Characteristics of Ice Storms in the United States

STANLEY A. CHANGNON

Changnon Climatologist, Mahomet, Illinois

(Manuscript received 18 July 2002, in final form 11 November 2002)

ABSTRACT

Freezing rainstorms in the United States during 1949–2000 resulted in 87 catastrophic events, storms causing property losses of more than $1 million, with resulting losses totaling $16.3 billion. Catastrophes and their losses were greatest in the northeast, southeast, and central United States, and only 3% occurred in the western United States. A greater percentage of the freezing-rain occurrences in the deep South produced catastrophes than did freezing-rain occurrences in the northern United States, a result of differences in storm-producing conditions. A dense network of observers who measured ice storms during a 9-yr period provided definitive data on damaging storm areas and ice thicknesses on wires. The geographic distribution of the 368 damaging–ice storm areas matched well with that of catastrophes; both were greatest in a belt from the Southwest, across the Midwest, and into New England. Storm-area sizes ranged from 205 to 796 000 km^2, with 50% being less than 21 840 km^2. Most storm-area shapes were elongated with length–width ratios from 2:1 up to 15:1, although 18% were oblate shaped, particularly those in the northern High Plains and upper Midwest. Two-thirds of the ice-storm areas and catastrophe loss patterns assumed one of seven spatial types. The most prevalent type was a storm restricted to the Northeast, the second had losses in the Midwest and Northeast, and third was a storm in both the Northeast and Southeast regions. Five large-sized catastrophes extended from the Southwest, through the Midwest, into the Northeast, and these caused $3.5 billion in losses, 21% of the 52-yr total. The radial thickness of damaging ice on telegraph wires was sampled at 1689 sites, and the greatest average (>1.3 cm) and maximum (>5 cm) sizes occurred in the deep South and southern plains where storms have long durations and ample moisture aloft. Maximum and average ice thickness were relatively large in New England and the Northeast. Ice-thickness values were least in the upper Midwest and Pacific Northwest. The results collectively show that the greatest risk of ice-storm damages (based on event frequency, ice thickness, storm size and shape, and financial loss) is in the northeastern United States, followed by the risk in the lower Midwest and that in the southern United States.

1. Introduction

Most past investigations of freezing rain across the United States have been done for one of three reasons: 1) for case studies of major storms, 2) for assessment of the risk of icing to facilities (structures, wires, or aircraft), or 3) for research relating to the forecasting of freezing-rain conditions. Past studies of damaging ice storms unfortunately have been limited either by datasets that were too short or by the use of questionable data. No past studies assessed ice storms based on their economic losses, largely because of the paucity of quality financial-loss data on weather extremes (NRC 1999). National-scale, climate-based approaches for assessing two key damage aspects—ice thickness and storm size—have been limited because of a lack of sufficiently detailed data for defining these two conditions. Two newly available datasets, one addressing the losses of damaging storms over 52 years and the other allowing spatially detailed definition of storm sizes and ice thicknesses on wires, have been used to define the national and regional aspects of damaging ice storms.

Engineering-based studies have estimated, using numerical models, ice loads and associated winds that are apt to occur on wires and other structural materials (Jones 1996). Concerns of the utility industry about ice on wires and transmission towers led to recent studies of damaging ice storms, and these studies largely relied on *Storm Data* (information currently available from NCDC, Federal Building, 151 Patton Ave., Asheville, NC 28801-5001) for information on estimated damages and icing thickness (Shan and Marr 1996; Jones et al. 1997). Storm conditions and financial-loss information in *Storm Data* are highly qualitative because the data often come from untrained informants who measure the ice and estimate losses, and the information is often inconsistent between states. Thus, *Storm Data* is a highly questionable source of data on storm conditions and financial losses (Branick 1997). For example, a recent assessment of U.S. natural disasters during 1975–94 utilized loss values from *Storm Data* and defined ice-storm losses as having a 10-fold range, being somewhere be-

Corresponding author address: Stanley A. Changnon, Changnon Climatologist, 801 Buckthorn, Mahomet, IL 61853.
E-mail: schangno@uiuc.edu

tween \$1.1 billion and \$11 billion (Mileti 1999). In sum, because of a lack of quality data, no one has been able to perform a definitive study of U.S. damage-producing storms and their losses.

Point measures of ice-storm occurrences collected by first-order stations (FOS) of the National Weather Service (NWS) are too widely separated to allow for meaningful measures of storm sizes. There has never been a long-term sustained measure of ice thickness by the NWS, and the ice information presented in *Storm Data* is highly questionable because there is no consistent method of ice-thickness measurement. For spatial comparisons, ice thickness must be systematically measured on a uniform surface, such as on wires of the same diameter and height above the surface. Several findings in this study of ice storms were related to those in a recent synoptic climatological analysis (Rauber et al. 2001). That study used *Storm Data* to define where freezing rain or drizzle occurred and used FOS data to define when ice occurred and what the synoptic conditions were that caused the 411 storms identified during 1970–94.

A newly developed database that consists of 52 years of insurance data on property losses from freezing rain provided an opportunity to pursue a definitive study of the physical dimensions and economic impacts of ice storms. Analysis of damaging freezing-rain events was pursued using an insurance dataset that consists of highly damaging storm events, classed as ''catastrophes'' by the insurance industry, during the 1949–2000 period. Catastrophe is a term used to label events in which losses equal or exceed \$1 million, although this base value has been shifted upward over time to compensate for inflation. The property-insurance industry has collected data on catastrophes since 1949. A recent assessment of loss data for natural hazards identified the insurance catastrophe data as the nation's best available loss data (NRC 1999).

The insurance data on all weather catastrophes were used to identify those due to freezing rainstorms, and these events formed a special ice-storm dataset. The catastrophe loss data required adjustments for temporal changes in various factors that influence insured property, including inflation, as described in the data section.

The other database utilized consisted of ice-storm data collected across the United States during 1928–37 by the railroads under the auspices of the Association of American Railroads (Hay 1957). All railroads participated, and their station agents, located 15–30 km apart across the eastern two-thirds of the nation (less dense spacing in the West because of fewer railroads), reported by date all freezing rain and ice accumulated on the local telegraph wires and noted when damages occurred. The dates and the ice measures were submitted to the association, creating a sizable database.

2. Data and analysis

a. *Catastrophe data*

In 1949 the property-insurance industry began keeping records of all natural hazards that caused losses to insured property of \$1 million or more in the United States. For each qualifying catastrophe, they recorded the condition(s) that caused the losses, the amount of loss, and the states in which the losses occurred. In 1983, the basis for identifying an event as a catastrophe was shifted from \$1 million to \$5 million. In 1997 a shift was made from \$5 million to \$25 million, as a further adjustment for the effects of ever-growing inflation on the selection of catastrophes.

A major insurance firm has analyzed the historical catastrophe data to assess risk, and each year they updated the past catastrophe values to match the latest-year conditions. This sizable updating effort required assessing each past event and its location, and three adjustments were made to the original loss value for each catastrophe. One adjustment was designed to correct for time changes in property values and the cost of repairs, and, hence, to adjust also for inflation. The second adjustment addressed the relative growth in the size of the property market in the areas affected by the catastrophe using census data, property records, and insurance records. This step adjusted losses for shifts in the insured property between the year of a given storm's occurrence and the updated year (2000 in this study). The third adjustment factor was based on estimates of the relative changes in the share of the total property market that was insured against weather perils, using insurance sales records. These three adjustments were used to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current-year values. Thus, adjustments made in 2000 for all past catastrophes dating back to 1949 allow for a comparative temporal assessment of their losses. For example, a storm-related loss in Pennsylvania during 1953 was adjusted upward by a factor of 31.3, whereas a 1953 catastrophe loss in Oregon, where coverage differed from Pennsylvania, was adjusted by 37.8. In the resulting adjusted catastrophe data, the loss from a catastrophe in 1949, 1973, or 1991 could be assessed in terms of the 2000 conditions. The adequacy of this adjustment method was examined using regional comparisons involving population data to address the demographic shifts over the last half of the twentieth century, when considerable movement and growth of population occurred in the western and southern sections of the United States, and was found to adequately measure ongoing changes (Changnon and Changnon 1998).

The cause of loss in the 52-yr insurance database was used to identify those catastrophes caused principally by freezing rainstorms. In many cases, the cause of loss also included some secondary damages from snow and/or high winds. These were classed in the insurance data as additional, but lesser, loss causative factors. Thus,

TABLE 1. The U.S. freezing-rain catastrophes during 1979. The losses have been normalized to 2000 dollars, and the locations are the climatic regions of the United States.

Date	Cause of loss*	Regional location	Loss, $ millions
31 Dec 1978–2 Jan 1979	Ic, Wi, Sn	Central, South	24
6 Jan	Ic, Wi, Sn	Central, South	7
20–24 Jan	Ic, Wi, Sn	Southeast, Northeast	90
6–7 Feb	Ic, Sn, Wi	Southeast	13
18–19 Feb	Ic, Wi	Southeast	11
8–9 Apr	Ic, Wi	East North Central	31

* Listed in order of importance of losses created: Ic = freezing rain, Sn = snow, and Wi = high wind.

the values of freezing-rain catastrophes and their losses presented herein are somewhat higher than the actual ice-caused losses, but these additional losses could not be estimated from the available insurance data. The catastrophe losses from freezing rain do not include all ice storm–caused property losses because some freezing-rain events did not create losses sizable enough to qualify as catastrophes. The underestimation factor is small, as revealed in prior assessments of various severe weather–caused property losses, which found that the catastrophe losses over time represent 90% of the total weather losses (Changnon and Hewings 2001).

Analysis of losses and frequency of catastrophes was done using the 87 freezing rain–caused events during 1949–2000. A sample of the freezing-rain catastrophes identified during the 1949–2000 period is shown in Table 1. The regions listed are based on the nine climatic regions in the contiguous United States (described later in Fig. 2), as defined by the National Climatic Data Center.

When a catastrophe occurred in two or more climate regions, the total loss value was allotted equally to each region. For example, a catastrophe on 20–24 January, 1979 (Table 1) caused losses of $90 million, with losses reported as occurring in the Southeast and Northeast regions. The total loss was divided by two and each region had $45 million assigned to it. Given the data available, this approach was the only equitable way to adjust losses for multiregional catastrophes.

b. Railroad ice-storm data

Railroads in the United States were dependent until the 1950s on telegraphy and telephones for controlling train movement, and the loss of communications that was caused by freezing-rain damage to wires caused major operational problems, as did the loss of electrical power for signal systems (Hay 1957). The continuing ice-storm problems led the Association of American Railroads to organize a nationwide project to collect data on damaging freezing-rain events to permit better planning and structural design. All railroads cooperated in this massive data collection effort, and their station agents located in every U.S. community served as observers of freezing-rain occurrences. When damaging ice accumulations on local telegraph wires, all with the same diameter and located 1–2 m above the surface at railroad depots, occurred, the agents reported the date and radial thickness of ice that had accumulated on the wires and whether any damage occurred. The data collection began in the winter of 1928/29 and continued through the 1936/37 winter, a 9-yr period. In the area east of the Rockies, stations were 15–30 km apart, and, this distribution resulted in a massively large and dense set of observers and ice measurements in the area where most freezing rain occurs in the United States (Bennett 1959). The results of this major sampling effort are reflected in the data, which can be illustrated by comparing their counts of glaze reports with those of the Weather Bureau, as published in the *Monthly Weather Review*. For example, during the 1932–37 period, the Weather Bureau reported damaging glaze events on 113 dates, whereas the railroad sample had damaging glaze events recorded on 143 dates.

The summarized data were obtained by the University of Illinois at Urbana–Champaign, Urbana, Illinois, in the 1950s as part of a multiyear study of how weather affected railroads (Hay 1957), and these data were used in this study. The available records list 1689 point measurements of damaging freezing rain showing storm date, thickness of ice on the telegraph wires, and location. The 174 reports defining a major ice storm in 1930 were used to construct the storm pattern shown in Fig. 1. Regions of varying ice thickness were defined based on the most common size reported at sites within the areas shown. Freezing-rain events that caused damage were reported on 227 days during the 9-yr period.

The data were used to construct maps of each ice storm. Some were 1-day events and others were multiday storms as shown by the 4-day storm in Fig. 1. Storm envelopes were constructed based on the places with reported ice on a given date, and the placement of the encircling lines defining the storm's boundary were positioned outward 20 km from each reported location. This scaling distance is based on findings from detailed field surveys of ice storms in Illinois and the resulting average point–area relationships developed (Changnon 1969). On some storm dates, two or three widely separated damaging storm areas were found. This mapping analysis led to identification of 368 separate areas la-

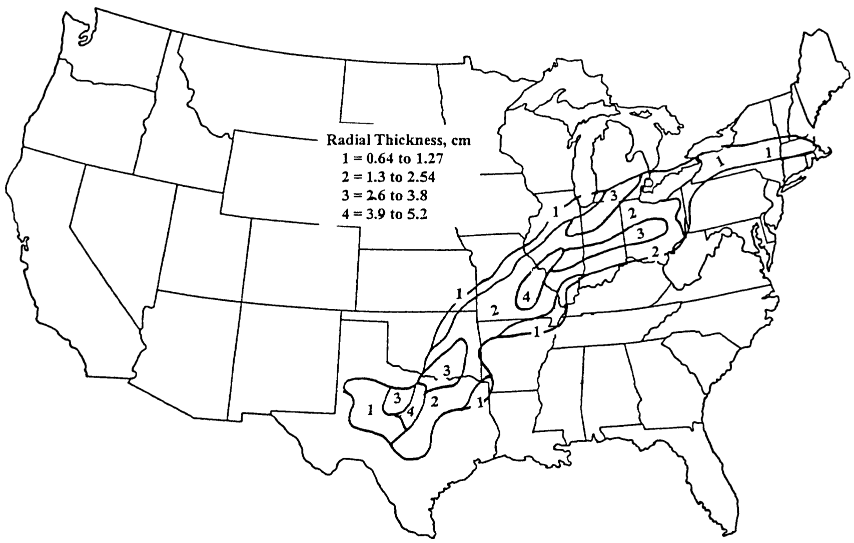

FIG. 1. The pattern of a major ice storm on 6–9 Jan 1930, based on 174 railroad observations of damaging freezing rain. Their reports of ice thickness on telegraph wires were used to categorize the most common sizes (radial thickness) and delineate discrete ice-size regions within the storm.

beled as ice-storm areas. Their geographic distributions were determined along with their size distributions and types of shapes. The ice-thickness values were sorted on a spatial basis to develop size distributions for various regions across the United States.

c. *Freezing-rain-day data*

Recent research developed a database for days with freezing rain at NWS stations across the nation (Changnon 2002). These data embrace all occurrences during the 1948–2000 period at 988 stations (first-order and cooperative substations). Spatial values based on these data were compared with the values for the freezing-rain catastrophes and the railroad-based ice storm areas.

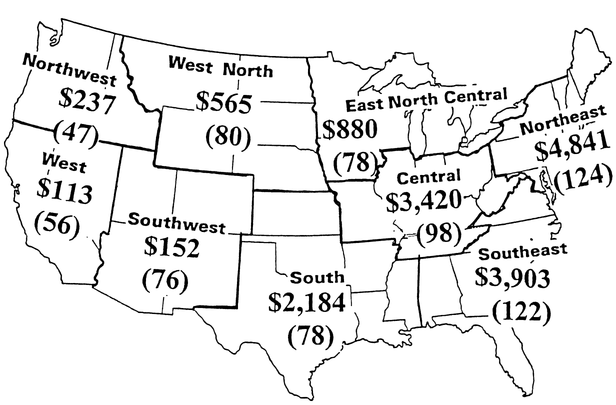

FIG. 2. The amount of loss (millions of dollars expressed in 2000 values) from ice-storm catastrophes in each climate region during 1949–2000. Values in parentheses are the average losses per catastrophe.

3. Spatial distributions

a. *Catastrophe losses*

During the 1949–2000 period there were 87 ice-storm catastrophes. National losses from freezing-rainstorm catastrophes were found to be sizable, with insured property losses amounting to $16.3 billion (in 2000 dollars) for the 1949–2000 period. The 52-yr national total of losses from all freezing-rain events is estimated to be $18 billion [based on the catastrophe total plus 10% estimated to be caused by noncatastrophic events; Changnon and Hewings (2001)]. Winter storms, which include snow and ice storms, averaged $375 million per year during 1988–95 (Kocin 1997). The average annual ice-storm loss, based on catastrophe losses in this 8-yr period, is $226 million, about 60% of the U.S. total winter storm losses. Ice storms also cause numerous deaths and account for 20% of all weather-caused injuries (Kocin 1997). The average loss for the 87 catastrophes, expressed in 2000 dollars, was $187 million, and the median value was $79 million. Storm losses ranged from a low of $6 million to a high of $1.2 billion.

The geographical distribution of losses from the 87 catastrophes (Fig. 2) reveals that the national regional maximum is $4.8 billion in the Northeast. The Southeast had $3.9 billion in losses, ranking second; the Central region with $3.4 billion ranked third; and the South ranked fourth with $2.2 billion in losses. These four regions had losses totaling $14.3 billion, 88% of the U.S. total for 1949–2000.

The regional average losses per catastrophe, a measure of storm intensity (Fig. 2), reveal that the highest values occurred in the Northeast ($124 million) and Southeast ($122 million). The average loss in the Cen-

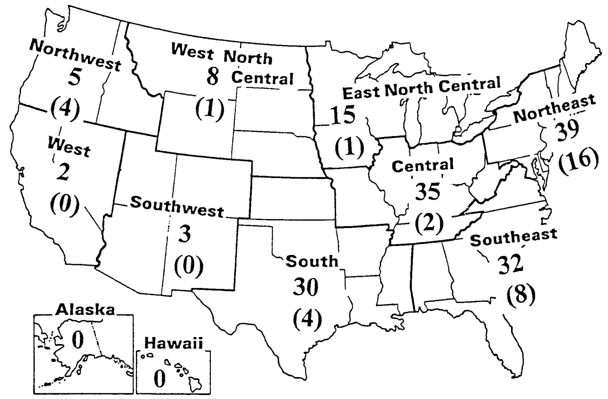

FIG. 3. The number of ice-storm catastrophes in each climate region during 1949–2000. Values in parentheses are those catastrophes that only occurred within the region.

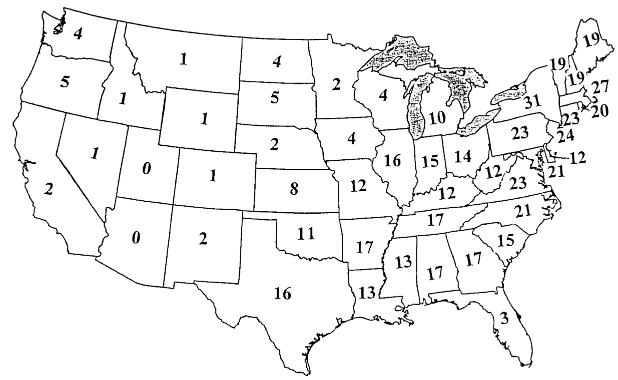

FIG. 4. The number of times each state experienced losses from ice-storm catastrophes during 1949–2000.

tral region is 21% less at $98 million, and the averages in most other regions are somewhat lower and of similar magnitudes, $76–$80 million. Only in the two western regions are averages markedly less, reflecting an area where catastrophes were very infrequent. In contrast, freezing-rain catastrophes are not only most frequent in the Northeast (see Fig. 3), but they also have a greater intensity there.

b. Frequency of catastrophes

The number of catastrophes that occurred in each climate region (Fig. 3) reveals that the Northeast, with 39 catastrophes, experienced nearly one-half of all 87 catastrophes. This result is in agreement with the peak in losses. Other regions with large frequencies included the Central, Southeast, and South. Very few catastrophes occurred in the four western regions. A past study of damaging storms reported during 1925–53 also found that most occurred east of the Rocky Mountains (Bennett 1959).

Also shown on Fig. 3 are the number of catastrophes with losses confined within each climate region. The Northeast led with 16 such events, 41% of the 39 catastrophes experienced there. The Southeast had 8 catastrophes just within its six states, representing 25% of all catastrophes affecting the region. The only other region with numerous localized losses was the Northwest, where four of the five ice-storm catastrophes were within the three states. Many of the ice storms in the Northeast and Southeast regions result from airmass interactions with the Appalachian Mountains, creating in-region ice storms (Rauber et al. 2001). Steenburgh et al. (1997) showed that topography also plays a major role in ice-storm development around the Columbia basin in the Northwest. The low frequencies of one-region-only catastrophes in the four climate regions of the central third of the U.S. indicate damaging storms in this area tended to be sufficiently large, as a result of their causative weather conditions leading to long durations and storm movement (Rauber et al. 2001), to affect two or more regions.

Figure 4 shows state catastrophe frequencies for the 52-yr period. The state values, although biased by the varying sizes of states, indicate the area of maximum frequencies, occurrences greater than 20, extended south from Massachusetts, along the East Coast, to North Carolina. The highest three values were in New York (31), Massachusetts (27), and New Jersey (24), defining the zone of greatest frequency of property losses. A lesser high-loss-frequency area exists in the lower Midwest. Earlier data-limited studies also showed a national peak of activity in the Northeast and mid-Atlantic region, and a secondary maximum in the Midwest (Bennett 1959). Rauber et al. (2001) found that 25% of the ice storms in the Central and Northeast regions had a deep layer of moisture aloft, helping to account for the frequent accumulations of ice and, hence, damaging storms. Four states had no catastrophe-produced losses (Alaska, Arizona, Hawaii, and Utah), and many other western states experienced only one or two ice-storm catastrophes. A recent study of damaging ice events during 1959–95, as determined from *Storm Data,* also indicated high storm frequencies in the Northeast and Southeast but also had a major storm maximum in the northern High Plains (Shan and Marr 1996), where catastrophes are infrequent (Fig. 4).

If an isofrequency line based on five or more catastrophes were drawn on Fig. 4, it would extend from west Texas to western Kansas, and then northeastward to Michigan. The nation's problems with ice-storm-caused property losses lie east of this line. Freezing-rain days were found to be frequent in the Dakotas, as shown on Fig. 5, but they do not result in large property losses. This may be a result of the low density of property at risk in that area and frequent short-duration storms (Rauber et al. 2001).

c. Freezing-rain days

The average annual number of days with freezing-rain (ZR) days, as based on data from 988 stations across

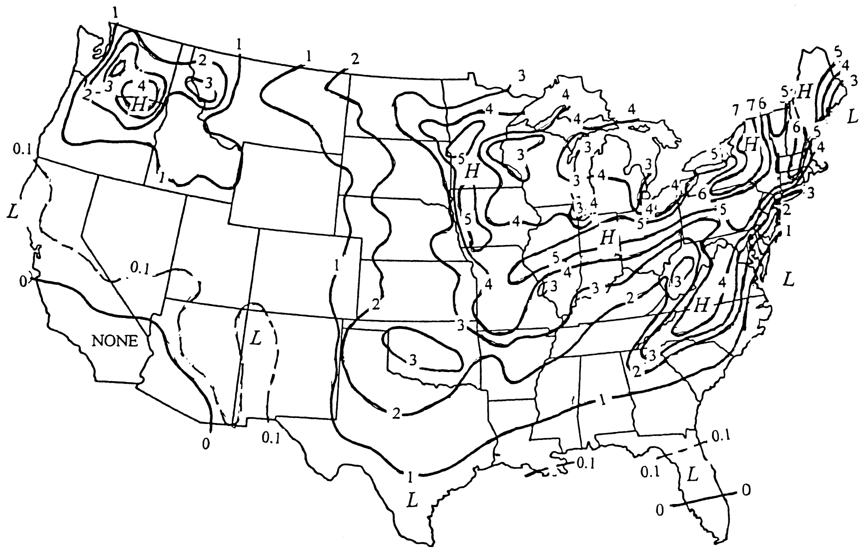

FIG. 5. Pattern based on the average annual number of days with freezing rain, as defined by 988 weather stations and data for 1948–2000.

the United States (Fig. 5), was compared with the catastrophe and ice-storm area patterns. The Northeast had the U.S. maximum with averages ranging from 5–7 ZR days per year in New York, where the state-based maximum of catastrophes was also centered (Fig. 4). The area of high values of four or more freezing-rain days in the lower Midwest had only moderately high catastrophe frequencies. Both of these regions also get ice storms generated by the Great Lakes (Bernstein 2000). A moderate high in ZR days in the Northwest climate region was also associated with a localized high in catastrophes (Fig. 4).

A regional disagreement between ZR days and catastrophe frequencies was found in the South. Points in the area from Texas eastward to Georgia experience, on average, only 1 day of freezing rain annually, and yet the state frequencies of catastrophes were relatively high, 13–17 events during 1949–2000 (Fig. 4). A 52-yr-based comparison yields a point–state ratio of about 3.5:1, ~52 ZR days (52 times 1 ZR day) to ~15 loss events per state for 1949–2000. The ratio in the Northeast is 12:1 (~300 ZR days to ~25 loss events), and that in the Central region is 16:1 (~250 ZR days to ~15 loss events). Thus, relatively more freezing-rain occurrences in the southern states created major losses than did freezing-rain events in the central and northeastern United States. Furthermore, most points farther north in the East North Central (ENC) region average 4 ZR days per year, but its states only experienced between 2 and 10 catastrophes (Fig. 4). Thus, its 52-yr ratio is about 25:1 (~200 ZR days to ~8 loss events). Thus, very few of the numerous ZR days in that region result in major damaging ice storms. Analysis of ice thickness on telegraph wires further revealed that the upper Midwest experienced, on average, thinner ice on wires than occurred in the South and Northeast regions (see Table 4).

The two storm-producing weather types most common in the West North Central (WNC) and ENC regions have relatively short durations, often less than 12 h (Rauber et al. 2001), and, with very shallow cloud layers aloft, the storms often produce nondamaging freezing drizzle, not freezing rain (Bernstein 2000). In converse, the most common U.S. storm-producing weather type (arctic front with a deep layer of overlying moist air) accounts for most ice storms in the South region, and, further, this type of event is the longest-lasting storm type (Rauber et al. 2001). This fact helps to explain the relatively high loss incidences when freezing rain does occur in the southern states. The relationship of ZR days with catastrophe frequencies reveals that the catastrophe loss per ZR day systematically decreases from south to north across the eastern two-thirds of the United States, and the differences relate primarily to regional differences in the primary storm-producing weather conditions, as defined by Rauber et al. (2001).

d. Ice-storm areas

Various results from the ZR databases were used to define ZR regions based on ice storm characteristics, and the resulting 10 regions appear on Fig. 6. These regions were defined using the features on the average ZR-day pattern (Fig. 5) and information on the seven regionally different synoptic weather conditions that cause freezing rain (Rauber et al. 2001). The locations of the 368 damaging ice-storm areas during 1928–37 were sorted according to occurrence in the 10 freezing rain regions. An ice area astride two or more of these regions was assigned to the region where the largest

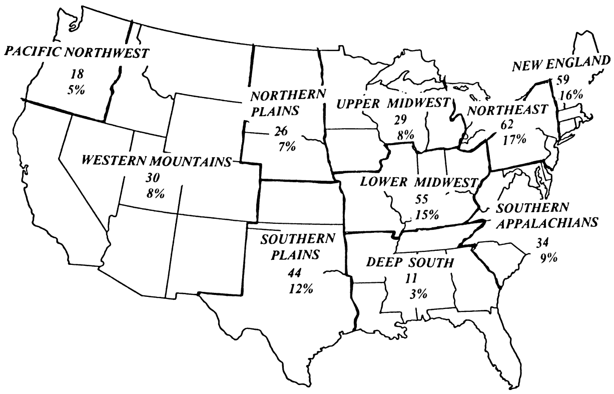

FIG. 6. Frequency of ice-storm areas during 1928–37 in selected regions. The percentages are the frequencies expressed as a percent of the 9-yr total of 368 areas in the United States.

portion of the area existed. Figure 6 presents the regional frequencies plus their values expressed as a percentage of the total 368 areas. In general, the ranks of the values of the ice-storm areas matched well with those based on catastrophe occurrences. The Northeast and New England regions had the highest frequencies, together experiencing 33% of the total areas. This outcome matched the peaks of catastrophe incidences (Fig. 4) and the ZR-day frequencies (Fig. 5). Ice-storm loss areas were frequent in the three climate regions (South, Central, and Northeast) where catastrophe losses peaked (Fig. 3). However, the number of loss areas in the Pacific Northwest was relatively lower than their ZR-day frequencies and catastrophe frequencies. This difference is likely a sampling vagary resulting from the 9-yr sample of ice-storm areas.

4. Storm sizes and shapes

Analysis of the sizes of the 368 ice-storm areas revealed a wide range. The smallest was 205 km^2, and the largest was 798 300 km^2. The sizes were ranked and were used to develop the distribution shown in Table 2. One-half of the sizes were 21 840 km^2 or less, whereas 10% were 231 900 km^2 or larger. The distribution is relatively skewed, with many relatively small areas (70% less than 62 330 km^2) and a few large ones (10% greater than 231 900 km^2).

Sizes of the 87 catastrophes could only be determined on a state-scale basis because this was the basis of loss reporting. Sizes ranged from a low of one state with a catastrophic loss, up to one storm in which losses occurred in 22 states. The average size was six states with loss, and the median was five states.

Most ice-storm areas were elongated, with length–width ratios ranging from 2:1 to 15:1. The average storm shape was 294 km long and 73 km wide. Eighteen percent had semicircular shapes, and most of these occurred in the northern plains and upper-Midwest areas (Fig. 6).

The major axis of the 302 elongated ice-storm areas assumed a variety of orientations, as shown in Table 3. Areas with southwest–northeast orientations were most common in the Central, Northeast, ENC, and WNC climate regions. Storm areas oriented south-southwest–east-northeast were prevalent in the Southeast region, and west–east orientations were most common in the South. Oblate-shaped areas occurred most often in the WNC and ENC regions, representing 45% and 40%, respectively, of their storm areas. In all other climate regions, oblate-shaped areas were 5% or less of the regional total.

TABLE 2. Distribution of the sizes of the 368 damaging-ice-storm areas during 1928–37.

Percent of areas	Size (km^2)	Percent of areas	Size (km^2)
100	$>$205	40	$>$37 490
90	$>$ 2310	30	$>$62 330
80	$>$ 6100	20	$>$124 630
70	$>$ 9570	10	$>$231 900
60	$>$14 340	5	$>$535 000
50	$>$21 840	1	$>$710 000

Examination of the shapes and placement of 368 ice-storm areas and the 87 patterns of catastrophe losses revealed seven frequently occurring types. These seven loss patterns accounted for 61 of the 87 catastrophes (70%) and 71% of all 368 areas based on the railroad data. The most common storm type was confined to the Northeast climate region (see Fig. 2). This included 16 catastrophes. This was where one synoptic weather type (cold-air trapping) was prevalent (Rauber et al. 2001). The next-most common storm pattern was elongated, occurred in portions of both the Central and Northeast regions, and included 11 catastrophes. This matched two of the frequent synoptic weather types (warm-front occlusion, and the western quadrant of the arctic high) identified by Rauber et al. (2001).

The third-most frequent type of storm existed in the Northeast and Southeast climate regions. Nine of the 87 catastrophes had this placement of their losses. The fourth-most frequent storm pattern was often narrow and confined to the Southeast climate region. Rauber et al. (2001) showed that two synoptic weather types (cold-air damming, and damming with a coastal cyclone) were responsible for most such storms in the Northeast–Southeast or Southeast alone. The fifth-most common storm pattern was large, with loss areas extending from the South region into the Central region, often associated with arctic fronts (Rauber et al. 2001). The sixth storm type was often small and confined to the northern or southern plains, a result of the presence of a cyclone and anticyclone (Rauber et al. 2002). The seventh-most frequent type was large, extending northeastward from the South region through various parts of the Central region, and on into the Northeast. The huge 1930 storm (Fig. 1) illustrates this type of storm. Five catastrophes of this type occurred and created losses, on average, in

TABLE 3. Orientation of the long axis of elongated storm areas in the primary climate regions, expressed as a percent of the regional totals.

Oriented	Central	Northeast	Southeast	South	East North Central	West North Central
West–east	13	4	2	57	37	7
Southwest-northeast	80	51	44	43	55	64
South-southwest–east-northeast	7	45	54	0	8	29

14 states, and their losses amounted to $3.5 billion, 21% of the 52-yr total. Such storms resulted from several synoptic weather types.

5. Ice thickness

The railroad database contained 1689 measures of damaging ice thickness (diameter) on the telegraph wires. The number of values in each of the regions shown in Fig. 6 provided a sample size adequate for assessing the size distributions in each region. Studies of structural damages from freezing rain have shown that damage increases as ice thickness increases (Bennett 1959; Jones 1996). The recent major damaging storm in Canada and the United States in January of 1998 had great ice thickness values (Jones and Mulherin 1999).

The four largest radial thicknesses, as measured on separate storm days, in each of the regions are shown in Table 4. The largest values, those 5 cm or larger, were found in the southern plains, New England, and the Deep South. The smallest of the maximum thickness values occurred in the upper Midwest and Pacific Northwest.

Average thickness values varied from 0.6 up to 1.6 cm, revealing major regional differences. The highest averages occurred in the deep South, lower Midwest, and southern plains. The ranks of the regional maximum sizes do not match well with the ranks based on the average sizes except in the deep South, southern plains, and northeast New England where both values are relatively large.

Also shown on Table 4 are sizes of ice thickness that separated the largest 25% of each region's values from the smallest 75% of the sizes. For example, 25% of the sizes measured in the deep South had radial thicknesses of 2.5 cm or more, whereas in the Northwest this value was only 1.3 cm.

6. Summary: Measures of risk

Two newly available datasets based on damaging ice storms were used to investigate ice-storm characteristics and to measure spatial aspects of the risk of damage from freezing rain. One dataset based on property insurance records revealed that the United States experienced 87 catastrophes caused by ice storms during the 1949–2000 period and that the losses totaled $16.7 billion. The national pattern shows a maximum of 39 events occurring in the Northeast climate region, and the Central region ranked second with 35 catastrophes. Most catastrophes (91%) occurred in the Northeast, Central, Southeast, and South climate regions. The Northwest region had only five events, the West had two, and the Southwest had three catastrophes in 52 years, with none in Hawaii or Alaska. The regional peak in storm losses occurred in the Northeast and was a function of both storm intensity (high average loss per event) and high frequency of storms capable of producing catastrophes.

Numerous one-region-only catastrophes occurred in the Northeast and Southeast regions, largely as a result of the localized effects of the Appalachian Mountains, which interact with low-level air masses to create regionally localized severe ice storms (Rauber et al. 2001). The Central, East North Central, and South climate regions had few one-region catastrophes, reflecting the frequent incidence of larger-scale storms in those areas.

Comparison of the frequencies of catastrophes and ZR days in the six climate regions of the eastern two-

TABLE 4. Regional radial thickness values of ice on telegraph wires during 1928–37, showing the four largest sizes measured, the average values, and the thickness values at which 25% of the sizes were larger. The ice values are centimeters.

Regions	Top four ranked largest sizes				25% had larger sizes	Average size
	1	2	3	4		
Northern plains	4.4	4.4	3.9	3.1	1.6	1.0
Southern plains	5.0	4.5	3.9	3.9	2.2	1.3
Upper Midwest	3.9	3.9	3.5	3.5	1.6	0.6
Lower Midwest	4.4	3.5	3.1	2.9	1.6	1.3
Northeast	4.4	3.9	3.5	3.5	2.0	1.0
New England	5.0	4.5	4.4	4.4	2.0	1.0
Southern Appalachia	4.0	3.5	3.2	3.2	1.6	1.0
Deep South	5.4	5.0	4.5	4.2	2.2	1.6
Northwest	3.9	3.1	2.7	2.6	1.3	0.6

TABLE 5. Regional frequencies of freezing-rain-caused catastrophes and damaging-ice-storm areas expected in an average 10-yr period.

Climate region	No. of catastrophes	No. of ice-storm areas
Northeast	7–8	65–70
Central	6–7	60–65
Southeast	6–7	35–40
South	5–6	45–50
East North Central	2–3	30–35
West North Central	1–2	25–30
Northwest	0–1	18–22

thirds of the United States revealed some interesting regional differences. For example, a much higher state ratio, 3.5 ZR days per catastrophe, existed in the South than in the East North Central region, where the ratio was 25 ZR days per catastrophe. That is, relatively more ZR days in the South became catastrophes. This situation results from major regional differences in the primary storm-producing conditions. For example, the South has very low frequencies of ZR days, but storm-producing conditions persist a relatively long time and result in large ice deposits. The northern plains and upper Midwest have frequent freezing-rain days, but their property losses due to ice storms are low, a result of short-duration storms and low values of ice thickness on wires.

The 9-yr sample of ice thicknesses was too short to develop reliable probabilities of the point frequency of damaging scale ice thickness. However, their frequencies and the expected frequencies of catastrophes and ice-storm areas could be assessed regionally. Table 5 shows their frequencies expected in an average 10-yr period. For example, the Northeast climate region would experience seven–eight catastrophic storms and 65–70 damaging ice-storm areas in an average 10-yr period.

Ice-storm areas and catastrophe-loss areas were found frequently to assume one of seven placements and shapes. The most common was an ice area restricted to the Northeast, and second was a larger storm event stretching from the Midwest into the Northeast. Five major ice storms extended from the Southwest through the Midwest and into the Northeast. These large multiday events caused five catastrophes, resulting in losses of $3.5 billion.

Sizes of the 368 storm areas defined from the dense railroad sampling project range from 205 to 798 300 km^2, and 80% of all areas were less than 124 650 km^2. Most (82%) of the damaging-ice-storm areas were elongated with length-to-width ratios ranging from 2:1 to 15:1, and the average storm area was 294 km $\times$ 73 km. Most ice storm areas were oriented southwest–northeast, although west–east was most common in the South and south–southwest–east-northeast was the prevailing storm orientation in the southern Appalachians.

Values of radial ice thickness measured on telegraph wires averaged between 0.6 (Northwest and upper Midwest) and 1.6 cm (South). Maximum ice values ranged from 3.9 (upper Midwest and Northwest) to 5.4 cm (South), and 75% of all ice thickness values were 2 cm or less. The various measures of ice thickness, as a measure of damaging conditions, reveal that the risk of damaging ice is greatest in the South and southern plains, closely followed by the threat in the Northeast and New England.

Several measures of the geographic distribution of freezing-rain events were assessed, including those of catastrophe losses, catastrophe frequency, freezing-rain-day frequencies, ice-storm areas, and ice thicknesses on wires. The area of greatest frequencies, as determined from all these measures, was the same—all showing that the Northeast (New York, Pennsylvania, and New England) is the area with the highest risk of ice-storm damage. In general, the lower Midwest ranks second highest, and the South and Southeast rank third. Freezing rain is relatively frequent in the northern plains, upper Midwest, and Northwest, but the risk of damage is low because of relatively short storm durations and resulting small ice deposits. The results agree well with those in a recent synoptic climatological study of freezing-rain conditions (Rauber et al. 2001).

Acknowledgments. This research was funded by a grant from National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration, as part of the Climate Change Enhanced Dataset Project, NA16GP1585. The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or NASA or any of their subagencies. The assistance of Jon Burroughs is gratefully acknowledged, and I greatly appreciate the insurance data provided by Gary Kerney of the Property Claims Service.

REFERENCES

Bennett, I., 1959: Glaze: Its meteorology and climatology, geographical distribution and economic effects. Quartermaster Research & Engineering Center Tech. Rep. EP-105, 234 pp.

Bernstein, B. C., 2000: Regional and local influences on freezing drizzle, freezing rain, and ice pellet events. *Wea. Forecasting,* **15,** 485–508.

Branick, M. L., 1997: A climatology of synoptic winter-type weather events in the contiguous United States, 1982–94. *Wea. Forecasting,* **12,** 193–207.

Changnon, D., and S. A. Changnon, 1998: Evaluation of weather catastrophe data for use in climate change investigations. *Climatic Change,* **38,** 435–445.

Changnon, S. A., 1969: *Climatology of Severe Winter Storms in Illinois.* Bulletin 53, Illinois State Water Survey, 45 pp.

——, 2002: Developing Data Sets for Assessing Long-term Fluctuations in Freezing Rain and Ice Storms in the U.S. Rep. CRC-46, Changnon Climatologist, 27 pp.

——, and G. D. Hewings, 2001: Losses from weather extremes in the U.S. *Nat. Hazard Rev.,* **2,** 113–123.

Hay, W. W., 1957: Effect of ice storms on railroad transportation. *The Effect of Weather on Railroad Operation, Maintenance, and Construction,* Geography Dept., University of Illinois at Urbana–Champaign, 88–117.

Jones, K. F., 1996: Ice accretion in freezing rain. Cold Regions Research and Engineering Laboratory, Tech. Rep., 96-2, 47 pp.

——, and N. D. Mulherin, 1999: An evaluation of the severity of the January 1998 ice storm in northern New England. Cold Regions Research and Engineering Laboratory Rep. for FEMA Region 1, 38 pp.

——, ——, and C. Ryerson, 1997: EPRI: Freezing rain mapping project: Region 2. Cold Regions Research and Engineering Laboratory Tech. Rep. CR-00020, 55 pp.

Kocin, P. J., 1997: Some thoughts on the societal and economic impacts of winter storms. *Proc. Workshop on Social and Economic Impacts of Weather,* Boulder, CO, NCAR, 55–60.

Mileti, D. S., 1999: *Disasters by Design.* Joseph Henry Press, 123 pp.

National Research Council (NRC), 1999: *The Costs of Natural Disasters: A Framework for Assessment.* National Academy Press, 68 pp.

Rauber, R. M., L. S. Olthoff, M. K. Ramamurthy, D. Miller, and K. E. Kunkel, 2001: A synoptic weather pattern and sounding-based climatology of freezing precipitation in the United States east of the Rocky Mountains. *J. Applied Meteor.*, **40,** 1724–1747.

Shan, L., and L. Marr, 1996: Ice storm data base and ice severity maps. Jones Power Delivery Tech. Rep. TR-106762, 39 pp.

Steenburgh, W. J., F. M. Mass, and S. A. Ferguson, 1997: The influence of terrain-induced circulations on wintertime temperature and snow levels in the Washington Cascades. *Wea. Forecasting,* **12,** 208–227.