

A Historical Overview on the Science of Derechos

Part I: Identification, Climatology, and Societal Impacts

Brian Joseph Squitieri, Andrew R. Wade, and Israel L. Jirak

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Derecho;
Severe storms;
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ABSTRACT: Research efforts from the last several decades to the present have aimed to better understand when and where derechos occur across the United States and other parts of the world, and what impacts derechos have on society. While the scientific community agrees that derechos are widespread wind storms associated with extratropical mesoscale convective systems, varying quantitative thresholds of what constitutes a derecho exist among peer-reviewed journal articles, introducing ambiguity throughout the literature of what is classified as a derecho, and where derechos most frequently occur. The scientific community would benefit from a summary on the more crucial aspects of derechos and where ambiguities or inconsistencies exist in the literature. Part I of this derecho historical overview discusses the history of derecho identification, and how differences in derecho identification strategies affect our understanding of their spatial climatology across the United States and Europe. Impacts to human life and commerce are also summarized.

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Corresponding author: Brian Joseph Squitieri, brian.squitieri@noaa.gov

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Strong, damaging surface winds have long been known to accompany thunderstorm clusters and squall lines, the most organized of which are classified as mesoscale convective systems (MCSs) (Houze 2018). Many studies during the midtwentieth century have contributed to the knowledge that MCSs generate surface outflow via a mesoscale vertical circulation, where deep convective overturning produces cooler, stable air that descends and extends toward the leading line of storms (Hamilton and Archbold 1945; Newton 1950; Tepper 1950; Fujita 1955, among many others). While research on MCS structure dates back to the 1900s, studies researching concentrated swaths of exceptionally damaging winds from thunderstorm outflows have been conducted as early as the late 1800s. Hinrichs (1888) was among the first in U.S. history to differentiate swaths of straight-line wind damage from tornado damage to better portray Iowa's tornado climatology (Fig. 1). These particularly damaging wind swaths were called *derechos*, a term of Spanish origin (which, among other things, means “straight”) that Hinrichs (1888) adopted to classify what were sometimes called the “Straight Blow of the Prairies.”

The derechos studied in Hinrichs (1888) were categorized by swaths of exceptionally damaging winds that produced damage of similar severity to tornadoes. Specifically,

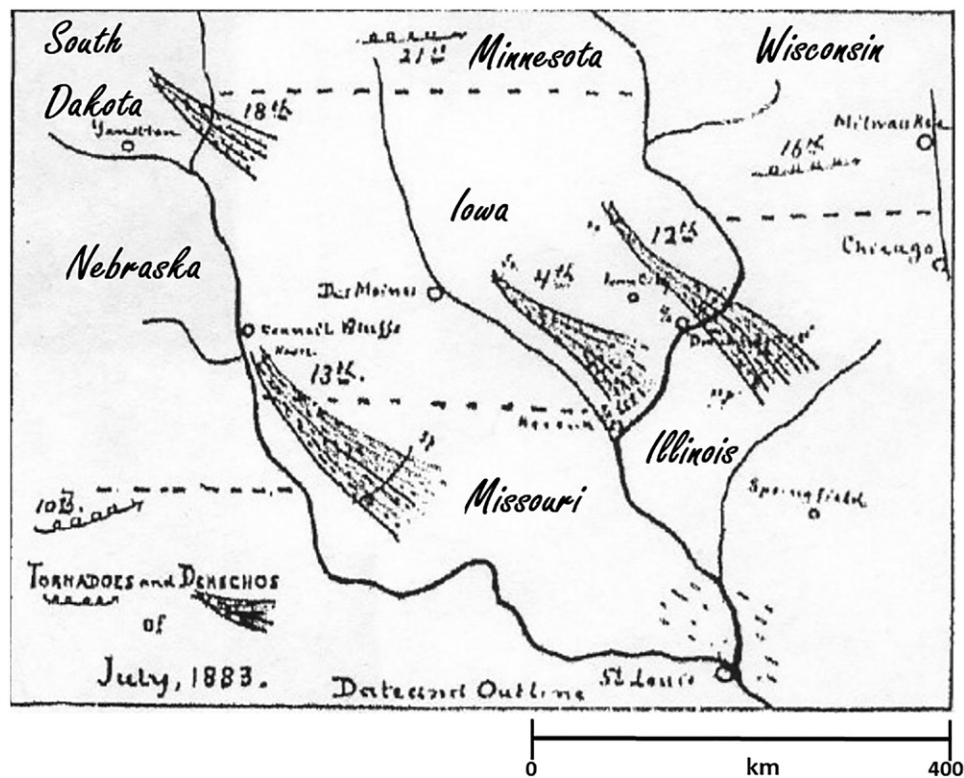


Fig. 1. A map showing the location of suspected derechos across Iowa in July 1883. Derechos are denoted by narrow tracks that widen with southeast extent and are labeled by the day of occurrence. State names were added for clarity on derecho locations. A length scale was added for reference (adapted from Hinrichs 1888, Fig. 2).

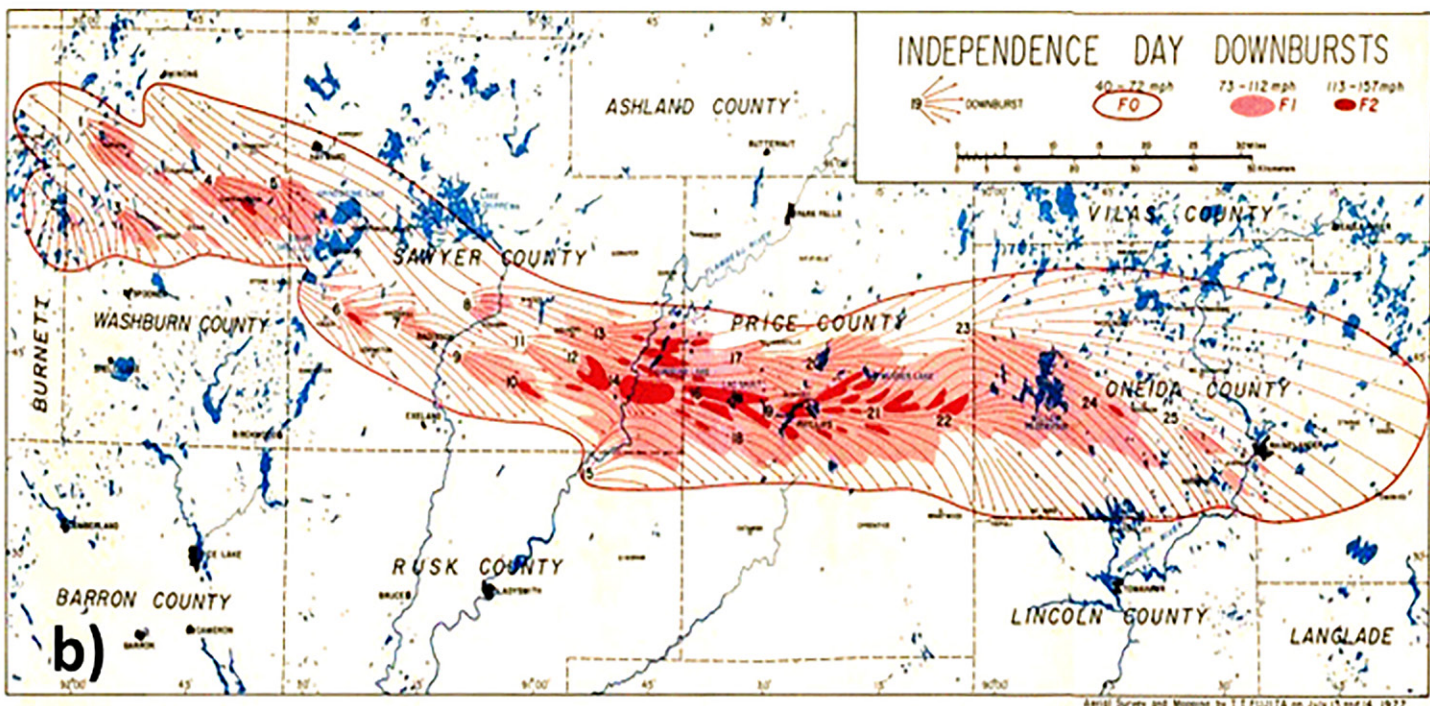
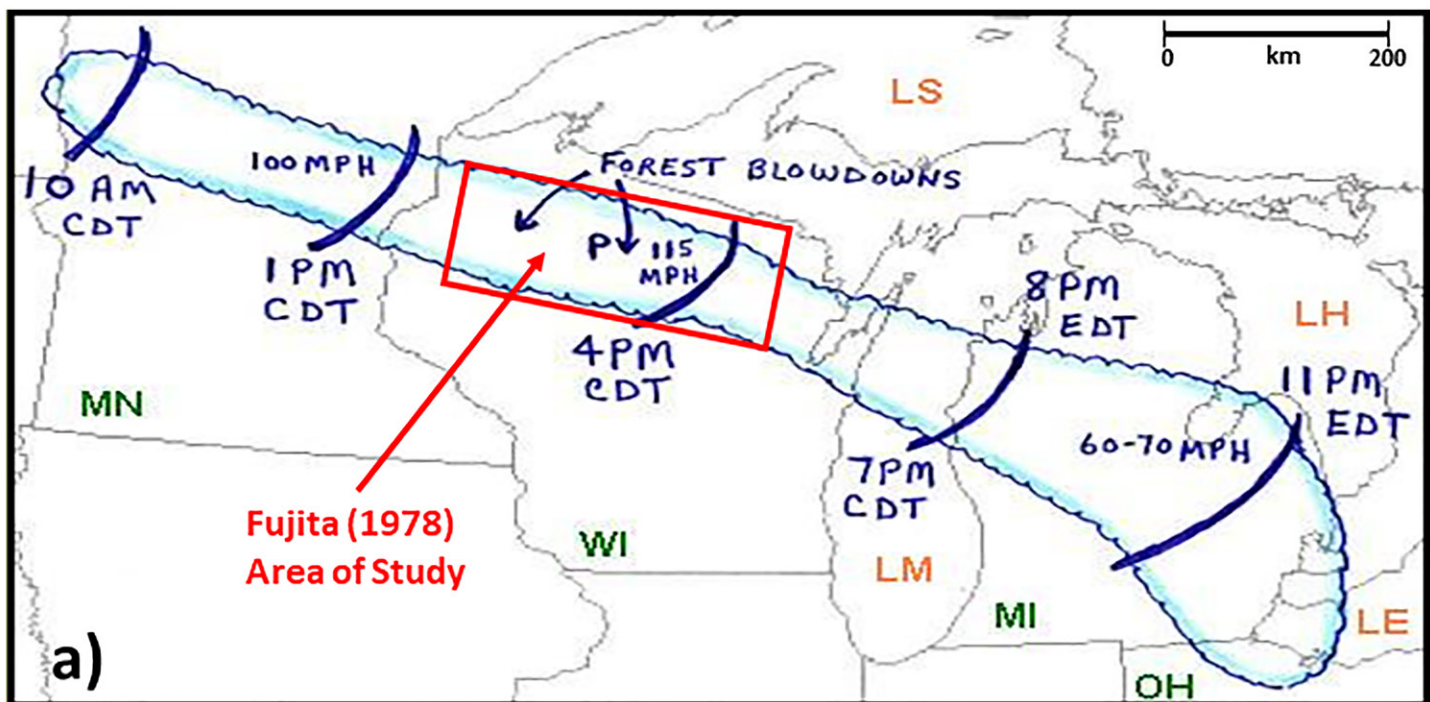


Fig. 2. (a) Estimated track and location times of the 4 Jul 1977 bow echo, with some of the most intense estimated wind speeds noted (Storm Prediction Center 2022). The area boxed in red denotes where Fujita performed a detailed damage survey; (b) a map of 25 surveyed downbursts embedded within a broader damaging wind swath (from Fujita 1978, Map 4).

Hinrichs (1888) mentioned that a derecho is a “powerfully depressing violently progressing mass of cold air, moving destructively onward in slightly diverging straight lines” and are capable of “blowing a train of cars off the tracks and un-roofing, overturning, or destroying houses.” Hinrichs (1888) asserted that unambiguous nomenclature was important for clearly defining the spatial scales and intensities of a broader class of phenomena. Hinrichs (1888) inferred that the term “derecho” should differentiate the most intense thunderstorm wind events from ordinary squalls. Nonetheless, the term derecho disappeared for nearly a century.

By the latter half of the twentieth century, interest in destructive MCSs reemerged during field projects studying damaging thunderstorm downburst events in great detail, including

the Northern Illinois Meteorological Research On Downbursts (NIMROD) project, which was initiated in 1978 to better understand the occurrences of damaging thunderstorm outflow (Fujita 1978). Fujita became aware of a particularly damaging downburst event on 4 July 1977 in northern Wisconsin associated with a destructive MCS (Fig. 2a). Fujita (1978) defined this parent MCS as a *bow echo* (based on available radar data, Fig. 3), introducing new meteorological nomenclature in the process. A more detailed review on MCS structures supporting derechos is provided in Part II (Squitiери et al. 2023). Fujita performed a detailed damage survey of the most significant damage across Washburn to Oneida Counties in Wisconsin, noting several localized downbursts with 33+ and even 50+ m s⁻¹ intensities embedded within the broader 17+ m s⁻¹ wind swath (Fig. 2b). Just a few years later, Fujita had the opportunity to perform another detailed damage survey on what he described as a “series of destructive windstorms” associated with a long-lived MCS that traveled from Chicago to Detroit on 16 July 1980 (Fujita and Wakimoto 1981). From this survey, it was deduced that the downburst series occurred on five spatial scales, with each progressively smaller-scale downburst event producing greater damage. The largest-scale downburst clusters occurred on the mesoscale (roughly 1,000 km) with embedded mesoscale downburst clusters spanning 100 km, which contained individual downbursts on the order of 10 km (Fig. 4). Even within individual downbursts, misoscale microbursts (1 km scale) were identified and produced burst swaths on the order of 100 m in length, where winds up to 40–50 m s⁻¹ occurred.

Shortly after the detailed downburst series surveys by Fujita, forecasters at the National Severe Storms Forecast Center (NSSFC; which became the Storm Prediction Center) identified synoptic-scale weather patterns during the summer months that often supported significant damaging wind swaths and tornado outbreaks (Johns 1982, 1984). Summer events with northwesterly flow aloft frequently resulted in some of the more impactful thunderstorm wind and tornado days (i.e., northwest flow events). One northwest flow event of particular interest was a destructive, long-lived MCS that happened on 19–20 July 1983 across the Upper Mississippi Valley (Fig. 5). It was in a detailed case study of this event that Johns and Hirt (1985) reintroduced the term *derecho* in peer-reviewed literature. It was also

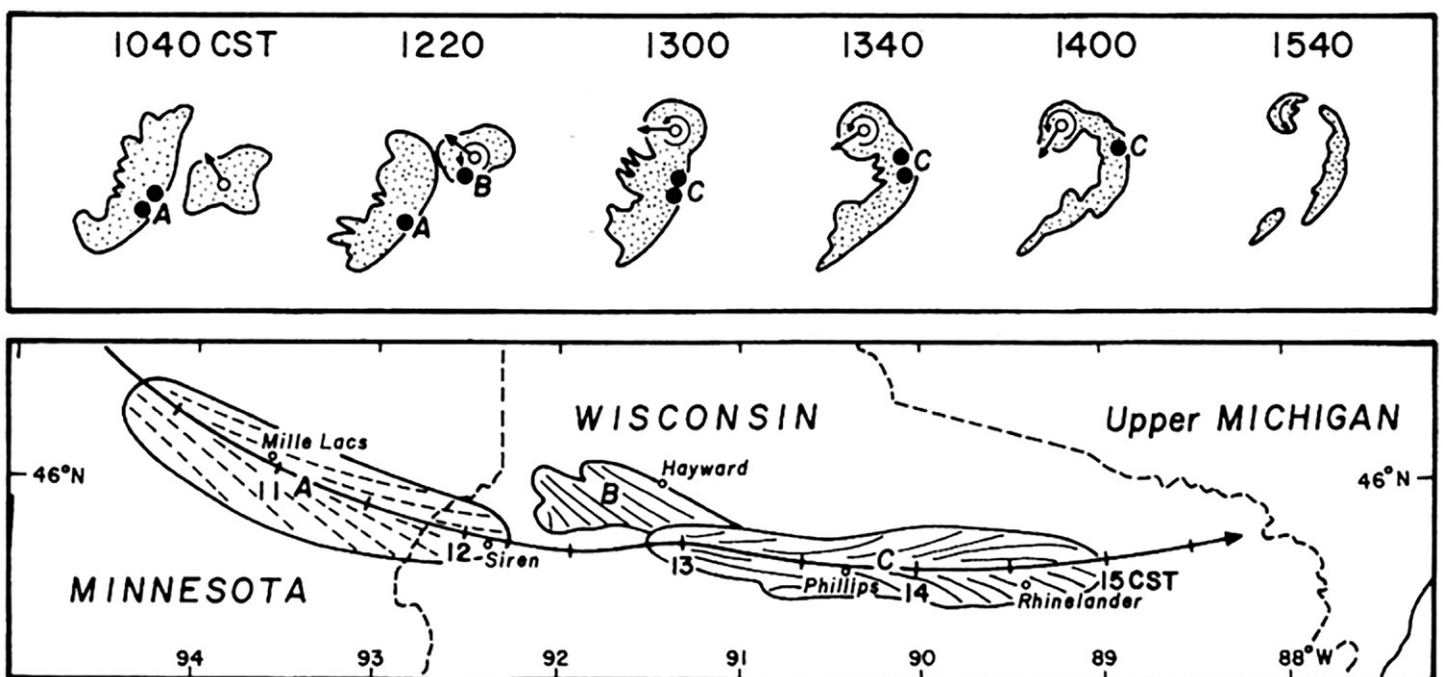


Fig. 3. (top) Time series depiction of the 4 Jul 1977 bow echo MCS through its varying stages of evolution, conceptualized via an analysis of available radar data. (bottom) A map estimating the location and expanse of the damaging wind swaths is provided. Letters A, B, and C depict the stages of the bow echo evolution with corresponding damage swaths (from Fujita 1978, Fig. 5.3).

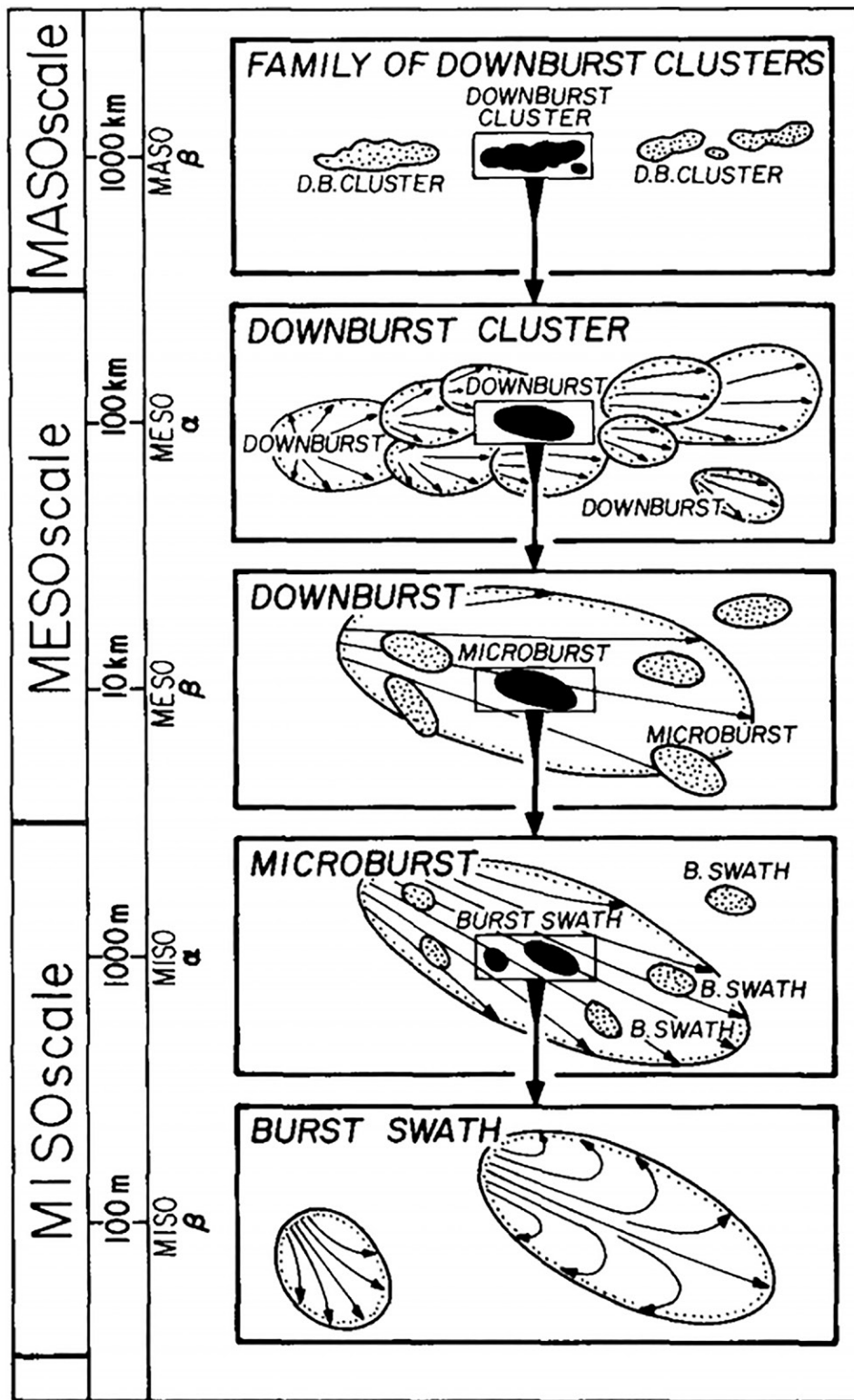


Fig. 4. Five scales of downburst damage patterns. A family of downburst clusters extends several hundred kilometers while a downburst cluster consists of a number of individual downbursts, which in turn contain microbursts. A burst swath, particularly a long and narrow one, is characterized by damage typical of tornadoes (from Fujita and Wakimoto 1981, Fig. 1).

evident to Johns and Hirt via their earlier synoptic studies of northwest flow events, and detailed damage surveys from Fujita, that derechos were a recurring, destructive force of nature that required more in-depth study.

Johns and Hirt (1987, JH87 henceforth) was the first comprehensive, peer-reviewed study that attempted to identify derechos based on spatial and temporal characteristics from

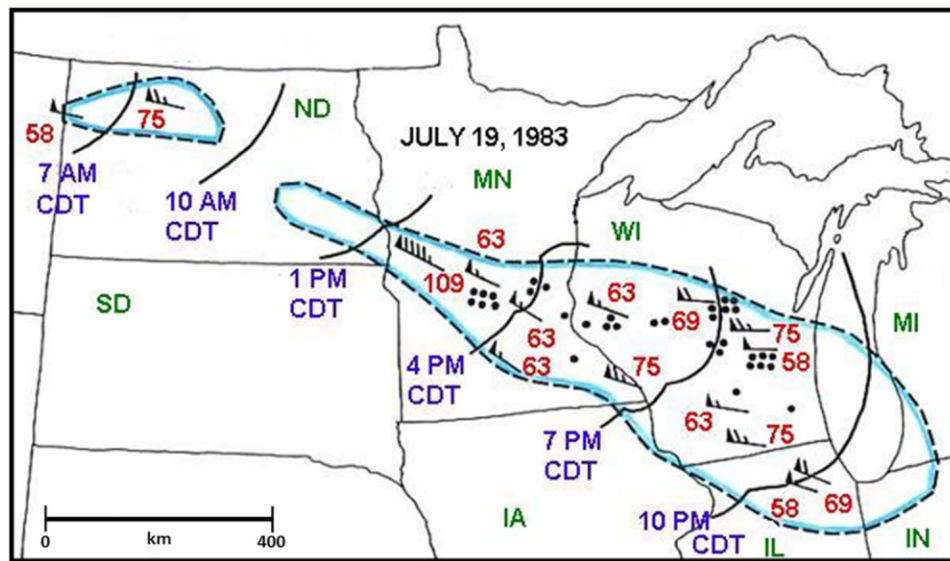


Fig. 5. Map plot of the 19 Jul 1983 derecho, with black lines depicting the MCS leading line at a given time (local time). Dashed lines with blue shading denote the broader damaging wind swaths containing the derecho. Observed surface wind directions and speeds are shown via wind barbs (in kt; 1 kt = 0.51 m s⁻¹; with speeds in mph also listed in red). Black dots show locations where injuries occurred [from Johns and Hirt (1985, Fig. 1) and augmented by Storm Prediction Center (2022)].

70 long-tracked, damaging MCS-driven wind events. In the spirit of Fujita's works showing the most severe MCS wind damage originating from multiple downbursts, JH87 qualitatively defined a derecho as "any family of downburst clusters produced by an extratropical MCS." Thereafter, the American Meteorological Society Glossary and nearly all peer-reviewed literature have adopted JH87's general notion that a derecho is a family of downbursts accompanying an MCS (American Meteorological Society 2023).

What are "progressive" versus "serial" derechos? Equipped with years of operational experience and an appreciable sample size of derecho cases, JH87 were able to identify two distinctly different derecho types based on convective structure and the synoptic environmental setup. One type is known as the "progressive derecho," which is typically produced by a singular, forward-propagating MCS (i.e., when an MCS progresses by downwind, discrete convective development; Corfidi 2003), and often develops during the warm season (i.e., May–August) in synoptic environments of weak forcing. JH87 found that progressive derecho-producing MCSs (DMCSs) frequently originate from smaller convective clusters that grow upscale into larger, more organized MCSs (e.g., Fig. 6a). Many progressive DMCSs frequently form into bow echoes (Fujita 1978; Przybylinski 1995). JH87 noted that since progressive DMCSs originate from weakly forced environments, they tend to be challenging to forecast and this remains the case today, with progressive derecho content comprising most of the derecho literature.

Serial derechos (the second type described in JH87) originate in strongly forced environments and develop from mature squall lines. With time, multiple bowing segments form along the squall line (e.g., Fig. 6b), producing enhanced swaths of wind damage. Serial DMCSs evolving from squall lines often resemble the line echo wave pattern (LEWP) defined in Nolen (1959). In some cases, cold-season bow echoes, squall lines, and cold-frontal rainbands (often accompanied by little lightning) have been referred to as DMCSs based on their damaging wind potential (Alfonso and Naranjo 1996; Bentley and Mote 1998, BM98 henceforth; Burke and Schultz 2004; van den Broeke et al. 2005; Gatzen et al. 2011; Pistotnik et al. 2011; Celiński-Mysław and Matuszko 2014; Celiński-Mysław et al. 2020; Mathias et al. 2019).

Arguments have been made whether serial events should be considered derechos. Hinrichs (1888) established the term "derecho" to describe a particular phenomenon that is separate

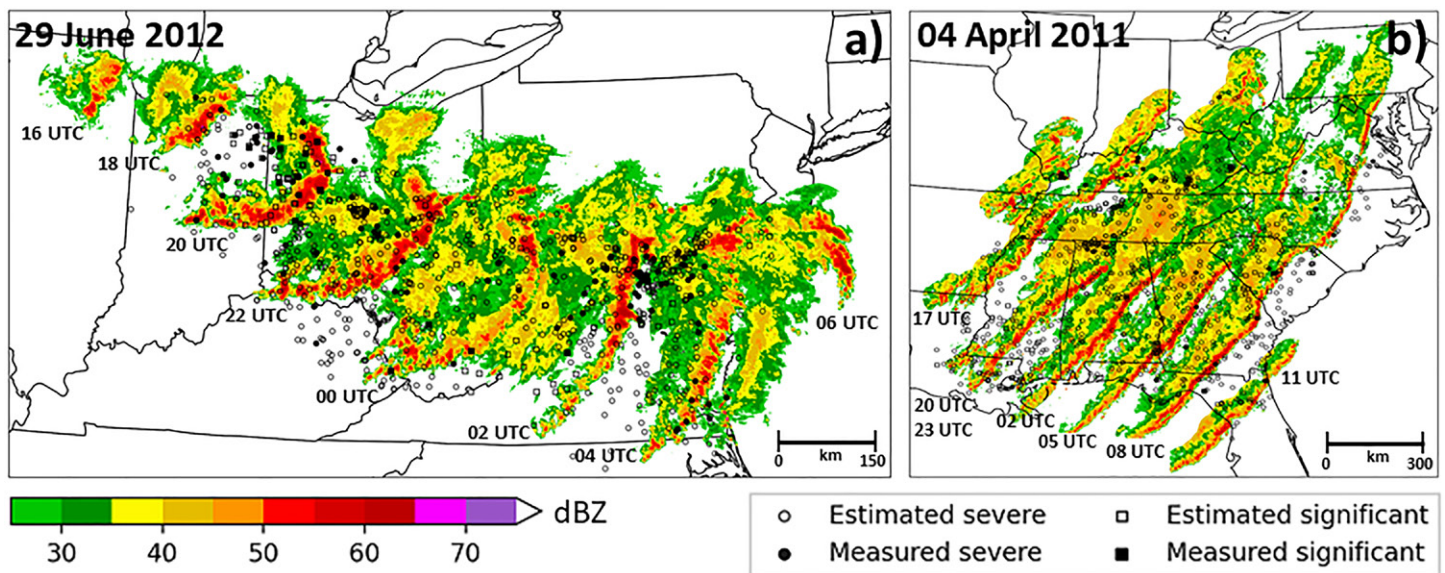


Fig. 6. (a) Composite radar reflectivity of a progressive DMCS, every 2 h, from 1600 UTC 29 Jun to 0600 UTC 30 Jun 2012; (b) composite radar reflectivity of a serial DMCS, every 3 h, from 1700 UTC 4 Apr to 1100 UTC 5 Apr 2011. Circles denote 26–33 m s⁻¹ gust reports, with squares representing 33+ m s⁻¹ reports. Measured reports have filled markers, with estimated reports shown with hollowed markers. Length scales were also added.

from a squall line, and Corfidi et al. (2016a) argued that the loose application of derecho nomenclature by the meteorological community and the public could lead to miscommunication. Corfidi et al. (2016a) stated that derechos should originate from progressive MCSs, where damaging surface winds are generated from internal storm-scale processes, as suspected in the summertime events documented by Hinrichs (1888), and that a new derecho definition should be formulated to reflect this point. A significant component of damaging surface winds in serial derechos come from channeled downward momentum of the ambient flow aloft and are more directly influenced by the synoptic environment, suggesting that serial derechos are much different from progressive events, as shown in example cases with low-topped convection in van den Broeke et al. (2005). Clearly, there are major meteorological differences between squall-line cases and MCSs resulting in progressive derechos, so the convective event that produces a derecho remains debatable, especially since the detrimental societal impacts inflicted by progressive and serial derechos can be similar in magnitude, as acknowledged by Corfidi et al. (2016a). Matters are complicated further by the fact that an infinite spectrum of linear storm modes between serial squall lines and progressive bow echo MCSs exists, with “hybrid” modes of parent DMCS structures and supporting ambient environments possible (Duke and Rogash 1992; Coniglio et al. 2004; Squitieri et al. 2023).

Discrepancies in quantitative criterion classifying derechos. While several studies agree that a derecho is a widespread convective windstorm generated by a series of downbursts from an extratropical MCS (JH87; Evans and Doswell 2001; Coniglio et al. 2004; Coniglio and Stensrud 2004, CS04 henceforth; Guastini and Bosart 2016; Corfidi et al. 2016a), the quantitative criterion for a damaging wind swath delineating the margins of what could be called a derecho varies throughout the literature (Table 1). JH87 employed operational forecasting experience, as well as Fujita and Wakimoto’s (1981) findings to establish rigid quantitative derecho criteria. A concentration of 26+ m s⁻¹ gusts with a long-axis length of 400 km must exist, with at least three 33+ m s⁻¹ gusts (64 km apart) required, and with no more than 3 h allowed to elapse between gusts. The reports must also show chronological progression in association with the same MCS and demonstrate temporal and spatial continuity.

Table 1. A summary of quantitative criteria employed in U.S. derecho studies with appreciable sample sizes (N). The highlighted studies compiled original databases, with their derecho-identifying quantitative criteria compared to JH87. The years the studies spanned and the intended type of derechos targeted for research are also provided.

	JH87	BM98	Evans and Doswell (2001)	BS03	CS04	Coniglio et al. (2004)	Cohen et al. (2007)	Guastini and Bosart (2016)	Corfidi et al. (2016a)
Years	1980–83	1986–95	1983–93	1986–2000	1986–2001	1980–2001	1998–2004	1996–2013	2010–14
N	70	112	67	230	244	270	51	256	365 (25)
Type	Progressive serial	Progressive serial	Progressive serial	Progressive serial	Progressive serial	Progressive serial	Progressive	Progressive	Progressive
1	There must be a concentrated area of convective wind gusts exceeding 26 m s^{-1} with a major axis path length of at least 400 km	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	Like JH87, but for a path length of 650 km (N = 25 cases that met this length criteria)
2	There must be at least three reports (separated by 64 km) of F1 damage or $33+ \text{ m s}^{-1}$ wind gusts during the MCS stage	Not used	As in BM98	As in BM98	Low end: As in BM98 Moderate: As in JH87 High end: Like JH87, but three reports must exceed 38 m s^{-1} , with two occurring at MCS stage	As in BM98	As in BM98	As in BM98	As in BM98
3	No more than 3 h can elapse between successive reports	No more than 2 h can elapse between successive reports	As in BM98	As in BM98	Like JH87, but for 2.5 h	As in CS04	As in JH87	As in CS04	No more than 1 h elapsed between successive reports
4	Wind reports must have chronological progression	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87
5	The associated MCS must have spatial or temporal continuity in surface pressure or wind fields	Continuity confirmed when no more than 2° lat–lon separation occurs between reports	Continuity confirmed via linear structures in radar data.	As in BM98	Like BM98, but no more than 200 km allowed between any reports in the swath	As in CS04	As in Evans and Doswell (2001)	As in CS04	Like CS04, but no more than 100 km allowed between any reports in the swath
6	All damage swaths must accompany the same MCS based on radar data	MCS confirmed by temporally mapping wind reports without radar data	As in JH87	As in BM98	As in JH87	As in JH87	As in JH87	As in JH87	As in JH87

BM98 [which partly provided derecho datasets for Bentley and Mote (2000b), Bentley et al. (2000), and Bentley and Sparks (2003, BS03 henceforth)] did not include 33+ m s⁻¹ gust reports as a requirement since there was no evidence of this criteria being employed in Fujita and Wakimoto (1981). Other studies excluded the 33+ m s⁻¹ gust requirement because of irregularities or biases associated with wind reports (Ashley and Mote 2005, AM05 henceforth; Corfidi et al. 2016a), or so that long-lived, impactful wind swaths from MCSs without 33+ m s⁻¹ winds would not be excluded from research (Coniglio et al. 2004; Corfidi et al. 2016a). CS04 tested the sensitivity of derecho classification when categorizing derechos as low end (BM98 criteria), moderate (JH87 criteria), and high end (three 38+ m s⁻¹ gusts are required, and two of these gusts must be associated with an MCS structure and not a supercell), finding that the $N = 244$ derecho sample decreased to nearly one-fifth its original size ($N = 55$) when implementing increasingly strict significant severe gust criteria. Cohen et al. (2007) classified 269 MCSs by intensity, and while the 33 m s⁻¹ wind criterion was excluded, JH87 criterion 1 or 3 in Table 1 needed to be met for a DMCS to be confirmed. Still, only 51 MCSs were classified as a DMCS. As such, the exclusion of the 33+ m s⁻¹ gust requirement likely has contributed to appreciably large sample sizes in many original derecho studies (Table 1).

Another inconsistency among original, large-sample-bearing derecho studies was the use (or lack thereof) of radar data to confirm the attribution of damaging wind swaths to MCS structures. BM98 used temporal mapping of wind reports to associate derecho swaths with deep moist convection. Johns and Evans (2000) commented that this methodology may potentially overinflate derecho occurrences since damaging wind swaths may originate from more isolated convective modes. Bentley and Mote (2000a) responded that the storm mode contributing to damaging, impactful convective wind events should be irrelevant when classifying derechos. In retrospect, Corfidi et al. (2016a) pointed out that convective structures (like supercells) should not be considered for derecho classification because they are inherently incapable of producing the large areas of damage that Hinrichs (1888) intended to identify. The inconsistency in mapping wind reports, as opposed to using radar data to confirm the presence of a derecho, complicated aggregating multiple original derecho datasets for studies in need of larger sample sizes over longer time periods, as in AM05 and Ashley et al. (2005). When Ashley et al. (2005) attempted to merge the derecho databases of BS03 and CS04, they found that both studies only share just over 50% of the combined cases even though both studies cover the same time period (1986–2000). This caused Ashley et al. (2005) (like AM05) to reanalyze all cases with radar data to confirm a derecho event.

Some studies varied the amount of time allowed between wind reports (Table 1). Johns and Evans (2000) attributed the higher report frequency requirement in BM98 to the considerable differences in their results to JH87, and that changes in report frequencies contributed to some of the inconsistencies in results between other studies. Most derecho research has adhered to using 400 km as the minimum length to identify derecho damage swaths, though Corfidi et al. (2016a) also suggested that derecho pathlengths should be expanded to 650 km to filter out lower-impact events. Still, even if derecho track length and chronological progression criteria are held constant among all derecho studies, varying JH87's quantitative criteria greatly impacts derecho identification, and would also have noticeable consequences on derecho climatology.

Derecho climatology in the United States and Europe

Similarities and disparities of derecho climatology across the United States. Several studies have developed or synthesized derecho databases to formulate a derecho climatology for the continental United States over the past 35 years, but for periods only spanning from 5 to under 20 years (JH87; BM98; Bentley and Mote 2000b; BS03; CS04; Ashley et al. 2005; Guastini and Bosart 2016). BM98/BS03 and CS04 overlapped in the 1986–2000

period, with an increase in the number of cases sampled in both studies after 1994 (Fig. 7a). The aggregation of BS03/CS04 cases in AM05 shows that derechos are more common in late spring into the summer compared to the cool season (Fig. 7b). The JH87, BM98, and CS04 studies also revealed that DMCSs initiated mainly during the late morning to evening hours, with late night into early morning DMCS initiation being less common (Fig. 7c), as also found by Bentley et al. (2000).

JH87 were able to derive a warm-season derecho climatology to illustrate where derechos would most frequently occur in May–August of 1980–83, finding that the Upper Mississippi Valley into the Ohio Valley were most prone to warm-season events (Fig. 8a). However, using modified quantitative criteria and methodology for identifying derechos in 1986–95 (Table 1), BM98 found the highest derecho frequency to be located over the Southern Plains in association with “burst-MCS” events, though a local maxima also existed over the eastern Ohio Valley (Fig. 8b). The Upper Midwest and Southern Plains maxima differences in JH87 versus BM98 prompted a discussion from Johns and Evans (2000), who mentioned that the exclusion of the $33+ \text{ m s}^{-1}$ criteria and not confirming MCS structures (as opposed to supercell and disorganized clusters) were among the main causes for the maxima differences. Bentley and Mote (2000a) pointed out that one-fourth of the cases in JH87 occurred in June–July 1980, which was an unusually favorable period for DMCSs across the Upper Midwest and may be responsible for their maxima. CS04 demonstrated how sensitive warm-season U.S. derecho climatology could be just by altering the $33+ \text{ m s}^{-1}$ gust criteria. When excluding $33+ \text{ m s}^{-1}$ gusts altogether, warm-season derechos were near-evenly spread across the Midwest into the Ohio Valley, but with a slightly higher density of events across the Southern Plains (Fig. 9a). However, when evaluating only high-end events (three or more $38+ \text{ m s}^{-1}$ reports; two of the reports associated with MCS structures), the Southern Plains maxima disappears, with only the Midwest depicting a relative derecho maxima (Fig. 9c).

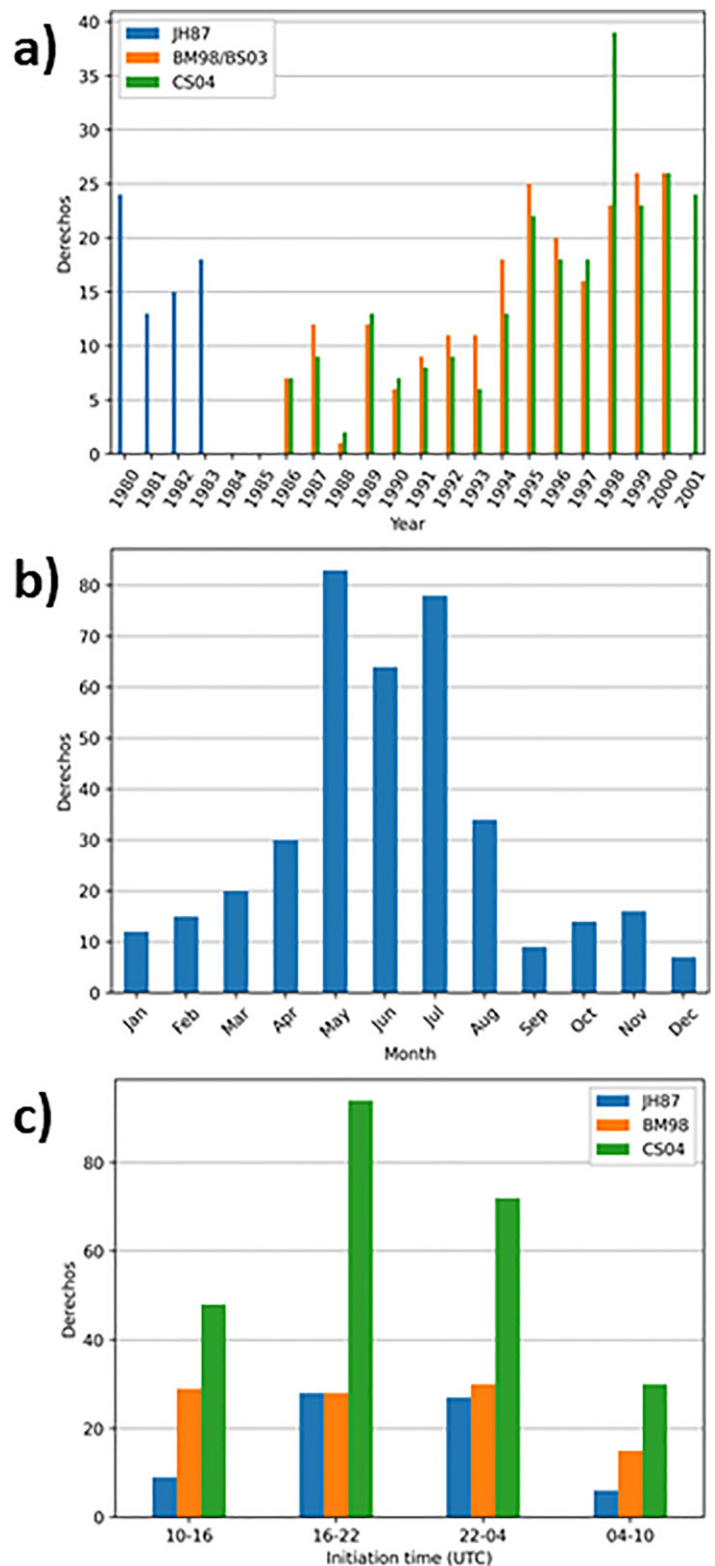


Fig. 7. (a) Number of derechos documented each year from 1980 to 2001 by JH87 (Table 1), BM98 (Fig. 21)/BS03 (Fig. 2), and CS04 (Coniglio 2004). (b) Number of derechos by month [adapted from AM05 (Fig. 3), merging the BS03/CS04 databases]. (c) Number of derechos initiating within 6-h time bins in JH87 (Table 2), BM98 (Fig. 19), and CS04 (Coniglio 2004). Times are in UTC.

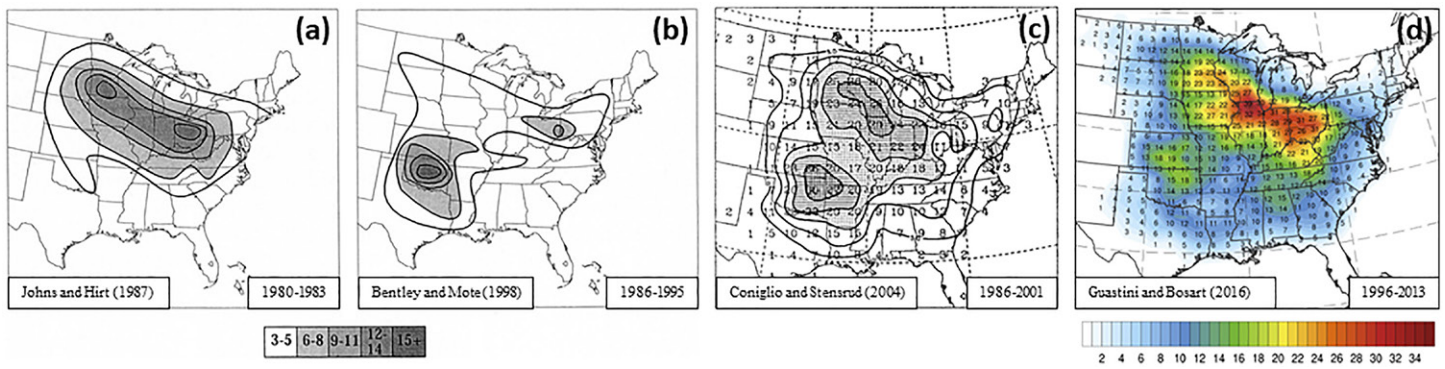


Fig. 8. Total number of derechos occurring in (a) 2° latitude \times 2° longitude squares for May–August of 1980–83 (JH87, Fig. 2), (b) 1.83° latitude \times 1.83° longitude squares for the warm season of 1986–95 (BM98, Fig. 1), (c) $200\text{ km} \times 200\text{ km}$ grid squares for May–August of 1986–2001 (CS04, Fig. 1a), and (d) $100\text{ km} \times 100\text{ km}$ grid squares for May–August of 1996–2013 (Guastini and Bosart 2016, Fig. 4).

Short time periods characterizing derecho climatologies may also explain several differences in results among core studies. While BM98’s 1986–95 derecho climatology showed the primary derecho occurrence maxima in the Southern Plains (Fig. 10a), a derecho maxima reemerged over the Midwest in the 1996–2000 period in BS03 with the addition of 118 derechos (Fig. 10b), influencing the 15-yr-long (1986–2000) calendar-year derecho climatology (Fig. 10c). BM98 and BS03 demonstrated that many of the derechos in the 1986–95 and 1996–2000 periods (thus 1986–2000 in total) were warm-season events (Figs. 10d–f), suggesting that the reemergence of the Midwest maximum derecho corridor is a summer occurrence. Since BM98 and BS03 classified derechos using the same quantitative criterion, the differences in their warm-season climatologies were likely caused by short, potentially inadequate sampling periods in BM98 (10 years). When sampling warm-season derechos into the 2000s to 2010s, over longer periods of time (15+ years), CS04 and Guastini and Bosart (2016) were able to support BS03’s summertime derecho maxima over the Midwest into the Ohio Valley, with a secondary maxima still evident in the Southern Plains (Figs. 8c,d, respectively).

In addition to the Midwest and Southern Plains warm-season derecho maxima (Fig. 11a), aggregating the BS03/CS04 datasets in AM05 showed the presence of a cool-season serial derecho frequency maximum across parts of the Lower Mississippi Valley (Fig. 11b). The CS04 cases likely had the greatest influence on the AM05 results (Figs. 11c,d). Still, BS03

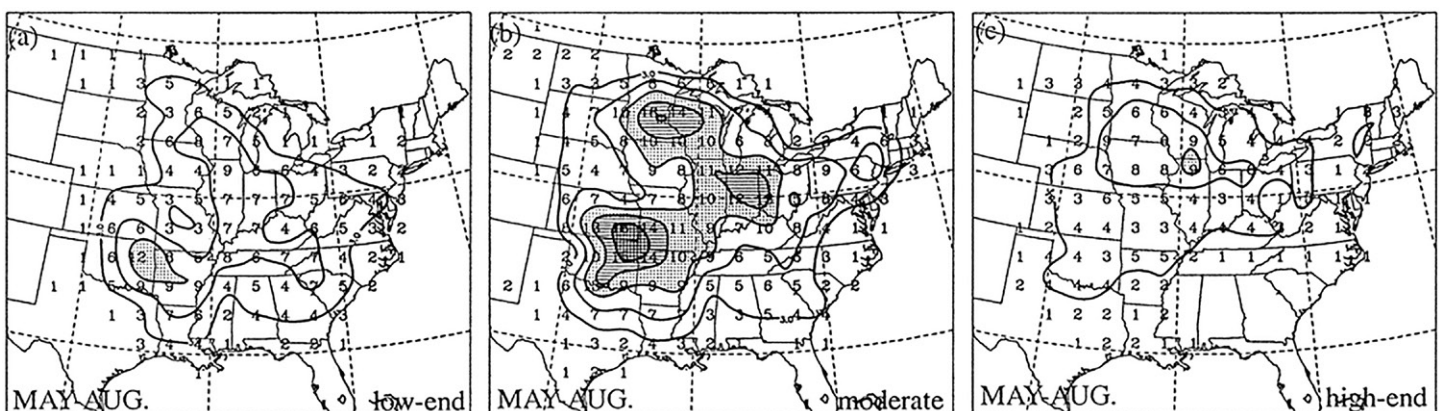


Fig. 9. The distribution of warm-season derechos from 1986 to 2001 for (a) 55 low-end events (no $33+\text{ m s}^{-1}$ reports), (b) 82 moderate events (three or more $33+\text{ m s}^{-1}$ reports), and (c) 31 high-end events (three or more $38+\text{ m s}^{-1}$ reports, two of which must occur at MCS stage) (from CS04, Fig. 5).

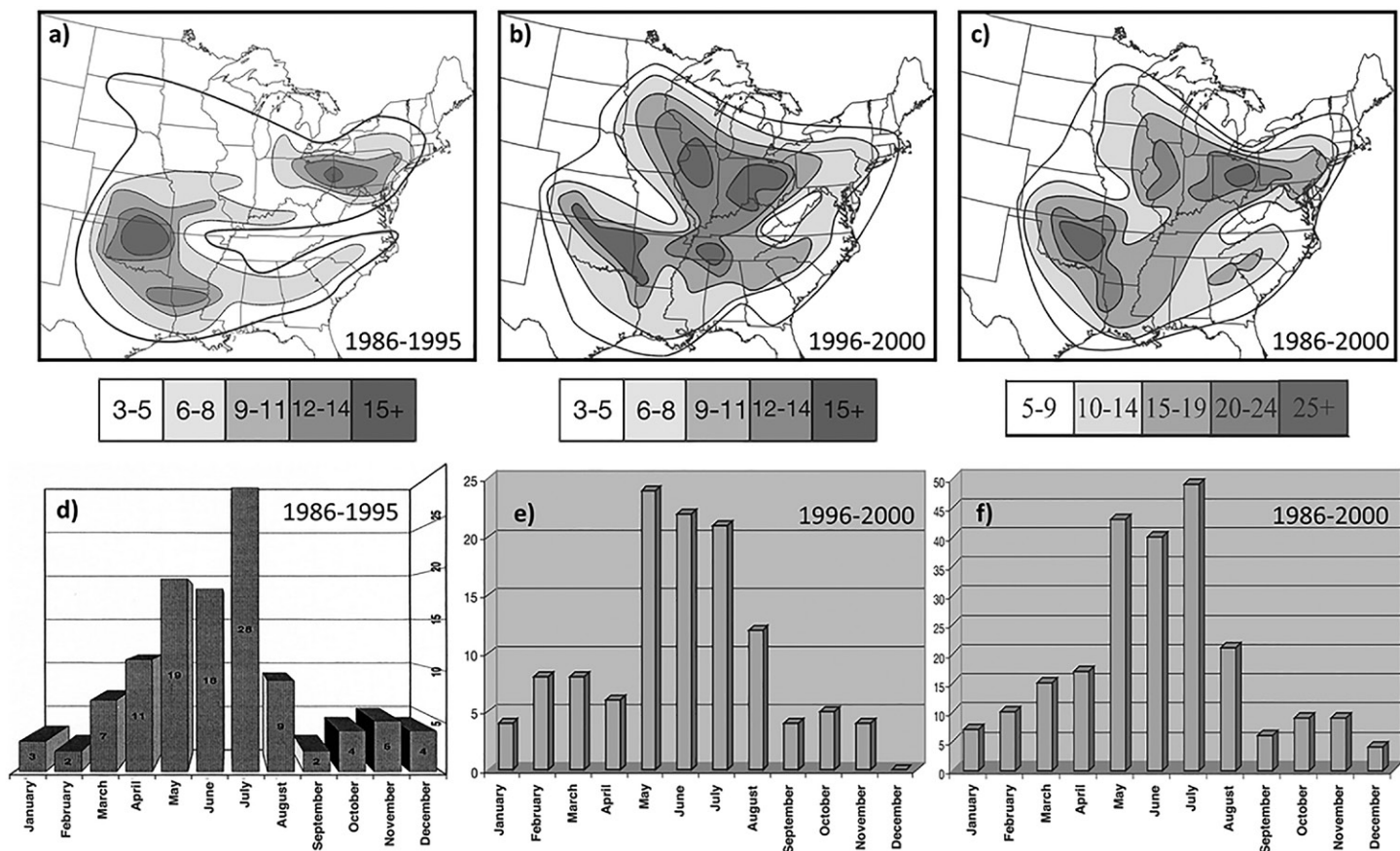
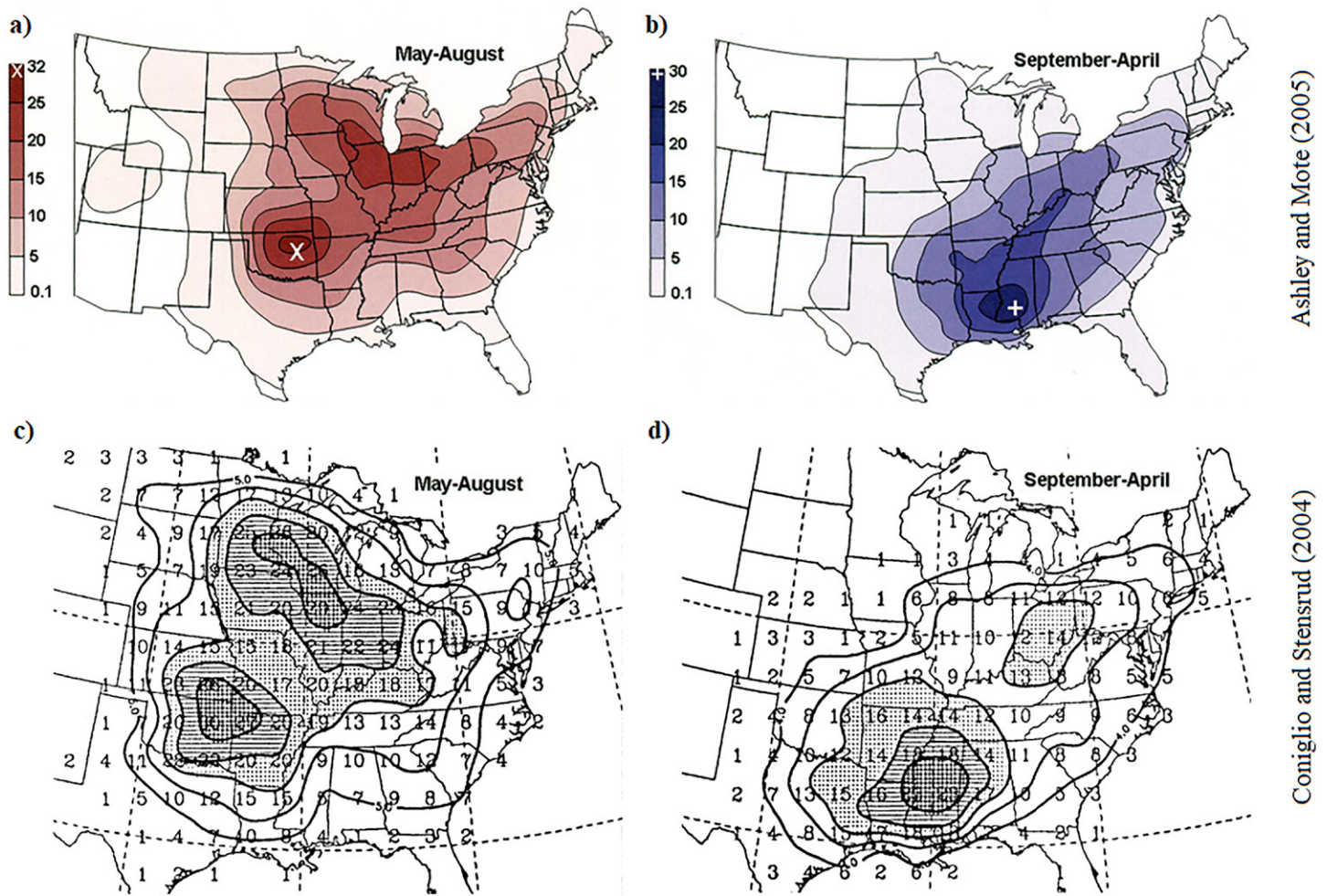


Fig. 10. Total number of derechos across the continental United States for the calendar year, occurring in 1° latitude × 1° longitude squares for (a) 1986–95 (as in BM98) (from BS03, Fig. 3b), (b) 1996–2000 (from BS03, Fig. 3a), and (c) 1986–2000 (from BS03, Fig. 14); (d) total number of derechos occurring by month in 1986–95 (from BM98, Fig. 9); (e) total number of derechos by month from 1996 to 2000 (from BS03, Fig. 1); (f) total number of derechos by month from 1986 to 2000 (from BS03, Fig. 13).

indicated a notable cool-season derecho frequency in the Lower Mississippi Valley (Fig. 10), which is the same cool-season corridor favoring the long-lived, severe bow echoes featured in Burke and Schultz (2004) and the derechos in Bentley and Mote (2000b).

Derecho occurrences across Europe. Derechos have occurred around the world and have been documented in peer-reviewed literature, including in Canada (Price and Murphy 2002), Cuba (Alfonso and Naranjo 1996), and China (Takemi 1999; Xia et al. 2012). Outside of the United States though, derechos have been reported most frequently over Europe, including Germany (Gatzen 2004; Mathias et al. 2017), Finland (Punkka et al. 2006), Spain (López 2007), Slovakia and Hungary (Simon et al. 2011), Austria (Pistotnik et al. 2011), Belgium (Hamid 2012), Poland (Celiński-Mysław and Matuszko 2014; Celiński-Mysław et al. 2020; Taszarek et al. 2019), Bulgaria (Gospodinov et al. 2015), Lithuania, Latvia, Estonia, and Belarus (Toll et al. 2015), along with Romania, Serbia (Sipos et al. 2021), and European Russia (Chernokulsky et al. 2022). Like the United States, Europe experiences derechos year-round, with cool-season derechos originating from squall lines that develop along cold fronts in strongly forced ambient environments (Gatzen et al. 2011; Mathias et al. 2019). Classic examples include the destructive squall-line events of 18 January 2007 and 1 March 2008 across Germany, Poland, and other surrounding countries. In both cool-season cases, low-topped convection preceded a surface cold front, denoted by weak reflectivity values (Figs. 12a,b) and were immediately followed by graupel and snow, but were otherwise accompanied by widespread damaging winds (Figs. 12c,d) (Gatzen et al. 2011;



Ashley and Mote (2005)

Coniglio and Stensrud (2004)

Fig. 11. Derecho frequencies depicted in AM05, aggregating the BS03 and CS04 databases for (a) May–August and (b) September–April. The “X” and “+” are locations where maximum values were observed before data interpolation. (AM05, Figs. 2a and 2b, respectively). Derecho frequencies in CS04 are for (c) May–August and (d) September–April (CS04, Figs. 3a and 4a, respectively).

Pistotnik et al. 2011; Celiński-Mysław and Matuszko 2014). Progressive derechos develop in summer, which (like U.S. events) can be difficult to forecast, yet are highly impactful. A classic example was the 25 June 2008 DMCS that traversed the Czech Republic during the afternoon (Fig. 13a), producing at least one wind damage swath over a 5-h period (Figs. 13b–d), yet was challenging to forecast (Púčik et al. 2011).

While the current derecho literature for Europe is mainly comprised of individual case studies, a few studies have focused on derecho recurrences in Germany and Poland. Gatzen (2013) found that derechos were relatively rare events for Germany, culminating in 5% of all convective wind events for April–September of 1997–2011 (one derecho per year), but were responsible for 45% of all warm-season convective wind gust reports, as well as the majority of extreme ($40+ \text{ m s}^{-1}$) gust reports. Gatzen et al. (2020) classified 40 derechos for 1997–2014 in the same manner as CS04, finding that the most intense derechos are quite rare (i.e., less than 5), but that it was relatively more common (10+ cases) for derechos to exceed 800 km lengths or 10 h lifespans (Fig. 14a). Nonetheless, most of Germany would only see moderate or high-end derecho once every couple of years (Fig. 14b). Neighboring Poland has a similar derecho climatology to Germany. Derechos comprised a considerable minority of convective wind events, with Celiński-Mysław and Palarz (2017) finding that a small portion of all bow echoes in Poland produced derechos in their 7-yr bow echo study. Surowiecki and Tazarek (2020) followed up with a 10-yr (2008–17) MCS climatology over

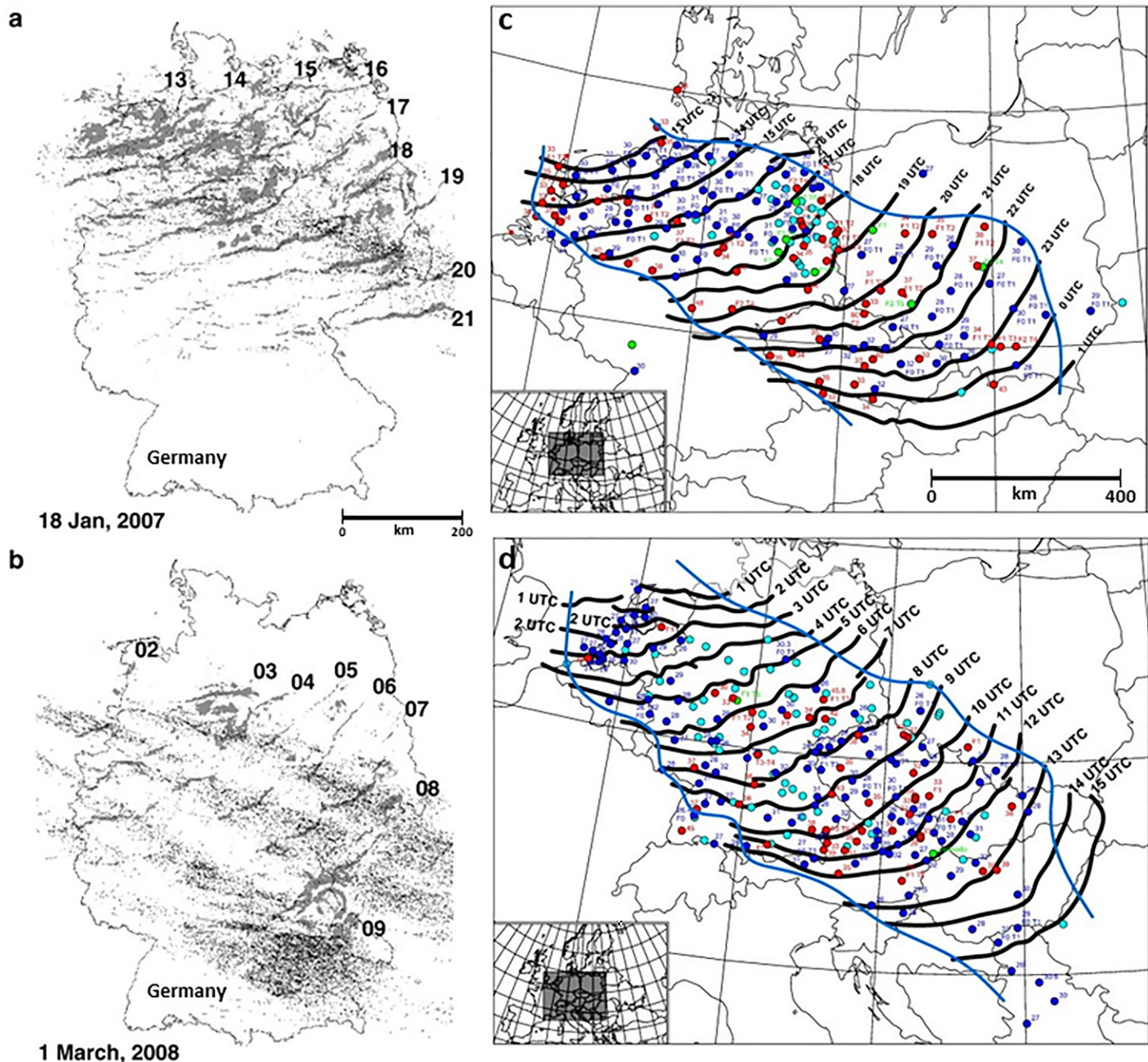


Fig. 12. Radar composite image and detected lightning for (a) 18 Jan 2007 and (b) 1 Mar 2008. The data of a lightning detection network (black dots) are given for the sampled time frames. The radar reflectivity of greater than 40 dBZ is plotted in hourly intervals and labeled by UTC times next to each line (from Gatzen et al. (2011, Figs. 2a and 2b). (c),(d) The damaging winds associated with the 18 Jan and 1 Mar events, respectively. Isochrones show squall locations and times. Blue, red, cyan, and green dots represent 26–33 m s⁻¹, 33+ m s⁻¹, wind damage, and tornado/gustnado reports, respectively (from Celiński-Mysław and Matuszko 2014, Figs. 2 and 9).

Poland, noting that 16 out of 766 MCSs (or 2%) produced derechos, most of which occurred during the warm season. Also similar to the derecho frequency in Germany found by Gatzen et al. (2020) is the derecho peaks of around 0.7 yr⁻¹ for Poland (Fig. 15b).

German warm-season DMCSs, dependent on the diurnal heating cycle, would develop or progress mainly during the early to late afternoon hours (Gatzen et al. 2020). However, cool-season events (while favoring afternoon development) often occurred anytime during the day or night (Fig. 14c), likely because they were more dependent on the strong forcing of

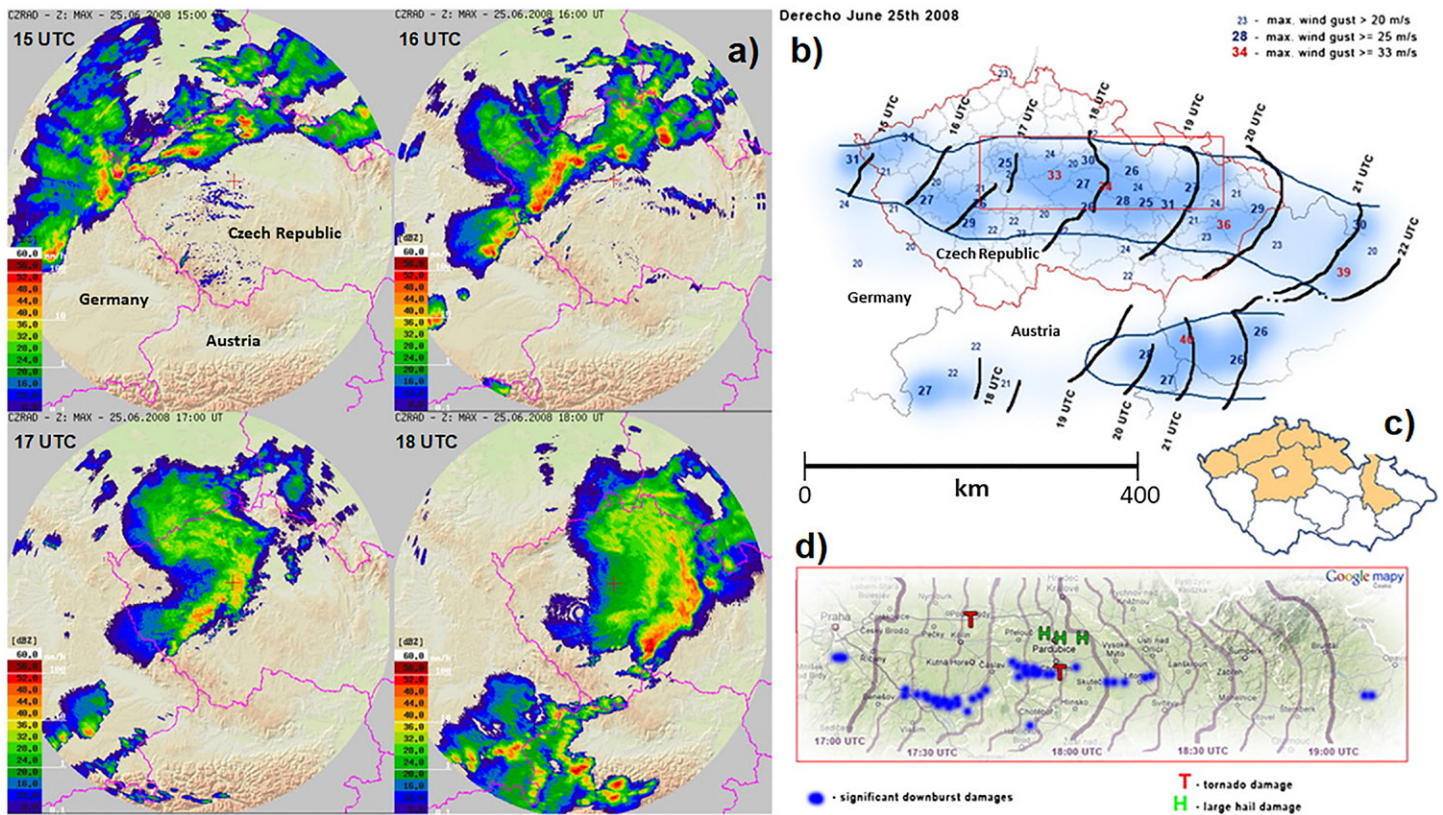


Fig. 13. (a) Composite reflectivity imagery showing the eastward progression of the DMCS across the Czech Republic from 1500 to 1800 UTC 25 Jun 2008. (b) Map depicting the progress of the leading edge of two severe MCSs (thick black lines) with an hourly step (times in UTC). Soft blue areas represent the regions with weak wind damage reported or measured wind gusts over 20 m s^{-1} , and dark blue areas represent regions with F1+ damage reported or measured wind gusts over 25 m s^{-1} , which characterize the derecho. (c) The areas (provinces) where a severe thunderstorm warning was issued. (d) The zoomed section depicted by the red rectangle in (b), with the leading edge of the severe MCS shown in 10-min steps (in UTC). Blue areas represent significant downburst damage [(a) and (b)–(d) are adapted from Púčik et al. (2011, Figs. 11 and 12, respectively)].

a cold front, as in the 18 January 2007 and 1 March 2008 derechos (Fig. 12). Like the United States, most of Germany's derechos occur during the summer months. Unlike the United States though, winter derechos are a bit more common in Germany (Fig. 14d), and it is unclear if this is because winter serial derechos are simply more frequent in Germany, or because differences in derecho classification schemes allow for more wind swaths from low-topped squall lines on strong fronts to be called derechos. Winter DMCSs forced by cold fronts may explain why cool-season events tracked from northwest to southeast, as opposed to warm-season events, which tracked from southwest to northeast (Fig. 14e). As in Gatzen et al. (2020), warm-season DMCSs in Poland took a more southwest-to-northeast track while cool-season events tracked from northwest to southeast (Fig. 15a), in tandem with strong surface cold fronts (Surowiecki and Taszarek 2020).

Many other European countries are as prone to derechos as Germany or Poland, but robust climatological studies are lacking to prove this—perhaps because derechos have only recently begun to be documented outside of the United States. For example, the first officially documented derechos in Europe's history were the 5 July 2002 Finland derecho (which is also the farthest-north-in-latitude derecho known to date; Punkka et al. 2006) and the 10 July 2002 derecho in Germany (Gatzen 2004), meaning that European derecho history only spans the last 20 years. Given the increases in surface observations, radar/satellite technology, and overall knowledge and interest in derechos, it is possible that better documentation of future derechos will lead to a more robust derecho climatology for all of Europe.

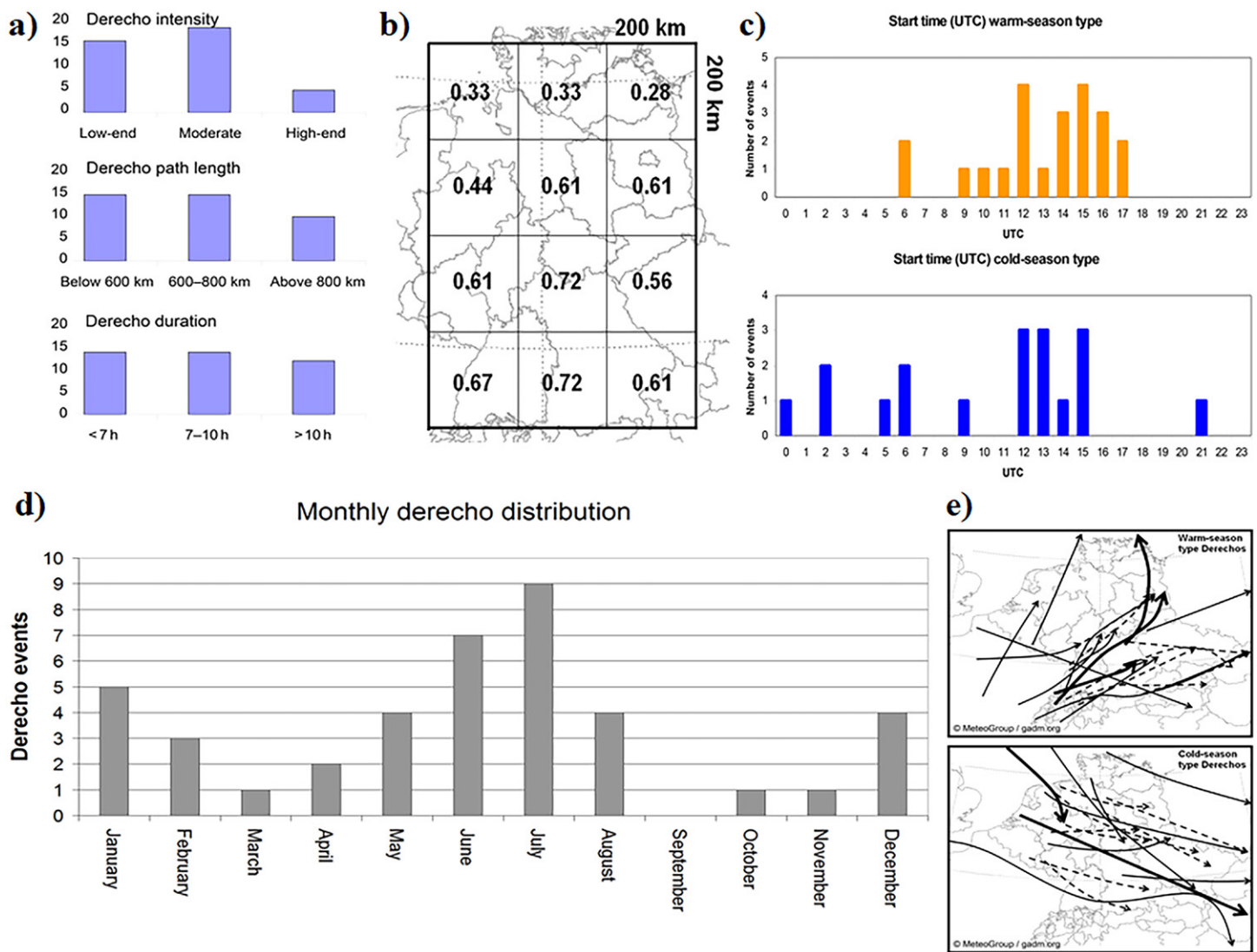


Fig. 14. (a) Characteristics of derechos over Germany by (top) intensity, (middle) pathlength, and (bottom) duration. (b) The annual number of moderate- and high-end-intensity derechos across Germany affecting grid boxes with 200 km side length. (c) Start time (UTC) of derechos for the warm and cool seasons. (d) Monthly distribution of derechos. (e) Tracks of warm- and cool-season derechos. Thick lines, thin lines, and broken lines relate to high-end-, moderate-, and low-end-intensity derechos, respectively. All derechos occurred from 1997 to 2014 [(a)–(e) are from Gatzen et al. (2020, Figs. 2, 1b, 5, 3, and 6, respectively)].

Societal impacts from derechos

Derecho impacts on ecosystems, property, and commerce. Over the last half-century, numerous memorable derechos have impacted the United States and abroad, with details of societal or meteorologically historical impacts for a subset of events cited in peer-reviewed journals (Table 2—U.S. events; Table 3—events outside the United States). In the worst-case scenarios, derechos can alter ecosystems and devastate local economies. As pointed out by AM05, derechos can cause forest blowdowns, as in the 4 July 1999 case along the Minnesota–Ontario border, which remains one of the more significant blowdowns known to date (Fig. 16). AM05 noted that blowdowns from derechos can have second-order impacts on ecosystems, such as an increased wildfire risk due to dead trees providing fuels for fire spread. AM05 also pointed out that intense political debates have occurred at state and federal levels when deliberating whether to salvage wood from fallen trees on preserves or leave them untouched. It was often decided to let dead trees remain as part of the ecosystem, as in the 15 July 1995 Adirondacks derecho blowdown. Derechos can also have serious secondary impacts on human life. An extreme example is the widespread power outages following the 29 June 2012 derecho across the Ohio Valley, which coincided with a record

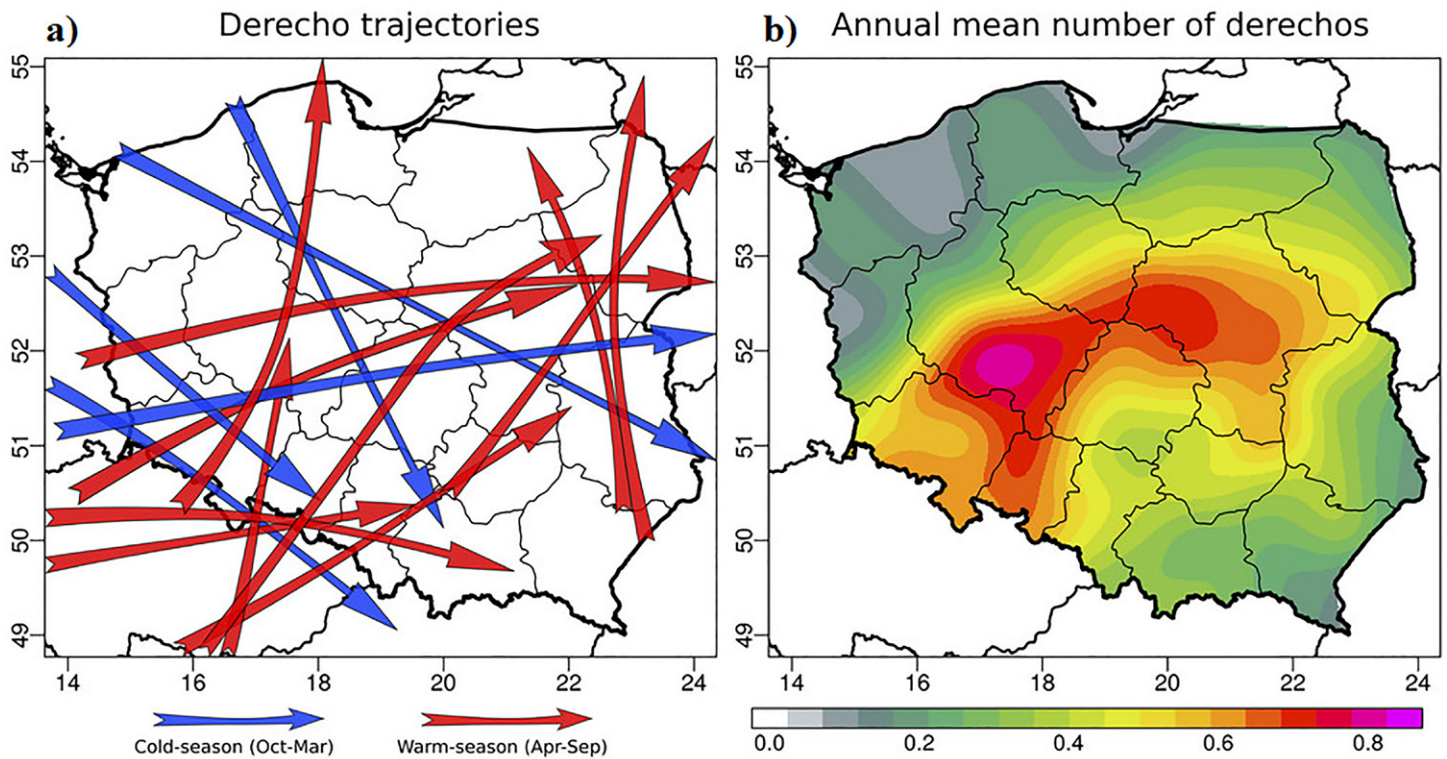


Fig. 15. (a) Derecho trajectories and (b) annual mean number of derechos across Poland. Derecho density was derived from the spatial extent of each case and by applying a 5 km × 5 km focal mean smoothing (from Surowiecki and Taszarek (2020, Fig. 11).

heatwave. While 22 fatalities occurred during the derecho, 34 people died afterward due to heat-related illnesses given the lack of power for air conditioning (Bentley and Logsdon 2016; Shourd and Kaplan 2021).

Devastated local economies often result from widespread crop loss, as was the case with the 10 August 2020 derecho across eastern Iowa into western Illinois (Fig. 17). At least 36 counties in Iowa had extensive crop damage, with millions of acres of corn/soybean lost, costing \$6.8–\$11 billion in agricultural losses, resulting in this derecho becoming the costliest thunderstorm event in U.S. history to date (Bell et al. 2022). Aside from the 10 August 2020 derecho, AM05 noted that the most impactful derechos (i.e., 16 July 1980) had (2003-inflation-adjusted) costs exceed \$1 billion in damage, outpacing not only some hurricanes in terms of final cost, but also the sum of expenses with all major tornadoes from 1890 to at least 16 July 1980. Separate from the most significant derechos, AM05 noted that many derechos from 1986 to 2003 still caused \$10+ million (2003-inflation-adjusted) in damage (see AM05, Table 5).

Derecho casualty statistics across the United States. Derechos pose a considerable threat to life as well as property. AM05 noted that nearly 40% of all thunderstorm wind-related fatalities and injuries occurred with derechos from 1993 to 2003. AM05 also found that (from 1986 to 2003) derechos were deadlier than F0–F1 tornadoes for most years, but were not deadlier than tornadoes when F2 events were included, or hurricanes, except for quiet seasons (see AM05, Table 3). While derecho fatalities were most prominent east of the Mississippi River, the relatively greatest density of derecho fatalities (entailing over one-third of all derecho fatalities) encompasses eastern Michigan and Ohio into upstate New York in AM05’s study (Fig. 18a), which is east of the yearly and warm-season derecho climatological maximum (Figs. 11a,c). Subsequently, Schoen and Ashley (2011) found that 21% of all thunderstorm wind fatalities occurred within this same corridor, with half of these

Table 2. Selected derechos of historical significance across the United States mentioned in peer-reviewed literature. Unverifiable deaths, injuries, or costs are labeled as “N/A.” Only direct fatalities from derecho winds are counted. AM05 cautions against using *Storm Data* to estimate derecho impacts, so *Storm Data* estimates, as well as states impacted, deaths, injuries, or costs were substituted (italicized) only when these statistics were not cited in the literature, which were retrieved from the Storm Prediction Center’s National Severe Weather Database Browser (Online SeverePlot 3.0).

Start date	States impacted	Historical significance	Injuries	Deaths	Cost (U.S. dollars)	References
4 Jul 1977	MN, WI, MI	This MCS led to Dr. Fujita introducing the term “bow echo” to meteorological nomenclature.	37	1	<i>\$30 million</i>	Fujita (1978)
16 Jul 1980	SD, MN, WI, IL, MI	Detailed survey by Dr. Fujita uncovered how derechos are produced by families of downbursts. Most intense “burst swaths” produced up to 55 m s ⁻¹ gusts. 2003-inflation-adjusted costs approach \$1.3 billion.	N/A	N/A	\$650 million	Fujita and Wakimoto (1981)
19 Jul 1983	MN, WI, IL, MI, IN	Rolled trailers and also caused numerous falling trees, with hundreds of thousands of residents losing power, resulting in the most extensive power failure in history for the Northern States Power Company (MN) and the Power and Light Company (WI). Prompted the pioneering research of JH87.	34	N/A	Several millions (estimated)	Johns and Hirt (1985)
8 Jul 1993	KS, NE, IA	Costliest single storm in Nebraska history up to the time of the derecho. Maximum gusts up to 40 m s ⁻¹ were observed.	38	0	\$100 million	Bentley and Cooper (1997)
15 Jul 1995	NY, VT, NH, MA, CT	Adirondack National Forest heavily impacted. Nearly 1 million acres of forest damaged or destroyed. Wind gusts up to 45 m s ⁻¹ occurred.	19	5	<i>\$443 million</i>	Bentley (1997)
26 Feb 1998	LA, MS, AL	Produced 45 m s ⁻¹ gusts near Natchez, MS. A classic case showing that some serial derechos are as impactful as progressive events.	24	0	\$35 million	Bentley and Mote (2000b)
30 May 1998	MN, IA, WI, MI,	One of the most impactful derechos of 1998 (a record year for derechos). Near 50 m s ⁻¹ winds produced damaged that was described as a “warzone” across parts of the Midwest. The derecho sank a tugboat while crossing Lake Michigan, with storm surge topping the channel walls in Muskegon County, Michigan. 1,600 km pathlength.	211	5	\$280 million	Bentley et al. (2000)
4 Jul 1999	MN, ME	Nearly 665,000 acres of forest leveled along the international border. Started in MN and crossed Ontario and Quebec before entering Maine 14 h later. One of the longest-lived/tracked derechos in history, traveling over 2,000 km for at least 21 h. Produced over 60 lightning flashes per minute at times, with a peak positive flash rate of 97%, an anomalous rate in lightning statistics.	70	2	<i>\$100+ million</i>	Price and Murphy (2002)
8 May 2009	KS, MO, IL, KY	Nicknamed the “super derecho.” This DMCS developed an intense warm-core mesovortex while also producing widespread hurricane-force wind gusts and several tornadoes. The unique storm structure and forecast problems this DMCS posed was the topic of numerous peer-reviewed publications.	4	1	\$115 million	Evans et al. (2014)
29 Jun 2012	IA, IL, IN, OH, KY, WV, VA, MD, DE, NJ, NC	This was the most impactful and costliest U.S. derecho up to the 10 Aug 2020 event. It was the third-costliest natural disaster in Ohio in 38 years. Over 5 million power outages also occurred along the derecho path.	9	22	\$3 billion	Fierro et al. (2014) Bentley and Logsdon (2016)
10 Aug 2020	IA, IL, WI, IN, MI	The costliest thunderstorm event in U.S. history. Nearly one-fourth of Iowa forests wiped out. Highest gusts up to 63 m s ⁻¹ occurred. Up to 1.9 million customers lost power.	113	4	\$11 billion	Bell et al. (2022)

Table 3. As in Table 2, but for derechos outside of the United States, with impacted countries abbreviated in the second column. Financial costs are in the units as reported in the peer-reviewed literature.

Date	Countries impacted	Historical significance	Injuries	Deaths	Cost	References
13 Mar 1993	CU, US (FL)	This serial derecho developed from the most widespread severe squall-line event in Cuba's history (at least up to 1993). Damage surveys suggest that gusts up to 60 m s ⁻¹ occurred.	N/A	10	1 billion U.S. dollars	Alfonso and Naranjo (1996)
5 Jul 2002	FI	Farthest-north-latitude derecho in recorded history, which developed from the only documented DMCS with any westward component of forward motion during its life cycle. Over 400 wind damage reports were received, with 1 million m ³ of trees destroyed and several areas of damage from 33+ m s ⁻¹ winds noted.	N/A	N/A	N/A	Punkka et al. (2006)
10 Jul 2002	DE	First documented derecho in Germany. A maximum gust of 42 m s ⁻¹ was observed, with widespread tree and power line damage resulting in closures of highways, railroads, and the Berlin Tegel Airport. Tens of thousands of trees were lost in Berlin. This derecho prompted the German Weather Service to reconceptualize severe weather warnings and the initiation of the European Storm Forecast Experiment.	39	8	N/A	Gatzen (2004)
17 Aug 2003	ES, FR	This DMCS crossed the Iberian Peninsula/Catalonia area toward the southeast coast of France, producing numerous instances of 33+ m s ⁻¹ gusts, unroofing houses, bending electrical towers, and causing widespread tree damage. Trains were blocked and the Barcelona Airport closed. 200,000 subscribers lost electricity and 500 fire department calls were received in Catalonia. A peak gust of 52 m s ⁻¹ was observed.	N/A	N/A	N/A	López (2007)
10 Mar 2008	BE, NL, DE, PL, CZ, AT, SK	This cold-season, serial DMCS was driven southeast by a cold front across several countries in central/eastern Europe, producing widespread 33+ m s ⁻¹ wind gusts. The strongest downburst in Austria's history was discovered during a damage survey, with a peak gust of 70 m s ⁻¹ estimated.	N/A	N/A	N/A	Pistotnik et al. (2011) Celiński-Mysław and Matuszko (2014)
14 Jul 2010	FR, BE, DE, NL	This derecho caused widespread significant damage, particularly where mesovortices in the parent DMCS developed, resulting in 45,000 insurance claims in Belgium alone. Some of the worst damage was comparable to EF2 tornado damage, including countless trees destroyed, homes completely unroofed, high-voltage towers toppled, and campers blown into a lake, resulting in the two reported fatalities.	20+	2	133 million Euros	Hamid (2012)
9 Jun 2014	BE, DE	This derecho was dubbed the "Pentecost Storm" and considered a 50-yr event for Germany by the German Weather Service. Up to 40 m s ⁻¹ gusts were reported, with the Düsseldorf Airport in Germany temporarily closing and widespread tree damage disrupting railways/roadways.	50	6	650 million Euros	Mathias et al. (2017)
11 Aug 2017	CZ, PL	Considered to be one of the strongest and most impactful derechos in Poland's history. Up to 42 m s ⁻¹ gusts damaged or destroyed around 20 million (79,700 ha of) trees. Around 20,000 structures were damaged and 500,000 customers lost power.	58	6	N/A	Taszarek et al. (2019)
17 Sep 2017	BA, HR, RS, RO	This derecho knocked down 460,000 m ³ of trees, with commerce disrupted on 12 national roads and 42 railway sections. Two hundred and four residents needed to be rescued in damaged areas.	137	8	N/A	Sipos et al. (2021)

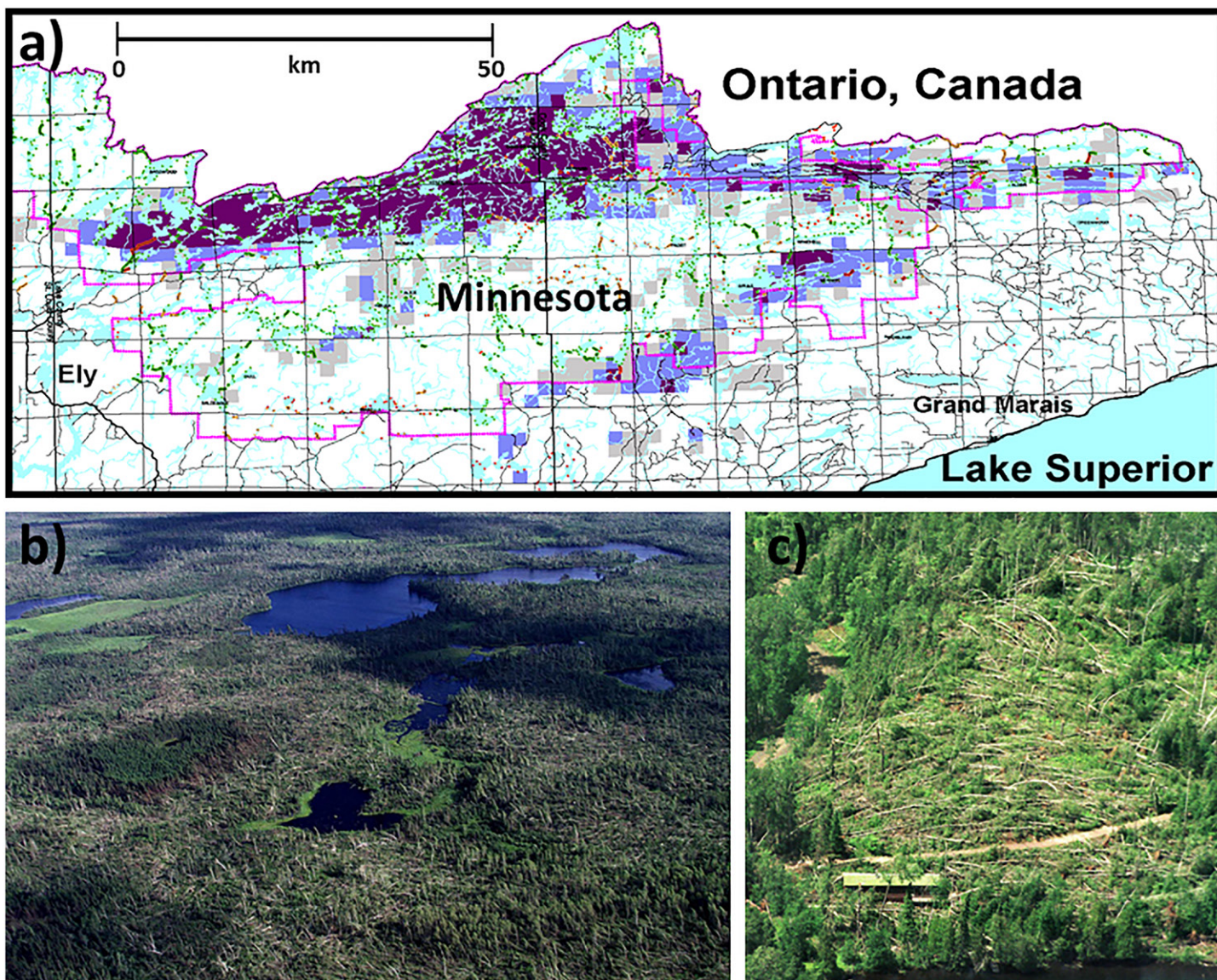


Fig. 16. (a) Amount of trees blown down per 1 mile in the Superior National Forest surveyed by a poststorm overflight. Legend: Gray = 0%–33%, light purple = 34%–66%, purple = 67%–100%. (b),(c) Areal survey photos of widespread tree damage (from the National Weather Service Duluth Weather Forecast Office).

fatalities associated with linear convection, suggesting that derechos may be the primary contributor to thunderstorm wind fatalities in this area. In addition to a higher population density across the eastern Great Lakes into the Northeast, AM05 mentioned that these fatality clusters may be related to many individuals being caught off guard while engaging in outdoor activities at parks or while boating. AM05 pointed out that nearly half of all derecho fatalities involved vehicles or boats [similar to Johns (1982) in northwest-flow severe wind events], with deaths associated with trees, camping, mobile homes, and permanent structures being secondary and near-evenly distributed (Fig. 18b).

Derecho injuries were roughly distributed in the same manner as fatalities in AM05 east of the Mississippi River (Fig. 18c). However, AM05 found locally higher maxima in injuries around Lake Michigan and across parts of the Southeast. While the Lake Michigan injury maximum roughly aligns with the peak frequency for warm-season derechos (Fig. 11a), the southeast injury frequency maxima are located east of the cool-season derecho frequency maxima (Fig. 11b). When investigating injury location of occurrence, AM05 found that nearly half of all injuries took place in vehicles or mobile homes

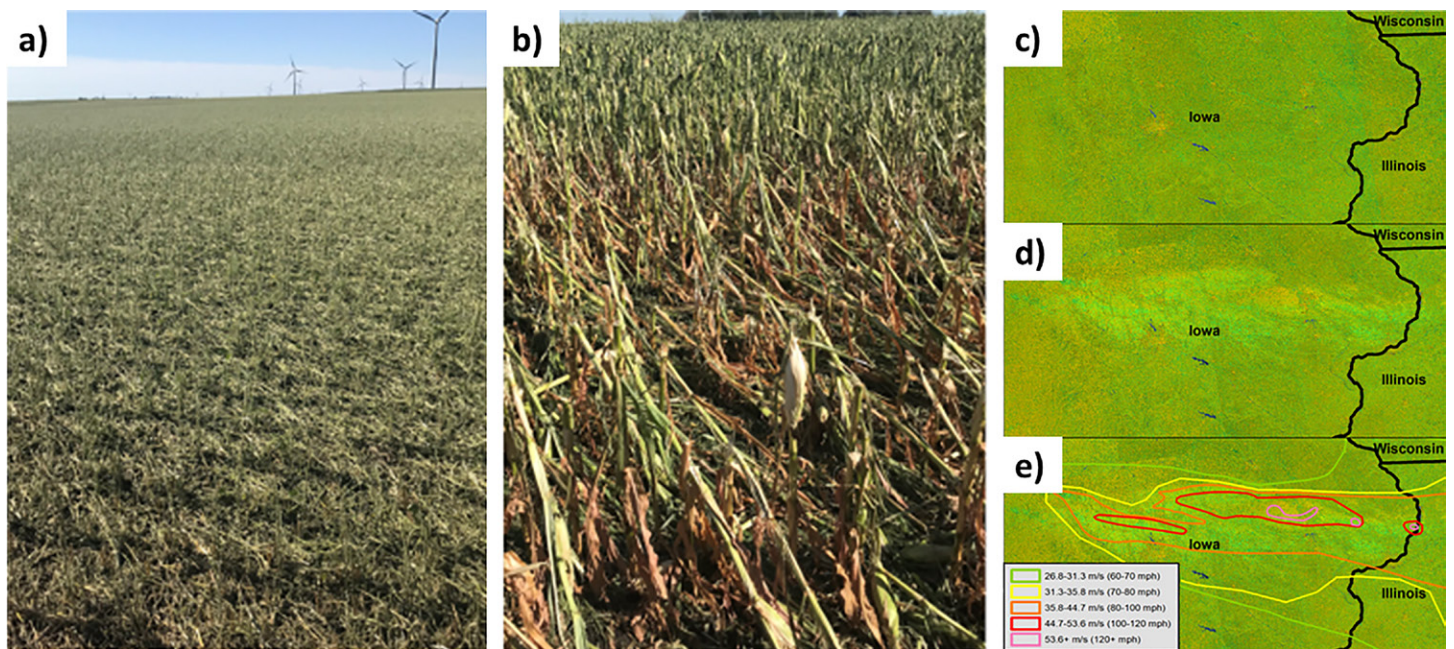


Fig. 17. (a) Soybean field damaged by wind-driven hail. (b) Corn field damaged by wind-driven hail. Photos in (a) and (b) were both taken on 11 Aug 2020, courtesy of Brett Greve, who provided the photos to the NOAA/National Weather Service Weather Forecast Office in Des Moines, Iowa (from Bell et al. 2022, Fig. 5). (c) Prederecho Sentinel-1 RGB satellite decomposition composite. (d) As in (c), but postderecho, depicting widespread crop loss in lighter shades of green. (e) As in (d), but with NWS peak wind gusts overlaid (from Bell et al. (2022, Fig. 10).

(roughly 20% each), with most of the rest of the injuries occurring with flying debris, or in permanent structures, outdoor recreational structures, or while camping (Fig. 18d). AM05 attributed the eastern displacement of injury and fatality maxima from derecho frequency maxima to social vulnerabilities.

Concluding remarks

Derechos result in widespread, significant damage, and therefore pose a serious threat to society. As such, a better understanding of derechos and their impacts should be a priority. Many knowledge gaps remain within the subtopic of derechos that need to be filled in order to increase society's resilience to their impacts. One of the biggest questions is "Which events constitute a derecho?" Quantitative criteria classifying derecho events vary in the peer-reviewed literature, so specific end goals to understanding basic concepts about derechos (like climatology) become a moving target. As such, a need exists for an affirmed set of criteria that characterizes a derecho that is consistently applied among stakeholders (i.e., forecasters, researchers, policy makers, emergency managers, the media, etc.) to better communicate exactly which thunderstorm wind events produce derechos, how they evolve, and what specific impacts society should expect.

As in many of the previous studies, multiple factors should be considered when formulating a derecho definition or quantitative criterion. Beyond wind-swath length, which has been discussed repeatedly in the literature, details of the expanse of a derecho wind swath, or a derecho's "footprint," has remained an elusive subject in the derecho literature, and when taken into account, could result in a better formulation of derecho criterion or even an improved definition. While derechos are understood to be associated with extratropical MCSs, more precise criteria defining the beginning and end of an MCS-derecho wind swath based on achieved MCS structure should be employed so that a better understanding of a derecho's association with MCSs/squall lines by all audiences is achieved. Since many MCSs develop from upscale-growing supercells (or contain embedded supercells), the employment

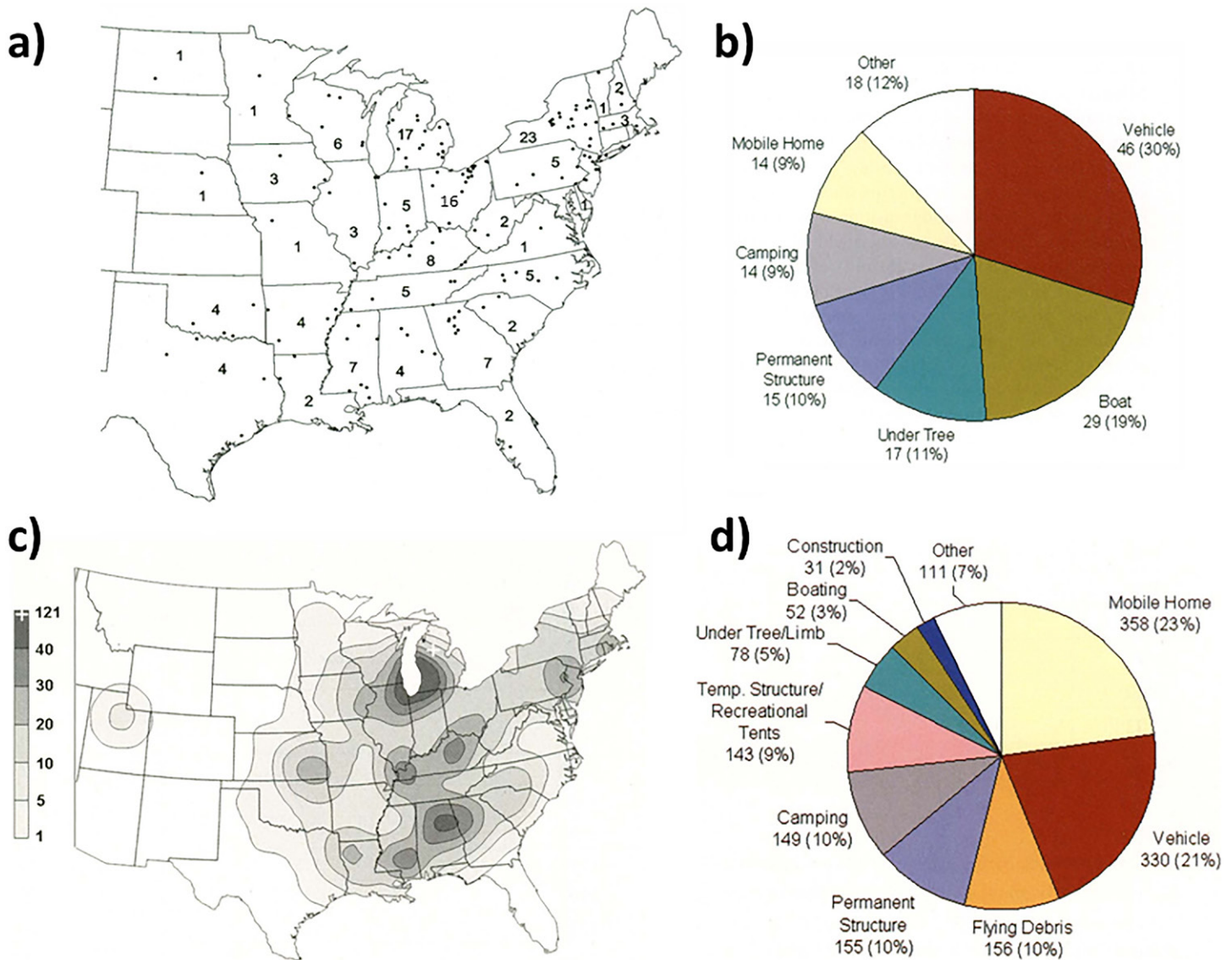


Fig. 18. (a) U.S. derecho fatalities by state. Circles indicate fatality locations. (b) Derecho fatalities by location of occurrence. (c) The distribution of U.S. derecho injuries. (d) Derecho injuries classified by location of occurrence. Only those injuries that were classified based on *Storm Data* descriptions were provided. All statistics were aggregated for the 1986–2003 period [(a)–(d) are from AM05 (Figs. 4–7)].

of objective criteria identifying the start of a derecho based on achieved MCS structure would allow for a more specific identification of derechos, which can be performed with greater consistency. This is possible today in the United States for most areas east of the Rocky Mountains given the availability of radar mosaics. Such a procedure may also be possible in other parts of the world where radar data are abundant enough to derive radar mosaics. Nonetheless, categorizing a wind event as a derecho purely objectively will still remain a challenge given geopolitical or geographical constraints, such as derechos crossing the U.S.–Canada border (i.e., 4 July 1999; Price and Murphy 2002), traversing narrow landmasses like the Florida Peninsula (13 March 1993; Alfonso and Naranjo 1996), or overspreading complex terrain, such as areas west of the Rocky Mountains (Corfidi et al. 2016b). As such, subjective decision making by subject matter experts may be made in derecho classification once all other objective measures have been exhausted.

Details in derecho climatology likely differed among core U.S. climatology studies due to the combination of short sampling periods, variances in the years studied, and changes in the quantitative criteria used to classify derechos. Studies employed differing quantitative

criteria because they were conducted over a period of several decades, in tandem with the evolution of technology and increased availability of observations. As such, many derecho identification and climatology studies derived quantitative criteria suitable for adequate sample sizes at the time of study, which should be considered when comparing derecho research efforts. Also, with the exception of Guastini and Bosart (2016), which mainly focused on warm-season derechos, no comprehensive derecho climatology studies have been done to cover the 2001–22 period. While it is generally understood that most derechos are warm-season progressive events across the Midwest and Southern Plains, with cool-season serial derecho events often occurring across the Lower Mississippi Valley, a need exists for a multidecadal derecho climatology that employs consistent, robust quantitative derecho criteria so that a more accurate derecho climatology can be derived for the United States. AM05 also pointed out that several factors contribute to inaccuracies in *Storm Data* regarding cost and casualty information. Some peer-reviewed literature retrieved their statistics from *Storm Data*, which may also update over time. AM05 also acknowledged that *Storm Data* is one of few comprehensive sources that compiles cost and casualty statistics for severe weather events, so few alternatives exist for weather researchers. As such, derecho casualty and cost information in Table 2 may vary among sources but should serve as a reasonable approximation for derecho impacts. Future work could include robust research to update derecho casualty and cost statistics in tandem with climatology research for the more recent events.

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Data availability statement. No datasets were generated with the current study. The only original figure was Fig. 6. Wind reports provided in Fig. 6 were retrieved from *Storm Data*, generated by the National Climatic Data Center, and are available for viewing via the Storm Prediction Center's Online Severe Plot (version 3.0) at www.spc.noaa.gov/climo/online/sp3/plot.php. Radar mosaics were retrieved from the Iowa Environmental Mesonet and are available at https://mesonet.agron.iastate.edu/docs/nexrad_mosaic/.

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