DERECHO HAZARDS IN THE UNITED STATES

BY WALKER S. ASHLEY AND THOMAS L. MOTE

Derechos are shown to be as hazardous as many tornadoes and hurricanes that affect the United States.

During the summer, hikers and canoeists often flock to Minnesota's Boundary Waters Canoe Area Wilderness (BWCAW) to observe the beauty and tranquility of this remote land that is filled with picturesque lakes and forests. However, on the July 4th weekend in 1999, the serenity so often identified with the region briefly gave way to a terrifying display of one of nature's most violent storms—a derecho.

On this holiday weekend, camp counselors Emily Boyd and Maddy Bennett were guiding a group of six teenage girls on a weeklong canoe exploration out of Moose Lake near Ely, Minnesota. Unknown to the group, a large windstorm producing gusts in excess of 40 m s^{-1} had already cut a swath of damage across northern Minnesota and was heading straight for them. The group was canoeing on Knife Lake in the BWCAW around noon when threatening skies brought the group to shore. The group quickly beached their canoes and took cover.

As the storm hit, Emily and Maddy quickly pulled the girls together and huddled over them. Watching trees crash around them, the two leaders hurried the group to an area that appeared safer near the water's edge. Although the storm seemed to last an eternity, blue sky appeared on the western horizon a mere 30 min later.

After the storm, the group returned back to the location where they had huddled to gather their life vests. To their shock, felled trees had crushed the vests. One can only imagine in horror what would have happened to the girls if Emily and Maddy had not moved them to the safer location. Emily later recalled that it was a "true miracle that no one [from their group] died in the storm that day." Shocked, yet uninjured, the group spent the next two days paddling over 20 miles and making six portages for home. Regrettably, 25 other hikers and canoeists in the area were not as lucky and suffered injuries, including broken backs and necks. During the next several days, rescue crews searched 2,200 campsites in the BWCAW and Superior National Forest, evacuating about 20 campers by air (Breining 2000). Unfortunately, the storm killed two campers farther downstream—one in Quebec, Canada (Mainville

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DOI:10.1175/BAMS-86-11-1577

In final form 20 July 2005

1999), and another in Vermont (NCDC 1999). The Vermont death occurred as a person camping in a tent on a raft was blown into the water, became entangled in the tent, and subsequently drowned.

Convectively generated windstorms occur over a wide array of temporal and spatial scales (Fujita 1978; Fujita and Wakimoto 1981; Golden and Snow 1999); however, the more widespread and longer lived of these windstorms are termed "derechos" (Hinrichs 1888; Johns and Hirt 1987). Though an extreme derecho case, the 4 July 1999 windstorm that swept through the BWCAW is an unforgettable example of the ferocity that can be associated with derechos.

Although, Johns and Hirt (1987), Johns (1993), and Wakimoto (2001) have claimed that derechos account for much of the structural damage and casualties resulting from convectively induced nontornadic winds, no study has examined the damage and casualty statistics from derechos. Changnon et al. (2001) suggest the threat from weather disasters is likely to grow because of a number of societal factors, including rapid population growth and expansion, together with increases in wealth, development, and urbanization. In order to illustrate the future risk and potential vulnerability of the U.S. population to these extreme windstorms, the following study reveals the hazards[1] associated with derechos by examining the climatology, casualty statistics, and damage estimates of events that occurred during the 18-yr period 1986–2003. It is initially hypothesized that derechos can be as hazardous, due to relatively high frequencies and large spatial extents, as some hurricanes and tornadoes.

BACKGROUND. In 1888, Iowa physical scientist Gustavus Hinrichs termed any convectively induced straight-line windstorm, or "straight blow of the prairie," a derecho (a Spanish derivative meaning "straight-ahead" or "direct") in correspondence with the Spanish derivative tornado (based on the Spanish word *tornar*—meaning to "to turn"). Fujita and Wakimoto (1981) illustrated many of the same characteristics of Hinrichs' definition, labeling these events as either a downburst cluster (major damage axis between 40 and 400 km) or for larger events, a family of downburst clusters (major damage axis of 400 km or more). Broadly, Johns and Hirt (1987) defined the derecho to include any family of downburst clusters (Fujita and Wakimoto 1981) produced by an extratropical convective system, but also developed specific criteria to define derechos utilizing contemporary terms and datasets (cf. their section 2). Later studies by Bentley and Mote (1998), Evans and Doswell (2001), Bentley and Sparks (2003), and Coniglio and Stensrud (2004) have utilized differing criteria to define derechos.

United States derechos have been documented in the literature since the early 1980s (e.g., Johns and Hirt 1983); only recently have enough events been documented over a sufficient period to begin to analyze the climatology of these windstorms. Johns and Hirt (1987) were the first to present a climatology of these events for the warm seasons from 1980 to 1983. Bentley and Mote (1998) and Bentley and Sparks (2003) recently analyzed the years 1986–2000, providing the basis for a 15-yr derecho climatology, including both cool- and warm-season events. These studies identified the tendency for derechos to occur in specific seasonal corridors in the eastern two-thirds of the United States. A separate study by Coniglio and Stensrud (2004) attempted to further interpret the climatology of derechos by classifying systematically, based on specific intensity classifications, 244 derechos from 1986 to 2001 (cf. their Table 1). These climatologies do contain minor differences but, in general, substantiate each other in regard to the relative spatial and temporal distributions. Nevertheless, none of the studies could be considered a definitive climatology because of issues regarding the severe storm wind-event database (e.g., Doswell and Burgess 1988; Weiss et al. 2002; and Schaefer et al. 2003), the varying criteria utilized (Coniglio and Stensrud 2004), and the relatively short time period examined (Bentley and Sparks 2003). Furthermore, no study has examined thoroughly the hazards associated with derechos. Therefore, this investigation examines the casualties and damage produced by these events in order to provide researchers, policy makers, and emergency managers with valuable information regarding the often-overlooked extreme straight-line windstorms known as derechos.

RESEARCH METHODOLOGY. *Derecho dataset.* The contiguous U.S. derecho dataset utilized in this study was compiled through several sources including two long-term climatological studies—Bentley and Sparks (2003) and Coniglio and Stensrud (2004). First,

[1] Derecho hazard encompasses some aspect of derecho climatology, but also includes the effect these storms have on people and the built environment. In terms of this study, a derecho hazard is defined as any derecho that results in a human casualty or any amount of reported economic damage. This is analogous to the "tornado hazard" description provided by Boruff et al. (2003).

a dataset containing 230 derechos identified by Bentley and Mote (1998) and Bentley and Sparks (2003) for the period 1986–2000 was obtained (M. L. Bentley 2003, personal communication). Data utilized in the Bentley and Mote (1998) and Bentley and Sparks (2003) studies were derived from the Storm Prediction Center's (SPC's) online database of several convective wind gusts and the SPC's *SeverePlot* software (Hart 1993). Bentley and Mote and Bentley and Sparks (2003) modified existing derecho identification methods proposed by Johns and Hirt (1987) in order to facilitate analysis of the large dataset (cf. their Table 1 or Coniglio and Stensrud 2004, their Table 1).

Second, the derecho database employed in studies by Coniglio and Stensrud (2004) and Coniglio et al. (2004), consisting of 244 events from 1986 to 2001, was acquired (available online at www.nssl.noaa.gov/users/mcon/public_html/derlist.htm). Coniglio compiled the database (hereafter Coniglio and Stensrud 2004 dataset) utilizing the SPC's severe convective wind database, *SeverePlot* software, and available radar data.

In addition to the Bentley and Sparks (2003) and Coniglio and Stensrud (2004) derecho datasets, the authors examined all derecho literature and documented any missing derechos not revealed by the aforementioned climatological studies. Finally, several additional events (e.g., 13 March 1993) were added where the Johns and Hirt (1987) length criteria were not met (e.g., squall line crossing the relatively narrow Florida peninsula), but were indeed derechos. Finally, the authors documented derechos from 2002 and 2003 by examining the SPC's daily online severe storm reports, SPC's severe thunderstorm event database, *Storm Data*, and *SeverePlot*.

In order to be consistent with the derecho identification methodology outlined by Coniglio and Stensrud (2004), all derechos that were previously not identified utilizing radar data [namely, those events identified by Bentley and Mote (1998) and Bentley and Sparks (2003)] were verified using available radar resources from the National Climatic Data Center (NCDC; DIFAX radar summaries, 1986–95), SPC (2-km regional composites, 2000–03), and the National Aeronautics and Space Administration's (NASA's) Global Hydrology Resource Center (8-km national composites, 1995–2003). All events in the database were scrutinized in order to make sure that multiple swaths of damage were a part of the same MCS as indicated by the radar data. Nine events from the Bentley and Mote (1998) and Bentley and Sparks (2003) dataset did not verify using this radar criterion and were removed from our dataset.

Every effort was made to remove from the dataset cases in which swaths of damage were caused solely by supercells rather than quasi-linear convective systems. However, the limitations of the composite radar data made it difficult in some cases to distinguish storm types, especially prior to 1995. Therefore, it is possible that some supercell, particularly high-precipitation supercell, cases remain in the dataset prior to 1995.

Additionally, no attempt was made to include the requirement of a minimum of three 33 m s^{-1} wind gust reports as originally suggested by Johns and Hirt (1987). There appear to be a number of unresolved issues that suggest that the inclusion of the 33 m s^{-1} wind gust criteria may promote irregularities and biases in the dataset. These unresolved issues include population biases (Johns and Evans 2000), changes in the verification practices (Schaefer et al. 2003), significant irregularities in extreme wind gust data when examined by National Weather Service (NWS) county warning areas of responsibility (Weiss et al. 2002), and the fact that Hinrichs (1888) and Fujita and Wakimoto (1981) made no reference to wind gust magnitudes in defining a derecho or a series of downburst clusters (Bentley and Mote 2000). Consequently, a set of consistent criteria (Table 1) without this secondary wind requirement was employed to construct the derecho dataset. This set of criteria is similar to that proposed and utilized by Bentley and Mote (1998), Bentley and Sparks (2003), Evans and Doswell (2001), Coniglio and Stensrud (2004, their "low end" criteria), and Coniglio et al. (2004).

After all events were compiled, the datasets cross-checked to form a unified dataset. The derecho tracks were used to extract individual severe wind reports from *SeverePlot* and *Storm Data*. In the case of differing start (end) times obtained from coinciding Bentley and Sparks (2003) and Coniglio and Stensrud (2004) events, the earliest (latest) wind report obtained was used to identify the derecho start (end) time and location. The wind reports were examined to ensure that each event had spatial and temporal continuity. Through the procedures above, a derecho dataset has been derived for the United States utilizing consistent criteria (Table 1). In all, 377 events were identified for the 18-yr period 1986–2003, an average of nearly 21 events per year (Table 2).

Wind damage and gust reports from each derecho were mapped onto a 1° latitude × 1° longitude grid to examine the spatial distribution of derechos. The distributions were determined by identifying grid cells with at least one wind report for a given event and then summing the number of events affecting

Table 1. Criteria used to identify derechos for this study.	
Minimum length	There must be a concentrated area of convectively induced wind gusts greater than 26 m s^{-1} that has a major axis length of 400 km or more (unless a land constraint necessitates using a shorter distance).
Chronological progression	The wind reports must have chronological progression, either as a singular swath (progressive) or a series of swaths (serial), and nonrandom pattern of occurrence by temporally mapping the wind reports of each event.
Temporal and spatial restriction	No more than 2.5 h can elapse between successive wind reports with no more than 2° of latitude and longitude separating successive wind reports.
Origin of wind swath	Multiple swaths of damage must be part of the same MCS as indicated by examining available radar data.
MCS continuity	The associated MCS, as indicated by available surface pressure and wind fields and/or radar data, must have temporal and spatial continuity.

each grid cell. Contour maps were created using inverse-distance interpolation (Davis 1986). This technique smoothes maximum values and therefore may underestimate extreme values in the plots. Thus, actual maximum values of derecho frequency are indicated on maps.

Casualty data. Since 1959, *Storm Data* has been the primary source of severe event data utilized by meteorologists and climatologists for locating areas of storm damage and determining the number of casualties produced by significant weather events. The process by which these data are gathered has been reviewed by Curran et al. (2000, their section 2) and Bentley et al. (2002).

Although Storm Data contains the best information on storms affecting the United States, it is not all-inclusive owing to the difficulties inherent in the collection of these types of data. Several studies have illustrated the problems associated with *Storm Data,* although most have focused on the underreporting of casualties or damage produced by lightning (Curran et al. 2000) or hail (Changnon 1999). As with hail and lightning casualty tallies and damage estimates, derecho-related casualties and damage likely receive less attention than "large-impact" events such as floods, hurricanes, and tornadoes. Thus, absolute values obtained from *Storm Data* should be considered with caution (Curran et al. 2000). As with any significant weather event, deaths and injuries are more likely to be accurately reported than damage, which can involve intricate estimating procedures (Changnon 2003). Therefore, there is more confidence in the casualty data than the damage estimate data. Finally, there are a number of casualties that are indirectly related to the storm (e.g., casualties due to "clean-up" operations). These fatalities and injuries are not included in storm causality tallies.

Despite these inherent problems with *Storm Data,* it is the only consistent data source for storm-induced casualties for the period of record. In this study, the casualty information from *Storm Data* was utilized without alteration.

For a particular derecho event, *Storm Data* casualty statistics were coordinated with the derecho wind report data in a geographic information system (GIS) to ensure that all casualties were a consequence of the *straight-line winds* from a corresponding derecho. No casualties due to tornadic winds within derecho-producing convective systems were included in the derecho-induced, straight-line wind casualty analysis. Finally, fatality data were obtained and tabulated for both hurricanes (Tropical Prediction Center 2004) and tornadoes (*SeverePlot* and *Storm Data*) in an attempt to compare contiguous U.S. derecho fatalities with those attributable to hurricanes and tornadoes. Only hurricane fatalities produced by a landfalling or "near miss" hurricane (i.e., in which the outer bands of the hurricane made it onto the contiguous U.S. shoreline) were included in the U.S. hurricane fatality statistics.

Finally, a similar interpolation procedure was utilized to reveal the spatial distribution of derecho casualties. In this case, the sum of all injuries on a 1°×1° grid was interpolated to illustrate the geographic patterns associated with derecho injuries.

Damage estimates. Storm Data is the primary U.S. government source of estimated storm-induced damage data available to researchers. Initially, *Storm Data* was utilized to estimate damage totals for derechos in this study. However, estimates extracted from *Storm Data* were promptly ruled inadequate by the authors because 1) damage estimates produced by NWS offices and compiled within the publication are arbitrary and subjective; 2) in few instances are

NWS offices provided with legitimate damage estimates from necessary parties, emergency managers, or insurance companies; 3) reporting inconsistencies and a difference in reporting policies between NWS offices (R. L. Beasley 2004, personal communication); and 4) lack of estimates for described damages. Therefore, a second, independent record of estimated losses to the insurance industry was employed to provide a potential assessment of the insured losses due to derechos and to illustrate further the major drawbacks when estimating damage totals using solely the resources of *Storm Data.* These data—the Property Claims Service's (PCS's) catastrophe database—were obtained from the Insurance Services Office, Inc. (ISO; G. Kerney 2004, personal communication). The catastrophe database includes estimated industry-wide insurance payments for property lines of insurance covering fixed property, building contents, time-element losses, vehicles, and inland marine diverse goods and properties (ISO 2004). Crop losses due to perils are not included but insured farm buildings and equipment are included in the catastrophe estimates.

From 1986 to 1996, the PCS database identified an event (or series of related events) as a catastrophe if that storm episode caused over $5 million in total insured property losses. In 1997, a shift was made from $5 to $25 million in order to adjust for the effects of inflation on the selection of catastrophes (Changnon 2001; ISO 2004). These data have been utilized in the past to estimate property losses resulting from thunderstorm perils (Changnon 2001) and hurricanes (Tropical Prediction Center 2004). Furthermore, a recent evaluation of loss data from natural hazards identified these PCS data as the nation's best available data (National Research Council 1999; Changnon 2001).

For each qualifying thunderstorm-caused catastrophe, the PCS dataset included the event date(s), the conditions/perils causing the losses, and the amount of insured losses by state. Unfortunately, the insured losses are estimated for *all* storm perils, making it difficult to separate the cost of each peril (e.g., hail from wind). In effect, then, extracting only derecho wind damage loss from the PCS estimates was not possible except in a single case (20 November 1989) where the only peril associated with the catastrophe was wind. In all other cases, losses from flooding, hail, and/or tornadoes were included in the catastrophe database. In these situations, only insured damage from derechos that *lack* considerable tornado, hail, and flood

Table 2. The number of derechos, fatalities, and injuries for the 18-yr period of record. Included are deaths and injuries from thunderstorm winds during years in which tallies were available in *Storm Data.* Italicized statistics indicate that the summary figures provided are for an 11-yr period. Asterisk indicates preliminary data.

Year	Derechos			Thunderstorm winds	
	Events	Deaths	Injuries	Deaths	Injuries
1986	10	6	134	—	—
1987	14	8	113	—	—
1988	2	0	3	—	—
1989	15	13	126	—	—
1990	10	7	196	—	—
1991	11	6	157	—	—
1992	12	2	136	—	—
1993	13	2	154	25	461
1994	21	6	93	15	337
1995	31	18	212	38	473
1996	24	11	142	23	335
1997	25	13	72	37	425
1998	42	21	606	41	860
1999	32	14	146	29	325
2000	31	10	87	25	296
2001	26	9	123	17	341
2002	29	6	42	17	287
2003	29	1	63	19	226*
Sum	377	153	2605	*286*	*4366*
Mean	20.9	8.5	144.7	*26*	*396.9*
Max	42	21	606	*41*	*860*
Min	2	0	3	*15*	*226*

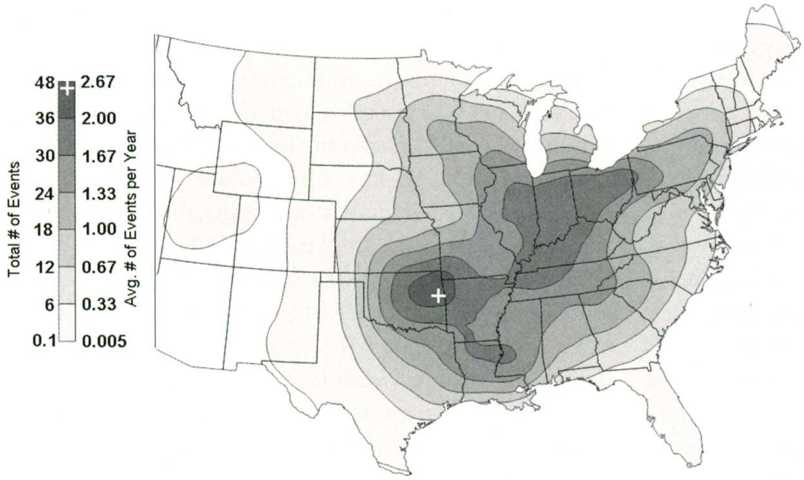

FIG. 1. The frequency of U.S. derechos, 1986–2003. Symbol indicates the location of maximum value before interpolation.

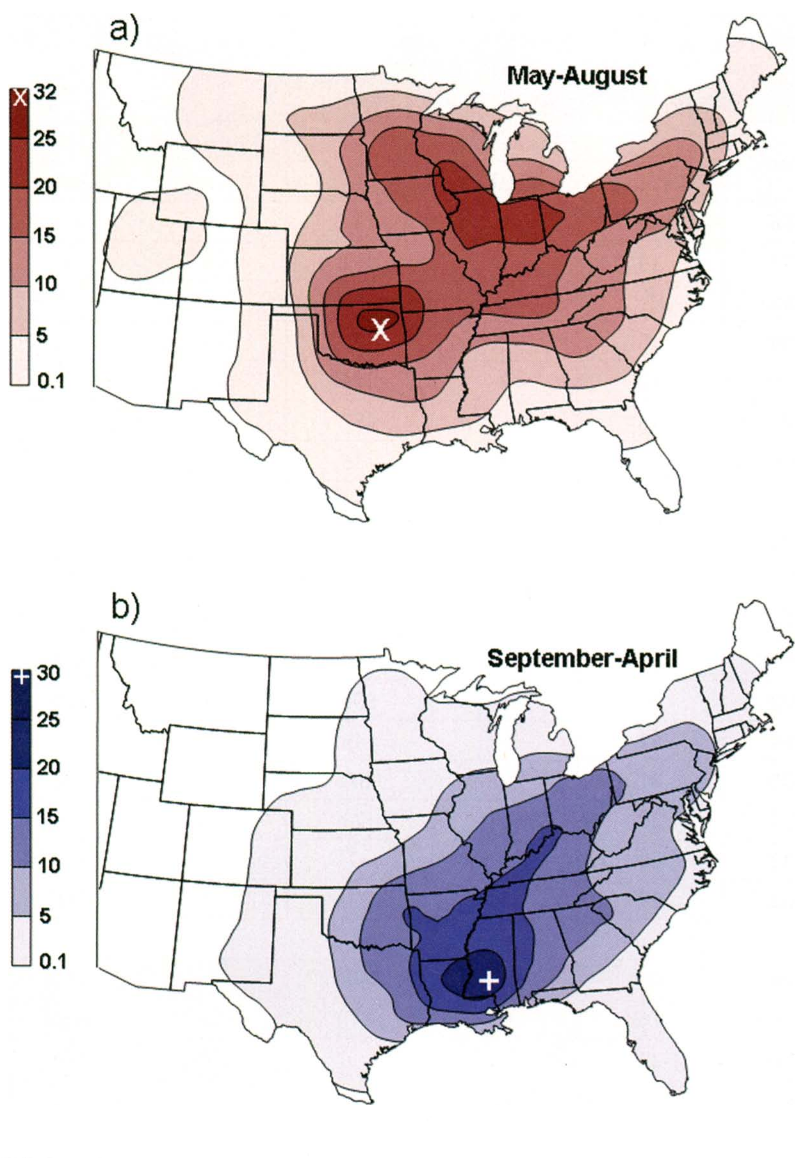

FIG. 2. The seasonal frequency of U.S. derechos, 1986–2003. Symbols indicate the locations of maximum values before interpolation.

events were tallied utilizing the PCS data. In making this subjective judgment, the use of detailed verbal descriptions of damage that often accompany the events in *Storm Data,* the analysis utilities of NCDC's Severe Storm Event database, and the mapping utilities of *SeverePlot* were employed to ensure that the damage losses were predominantly due to the straight-line winds associated with a derecho. Events that had substantial damage due to a tornado along the leading edge of a bow-echo-producing system were *not* excluded. Conversely, events that had any significant (F2 or greater) tornadoes that were separate from the derecho-producing MCS and produced considerable damage were removed from the estimating procedure. Only 42 derechos met these criteria and were included in derecho insured-loss analysis.

The aforementioned procedure indicates the difficulty in trying to estimate damage losses strictly from derechos. Estimating damage tallies from *any* storm peril is a subjective procedure (Changnon 2003). The estimates provided are utilized for comparative purposes and to obtain a sense of the damage potential from these extreme windstorms. The estimates are not intended to be accurate enough to provide precise, flawless derecho damage tallies.

For comparison purposes, the estimated loss data were adjusted for inflation (to 2003 dollars in this study), utilizing an implicit price deflator for gross national product, as reported in the Economic Report of the President (Office of the President 2004). Because this study does not examine trends in normalized damage tallies, it is not as important to control for wealth or population as was the case in previous research on hurricanes and tornadoes (Pielke and Landsea 1998; Brooks and Doswell 2001).

RESULTS. *Climatology.* Studies by Johns and Hirt (1987), Bentley and Mote (1998), Bentley and Sparks (2003), and Coniglio and Stensrud (2004) have revealed the major geographical distributions and high-frequency corridors of derechos. However, each of the climatologies presented in the past have employed differing datasets and mapping techniques to reveal the distribution of derechos in the United States. The jointly compiled dataset utilized in this study [i.e., including events from two recent long-term derecho climatologies—Bentley and Sparks (2003) and Coniglio and Stensrud (2004)] provides a unique opportunity to extend (i.e., with addition of 2002/03 derechos) and briefly reevaluate the preexisting climatology of derechos. This process highlights the threat of derechos to any one particular region of the United States and subsequently may be employed to develop a risk assessment of derechos.

When examining derechos for the entire year for the 18-yr period of record (Fig. 1), a similar derecho spatial pattern to that produced by Bentley and Sparks (2003, their Fig. 14) is evident. Prominent features in the derecho geographical distribution include 1) a Southern Great Plains maximum located over the northeast portion of Oklahoma, 2) an axis of higher derecho frequencies extending from the Oklahoma maximum southeastward toward the southern Mississippi Valley region, and 3) a high-frequency axis that corresponds with Johns' (1982, 1984) northwest-flow severe weather events extending from the upper Midwest into the Ohio Valley. The Southern Great Plains maximum likely occurs since this region is affected by *both* cool- and transition-season serial (Johns and Hirt 1987) events associated with traveling midlatitude cyclones (Fig. 2b) *and* warm-season, progressive (Johns and Hirt 1987) events (Fig. 2a) while more poleward locales are affected by primarily warm-season, progressive events. Similar to the results of Bentley and Mote (1998) and Coniglio and Stensrud (2004), cool-season derecho maxima are found along the southern Mississippi Valley, while warm-season event maxima are found in the south-central Great Plains and the Ohio Valley.

Temporally, derechos are primarily warm-season events, with 69% of the events in the compiled data-set occurring between May and August during the 18-yr period (Fig. 3). As established in Bentley and Sparks (2003), May has the highest derecho monthly frequency with, on average, nearly five events occurring annually during this month.

Casualties. Summary studies of thunderstorm-induced, straight-line wind casualties are limited. In fact, most investigations that examine annual summaries of weather-related fatalities or injuries typically focus on floods, lightning, hurricanes, and/or tornadoes (e.g., Riebsame et al. 1986; Curran et al. 2000). Therefore, it is important to illustrate the hazards associated with derechos by first examining the number of casualties these events have produced in the past and compare those statistics with those of other thunderstorm-related perils.

Fatalities and injuries were tallied for all 377 derechos in the study. There were 153 fatalities during the 18-yr period of record (8.5 yr^{-1}) attributable to damaging straight-line winds from derechos. The number of fatalities per year is highly variable—from 21 in 1998 to no fatalities in 1988. Examining the derecho fatalities spatially (Fig. 4) indicates an interesting distribution that does not necessarily correspond with derecho frequencies across the United States (Fig. 1). Three northern states—Michigan (17 fatalities), New York (23), and Ohio (16)—contain nearly 37% of all derecho fatalities. This is somewhat counterintuitive as one would expect the highest fatality rates in regions with the greatest likelihood of derecho occurrences (i.e., across the south-central

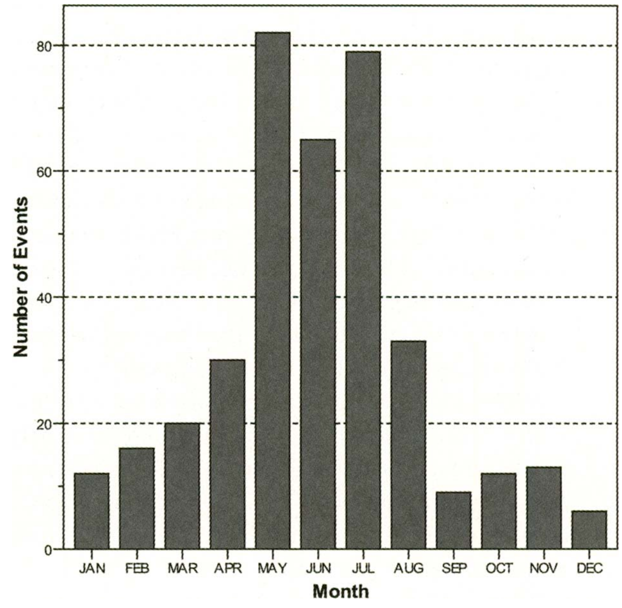

Fig. 3. Monthly U.S. derecho frequency, 1986–2003.

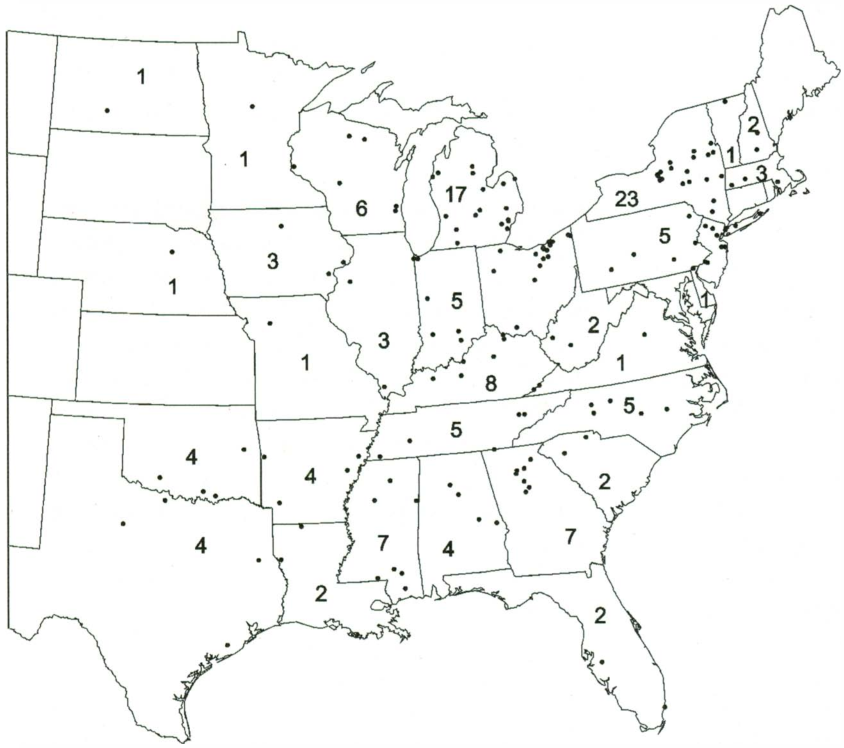

FIG. 4. U.S. derecho fatalities by state, 1986–2003. Circles indicate fatality locations.

Great Plains). Several possible explanations could account for this unusual distribution, including 1) the tendency for more outdoor-related activities (e.g., camping) in state parks and wilderness areas of Michigan and New York (increased vulnerability); 2) boating activities along the Great Lakes (increased vulnerability); 3) the increased likelihood of particularly intense, warm-season derechos across the northern tier of the United States (Coniglio and Stensrud 2004) (increased vulnerability); 4) a heightened awareness of severe storms by people in the Southern Great Plains states due to the high frequency of extreme thunderstorm-related perils in this region (reduced vulnerability); and 5) the existence of better warning systems in the Southern Great Plains (reduced vulnerability). Thus, it is possible that there is some underlying integration of both physical and social vulnerabilities attributable to the observed derecho fatality distribution (Riebsame et al. 1986).

When examining derecho fatalities by type, boating and vehicular deaths accounted for nearly 50% of all fatalities (Fig. 5). In the majority of cases, vehicular fatalities occurred in one of three ways: 1) overturned tractor semi-trailer, 2) felled tree landing on automobile, or 3) an automobile driven into a felled tree. Marine fatalities principally occurred as drownings when either sailing vessels or motorized boats were overturned due to high derecho winds.

The deadliest derechos on record include events occurring on 16 August 1997 (8 fatalities), 31 May 1998 (6), 15 July 1995 (6), 12 July 1995 (5), and 20 July 1987 (5). In terms of total injuries and fatalities, there are several derechos that have caused over 100 reported casualties, including 31 May 1998 (210), 9 April 1991 (135), 4 June 1993 (110), and 10 February 1990 (103).

On average, 145 injuries per year were attributable to derechos; however, annual values were highly variable with a maximum of 606 injuries occurring in 1998 and a minimum of 3 injuries occurring in 1988 (Table 1). In terms of spatial distribution (Fig. 6), derecho injuries were clustered around several specific regions including 1) Lake Michigan, 2) the Interstate-95 corridor in the Northwest, 3) the Ohio River Valley, 4) the interior of the Southeast, and 4) the south-central Great Plains. Like fatalities, the higher frequencies of injuries tend to occur outside of regions of the highest derecho frequency maxima. The states of Kentucky

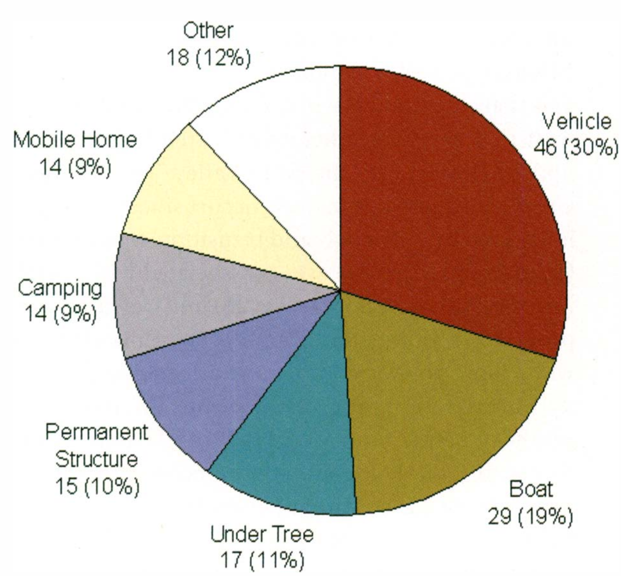

FIG. 5. 1986–2003 derecho fatalities as classified by location of occurrence.

(333 injuries), Michigan (200), and Illinois (187) are highest in terms of derecho injuries.

Unlike fatalities, a considerable number of the injuries reported in *Storm Data* are not accompanied by a description of how the injuries occurred other than that they were caused by thunderstorm-related winds. In fact, nearly 40% of all derecho injuries reported in *Storm Data* have no description of injury type. The remaining 60% of injuries were classified according to how or where the injury occurred, revealing a different distribution by type (Fig. 7) than derecho fatalities (Fig. 5). Injuries in mobile homes (23% of classifiable injuries) and vehicles (21% of classifiable injuries) lead all other injury types by a considerable margin. Other high-frequency injury types (accounting for nearly 10% of classifiable injuries each) include camping, flying debris, permanent structures/homes, and temporary structures (i.e., recreational or special-event tents).

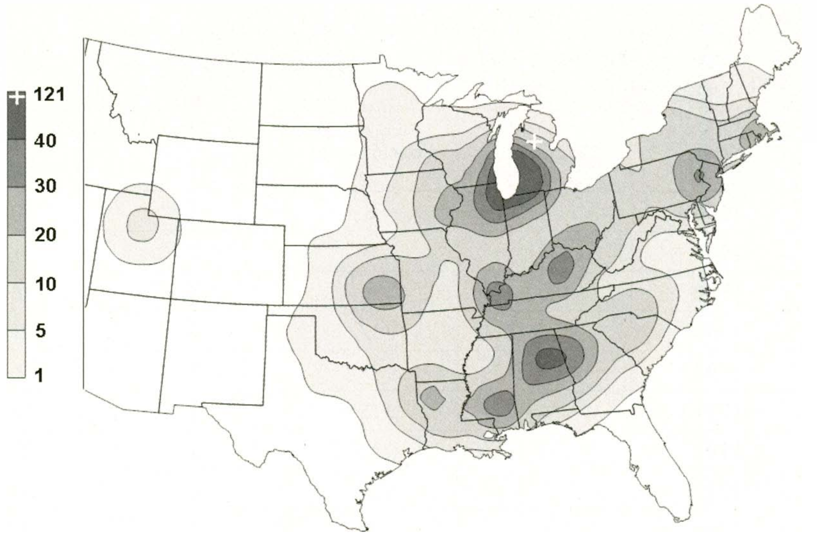

Fig. 6. The distribution of U.S. derecho injuries. Symbol indicates the gridded maximum value before interpolation.

Comparing derecho casualties to those produced by all thunderstorm winds for the period 1993–2003 indicates that derechos do not account for the majority of casualties due to nonhurricane and nontornadic winds. In terms of fatalities (injuries), derechos accounted for 38.8% (39.9%) of all fatalities (injuries) caused by thunderstorm winds during this 11-yr period.

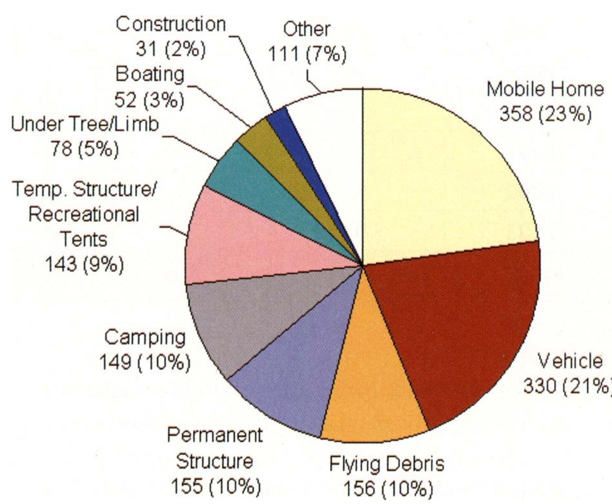

Fig. 7. 1986–2003 derecho injuries as classified by location of occurrence. Only those injuries that were classifiable based on *Storm Data* descriptions are provided.

Derecho, hurricane, and tornado casualty comparisons. In order to illustrate that derechos can be as hazardous as most hurricanes and tornadoes, a comparison between derecho-induced fatalities and those produced from contiguous U.S. hurricanes and tornadoes was constructed for the derecho dataset period of record (Table 3). Derecho fatalities exceed fatalities from F0 and F1 tornadoes by a wide margin, but account for fewer deaths than those produced by F0, F1, and F2 tornadoes combined. If one considers that F0 and F1 tornadoes account for nearly 88% of all U.S. tornadoes from 1986 to 2003, then derecho fatalities exceed the number of fatalities produced by most tornadoes. Notwithstanding, "significant" (F2 or greater) tornadoes contribute a disproportionate number of tornado deaths, with these "strong" to "violent" events accounting for 92.7% of all tornado fatalities occurring in the United States during the period of study.

Hurricane fatalities surpass those caused by derechos; however, if the anomalously high fatality rates from Floyd (56) and Fran (34) are removed, the fatality statistics are essentially comparable. It is important to consider that hurricane fatality statistics *include* deaths related to hurricane-spawned tornadoes, floods, and riptides. For this study, those deaths attributable to tornadoes embedded within or floods attributable to derecho-producing convective systems were not included. Hence, it is possible that fatalities from derechos exceed those fatalities induced solely by hurricane winds.

TABLE 3. The number of fatalities due to derechos, hurricanes, F0 and F1 tornadoes, and F0, F1, and F2 tornadoes for the 18-yr period utilized in this study.

Year	Derechos	Hurricanes	F0 and F1 tornadoes	F0, F1, and F2 tornadoes
1986	6	8	0	10
1987	8	0	2	11
1988	0	4	3	16
1989	13	37	9	21
1990	7	0	2	9
1991	6	15	8	12
1992	2	23	3	5
1993	2	3	6	19
1994	6	8	2	9
1995	18	23	3	12
1996	11	48	3	9
1997	13	2	7	14
1998	21	5	2	17
1999	14	60	6	14
2000	10	1	1	5
2001	9	0	5	19
2002	6	0	6	22
2003	1	17	3	5
Sum	153	254	71	229

Damage estimates. Straight-line winds associated with derechos have been officially measured at over 60 m s^{-1} (e.g., 64.4 m s^{-1} on 22 April 1997, 67.5 m s^{-1} on 16 July 1980), equivalent to the sustained winds of a category 4 hurricane. A number of damage surveys from *Storm Data* suggest higher wind gusts have occurred with some events. Although most wind speeds in derechos never approach these levels of severity, the straight-line winds meeting even minimal derecho criteria (26 m s^{-1}) can topple trees onto automobiles, overturn tractor semi-trailers, or damage mobile homes. Undoubtedly, derechos have the ability to produce substantial damage in regions impacted by these events.

Previous studies that have documented derechos have very limited descriptions regarding damage summaries or estimates. When estimates are presented for events, they are typically deduced from *Storm Data*. There is only one case in the literature that highlights, in detail, the damaging potential of a derecho. Fujita and Wakimoto (1981) provided extensive documentation of the 16 July 1980 derecho that produced widespread damage across large areas of Michigan, Illinois, Wisconsin, and Minnesota. They indicated that this storm produced approximately $650 million in damage as it traversed the four-state region. Accounting for inflation (to 2003 dollars), this storm produced an estimated $1.3 billion in damage from strictly straight-line winds. This estimate exceeds many damage tallies from U.S. hurricanes and is larger than the inflation-adjusted damage estimates from all major tornadoes that have affected the United States since 1890 (Brooks and Doswell 2001). This single event illustrates that derecho damage can exceed the damage from most hurricanes and tornado events affecting the contiguous United States.

Unfortunately, detailed damage summaries such as those provided by Fujita and Wakimoto (1981) are not available for other derechos. Therefore, the PCS catastrophe dataset was employed to estimate the impact derechos have had on the insured built environment. In total, 206 of the 377 derechos in the dataset (54.6%) were associated with 129 separate PCS catastrophe events. All thunderstorm perils (flooding, hail, tornadoes, and wind) associated with these 129 catastrophe events were responsible collectively for nearly $33 billion (2003 dollars) in insured losses. In some cases multiple derechos [i.e., derecho "families" (Bentley and Sparks 2003; Ashley et al. 2004)] were a part of the same PCS-defined catastrophe.

A detailed process was utilized to extract PCS damage estimates for derechos. Estimated insured losses due to derechos are provided to illustrate the devastating impact these events can have on the built environment and compare these statistics with analogous data from U.S. hurricanes. A number of extremely intense derechos or families (e.g., 8 July 1993, 15 May 1998 family, 4–7 July 2003 family) were excluded from this analysis because these events were accompanied by considerable damage produced by flooding, hail, or tornadoes and, therefore, could not be accurately assessed for damages solely due to derecho winds. Hence, the "high end" damage potential of the most intense derechos is likely not illustrated in this analysis.

In all, nine derechos and derecho families producing more than $100 million in insured losses were identified from the methods utilized in this study (Table 4). The costliest derecho identified was

TABLE 4. Estimated insured losses due to catastrophic derechos identified in this study. A derecho or series of derechos is indicated for each catastrophe. Asterisks indicate that two separate derechos occurred on the same day and are included in the same catastrophe damage estimate. Parenthetical state identifications designate states that were not included in the PCS or *Storm Data* estimates but were impacted by the derecho. Estimated (insured and uninsured) property damage totals from all perils for the corresponding PCS catastrophe data were constructed from *Storm Data* for 1996–2002 events. All estimates account for inflation and are adjusted to 2003 dollars.

Derecho event(s)	States affected	Damage estimate (millions of $)	
		PCS	*Storm Data*
6 Jul 1987	IL, IN, KY, MO	43	—
4 May 1989	OK, TX (LA)	180	—
22 May 1989	AR, KS, MO, OK	20	—
2 Jul 1989	LA, OK, TX (AR)	61	—
20 Nov 1989	CT, DE, MD, NJ, NY, PA	74	—
7 Jul 1991	IN, MI, OH, WI (IA, NY, PA)	77	—
2 Jul 1992	IL, IN (IA, MO)	37	—
1 May 1993	TX (NM)	48	—
4 Jun 1993	IL, IN, KY, MO, VA, WV (NC, TN)	78	—
10 Jul 1993	OH (WV, PA)	42	—
31 May 1994	UT (CO, WY)	42	—
1 Jul 1994	KS, NE (OK)	48	—
4 Apr 1995	CT, MA, NJ, NY	69	—
15 Jul 1995	MA, NY, PA	75	—
24 Jul 1995	OK (AR, KS)	63	—
21 May 1996	CT, MA, RI (NJ, NY)	39	5
6 Aug 1996	MN, WI (IA, MI, NE, SD)	23	3
29 Oct 1996	IL, IN, OH (IA, MI, WI)	68	7
19 May 1997	PA (OH, NY)	28	1
31 May 1998	MI, MN, WI (IA, NY)	432	455
4, 5, 6 Jun 1998	AL, AR, GA, MS, TN, TX	191	18
18, 20, 21 Jul 1998	IN, MI, OH, WI (MN, PA)	98	58
7 Sep 1998	CT, MD, MI, NH, NJ, NY, PA, VT, WV	252	203
10 Nov 1998*	IL, IN, MI, MO, OH (AR, MS, TN, TX, OK)	98	12
26 Apr 1999	AR, LA, OK, TX	162	2
23, 25 Jul 1999	MI, MN, WI (SD)	103	3
30 Jul 1999	MI, WI (MN)	92	4
9 May 2000*	IL, IN, MI, OH (MO)	106	19
18 May 2000	CT, NJ, NY, PA (MA)	79	3
16 Feb 2001	AL, GA, LA, MS	176	27
27 May 2001	KS, OK (TX)	98	28
9 Mar 2002*	IA, IL, KS, MO, NY, OH, PA, WV	137	24
7, 8 Apr 2002	LA, MS	20	1

the 31 May 1998 event that affected the Great Lakes region. This event was responsible for $432 million in insured property losses across the states of Minnesota, Wisconsin, and Michigan. Interestingly, this is the only event in which *Storm Data* property damage estimates exceeded values obtained from the insured losses estimated from PCS. In all other derecho cases from 1996 to 2002, PCS estimates exceed, in some instances, by an order of magnitude, the estimates provided by *Storm Data*. *Storm Data* accounts for only 39.6% of the PCS damage losses from the 27 events in which both *Storm Data* and PCS data were available. This is especially troubling since *Storm Data* estimates account for both insured and noninsured losses while PCS data report only insured losses. This suggests that estimated damage totals from derechos cannot be deduced from *Storm Data*.

The PCS catastrophe database includes insured losses from hurricanes and is the primary dataset employed by NOAA's Tropical Prediction Center to estimate damage from Hurricanes. [The Tropical Prediction Center utilizes a 2:1 ratio to estimate *total* damage from hurricanes and therefore multiplies the PCS insured loss estimate by two to obtain a hurricane total (J. L. Beven 2004, personal communication). Since there is no published research to support this ratio, it was not utilized in this study.] The most damaging hurricanes affecting the United States from 1986 to 2003 were compared to the estimated insured damages from derechos obtained from this study (Table 5). Clearly, certain hurricanes (e.g., Andrew, Hugo, etc.) are in a category unto themselves and result in enormous insured damage estimates. However, individual derechos or families of derechos appear to approach the damage potential of some of the most damaging hurricanes in the 18-yr period of record. For example, the 31 May 1998 case exceeded estimates from Hurricanes Erin and Bonnie and approached the insured losses produced by Hurricane Lilly. It is likely that other extreme derecho events have exceeded the 31 May 1998 case (e.g., 16 July 1980) and are comparable to the most damaging hurricanes in U.S. record.

Table 5. The most damaging hurricanes that have directly impacted the contiguous United States from 1986 to 2003 in comparison to the most damaging derechos (highlighted in red) identified in this study utilizing the procedures outlined in the methodology. "Category" indicates the intensity (using the Saffir–Simpson hurricane scale) of each hurricane as it made landfall or approached the coast (for non-landfalling hurricanes). Asterisks indicate that two separate derechos occurred on the same day and are included in the same catastrophe damage estimate. All estimates account for inflation and are adjusted to 2003 dollars.

Year	Storm	Catagory	PCS estimate (millions of $)
1992	Andrew	5	18,985
1989	Hugo	4	3,993
1995	Opal	3	2,411
1999	Floyd	2	2,117
1996	Fran	3	1,803
2003	Isabel	2	1,685
1998	Georges	2	1,264
1991	Bob	4	766
2002	Lili	1	437
1998	31 May	—	432
1995	Erin	1	431
1998	Bonnie	3	394
1998	7 Sep*	—	252
1998	4, 5, 6 Jun	—	191
1989	4 May	—	180
2001	16 Feb	—	176
1999	26 Apr	—	162
1996	Bertha	2	152
2002	9 Mar*	—	137
1999	Irene	1	108

Forest blowdowns. Not included in either PCS or *Storm Data* estimates is the impact derechos have on both private and public forests throughout the United States. Several derechos have produced extensive forest blowdowns, including the "Independence Day Downbursts" 4 July 1977 (3440 km^2 of forest affected; see Fujita 1985), the two Minnesota derechos of 13 and 14 July 1995 (810 km^2 destroyed; NCDC 1995), the "Adirondack" derecho of 15 July 1995 (3642 km^2 affected, 505 km^2 sustaining moderate to severe damage; NCDC 1995), and the "Boundary Waters" derecho of 4 July 1999 (2691 km^2 affected, 1934 km^2 destroyed; Parke and Larson 2004; Price and Murphy 2002). The meteorological community often labels these blowdown events as Pakwashs after the Pakwash Provincial Forest in northwest Ontario, Canada, that was impacted severely by a windstorm produced by a high-precipitation supercell that occurred on 18 July 1991 (Cummine et al. 1992). Derecho-produced blowdowns have altered forest landscapes and community dynamics by influencing tree mortality rates, reducing tree size and structure, decreasing forest diversity, and modifying species composition by advancing succession status (Peterson 2000).

The financial impact these events have on forests is difficult to approximate. Some assessments have been provided, including a monetary estimate of the impact the 15 July 1995 derecho had on the Adirondack Park in New York. The New York Department of Environmental Conservation indicated that the timber damage due to the derecho was estimated at 1 billion board feet with an estimated value of $234 million (2003 dollars; NCDC 1995). Unfortunately, damage to forests is not the only hazard realized by these events. In some cases, campers and hikers visiting these forests during the height of the tourist season have been killed or seriously injured by derecho-felled trees.

Derechos have even sparked intense political debates at the state and federal levels regarding what to do with the disturbed forests left in the wake of these windstorms. Both the "Adirondack" and "Boundary Waters" derechos were responsible for extremely contentious debates on whether salvage logging operations should be permitted in public forests after large blowdowns. In the case of Adirondack Park, salvage operations had been in place for nearly 50 yr on the grounds of fire prevention and forest conservation. However, following the assessment of state conservation officers and consulting ecologists, the state of New York enacted to forego salvaging operations in the Adirondack forest after the derecho. The final assessment concluded that the large forest disturbance produced by the derecho should be treated as a normal ecosystem process (Robinson and Zappieri 1999).

Finally, the potential for catastrophic fires in forests affected by derechos is often extremely high due to dramatic increases in the volatility and fuel loading brought about by the felled timber. For example, the U.S. Forest Service Fuels Risk Assessment report detailing the 4 July 1999 derecho impacts on the BWCAW suggested that it is not a matter of if, but when, a large significant wildland fire will threaten the wilderness (Leuschen et al. 2000).

SUMMARY AND CONCLUSIONS. Assessing the human and economic impacts of derechos has received considerably less attention in comparison to "large impact" events such as floods, hurricanes, and tornadoes. By consolidating and extending the record of U.S. derechos, this investigation quantitatively and qualitatively revealed the impacts derechos have had on the nation from 1986 to 2003. Results indicate that derecho hazards (defined as derechos that result in injury, death, or economic loss) can be as substantial as hurricanes and tornado hazards.

For the 18-yr period investigated, derechos were responsible for 153 fatalities and over 2,600 injuries. These casualties were highly variable yet appeared to be coupled with the corresponding annual frequency of derechos. Derecho fatalities are comparable to those produced by recent U.S. hurricanes and exceed the fatalities caused by more than 88% of the tornadoes that have affected the United States from 1986 to 2003. Individually, derechos were responsible for up to 8 fatalities and 204 injuries, indicating that these storms can have a substantial human impact. Derecho fatalities have a propensity to occur more frequently in vehicles or while boating, while injuries are more likely to happen in vehicles or mobile homes. Both fatalities and injuries are more inclined to occur outside of the region that possesses the highest derecho frequency. An underlying synthesis of both physical and social vulnerabilities is suggested as the cause for the casualty distribution. Contrary to assertions in previous studies (Johns and Hirt 1987; Johns 1993; Wakimoto 2001), results from this investigation suggest that derechos do not account for a majority of the casualties owing to convectively induced nontornadic winds.

Utilizing catastrophe statistics compiled from the insurance industry, this investigation was able to obtain a sense of the financial impact derechos can incur. Damage estimates obtained from the PCS insurance catastrophe database were compared with similar figures from *Storm Data* to reveal inadequacies in the U.S. government's only publication estimating losses from natural disasters. Results suggest that *Storm Data* severely undercounts derecho damage totals (in some cases, by an order of magnitude) and is therefore inadequate for estimating damage totals from derechos. It is likely that *Storm Data* is not practicable for estimating damage totals for other thunderstorm-related perils, as well.

A number of derechos were extracted from the dataset with the intention of providing an estimate of the insured loss due to these windstorms. Insured losses from many derechos and derecho families were found to exceed \$100 million dollars, with one event (31 May 1998) nearing \$500 million in estimated insured losses. These estimated losses are comparable to some of the most noteworthy U.S. hurricanes in the last 18 yr and are equivalent to the most damaging tornadoes in the U.S. history (Brooks and Doswell 2001). According to Fujita and Wakimoto (1981), derechos have exceeded the \$1 billion dollar threshold in the past; however, in this study no events inducing this amount of economic impact were identifiable due to constraints imposed by the data and procedures employed. Derecho damage tallies are likely to be even higher than those measured in this study as no estimate was provided for noninsured damages or governmental expenditures, since some states that were impacted by derechos were not included in the damage estimates, and because several of the most extreme derechos in the past 18 yr were not included in the damage analysis. Further, the economic impact due to derecho-induced forest blowdowns is often indeterminate and is therefore typically excluded from the loss estimates. In one case (15 July 1995), an official estimate suggested that over \$230 million in timber was lost due to a derecho.

Future study should try to extend the climatological record to increase our understanding of how these events form and where they are most frequent. A considerable effort should be made to increase the amount of in-depth loss investigations into future derechos in order to obtain meaningful estimates of actual economic impacts produced by these windstorms. For example, detailed studies of the 1988 drought (Riebsame et al. 1991), Hurricane Andrew (Pielke 1995), and the Great Flood of 1993 (Changnon 1996) have assisted in creating a new awareness of data problems and have improved the estimating procedures associated with each of these perils (Changnon 2003). As suggested by Changnon (2003), the nation needs a concerted effort, and a continuing program, to routinely assess and measure the losses from weather extremes, including derechos, in order to adequately monitor the ever-growing impact of weather disasters, improve mitigation efforts, and make informed decisions on policies that address hazard issues.

In summary, the results of this analysis indicate that derechos can be as hazardous, and are comparable in magnitude to, most U.S. tornadoes and hurricanes. The study has attempted to inform scientists, emergency managers, insurers, and the public about the severity of derechos so that they may take steps to mitigate the potential future hazards of these tremendous windstorms.

ACKNOWLEDGEMENTS. Thanks to Dr. Mace Bentley for providing insightful comments that improved the initial version of the manuscript, Jamie Dyer for providing an analysis routine, Drs. Mace Bentley and Michael Coniglio for the availability of their derecho datasets, and Gary Kerney and Jim Welsh for supplying the PCS data and answering many questions regarding the collection of these data. The suggestions from three anonymous reviewers improved substantially the quality of this manuscript. Finally, sincere thanks to Emily Boyd who graciously shared her "Boundary Waters" derecho account and answered numerous questions about the event as well as provided pictures of the damage. This research was supported by a cooperative agreement between the USDA Forest Service and the University of Georgia.

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