climatologies presented by Bentley and Sparks (2003) and Coniglio and Stensrud (2004). All derechos, which were identified for this period, met a set of consistent criteria 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 revised criteria have been examined and discussed elsewhere (see Section 2.1 and Table I of Ashley *et al.* (2005)).

In order to evaluate the environments of DMCSs, observed surface and upper-air archived data were examined. The NCEP *Daily Weather Map Series* (NOAA, 1998a), NCAR 'Image Archive,' and the NASA Global Hydrology Resource Center's (GHRC) 2-km radar composites were also employed to evaluate various surface and upper-air analyses as well as remotely sensed imagery (e.g. radar, satellite, and profiler data) during all the cases. In addition, NCEP-NCAR reanalysis data (Kalnay *et al.*, 1996) were utilized to investigate the large-scale flow patterns during the active period and at various stages of individual DMCS evolution. However, because the reanalysis grids are spatially and temporally coarse, hourly, 40 km rapid update cycle-2 (RUC-2) model/analysis system data (Benjamin *et al.*, 1998) were obtained in order to supplement the analysis of observational and reanalysis datasets. Although the hourly analyses are sensitive to the accuracy of the short-term model forecasts (Thompson *et al.*, 2003), these data offer superior temporal and spatial resolution compared to the observing network or reanalysis grids. Thompson *et al.* (2003), Markowski *et al.* (2003), and Davies (2004) illustrated recently the utility and advantage of using RUC-2 grids to evaluate severe convective environments.

In order to examine the meso-scale environments of derechos during initiation, sustenance, and decay periods, RUC-2 analysis gridpoint soundings, constant pressure fields, near-surface fields (e.g. 2 m winds), and thermodynamic and kinematic fields were analysed. RUC-2 analysis gridpoint soundings were generated at the point directly downstream (i.e. within the inflow) of derecho initiation (first wind report), maximum intensity (as subjectively determined by severe wind report density/intensity data and base reflectivity WSR-88D imagery), and decay (last wind report) locations, noting that the initiation and decay are subjectively determined by the wind report database. In order to correct for any RUC-2 biases near the surface owing to terrain

Table I. Derechos during the May–June 1998 episode. Derecho intensity (low, moderate, and high) and pattern classification based on criteria from Coniglio and Stensrud (2004) and Coniglio *et al.* (2004), respectively. Several 'upstream-trough' events are not classified by cluster since these cases do not fit any of the clusters identified by Coniglio *et al.* (2004). The table includes maximum DMCS speed and whether the DMCS initiated from supercells (Section 2 for details).

Event ID	Series ID	Coniglio *et al.* class	Coniglio *et al.* pattern	Max. DMCS speed (m s^{-1})	Supercell intially?
5/15 I	A	Moderate	Upstream-trough 1	34	No
5/15 II	A	Moderate	Upstream-trough 1	28	No
5/19	B	Low	Ridge-3	26	Yes
5/20 I	B	Moderate	Ridge-1	24	Yes
5/20 II	B	Low	Ridge-3	22	No
5/21 I	B	Low	Ridge-3	22	Yes
5/21 II	B	Moderate	Ridge-2	23	No
5/28	C	Moderate	Zonal	25	Yes
5/29	C	Moderate	Hybrid	21	No
5/31	C	High	Hybrid	36	Yes
6/01	C	Moderate	Upstream-trough 3	26	Yes
6/04	D	Moderate	Upstream-trough 3	24	Yes
6/05 I	D	Moderate	Hybrid	32	Yes
6/05 II	D	Moderate	Zonal	25	Inconclusive
6/09	n/a	Low	Ridge-1	21	Yes
6/12	E	Low	Upstream-trough	22	Yes
6/15	E	Moderate	Upstream-trough 3	29	Inconclusive
6/16	E	Low	Upstream-trough	23	No
6/18	F	Moderate	Upstream-trough	25	Yes
6/19	F	Moderate	Unclassifiable	15	No
6/22 I	G	Low	Zonal	24	No
6/22 II	G	Low	Unclassifiable	20	No
6/25	G	Moderate	Upstream-trough 4	25	Yes
6/26	G	Low	Hybrid	22	Yes
6/27 I	G	Moderate	Ridge-3	27	Yes
6/27 II	G	High	Upstream-trough	27	Yes
6/28	G	Moderate	Ridge-3	20	Yes
6/29	G	High	Hybrid	30	Yes
6/30	G	Moderate	Upstream-trough 3	29	Yes

elevation and land-use specifications (Thompson *et al.*, 2003), the surface temperature and dew point temperature were modified in the NSHARP software system (Hart and Korotky, 1991) using values obtained from the nearest downstream surface-observation site at the time closest to sounding selection. In order to obtain storm-related kinematic fields from the grid point sounding data, convective system motion and speed were calculated in the initiation, maximum intensity, and decay regions using WSR-88D base reflectivity data. As with any model product, the analyses can be impacted by convective parameterization (Grell, 1993; Thompson *et al.*, 2003); hence, only non-convectively contaminated gridpoint soundings closest to the DMCS were chosen for analysis. Despite superior spatial and temporal resolution compared to the upper-air observation network, the RUC-2 data are employed as an *estimation* of the near DMCS environment.

3. Analysis

The late spring and early summer of 1998 was an abnormally active season for severe weather in the U.S. From 15 May to 30 June 1998, there were more than 11 000 reports of severe weather in the U.S., well above the average number of reports for 1993–2002 average of 6700. Of the 11 000 severe weather reports, more than 6200 were severe wind gust or damage reports; nearly twice the annual average for the same 47-day period from 1993–2002. A large number (56%) of the severe wind reports during this active warm-season period resulted from 29 derechos that moved across the eastern two-thirds of the U.S., more than three times the average number of derechos that typically occur during this 47-day period. These derechos were responsible for a reported 12 fatalities and 440 injuries in the U.S. (NOAAb, 1998). In addition, these storms produced hundreds of millions of dollars in damage, with one event (31 May) responsible for nearly half a billion dollars in insured losses alone (Ashley and Mote, 2005). The subsequent sections describe (1) the large-scale environment that was conducive to this active severe weather period, (2) the synoptic and meso-scale characteristics of derecho series formation, and (3) some of the characteristics of derechos during this period.

3.1. Large-scale setting

Because meso-scale events, including DMCSs, are determined in large part by large-scale processes (Doswell, 1987), it is important to evaluate the hemispheric- and synoptic-scale setting that provided the necessary ingredients for severe convection during this DMCS episode. The active severe weather period during mid May–June 1998 was a manifestation of several large-scale mean atmospheric circulations that have been summarized by Bell *et al.* (1999), Barnston *et al.* (1999), and Hong and Kalnay (2002). This pattern included anomalously strong subtropical ridges centred along the Gulf Coast and the eastern North Pacific, a large, persistent trough anchored across the West Coast, a weaker than normal Hudson Bay vortex, and an unseasonably strong jet stream with speeds 1.5–2 times normal from the desert southwest to the lower Great Lakes (Figure 2).

Bell *et al.* (1999) and Barnston *et al.* (1999) suggest that the persistent anomalous upper-level circulation pattern that developed during this period may have been linked to the unique manner in which the 1997–98 El Niño ended. Barnston *et al.* (1999) found that during the

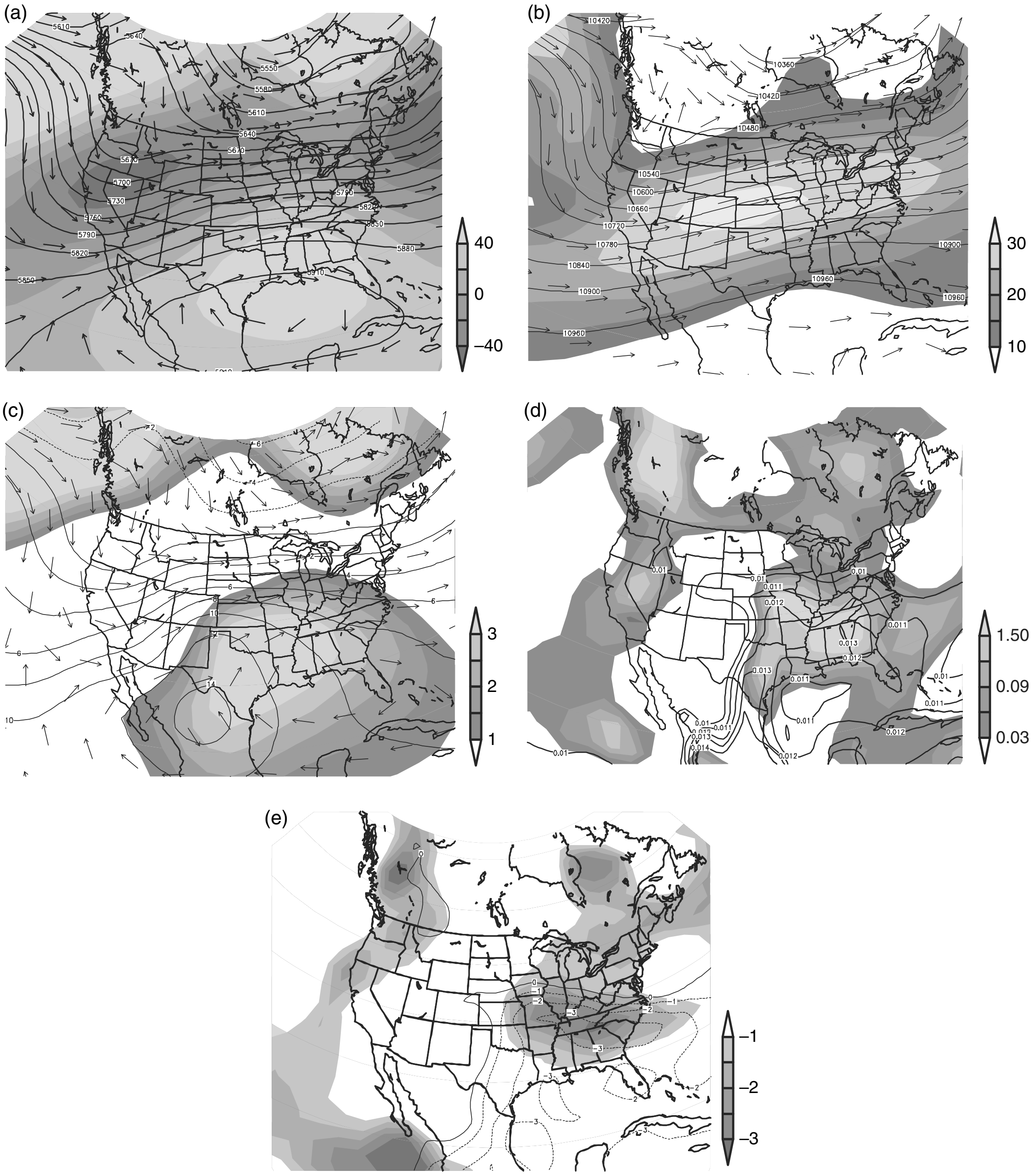


Figure 2. Mean fields for 15 May–30 June 1998. Panels included (a) mean 500 hPa heights (isolines every 30 gpm), anomalies (gpm; shaded), and wind direction vectors, (b) 250 hPa heights (isolines every 60 gpm), isotachs (ms^{-1}) (shaded), and wind direction vectors, (c) 700 hPa temperature (isotherms every 2 °C; dashed less than 0 °C), temperature anomalies (shaded greater than 1 °C), and wind direction vectors, (d) 925 hPa specific humidity (isohumes greater than 0.01 kg kg^{-1}) and anomalies (shaded greater than 0.08 kg kg^{-1}), and (e) Lifted Index isotherms (less than 0 °C) and anomalies (shaded less than −1 °C). Composites created using NCEP-NCAR reanalysis data plots produced using the NOAA–CIRES Climate Diagnostics Center web site (http://www.cdc.noaa.gov/).

final stages of the 1997–98 El Niño, tropical convection moved eastward toward a significant residual warm sea-surface temperature (SST) anomaly pool that persisted in the eastern tropical Pacific during May and June. Consequently, the increased tropical convection and associated upper-level divergence in this region, led to a region of upper-level convergence immediately downstream that ultimately produced a strong subtropical ridge in the vicinity of northern Mexico and the south-central U.S. Hence, the subtropical ridge in the Northern Hemisphere associated with the El Niño moved to the east over North America with the remaining anomalous tropical convection, and thereafter migrated northward into the southern U.S. in association with the normal seasonal solar progression. The poleward shift of the anomalous ridge in the subtropics heralded the active period of severe weather that commenced in mid-May across the U.S. Prior research by Johns (1982, 1984), Bosart *et al.* (1999), and Bentley and Sparks (2003) have illustrated the importance of ridge formation, strength, sustenance, and placement in providing necessary ingredients for severe convection, including DMCSs.

During the active period examined in this study, the anomalous subtropical ridge across the southern U.S. was an important feature in the mean pattern that affected the primary derecho initiation and sustenance regions (Figure 2(a)). Along the periphery of this anticyclone, several transient mid-level troughs and closed lows were observed. These disturbances resulted in reduced mean mid-tropospheric heights across the inter-mountain West through the northern-tier of the U.S. and southern Canada. The juxtaposition of these lowered heights with the anomalously strong ridge to the south created unusually strong mid and upper-level flow across the derecho initiation and propagation regions (Figure 2(b)). Although the subtropical high was persistent and rather strong, we will illustrate in Section 3.2 that the ridge did 'pulse' in strength and tended to shift, ultimately adjusting the regions favourable for DMCS formation across the eastern two-thirds of the U.S.

In addition to intensifying the height gradient and tropospheric winds across the U.S., the anomalous ridge was influential in promoting and focusing two additional ingredients necessary for severe, deep convection – moisture and instability. An abnormally moist lower troposphere was anchored across the eastern two-thirds of the U.S. with 925 hPa specific humidity anomalies over 0.01 kg kg^{-1} across the region where derechos traversed (Figure 2(d)). Further, instability across the same region was abnormally high as illustrated by the composite Lifted Index anomaly (Figure 2(e)).

The large-scale subsidence under the ridge, persistent southwest flow from elevated mixed-layer source regions in Mexico and the southwestern U.S., and a tradewind easterly airstream (see Hagemeyer, 1991) that flowed around the southern periphery of the ridge (Figure 2(c)) reinforced a capping inversion that inhibited convection across regions equatorward of the derecho initiation areas. In preventing the release of potential energy under the ridge, this capping inversion supported the amplification and storage of moisture and instability (Figure 2(d–e)). Therefore, the subtropical ridge was instrumental in promoting the condition of 'underrunning' – the process where low-level ageostrophic flow, containing warm, moist (i.e. high theta-e) air emerges from under the margins of an elevated mixed layer, producing deep, moist convection that characterize DMCSs and other severe weather outbreaks (Carlson *et al.*, 1983; Farrell and Carlson, 1989; Lanicci and Warner, 1991; Bentley *et al.*, 2000). The capping inversion promoted by the ridge was also important in restricting the development of convective activity downstream of the derecho initiation and propagation tracks. This condition tended to prevent organized convective system formation downstream of the DMCSs, which prohibited the premature release of potential instability by the downstream convection that could have produced convective overturning of the atmosphere and/or promoted storm interactions detrimental to the organized DMCS.

Finally, the strength and placement of the ridge were important in determining the location of lower-tropospheric frontogenetical forcing (Augustine and Caracena, 1994). As cold fronts moved toward the ridge, they would typically stall and remain quasi-stationary or retreat poleward as warm fronts. These boundaries, which lingered along the ridge periphery, would (1) promote the focusing of low-level moisture and (2) provide a source of lift for deep, moist convection through low-level convergence and/or warm-air advection along relatively steep isentropic surfaces induced by the boundaries. The semi-stationary placement of these boundaries led ultimately to preferred latitudinal bands of severe convection and DMCS groupings (Figure 1). Such features not only promoted the grouping of DMCSs, but also led to a coherent succession of rainfall events, or 'warm-season precipitation episodes', during the 1998 warm season (Carbone *et al.*, 2002).

The May–June 1998 large-scale setting was unique in that it brought the necessary ingredients for severe organized convection (Johns and Doswell, 1992) together for an extended period across the eastern two-thirds of the U.S. An analysis of the same 47-day period for all other years in the 1994–2003 period (Figure 3) illustrates that no other year was exemplified by such a unique and persistent juxtaposition of abnormally large amounts of low-level moisture, instability, and shear (using 500 hPa winds as a proxy) across climatologically favoured derecho-genesis regions (Bentley and Sparks, 2003; Coniglio and Stensrud, 2004). This suggests that the large-scale setting is critical in producing a thermodynamic environment that is either favourable or unfavourable for the production of large, long-lived MCSs and active severe weather episodes that occur on the meso-scale.

The final ingredient, localized forcing, was provided by the active series of migratory disturbances that interacted with thermal boundaries along the periphery of the ridge. These dynamic features moved over a region of

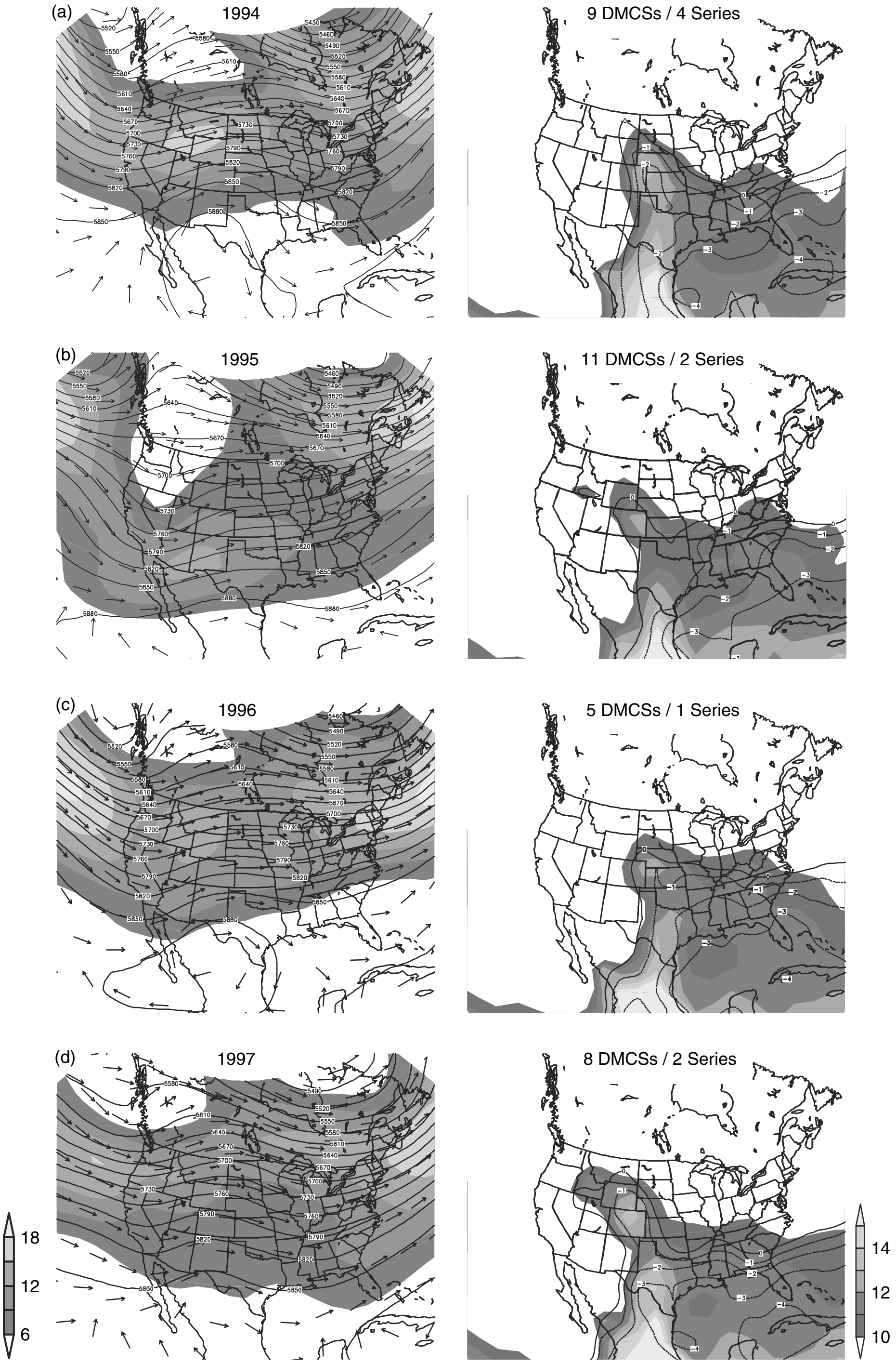


Figure 3. Mean fields for the 15 May–June 30 period during 1994–2003. Left column includes mean 500 hPa heights (isolines every 30 gpm) and isotachs (shaded) labeled sequentially from a to j. As in the left column, except plots of Lifted Index (contoured every 1 °C less than 0 °C) and 925 hPa specific humidity (isohumes plotted for values greater than 10 g kg^{-1}). Colour bars for the shaded images provided on the row corresponding to the last year on each panel. Composites created using NCEP-NCAR reanalysis data plots produced using the NOAA–CIRES Climate Diagnostics Center web site (http://www.cdc.noaa.gov/).

favourable instability and shear – producing an environment conducive to the development of numerous DMCSs across the U.S. Although some of these dynamic features were not as strong as their cool and transition season counterparts, the overall increase in lapse rates during the warm season makes a given amount of forcing more effective in producing large-scale vertical motion (Doswell, 1987).

Evidence suggests the Southern U.S. ridge was the most important feature that established the environment conducive to a large number of successively occurring derechos and likely focused their tracks through the Midwest, Ohio Valley, and lower Great Lakes. The circulation changed by early July, signaling the end of the 1997–98 El Niño's influence on North American weather patterns (Bell *et al.*, 1999; Hong and Kalnay, 2002), and

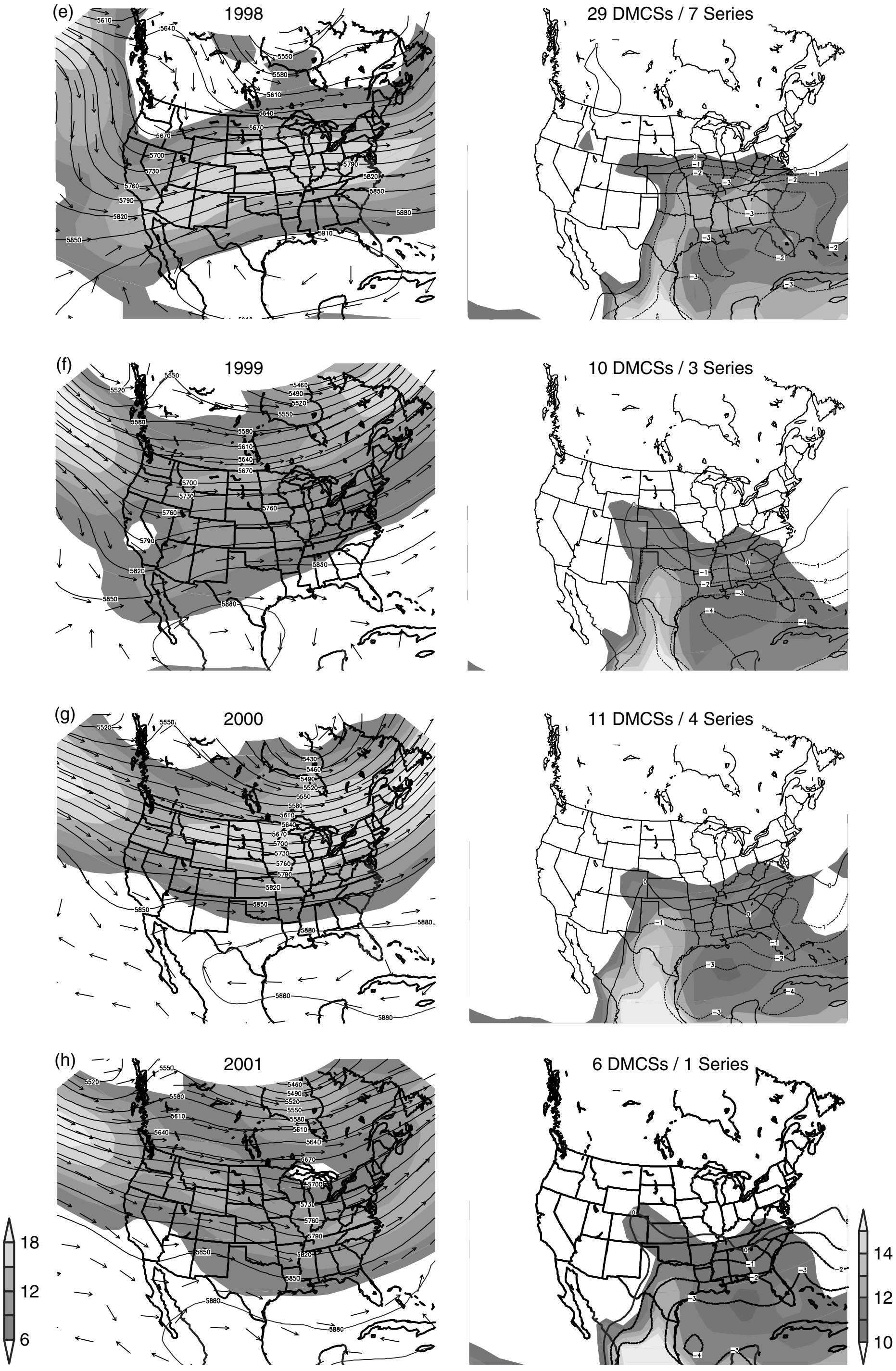


Figure 3. (*Continued*).

corresponds to the time when this DMCS episode ended. This dissipation pattern corresponds to the time when this DMCS episode ended. Warming temperatures and weak flow aloft along with diffuse and weak surface boundaries prevented the intense concentration of organized convection from continuing through the remainder of the warm season. Seven additional derechos in July (4), August (1), and early September (2), including two series, did occur in primarily northwest flow scenarios (Johns, 1982, 1984) typical of late summer mid-tropospheric patterns across the U.S.

The three El Niño's of 1994–1995, 1997–1998, and 2002–03 have been followed by above-normal derecho tallies for the warm-season months of May, June, and July based on the past 10 years of data (28 during 1995, 33 during 1998, and 24 during 2003, as compared with an average of 18.5 for the entire period). Undoubtedly, the climatological record of derechos must be extended before any inference between derecho tallies during the warm season and SST anomalies in the tropical Pacific can be demonstrated with statistical rigour. Nevertheless, Anderson and Arritt (2001) noted that there have been

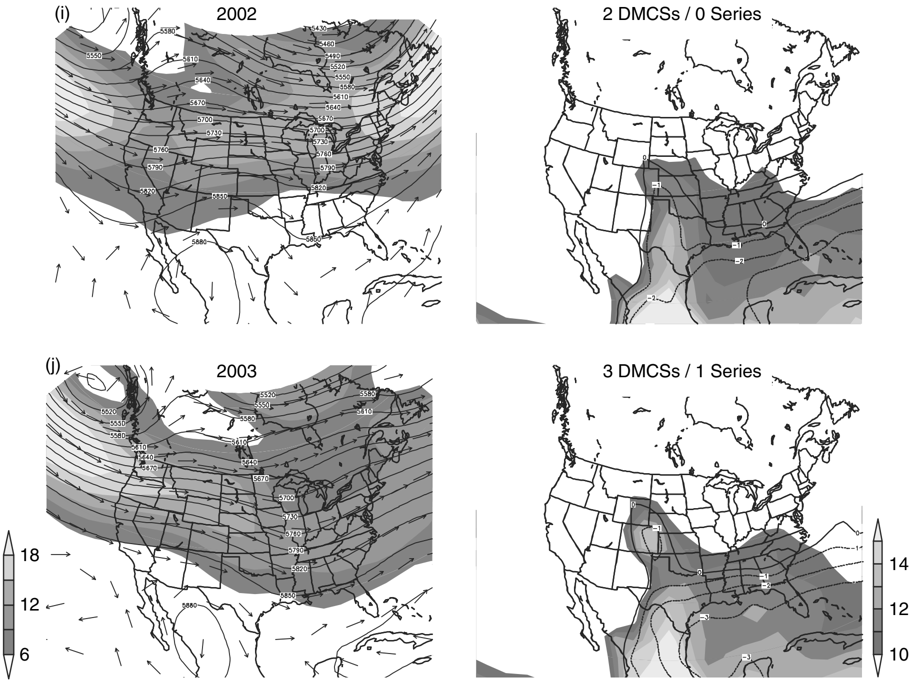


Figure 3. (*Continued*).

shifts in the mean position and clustering of MCSs that had occurred during the demise of El Niño events, specifically in 1983 and 1998. Future derecho research should examine the role that the larger-scale hemispheric conditions such as teleconnections and SST anomalies have on the formation and clustering of DMCSs. Identifying any linkages across these various scales is an important consideration for the difficult task of medium and long-range forecasting of severe convection.

3.2. Derecho series characteristics

Ashley *et al.* (2005) illustrated the tendency for DMCSs to group together temporally and/or spatially, forming series. According to the Ashley *et al.* (2005) definition, a derecho series is any succession of derechos occurring within a similar synoptic environment, with no more than 72 h separating the individual events constituting the series. Derecho groupings between 1994–2003 were found to be rather common during the warm season, with 82% of May, June, and July derechos occurring in a series. Results of Ashley *et al.* (2005) suggest further that derecho series can be highly variable on annual and seasonal bases, with their numbers appearing to be dependent upon the existence of a favourable large-scale environment. Owing to the extensive number of sequentially occurring events during the mid May–June 1998 episode, a large number of series were identified. Thus, the May–June 1998 episode of derechos provides an exceptional opportunity to investigate a multitude of derecho generation mechanisms and environments favourable for derecho series development.

Three distinct derecho series types were established on the basis of the analysis of the May–June 1998 episode and others in the compiled derecho dataset (series events from 1994–2003 were examined), including 'direct', 'indirect', and 'hybrid' series. Direct series occur when a preceding DMCS generates outflow boundaries, gravity waves (Carbone *et al.*, 1990), meso-scale convective vortices (MCVs; Trier *et al.*, 2000), or influences cyclogenesis by increasing low-level baroclinicity (Stensrud, 1996), which later facilitates the growth of subsequent DMCSs downstream or along the margin of the preceding convective system (one DMCS begets another DMCS). Series of this variety often occur within environments that are synoptically benign with an absence of significant upper-level forcing. These events tend to develop in immediate succession and may produce long, coherent precipitation structures in time–longitude diagrams, which were recognized by Carbone *et al.* (2002) as convective episodes. The 4–5 June and 18–19 June 1998 series (Figure 1) are examples of direct series type. Keighton *et al.* (2001) provide an additional example in a northwest flow scenario.

Indirect series occur in large-scale environments where thermodynamics or synoptic patterns are favourable for the subsequent development of derechos. Such favourable tropospheric environments have been illustrated by Johns (1984), Johns and Hirt (1987), Johns (1993), Bentley and Mote (2000), Bentley *et al.* (2000), and Coniglio *et al.* (2004). Derechos in these series usually propagate with migratory upper-level features or are anchored across a particular region, embedded within a stagnant pattern, with redevelopment linked to the diurnal cycle (i.e. daily maxima in solar heating or nocturnal maxima in low-level jets) or embedded disturbances in the upper-level flow. Several series within the May–June 1998 DMCS episode were classified as indirect.

DOI: 10.1002/met

'Hybrid' series combine the effects of the convectively induced mechanisms of direct series with an environment favourable for indirect derecho series. In a hybrid situation, all the events in the series occur within the same favourable synoptic pattern with some of the events generated by migrating synoptic-scale features (e.g. jet streaks, troughs) and other events initiated by convectively generated, meso-scale mechanisms (e.g. outflow boundaries, MCVs) from a prior DMCS. Two series during the active episode investigated in this study were classified as hybrid-type series (Bosart *et al.* (1999) for another example). As with most convection, DMCSs occur across a spectrum of conditions and it may be difficult to classify all the series into these three types based upon their promoting mechanisms or environments.

3.2.1. 15–16 May series

The first series of the mid May–June 1998 period consisted of two events (Figure 1; 15 May I and II; roman numbers indicates the order of sequentially occurring events on the same day) that spanned the Great Plains, from Texas to Lake Superior. These two sequentially occurring derechos are part of an example of an 'indirect' series forming in a 'dynamic' (Johns, 1993) or 'upstream-trough' (Coniglio *et al.*, 2004; their 'cluster 1') pattern (Table I). Interestingly, both of these upstream-trough events occurred outside the region, climatologically favoured by such events (Coniglio *et al.*, 2004; their Figure 4(a)). The two derechos were generated by a vigorous, negatively tilted trough and associated mid-latitude cyclone that migrated parallel to the derecho tracks (Figure 4(a)). In addition, strong mid- (36–46 m s^{-1} at 500 hPa) and upper-level (41–57 m s^{-1} at 250 hPa) jet streaks produced strongly diffluent flow aloft that, when combined with forcing along a hybrid cold front-dryline structure, initiated two successively occurring DMCSs (Table II). The low-level jet (LLJ; identified by analysing the 850 hPa wind field) in this situation was also exceptionally strong (21–41 m s^{-1} at 850 hPa) and was oriented nearly parallel to the mid and upper-level jets, a setting that Johns (1993) suggests assists in differentiating derecho environments from the 'classic' tornado outbreak pattern (Figure 5 in Johns (1993)). A dry-air intrusion impinged on the DMCSs from the upstream side, indicating that, in addition to the transfer of horizontal momentum by downdrafts in this

Table II. Derechos during the May–June 1998 period and associated surface boundaries and primary initiating/forcing mechanisms as identified from analysis of observational, reanalysis, and RUC-2 data.

Event ID	Surface boundary character at initiation	Primary initiating and forcing mechanism (s)
5/15 I	Cold front-dryline	Strong negatively tilted trough
5/15 II	Cold front-dryline	Strong negatively tilted trough and associated vorticity maximum
5/19	Other (surface heating)	Surface heating
5/20 I	Other (upslope flow)	Upslope flow
5/20 II	Outflow boundary from prior DMCS	Outflow boundary
5/21 I	Quasi-stationary front	Quasi-stationary front
5/21 II	Warm front	Warm-air advection along boundary
5/28	Cold front/outflow boundary interaction	Warm-air advection and cold front/outflow boundary interaction
5/29	Cold front	Cold front
5/31	Warm front	Warm-air advection along boundary and jet-streak coupling
6/01	Cold front/outflow boundary interaction	Boundary interaction
6/04	Quasi-stationary front	Short-wave trough; sustained warm-air advection along quasi-stationary boundary
6/05 I	Outflow boundary	Minor short-wave trough interaction with outflow from previous DMCS
6/05 II	Cold front/outflow boundary interaction	Minor short-wave trough interaction with cold front and outflow from previous DMCS
6/09	Dryline and decaying cold front	Boundary interaction
6/12	Surface trough	Short-wave trough and exit region of upper-level jet
6/15	Cold front	Warm-air advection ahead of cold front
6/16	None	Vorticity maximum
6/18	Cold front	Short-wave trough and cold front
6/19	Outflow boundary from prior DMCS	Outflow boundary
6/22 I	Other (upslope flow)	Upslope flow
6/22 II	Outflow boundary from prior MCS	Outflow boundary
6/25	Warm Front	Vorticity maximum
6/26	Warm Front	Warm-air advection along boundary
6/27 I	Outflow boundary from prior DMCS	Outflow boundary
6/27 II	Warm front	Warm front
6/28	Pre-frontal wind shift	Pre-frontal wind shift
6/29	Outflow boundary and quasi-stationary front	Warm-air advection along boundaries
6/30	Cold front/outflow boundary interaction	Short-wave trough

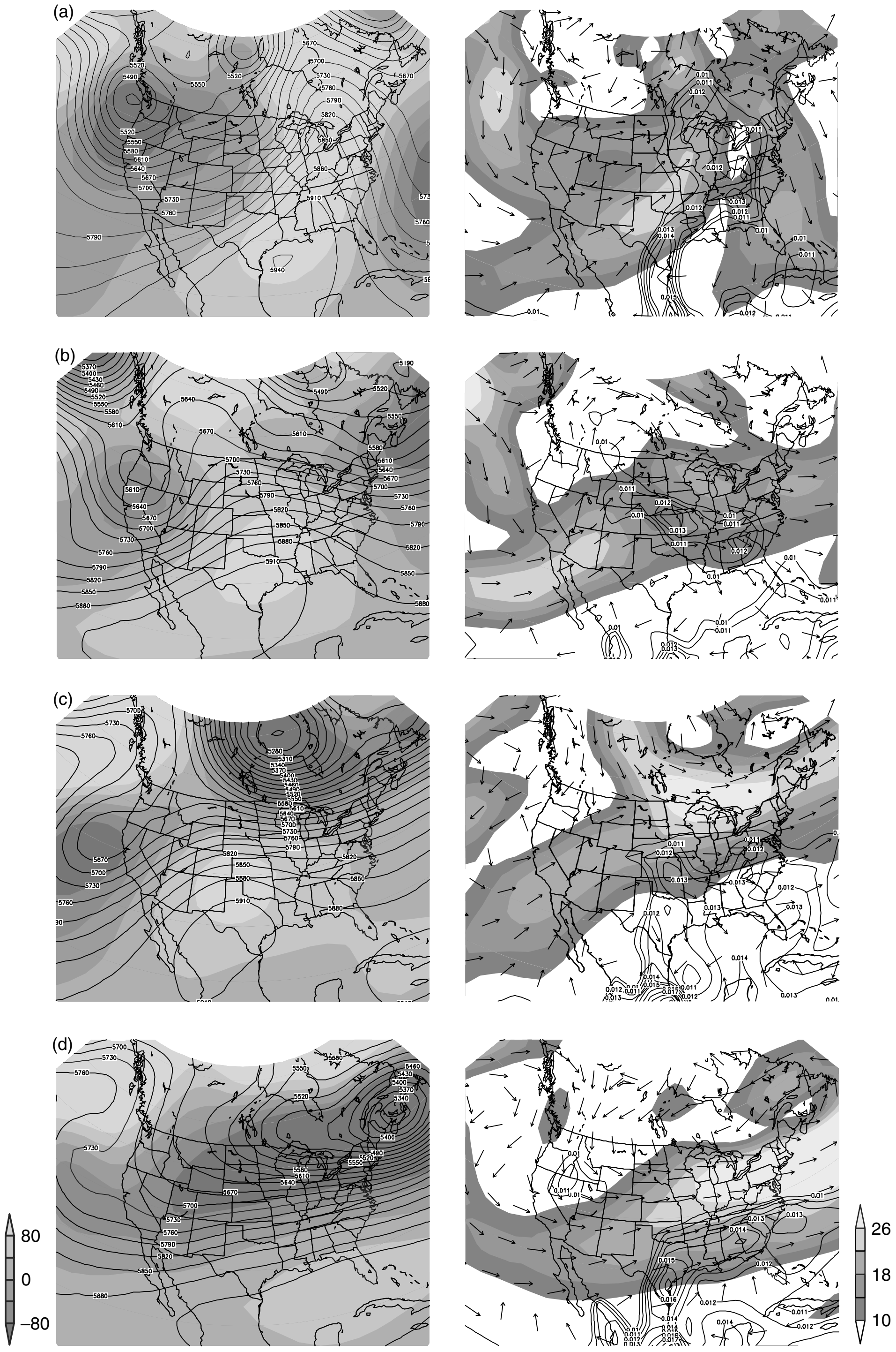


Figure 4. Mean fields for the seven series periods during the May–June 1998 episode. Left column includes mean 500 hPa heights (isoheights every 30 gpm) and height anomalies (shaded), while right column includes mean 500 mb isotachs (shaded) and 925 hPa specific humidity (isohumes greater than 0.01 kg kg^{-1}). Mean periods, by row, include: (a) 15–16 May, (b) 19–22 May, (c) 28 May–1 June, (d) 4–6 June, (e) 12–17 June, (f) 18–19 June, and (g) 22–30 June. Composites created using NCEP-NCAR reanalysis data plots produced using the NOAA–CIRES Climate Diagnostics Center web site (http://www.cdc.noaa.gov/).

environment, the severe outflow winds produced by the derechos were likely enhanced by the influx of dry air into the downdraft entrainment region. The derecho developed in a 'dynamic' environment, but contained progressive characteristics, such as a large bow echo, that propagated parallel to the mean mid-level flow. Hence, this system illustrates that DMCSs in 'dynamic' environments can be associated with not only 'serial', but also 'progressive' characteristics.

The second derecho occurred immediately behind the first DMCS as it exited the central Missouri Valley at 34 m s^{-1} (Table I). Rapid destabilization occurred within the region directly behind the first DMCS, as a mid-level dry slot left a moist boundary layer in the warm sector of

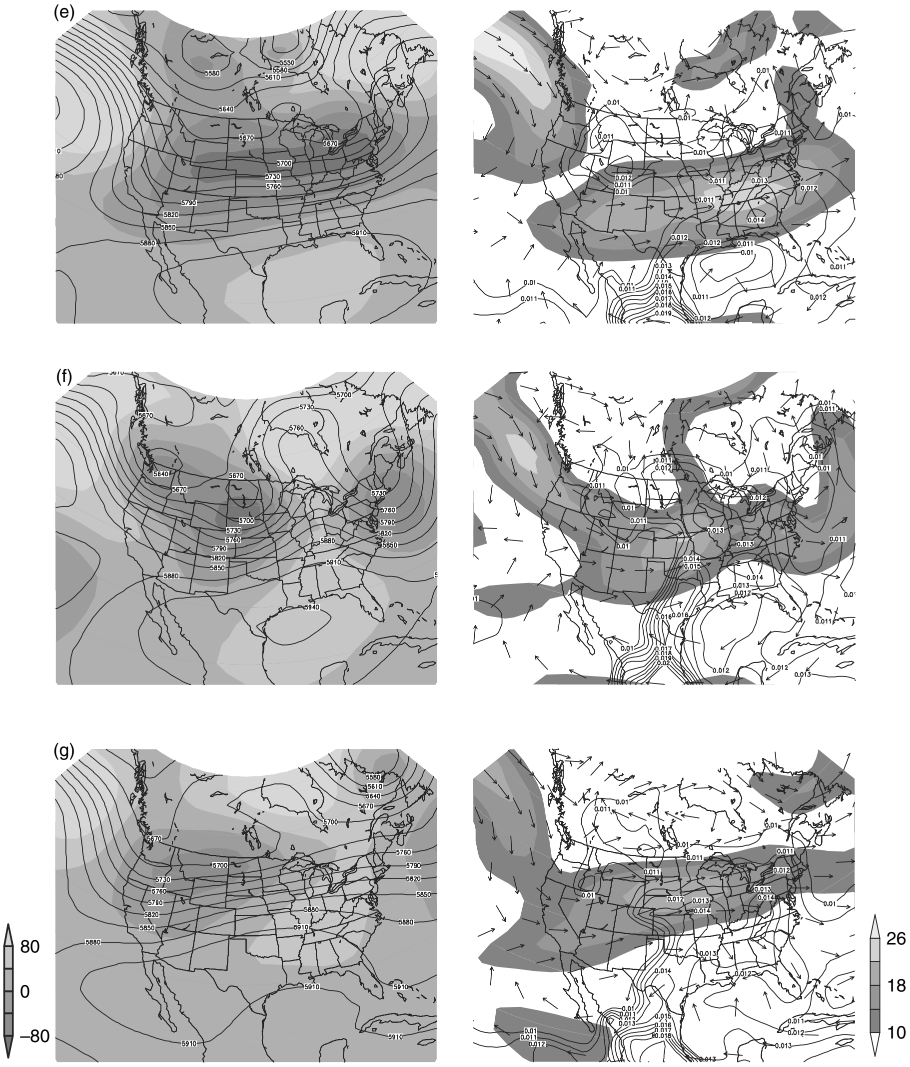


Figure 4. (*Continued*).

the cyclone exposed to insolation. As illustrated by Carr and Millard (1985), the dry-slot region in mid-latitude cyclones is favourable for secondary lines of convection.

Bentley and Sparks (2003) found that northeast-moving, central Plains events are often precursors to northern-tier U.S. derechos, which tend to cluster and propagate along the primary high-frequency derecho axis during the warm season (Figure 4.2 in Johns and Hirt (1987)). Bentley and Sparks (2003) suggest that northeast-moving, central Plains events manifest themselves in the early stages of low-amplitude anticyclones when the flow is southwesterly over the central Plains. As the subtropical high shifts poleward and amplifies, the periphery of the ridge, which is typically characterized by strong west-to-northwesterly flow aloft and surface convergence along a quasi-stationary latitudinally oriented thermal boundary, activates a corridor of east-to-southeast propagating derechos along the poleward margins of the ridge. This pattern shift was found in our analyses during the mid and late May 1998 -period, as the two northeast-moving derechos in series 'A' were followed by nine derecho events (series 'B' and 'C' in Figure 1) that developed and propagated along the periphery of the ridge situated across the south-central U.S. over 13 days.

3.2.2. 19–22 May series

The second series of derechos (series 'B' in Figure 1) is an illustration of an 'hybrid' series, consisting of events that formed within the same favourable synoptic pattern with one of the events (20 May II) initiating along a prior DMCS's outflow (Table II). The series occurred within a region of strong, low-level moisture pooling (Figure 4(b)), with the location, formation, and propagation of the DMCSs influenced by the anticyclonic flow around a stagnant subtropical ridge centred over northern Mexico and Texas (refer to Section 3.1 for a discussion of ridge formation in this situation). This setting is similar to those described by Coniglio *et al.* (2004) as a 'ridge' pattern and by Johns (1993) as a 'warm-season' pattern (Table I). Johns (1993) and Coniglio *et al.* (2004) suggest that in these patterns, derechos typically initiate along the periphery of the anticyclone, with low-level warm-air advection providing a mechanism for system initiation

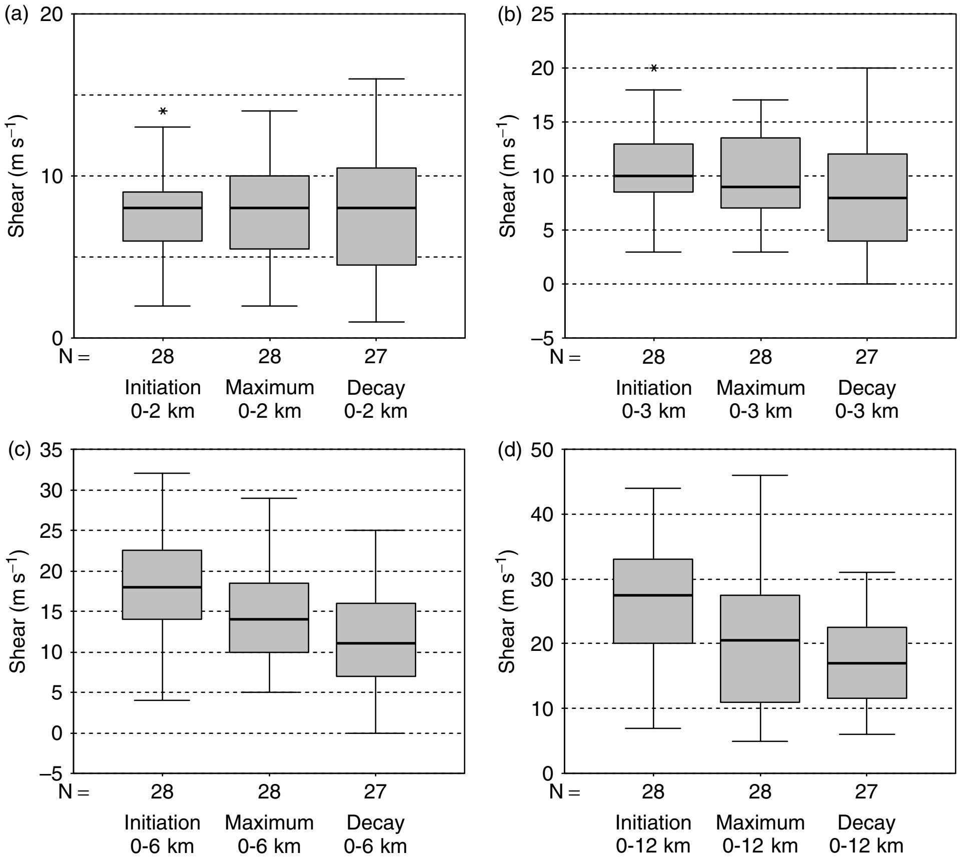


Figure 5. Plot of the range of (a) 0–2, (b) 0–3, (c) 0–6, and (d) 0–12 km shear vectors associated with DMCSs during initiation, maximum intensity, and decay stages during the 15 May–30 June 1998 derecho episode. Box and whisker plot of shear vector magnitude, with each proximity sounding from either observed data or RUC-2 analyses. Each box plot shows the median, 25th and 75th percentiles (quartiles; box), 10th and 90th percentiles (whiskers), and outliers (asterisk) within a category.

and sustenance. However, in only three of the five cases in this series did an LLJ (Table III), and hence moderate-to-strong warm-air advection, directly influence derecho formation and sustenance. Two of the cases associated with LLJs and warm-air advection initiated in an elevated environment poleward of low-level boundaries and thereafter propagated along the boundaries – a condition common to 'warm-season' patterns (Johns, 1993).

Despite the similar synoptic-scale environment, four different mechanisms were associated with DMCS initiation in this series (Table II), with events initiating in all poleward regions (upstream, atop, and downstream of the axis) of the ridge setting identified by Coniglio *et al.* (2004) as favourable for DMCS formation. This series illustrates how a multitude of mechanisms (e.g. surface heating, breaking capping inversion, upslope flow, outflow boundary, and warm-air advection along warm or quasi-stationary boundaries) can initiate DMCSs within a similar environment containing the necessary ingredients for severe, long-lived MCSs.

3.2.3. 28 May–1 June series

The third series of derechos (Series 'C' in Figure 1) was classified as 'indirect' and formed in a unique environment that was not characteristic of either the idealized 'dynamic' or 'warm-season' patterns described by Johns (1993). During late May, the upper-level pattern across the northern-tier of the U.S. featured extremely strong zonal flow situated between the persistent ridge in the south-central U.S. and a deepening Hudson Bay vortex (Figure 4(c)). The persistent strong flow aloft, and diffluent and divergent flow east of the ridge apex produced an environment supportive of synoptic-scale ascent maximized in the proximity of upper-level jet streaks.

All four derechos in this series developed either under the right-entrance or left-exit region of upper-level jet streaks (57–72 m s^{-1} at 250 hPa). In fact, two of the events (31 May and 1 June) formed beneath a coupled upper-level jet structure, with the 31 May case featuring an LLJ that was oriented nearly perpendicular to the upper-level flow. Such jet stream configurations can produce ageostrophic circulations that are associated with areas of enhanced upward motion (Uccellini and Johnson, 1979; Uccellini, 1990). The ageostrophic transverse circulation patterns in these series events were instrumental in destabilizing the preconvective storm environment through increasing thermal advections and enhancing underrunning by intensifying the LLJ.

3.2.4. 4–6 June series

The fourth series (Series 'D' in Figure 1) was unusual in that it featured three intense derechos that formed

DOI: 10.1002/met

Table III. Thermodynamic environment that characterized DMCSs during the May–June 1998 episode as identified from analysis of observational, reanalysis, and RUC-2 data. Mixed-layer convective available potential energy (CAPE) thresholds include marginal (<1000 J kg^{-1}), moderate (1000–2499 J kg^{-1}), strong (2500–3999 J kg^{-1}), and extreme (>4000 J kg^{-1}). Influence of capping inversion was subjectively determined by examining convective inhibition in proximity soundings, 700 hPa temperatures, and upstream (relative to system inflow) convective conditions based on radar and satellite data. Warm-air advection regime was established by examining 850 hPa thermal advection and using weak (<8 K s^{-1}), moderate (9–24 K s^{-1}), and strong (>25 K s^{-1}) thresholds. Strength of LLJ based on maximum 850 hPa wind velocities upstream (relative to system inflow) of developing or strengthening DMCSs. The LLJs were classified as either weak (<7.7 m s^{-1}), moderate (7.8–18 m s^{-1}), strong (18.1–28.2 m s^{-1}), or extreme (>28.3 m s^{-1}). To be classified as a LLJ, the stream had to contain a significant southerly component; hence, westerly and upslope flow scenarios were not catalogued.

Event ID	Initiation CAPE	Max. intensity CAPE	Decay CAPE	CAP influence	Strength of warm-air advection regime	Strength of LLJ
5/15 I	Strong	Moderate	Moderate	Strong	Strong	Extreme
5/15 II	Moderate	Strong	Moderate	Strong	Strong	Extreme
5/19	Extreme	Extreme	Marginal	Weak	Moderate	Moderate
5/20 I	Strong	Extreme	Moderate	Strong	Moderate	n/a (easterly)
5/20 II	Strong	Strong	Moderate	Weak	Weak	Moderate
5/21 I	Moderate	Extreme	Marginal	Strong	Weak	Weak
5/21 II	Marginal	Moderate	Moderate	Strong	Strong	Strong
5/28	Extreme	Strong	Marginal	Strong	Strong	Moderate
5/29	Moderate	Moderate	Marginal	None	Moderate	Moderate
5/31	Strong	Strong	Moderate	Strong	Strong	Extreme
6/01	Strong	Strong	n/a	Weak	Weak	Strong
6/04	Extreme	Strong	Moderate	Strong	Moderate	Moderate
6/05 I	Moderate	Moderate	Moderate	Strong	Moderate	Moderate
6/05 II	Extreme	Strong	Moderate	Strong	Weak	Weak
6/09	Extreme	Extreme	Moderate	Strong	Weak	Moderate
6/12	Extreme	Moderate	Missing	Weak	Moderate	n/a (westerly)
6/15	Strong	Moderate	Marginal	Strong	Weak	Strong
6/16	Moderate	Marginal	Marginal	Weak	Weak	Moderate
6/18	Strong	n/a	Strong	Strong	Weak	Moderate
6/19	Extreme	Strong	Strong	Weak	Weak	Weak
6/22 I	Moderate	Strong	Moderate	Strong	Strong	Strong
6/22 II	Moderate	Strong	Marginal	Strong	Moderate	Moderate
6/25	Extreme	Extreme	Marginal	Strong	Strong	Strong
6/26	Strong	Strong	Moderate	Strong	Strong	Strong
6/27 I	Extreme	Strong	Strong	Strong	Weak	n/a (westerly)
6/27 II	Extreme	Extreme	Moderate	Strong	Moderate	Moderate
6/28	Strong	Strong	Moderate	Strong	Weak	Weak
6/29	Extreme	Extreme	Marginal	Strong	Strong	Moderate
6/30	Moderate	Moderate	Moderate	Weak	Weak	Moderate

and traversed the Gulf Coast and mid-South during, climatologically, an unfavourable time for derecho formation in this region (*cf* Figure 2(a) in Ashley and Mote, 2005). The pattern that spawned these events included the enduring subtropical ridge anchored across the Gulf of Mexico; however, the ridge was suppressed by the remnants of the West Coast trough that had propagated and sheared eastward toward the High Plains and a zone of reduced heights extending southwestward from a Canadian Maritimes vortex (Figure 4(d)). The concurrence of these mid-tropospheric features induced a strong height gradient with fast zonal flow across the eastern two-thirds of the U.S. As a series of short-wave troughs embedded within the subtropical flow traversed outflow-reinforced cold and quasi-stationary fronts, DMCSs initiated (Table II). This setting is consistent with the 'warm-season' pattern described by Johns (1993) – albeit at a location atypical of this pattern with the setting featuring unusual, fast zonal flow.

This mid-South series was classified as 'direct', as the two latter systems tended to form and propagate along convective outflow from the preceding DMCS. The cap beneath the ridge was instrumental in supporting the strong, long-lived MCSs during this series. The capping inversion suppressed convection equatorward of the DMCSs, allowing for quick, convectively uncontaminated moisture return off the Gulf in the wake of each convective cluster.

3.2.5. *12–17 June series*

The fifth series during the May–June 1998 episode (Series 'E' in Figure 1) developed in an environment that featured the continuation of a strong, but suppressed ridge across the Gulf in addition to broad cyclonic flow throughout a large part of the U.S. (Figure 4(e)). Embedded within the cyclonic flow was a series of closed, mid-tropospheric lows (not identifiable in the means) and/or mid-level vorticity maxima. These features appear to be the primary influence on the development of the DMCSs. The cases appear to fit the 'upstream-trough' pattern described by Coniglio *et al.* (2004); however, two of the DMCSs in this series initiated upstream of *closed* lows – a feature previously unidentified in DMCS initiation regions (Table I). In all the cases, the upper-level trough or closed lows were influential in increasing the instability by overspreading unseasonably cold mid and upper-level air atop a warm, moist boundary layer. This 'indirect' series illustrates that the conceptual models describing DMCS settings in the literature do not illustrate all the features found in DMCS environments.

3.2.6. 18–19 June series

The sixth series (Series 'F' in Figure 1) is an unique 'direct' series that demonstrates how a mid-level synoptic-scale feature can initiate a convective complex, which can ultimately induce another convective system well removed from the initiating large-scale feature. Hence, this extraordinary situation is an example of a series that featured two events with direct association occurring in two distinctly different large-scale environments – an exception to the derecho series definition by Ashley *et al.* (2005). The setting during this series was characterized by a strengthening and retrograding subtropical ridge across the northwestern Gulf in addition to a strong, mid-level cut-off low meandering northeastward across the northern Great Plains (Figure 4(f)). The first DMCS commenced in an environment characterized by strong instability and moderate shear ahead of a cold front moving through the middle Mississippi Valley. The scenario conforms to an upstream-trough configuration described Coniglio *et al.* (2004), except that it featured a cut-off low rather than an open wave. The DMCS eventually decayed across the Ohio River Valley region as the gust front surged ahead of the convection. The outflow from this system continued to move southeastward into the southern Appalachian Mountain region during the early morning hours of 19 June. As the outflow progressed into an extremely unstable environment across the piedmont region of Georgia and South Carolina later that morning, convection reinitiated along the outflow boundary in a weakly capped environment. Though the convection formed in a weakly sheared environment, storm organization and system translation was supported by cold pool formation and a pressure fall/rise couplet that were identifiable in surface analyses.

3.2.7. 22 June–1 July series

The final derecho series during the May–June 1998 episode (Series 'G' in Figure 1) is one of the two largest series identified during the 1994–2003 period examined by Ashley *et al.* (2005). The series was classified as hybrid because two events in the series formed along outflow boundaries produced by prior DMCSs. The nine derechos in the series all formed and migrated along the periphery of the broad, flat subtropical ridge, which strengthened and migrated poleward into the south-central U.S. (Figure 4(g)). The ridge, and associated strong capping inversion, was instrumental in producing an environment conducive to the underrunning of high theta-e air into DMCS initiation and downstream regions (Table III). The systems all developed within or along the immediate southern periphery of strong mid-to-upper level, west-northwest flow that, when combined with LLJs, produced sufficient deep-layer shear for convective system organization. Furthermore, the strong southwesterly and westerly flow between the long wave trough anchored across the western U.S. and subtropical ridge forced 700–500 hPa elevated mixed air (with steep lapse rates) eastward into the DMCS genesis regions. Nearly all of the derechos during this series were associated with strong to extremely unstable environments (Table III) typical of mid-summer derecho environments (Johns and Hirt, 1987; Johns *et al.*, 1990; Johns, 1993; Bentley *et al.*, 2000). Hence, most of the DMCSs during this series exhibited features characteristic of the 'warm-season' pattern (Johns, 1993), including moderate west-to-northwest flow aloft, an east-to-west oriented, low-level thermal boundary, and high theta-e air in the low-levels. In addition, seven of the nine DMCS during this series had features consistent with Bentley *et al.* (2000) northeast-moving Great Plains DMCSs or southeast-moving northern-tier DMCSs.

A moderate-to-strong warm-air advection regime occurring along the periphery of the ridge and quasi-stationary boundaries or warm fronts were identified in the initiating environments (Table II). Beyond these thermal boundaries, several other influential features were upslope flow in the High Plains (22 June I), outflow from a prior MCS (22 June II) or DMCS (27 June I), a pre-frontal wind shift line (28 June), and a strong mid-level vorticity maximum (25 June). The setting in this series illustrates that the necessary ingredients for organized convection were typically provided and focused by the subtropical ridge, while various mechanisms along the ridge periphery supplied localized forcing.

Finally, 14 additional convective systems during the 15 May–30 June period contained features typical of quasi-linear convective systems including bow echoes, line echo wave patterns (LEWPs) or squall lines. These systems were not classified as DMCSs because they failed to produce sufficiently strong wind gusts across the required 400 km distance in defining a derecho. These events tended to decay quickly as they outran narrow instability axes or moved away from the upper tropospheric forcing.

3.3. Additional DMCS characteristics

During the May–June 1998 derecho episode, 18 of the 29 derechos evolved from supercells (an additional two cases were inconclusive because of inadequate radar coverage to distinguish possible supercellular convection; Table I). Other case studies in the literature (Johns and Leftwich, 1988; Smith, 1990) have illustrated that DMCSs can develop from supercells. In many DMCSs during the May–June 1998 period, specifically during the mature phase, supercells were embedded within the DMCS (see Miller and Johns (2000) for examples) and/or occurring in close proximity to the organized convective structure associated with the DMCS. Since DMCSs and supercells can be present contemporaneously, differentiating their environments may not be feasible in most warm-season settings. Evidence suggests that there are often similarities between the DMCS and supercell environments as noted by Doswell and Evans (2003).

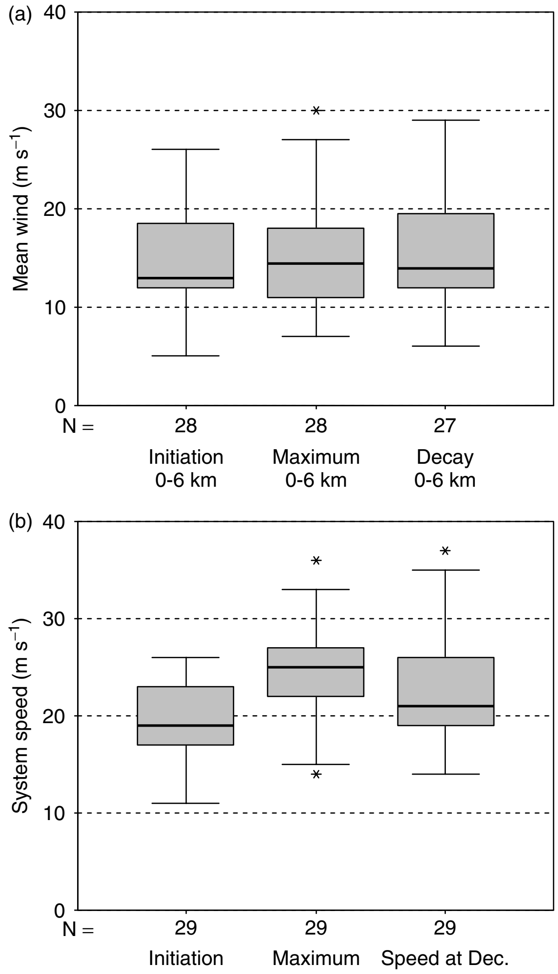


Figure 6. As Figure 5, except (a) 0–6 km (AGL) mean wind and (b) system speeds associated with DMCSs during initiation, maximum intensity, and decay stages.

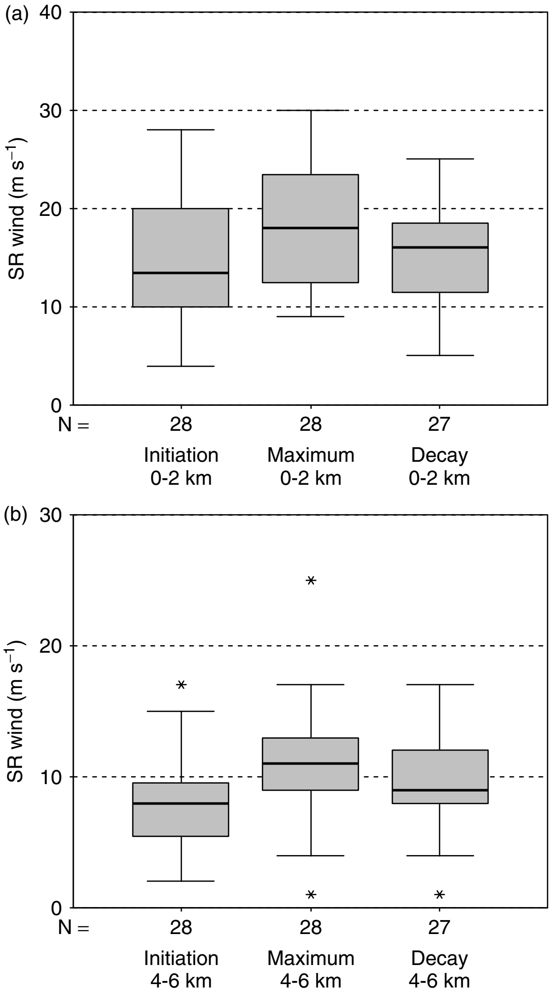


Figure 7. As Figure 5, except plot of the range of (a) 0–2 and (b) 4–6 km (all AGL) storm-related (SR) winds associated with DMCSs during initiation, maximum intensity, and decay stages.

In order to estimate the wind shear conditions associated with DMCSs during this episode, various kinematic fields for the initiation, maximum, and decay stages of the events were estimated from RUC-2 proximity soundings and a small set of observed proximity soundings that met the criteria proposed by Evans and Doswell (2001). Shear values from the 0–2, 0–3, 0–6, and 0–12 km layers for events during this episode illustrate a wide range of values during all stages of the DMCSs (Figure 5). Similar to the results of Evans and Doswell (2001), all DMCSs during this episode occurred or persisted in an environment characterized by 0–2 km shear vector magnitudes less than 15 m s^{-1}, with 64% (86%) of events initiating (attaining maximum intensity) in environments with 0–6 km shear vector magnitudes less than or equal to 20 m s^{-1}. As illustrated by Coniglio *et al.* (2004), deep-layer shear tended to decrease as DMCSs moved into decay regions – indicative of DMCSs moving away from the influence of mid and upper-level jets. In addition, our results agree with Coniglio *et al.* (2004) in that there is little change in 0–2 km shear, but much more difference in the 0–12 km shear as derechos decay.

As is typical of warm-season derechos (Johns and Hirt, 1987), DMCSs during this period moved at extremely fast speeds (mean of 25 m s^{-1} at maximum derecho intensity) and often faster than the mean wind speed (average 0–6 km mean wind 15 m s^{-1} at maximum intensity) (Figure 6). The DMCS speed is consistent with relatively strong low-level, storm-related inflow with average 0–2 km storm-related winds in initiation and maximum-intensity regions of greater than 15 m s^{-1} (Figure 7).

DOI: 10.1002/met

Storm-related winds in the 4–6 km layer were consistently weak compared to the low-levels, similar to the results of Evans and Doswell (2001). As suggested by Brooks *et al.* (1994), Thompson (1998), and Evans and Doswell (2001), storms that persist in weak, mid-level storm-related wind environments tend to be outflow dominant. Hence, mid-level, storm-related winds may be helpful in identifying environments where supercells become outflow dominant and transition into bow echo complexes (as found in a number of cases during this episode).

Mid and upper-level jet streaks appeared to influence a number of the DMCS environments during this episode. In 21 of the 29 cases, a DMCS developed either along the nose or in close proximity to a mid-level jet streak. Several additional cases developed within or along the periphery of stronger mid-level flow in which no jet streak could be identified. Although several of the mid-level jet streaks contained winds of only 21–26 m s^{-1} in the core, these jet streaks were significantly stronger than winds in the surrounding mid-levels. Hence, the relative strength of these wind maxima are what led to the generation of ageostrophic motions conducive to lift. Further, 14 of the 29 cases developed under or within the close proximity of strong upper-level jets (41–72 m s^{-1}). These features were instrumental in providing synoptic-scale upward motion and in increasing the depth of tropospheric shear, which has been found to be important contributors to DMCS environments (Coniglio and Stensrud, 2001; Evans and Doswell, 2001; Coniglio *et al.*, 2004).

4. Summary and conclusions

During mid May–June 1998, an exceptional series of derechos developed and migrated across the eastern two-thirds of the U.S., producing hundreds of casualties and hundreds of millions of dollars in damage (Ashley and Mote, 2005). This study has examined, using a multi-scale approach, the environments that produced the DMCSs during this unique episode.

Results illustrate that the large-scale environment was instrumental in producing the necessary ingredients required for the severe, organized convection in this setting. In particular, the semi-stagnant subtropical ridge across the southern tier of the U.S. produced a thermodynamic environment that was characterized by high values of low-level moisture and strong instability across DMCS genesis and sustenance regions. The cap beneath the ridge was influential in amplifying the moisture and instability across the region, while suppressing convection downstream of DMCS tracks. As mid and upper-level tropospheric disturbances interacted with surface boundaries along the ridge periphery, deep, moist convection initiated and often organized into DMCSs. Regions of preferred DMCS formation appeared to correspond to shifts in the overall strength and position of the ridge, illustrating its importance in focusing successive organized convection.

Evidence suggests the anomalous ridge across the southern tier of the U.S. was induced by tropical convection in a decaying El Niño (Barnston *et al.*, 1999). As stated, DMCSs during the May–June 1998 episode tended to cluster along the mean ridge periphery. Studies by Johns (1982, 1984), Bosart *et al.* (1999), and Bentley and Sparks (2003) have illustrated the importance of ridge placement and strength on severe convective system clustering. Hence, it is plausible that severe weather episodes of exceptional duration may be linked to large-scale atmospheric features induced by SST anomalies in the tropical Pacific. Clearly, the climatological record of DMCSs and other forms of organized convection needs to be extended before any such inferences are found to be significant. With improved climatological records, numerical modelling methods utilized to identify the physical mechanisms associated with extratropical climate extremes, such as that employed by Hong and Kalnay (2000, 2002), could be modified to evaluate DMCSs and/or other organized convective system activity.

Analysis of the seven derecho series during the May–June 1998 period (among others in the Ashley *et al.* (2005) DMCS series dataset) revealed three distinct series types – direct, indirect, and hybrid. Direct series during this period occurred when outflow from a previous DMCS initiated or directly influenced subsequent DMCSs, while indirect series were associated with a variety of initiating mechanisms occurring across the same synoptic-scale regime. Hybrid series contained characteristics of both direct and indirect series. This investigation only highlighted a small fraction of the 59 series that occurred during the 1994–2003 period outlined by Ashley *et al.* (2005). Additional study should continue to evaluate environments that contribute to the formation of derecho series. Identifying the environments that produce DMCS series has important implications for medium and long-range forecasting of these devastating windstorms.

The conceptual models of large-scale derecho environments described in the literature (e.g. Johns, 1993; Bentley *et al.*, 2000; Coniglio *et al.*, 2004) are useful in evaluating many DMCS cases. However, not all derechos during this period were associated with features described in the ‘warm-season’ and ‘dynamic’ patterns (Johns, 1993) or found in other composites of large-scale environments of DMCSs (e.g. Bentley *et al.*, 2000; Coniglio *et al.*, 2004). For example, features such as closed lows or strong vorticity maxima were found to be influential in initiating DMCSs during this period. Existing conceptual models only capture some of the conditions under which DMCSs can form. This work shows that these models need to be extended if reliable forecasts are to be achieved. In the mean time forecasters must exercise caution when considering the probability that such damaging events may occur.

An analysis of various kinematic fields for the event during this episode substantiate the results of Evans and Doswell (2001) and Coniglio *et al.* (2004), which suggest that DMCSs can occur within a wide range of environmental shear conditions not outlined in previous modelling and observational studies. Additionally, a majority of the DMCSs in this study initiated from or contained supercellular structures indicating that differentiating between DMCS and isolated supercellular environments may be particularly difficult.

Recent research has increased our knowledge of the causal factors, internal dynamics, and climatology of derechos, derecho series, and their parent MCSs. Nevertheless, significant discrepancies between observational and numerical modelling studies continue to highlight the need to explore the range of environmental conditions conducive to derechos. Ongoing efforts to document and illustrate the environments conducive to DMCSs, in both observational and numerical modelling frameworks, will improve the often extremely difficult task of forecasting successfully these large windstorms.

Acknowledgements

We appreciate the efforts of two anonymous referees who provided thoughtful and beneficial reviews.

References

Anderson CJ, Arritt RW. 2001. Mesoscale convective systems over the United States during the 1997–1998 El Nino. *Monthly Weather Review* **129**: 2443–2457.

Ashley WS, Mote TL. 2005. Derecho hazards in the United States. *Bulletin of the American Meteorlogical Society* **86**: 1577–1592.

Ashley WS, Mote TL, Bentley ML. 2005. On the episodic nature of derecho-producing convective systems in the United States. *International Journal of Climatology* **25**: 1915–1932.

Augustine JA, Caracena F. 1994. Lower-tropospheric precursors to nocturnal MCS development over the central United States. *Weather Forecasting* **9**: 116–135.

Barnston AG, Leetmaa A, Kousky VE, Livezey RE, O'Lenic EA, Van den Dool H, Wagner AJ, Unger DA. 1999. NCEP forecasts of the El Nino of 1997-98 and its U.S. impacts. *Bulletin of the American Meteorological Society* **80**: 1829–1852.

Bell GD, Halpert MS, Ropelewski CF, Kousky VE, Douglas AV, Schnell RC, Gelman ME. 1999. Climate assessment for 1998. *Bulletin of the American Meteorological Society* **80**: S1–S48.

Benjamin SG, Brown JM, Brundage KJ, Schwartz BE, Smirnova TG, Smith TL. 1998. *RUC-2–The Rapid Update Cycle Version 2*. NOAA/NWS Technical Procedures Bulletin 448.

Bentley ML, Mote TL. 1998. A climatology of derecho-producing mesoscale convective systems in the central and eastern United States, 1986–95. Part I: Temporal and spatial distribution. *Bulletin of the American Meteorological Society* **79**: 2527–2540.

Bentley ML, Mote TL. 2000. A synoptic climatology of cool-season derecho events. *Physical Geography* **21**: 21–37.

Bentley ML, Sparks JA. 2003. A 15 yr climatology of derecho-producing mesoscale convective systems over the central and eastern United States. *Climatic Research* **24**: 129–139.

Bentley ML, Mote TL, Byrd SF. 2000. A synoptic climatology of derecho producing mesoscale convective systems in the north-central Plains. *International Journal of Climatology* **20**: 1329–1349.

Bosart LF, Bracken WE, Seimon A, Cannon JW, LaPenta KD, Quinlan JS. 1999. The evolution of warm season continental anticyclones and their contribution to derecho environments. Preprints, *17th Conference on Weather Analysis and Forecasting*. American Meteorological Society: Denver, CO, 100–103.

Brooks HE, Doswell CA III, Cooper J. 1994. On the environments of tornadic and nontornadic mesocyclones. *Weather Forecasting* **9**: 606–618.

Carbone RE, Conway JW, Crook NA, Moncrieff MW. 1990. The generation and propagation of a nocturnal squall line. Part I: Observations and implications for mesoscale predictability. *Monthly Weather Review* **118**: 26–49.

Carbone RE, Tuttle JD, Ahijevych D, Trier SB. 2002. Inferences of predictability associated with warm season precipitation episodes. *Journal of the Atmospheric Sciences* **59**: 2033–2056.

Carlson TN, Benjamin SG, Forbes GS, Li YF. 1983. Elevated mixed layers in the regional severe storm environment: conceptual model and case studies. *Monthly Weather Review* **111**: 1453–1473.

Carr FH, Millard JP. 1985. A composite study of comma clouds and their association with severe weather over the Great Plains. *Monthly Weather Review* **113**: 370–387.

Coniglio MC, Stensrud DJ. 2001. Simulation of a progressive derecho using composite initial conditions. *Monthly Weather Review* **129**: 1593–1616.

Coniglio MC, Stensrud DJ. 2004. Interpreting the climatology of derechos. *Weather Forecasting* **19**: 595–605.

Coniglio MC, Stensrud DJ, Richman MB. 2004. An observational study of derecho-producing convective systems. *Weather Forecasting* **19**: 320–337.

Davies JM. 2004. Estimations of CIN and LFC associated with tornadic and nontornadic supercells. *Weather Forecasting* **19**: 714–726.

Doswell CA III. 1987. The distinction between large-scale and mesoscale contribution to severe convection: A case study example. *Weather Forecasting* **2**: 3–16.

Doswell CA III, Evans JS. 2003. Proximity sounding analysis for derechos and supercells: An assessment of similarities and differences. *Atmospheric Research* **67–68**: 117–133.

Evans JS, Doswell CA III. 2001. Examination of derecho environments using proximity soundings. *Weather Forecasting* **16**: 329–342.

Farrell RJ, Carlson TN. 1989. Evidence for the role of the lid and underunning in an outbreak of tornadic thunderstorms. *Monthly Weather Review* **117**: 857–871.

Fujita TT, Wakimoto RM. 1981. Five scales of airflow associated with a series of downbursts on 16 July 1980. *Monthly Weather Review* **109**: 1438–1456.

Gallus WA, Correia J, Jankov I. 2004. The 4 June 1999 derecho: the ultimate challenge for numerical weather prediction? Preprint CD-Rom, *22nd Conference on Severe Local Storms*. American Meteorological Society: Hyannis, MA.

Grell GA. 1993. Prognostic evaluation of assumptions used by cumulus parameterizations. *Monthly Weather Review* **121**: 764–787.

Hagemeyer BC. 1991. A lower-tropospheric thermodynamic climatology for March through September: Some implications for thunderstorm forecasting. *Weather Forecasting* **6**: 254–270.

Hart J, Korotky J. 1991. The SHARP workstation v1.50, A skew-t/hodograph analysis and research program for the IBM and compatible PC, user's manual. National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, 62.

Hinrichs G. 1888. Tornadoes and derechos. *American Meteorological Journal* **5**: 341–349.

Hong S-Y, Kalnay E. 2000. Role of sea-surface temperature and soil moisture feedback in the 1998 Oklahoma-Texas drought. *Nature* **408**: 842–844.

Hong S-Y, Kalnay E. 2002. The 1998 Oklahoma-Texas drought: mechanistic experiments with NCEP global and regional models. *Journal of Climate* **15**: 945–963.

Johns RH. 1982. A synoptic climatology of northwest flow severe weather outbreaks. Part I: Nature and significance. *Monthly Weather Review* **110**: 1653–1663.

Johns RH. 1984. A synoptic climatology of northwest flow severe weather outbreaks. Part II: Meteorological parameters and synoptic patterns. *Monthly Weather Review* **112**: 449–464.

Johns RH. 1993. Meteorological conditions associated with bow echo development in convective storms. *Weather Forecasting* **8**: 294–299.

Johns RH, Hirt WD. 1987. Derechos: widespread convectively induced windstorms. *Weather Forecasting* **2**: 32–49.

Johns RH, Leftwich PW Jr. 1988. The severe thunderstorm outbreak of July 28–29, 1986: A case exhibiting both isolated supercells and a derecho producing convective system. Preprints, *15th Conference on Severe Local Storms*. American Meteorological Society: Baltimore, MD, 448–451.

Johns RH, Doswell CA III. 1992. Severe local storms forecasting. *Weather Forecasting* **7**: 588–612.

Johns RH, Howard KW, Maddox RA. 1990. Conditions associated with long-lived derechos–an examination of the large-scale environment. Preprints, *16th Conference on Severe Local Storms*. American Meteorological Society: Kananaskis Park, AB, 408–412.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woolen J, Zhu Y, Chelliah M,

DOI: 10.1002/met

Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetma A, Reynolds R, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society* **77**: 437–471.

Keighton S, Noqueira S, Belk N. 2001. Synoptic and mesoscale analysis of the 9 August 2000 Appalachian-crossing derechos. Preprints, *18th Conference on Weather Analysis and Forecasting*. American Meteorological Society: Fort Lauderdale, FL, 439–443.

Lanicci JM, Warner TT. 1991. A synoptic climatology of the elevated mixed layer inversion over the southern Great Plains in spring. Part 1: structure, dynamics and seasonal evolution. *Weather Forecasting* **6**: 181–197.

Markowski P, Hannon C, Frame J, Lancaster E, Pietrycha A, Edwards R, Thompson RL. 2003. Characteristics of vertical Wind Profiles near supercells obtained from the rapid update cycle. *Weather Forecasting* **18**: 1262–1272.

Miller DJ, Johns RH. 2000. A detailed look at extreme wind damage in derecho events. Preprints, *20th Conference on Severe Local Storms*. American Meteorological Society: Orlando, FL, 52–55.

National Oceanic and Atmospheric Administration (NOAAa). 1998. *Daily Weather Map Series*. U.S. Department of Commerce, NOAA Central Library Data Imaging Project, National Climatic Data Center: Silver Spring, MD, [Available online at: http://docs.lib.noaa.gov/rescue/dwm/data_rescue_daily_weather_maps.html].

National Oceanic and Atmospheric Administration (NOAAb). 1998. *Storm Data with Unusual Weather Phenomenon and Late Reports and Corrections*. U.S. Department of Commerce, National Environmental Satellite Data and Information Service, National Climatic Data Center: Asheville, NC, 28–45 [Available online at: http://www5.ncdc.noaa.gov/pubs/publications.html].

Smith BE. 1990. Mesoscale structure of a derecho-producing convective system: The southern Great Plains storm of 4 May 1989. Preprints, *16th Conference on Severe Local Storms*. American Meteorological Society: Kananaskis Park, AB, 455–460.

Stensrud DJ. 1996. Effects of persistent, midlatitude mesoscale regions of convection on the large-Scale environment during the warm season. *Journal of the Atmospheric Sciences* **53**: 3503–3527.

Thompson RL. 1998. Eta Model storm-relative winds associated with tornadic and nontornadic supercells. *Weather Forecasting* **13**: 125–137.

Thompson RL, Edwards R, Hart JA, Elmore KL, Markowski P. 2003. Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Weather Forecasting* **18**: 1243–1261.

Trier SB, Davis CA, Tuttle JD. 2000. Long-lived mesoconvective vortices and their environments. Part I: Observations from the central United States during the 1998 warm season. *Monthly Weather Review* **128**: 3376–3395.

Uccellini LW. 1990. The relationship between jet streaks and severe convective storm systems. Preprints, *16th Conference on Severe Local Storms*. American Meteorological Society: Boston, MA, 121–129.

Uccellini LW, Johnson DR. 1979. The coupling of upper- and lower-tropospheric jet streaks and implications for the development of severe convective storms. *Monthly Weather Review* **107**: 682–703.

Weisman ML. 1992. The role of convectively generated rear-inflow jets in the evolution of long-lived mesoconvective systems. *Journal of the Atmospheric Sciences* **49**: 1826–1847.

Weisman ML. 1993. The genesis of severe, long-lived bow-echoes. *Journal of the Atmospheric Sciences* **50**: 645–670.

Weisman ML, Rotunno R. 2004. "A theory for strong long-lived squall lines" revisited. *Journal of the Atmospheric Sciences* **61**: 361–382.

DOI: 10.1002/met