Temporal and Spatial Variations of Freezing Rain in the Contiguous United States: 1948–2000

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ABSTRACT

A new freezing-rain-days database was used to define the spatial and temporal distributions of freezing-rain days across the contiguous United States. The database contained 988 stations, spanning the period 1948–2000. Areas averaging one or more days of freezing rain annually included most of the eastern half of the United States and the Pacific Northwest. The national maximum is in portions of New York and Pennsylvania, a result of several weather conditions conducive to freezing rain. Other maxima included an east–west zone across the Midwest, an area along the eastern Appalachians, and the Pacific Northwest. The latter two maxima have high frequencies as a result of the mountains, which trap low-level cold air with warm air moving above, resulting in freezing rain. National maximum annual values during 1948–2000 were 3–5 times as great as annual averages, but the two patterns were similar. Average patterns for three discrete 17-yr periods between 1948 and 2000 were very similar, but the magnitudes of values differed greatly between periods. The earliest period, 1948–64, had many more freezing days than the latter periods. The high early values resulted in significant down trends for 1949–2000 in the Northwest, central, and Northeast regions. The 1965–76 period had the lowest frequency of freezing-rain days during 1949–2000. Months of first freezing-rain occurrences ranged from September to December, with November the predominant month in the eastern United States and October in the West. Months of last freezing events shifted latitudinally, with February being last along the Gulf of Mexico and April being last in the northern half of the United States. Nationally, peak months of freezing-rain days are December and January, and both have similar patterns. January averages are highest in the eastern half of the United States, and those in December are highest in the west. Freezing-rain days in these two months are more than one-half of those experienced each year in much of the United States.

1. Introduction

The spatial distribution and frequency of freezing-rain events has long been a topic of study because ice storms are so damaging to property and the environment. Insured property losses from ice storm catastrophes average $326 million (in 2000 dollars) annually (Changnon 2003a). Major damages also occur to the natural and planted environments. For example, a January 1998 ice storm in northern New England caused tree damages estimated at $1 billion (President's Long-Term Recovery Task Force 1998).

Problems caused by freezing rain have led several groups and individuals to address the regional and national distributions of freezing rain. Those who have pursued studies of freezing rain include the military, the communications industry, the railroads, weather forecasters, and the electric power industry. Review of the results of numerous studies of freezing rain and related conditions (freezing drizzle and sleet) reveals three major limitations from a climatological perspective.

First, some studies based their spatial analysis of freezing rain (FZRA) events on data from first-order stations (FOS). These stations are too few to adequately define important features in the average or extreme patterns of FZRA across the United States. The *Climate of the U.S.* (Baldwin 1973) used data from only 95 FOS for the 1950–69 period to develop the average pattern for the United States. Several other climatological studies have also used FOS data (Bennett 1959; Tattleman and Gringorten 1973). In an effort to define the average patterns of FZRA occurrences in greater detail than offered by FOS, Konrad (1998) devised an empirical relationship between surface temperatures and FZRA events, as measured at 23 FOS in the Appalachian region, to estimate FZRA occurrences at the more numerous cooperative substations in the region. This study showed greater detail in the shape of the average pattern

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and in magnitudes of values than those based on the 23 FOS. However, actual FZRA occurrences, as extracted from quality data of cooperative substations across the United States and described in this study, have provided the detailed spatial patterns of actual FZRA events on a national scale, not just those based on proxy frequencies.

A second data problem found in past studies concerns the use of record lengths too short to adequately define the average and extreme patterns of FZRA events. Bennett's (1959) study of freezing rain addressed the U.S. spatial climatology using three different datasets. One dataset was from a 9-yr special study by U.S. railroads, another used Weather Bureau reports of damaging ice events as collected over a 28-yr period, and the third employed FZRA-days data from FOS for a 10-yr period. The railroads established a nationwide observation system for 9 yr (1927–36), using their numerous extensive staff members as FZRA observers across the United States (Hay 1956). Cortinas (2000), in a climatological assessment of FZRA around the Great Lakes, employed 15 yr of FOS data. These data are reliable but simply too short to adequately define the average spatial frequencies. Several other studies relied on FOS data or information from *Storm Data*, but only for short, 10- to 20-yr periods (Vilcans and Burham 1989; Robbins and Cortinas 2002).

Third, several risk-based studies have used data of questionable quality for defining climatological descriptions of freezing rain. For example, the FZRA loss information presented in *Storm Data* and its predecessor publications (National Climate Summary and Monthly Weather Review) has well-known shortcomings. These include the fact that most of the information comes from untrained observational sources, and there is no concern for continuous quality observations of FZRA at a given site (Branick 1997). Unfortunately, information from *Storm Data* is incomplete for many states and is simply inadequate for defining the climatology of many conditions like FZRA (Changnon 1997). Regardless, Tattleman and Gringorten (1973) used information from *Storm Data* and the prior (pre-1959) storm-loss records of the Weather Bureau to assess U.S. ice storm climatology for the 1920–69 period, but they carefully described the limitations of the data used. Shan and Marr (1996) developed an ice storm climatology for the United States for utilities using only information from *Storm Data*.

Others have developed FZRA databases that can be used to estimate ice accretion on structures. One used FOS hourly data on FZRA, associated winds, and rainfall (Jones et al. 1997) as input to an ice accretion model, a potentially reasonable approach for assessing point risk, but one considered inadequate for defining the spatial variability of FZRA. A recent model-based assessment of ice loads led to the mapping of once-in-50-yr load levels in the United States based on FOS data (Jones et al. 2002). In summary, none of the aforementioned studies had the data considered adequate to define the spatial climatology of FZRA across the United States. Furthermore, none of the aforementioned studies addressed the temporal distributions of FZRA.

A new dataset based on the days with FZRA, as measured at all FOS and at hundreds of cooperative substations of the NWS in the 48 contiguous states, has been created. The historical data for the 1948–2000 period have undergone rigorous evaluation procedures to determine which stations in the United States had quality data (Changnon 1967, 2001). This database provides two ingredients that past studies lacked: 1) highly reliable FZRA values collected over a long period (53 yr) and 2) quality data in a dense spatial array. Thus, both the temporal and spatial aspects of freezing-rain-day distributions and their associated design-related risks could be adequately addressed.

2. Data and analysis

A project to delineate weather stations with quality FZRA data has been completed (Changnon 2002). The study did not include analysis of freezing-drizzle data. This study first identified cooperative substations with quality records during the 1948–2000 period, and most were found in the area where FZRA averages are at least 1 day every 10 yr. Most of the western third of the United States has very low FZRA-day frequencies, and parts of Arizona, Nevada, and southern California had no FZRA occurrences during 1948–2000. The cooperative substation observers were asked by the Weather Bureau to begin recording the occurrences of FZRA during the late 1940s, and these volunteer observers over the 1948–2000 period may or may not have done a good job of recording days when FZRA occurred. Thus, a three-step method for assessing the quality of substation records of ‘‘days with’’ data, which includes FZRA, thunder, hail, and high winds, was used to assess the historical records of the long-term substations in each state (Changnon 1967). Data for more than 2500 substations were evaluated, and 755 were found to have quality records of 20 or more years.

The data evaluation also included FOS data. These data were also assessed for discontinuities using the Easterling and Petersen (1995) process, which is based on a two-phased regression scheme using neighboring stations to detect discontinuities. A similar evaluation process was used to determine high-quality FOS thunder-day data (Changnon 2001). Quality FZRA records were found for 233 FOS, and most had complete FZRA data for the 1948–2000 period. These also are part of the new national FZRA-day database, which contains data for 988 stations for the 1948–2000 period, and their locations are shown in Fig. 1. Most stations are in the areas where FZRA occurrences are most common—east of the Rockies and in the northwestern United States.

Analysis included calculation of the 53-yr average number of FZRA days, as well as averages for shorter

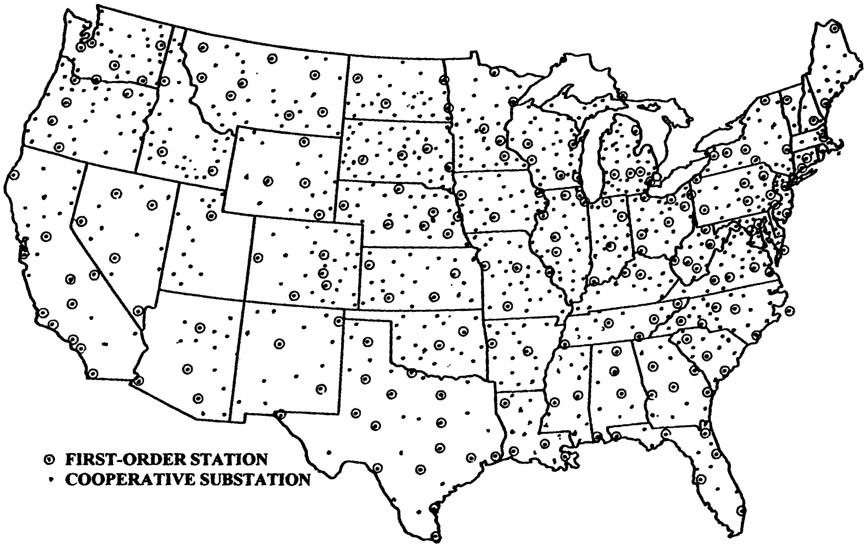

FIG. 1. Stations with quality freezing-rain-day data during the 1948–2000 period.

periods used to assess temporal variability. Variability was assessed for relatively long periods and relatively short periods. The variability over extended periods was based on averages for three separate 17-yr periods during 1948–98, and that for short-term variations was based on values for the thirteen 4-yr periods during 1949–2000. This short-term analysis involved examination of FZRA-day frequencies for the seven climate regions of the nation, as defined by the National Climatic Data Center, where FZRA is most common. All stations with quality data in each district were used to calculate a region-wide average FZRA value for each 4-yr period. These averages were expressed as percentages of the 52-yr average, allowing meaningful intercomparions of regional distributions.

The FZRA season was delineated by defining the months when FZRA first occurred in the autumn and those when FZRA last occurred in the winter or spring. The available involved FZRA counts per month, not dates of each event. The pattern based on the months of maximum average FZRA occurrences is also presented. The average FZRA patterns for the prime months of activity were determined, along with the pattern based on the maximum 1-yr total of FZRA days during 1948–2000.

3. Annual frequencies

a. Average pattern

The pattern of the average annual frequency of FZRA days for 1948–2000 (Fig. 2) reveals that, except for the Pacific Northwest, most FZRA activity in the contiguous United States occurs east of the Rocky Mountains. The pattern has several notable features, including five high-incidence areas. These include:

1) an area of >5 days from eastern Missouri into Pennsylvania,
2) an area >4 days from North Carolina to Maine,
3) two isolated areas with >5 days in western Iowa and Minnesota,
4) an area >4 days in the Columbia River basin, and
5) a high of >7 days in and south of the Adirondack Mountains of New York.

The incidence of FZRA decreases rapidly westward across the High Plains with north–south-oriented isofrequency lines from Texas to North Dakota and Montana. Similarly, FZRA frequencies from North Carolina to Massachusetts sharply decrease from inland locations to the shore areas along the Atlantic coast. Another interesting feature relates to the fact that there are regions in the southwest and Florida where no FZRA has occurred. Last, the pattern around the Great Lakes suggests that decreases in FZRA days occur to the west of certain lakes.

The average pattern has several small-scale variations, tight gradients, and important highs and lows detected solely by the data from the cooperative substations, for example, the low-incidence areas of <3 FZRA days along the west side of Lake Michigan, the >5 day areas in western Iowa and Minnesota, the isolated area of >3 days in West Virginia, the two areas of >6 days in the Northeast, and the tight gradient of FZRA days in west Texas. These, and most of the elongated east–west area of >5 days from Missouri to Pennsylvania, were detected solely by substation data and would not appear on a pattern based only on the data from the 233 FOS. Hence, this average pattern is quite varied and, thus, different than those in earlier climatological studies of FZRA (Bennett 1959; Tattleman and Gringorten 1973; Baldwin 1973).

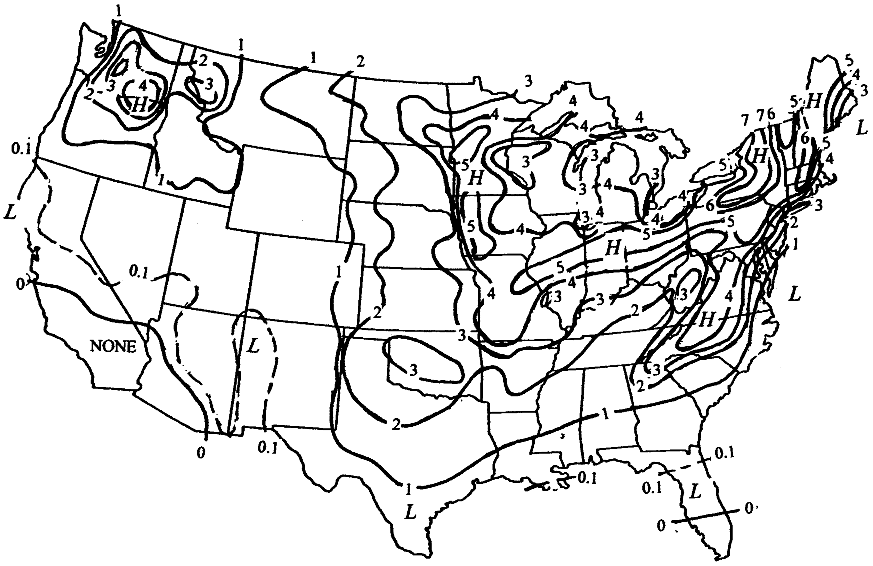

FIG. 2. The average annual number of days with freezing rain, based on 1948–2000 data.

The average pattern of FZRA reflects the varying causes of freezing rain. Freezing rain occurs when raindrops descend into a near-surface layer of air that has below-freezing temperatures. Two different atmospheric processes create FZRA in the United States. Freezing rain in most areas occurs as precipitation generated in snow melts in an elevated layer of warm, moist air, present as a result of overrunning, above more dense, cold air at the surface (Bennett 1959). This situation is often caused by strong baroclinic systems that advect low-level warm, moist air over a shallow layer of subfreezing air at the surface (Cortinas 2000), and this situation is frequently found north of a warm or stationary front or near a low pressure center (Rauber et al. 2000). Another circumstance causing FZRA occurs when near-surface cold air becomes dammed, or trapped, by mountains as warm, moist air passes overhead. The frontal overrunning process occurs in almost all parts of the nation under four synoptic conditions (Rauber et al. 2001), whereas the damming condition is restricted to the mountainous areas of the East Coast (from Georgia to Maine).

The typical winter condition with colder air to the north across the High Plains, Midwest, and Northeast, coupled with frequent frontal activity that advects warmer, moist air aloft, cause this region to experience frequent FZRA (Fig. 2). This situation, coupled with the damming of air on the east side of the Allegheny Mountains and the trapping of cold air in the valleys, creates the national maximum of freezing-rain days found in the New York–Pennsylvania region.

The lack of moisture in most winter air masses over the Great Plains and Rocky Mountains, for example, low dewpoints, limits FZRA production (Rauber et al. 2000). There is an abrupt decrease of FZRA westward across the High Plains shown to occur because of the absence of the necessary thermal structure with cloud tops colder than $-10°C$ not present (Bernstein 2000). This leads to the north–south-oriented isofrequency lines in the plains (Fig. 2). The lack of cold air intrusions into the Southwest and deep South keeps the number of FZRA days extremely low.

A variety of forecast-oriented studies of weather conditions associated with FZRA occurrences provide explanations for the major features found in the average freezing-rain-day pattern. Analysis of the vertical distributions of atmospheric conditions, as based on soundings, associated with FZRA and/or FZDZ events revealed six thermodynamic structures conducive to the formation of freezing rain or freezing drizzle (Rauber et al. 2000). Three types related to moist air overrunning Arctic fronts all led to freezing rain, but, usually, freezing drizzle rather than FZRA in the High Plains. One of these types produce most FZRA events in the deep South.

The high frequency of FZRA days found in western Iowa and Minnesota is largely a result of FZRA produced in the western quadrants of Arctic high pressure centers where southerly flow of warm air occurs (Rauber et al. 2001). This area of the United States also experiences a relatively high frequency of low pressure centers during December when these peaks of FZRA days occur (Morgan et al. 1975).

Advection of warm air over warm or stationary fronts is the major cause of FZRA in the Midwest (Rauber et al. 2000). The west–east-oriented maximum of FZRA days from Missouri into Pennsylvania (Fig. 2) is closely aligned with a maximum in the number of warm fronts in winter (Morgan et al. 1975).

Most FZRA events in and east of the Appalachian Mountains, which stretch from northern Alabama to northern Maine, are caused by synoptic weather patterns

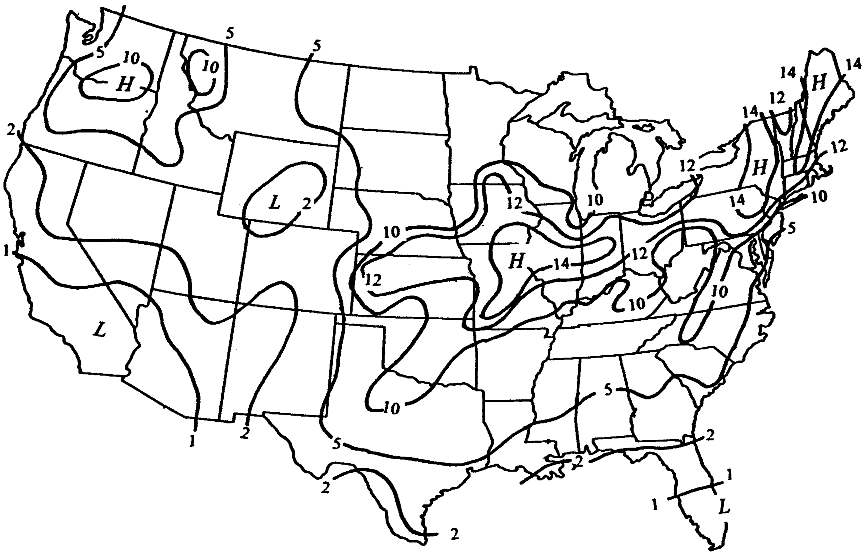

FIG. 3. The pattern based on the maximum number of freezing-rain days recorded in any year between 1948 and 2000.

that interact with the mountains (Rauber et al. 2000). One situation involves cold-air damming with the passage of an Atlantic cyclone that is responsible for feeding warm moist air over the trapped cold air, and is responsible for many FZRA events in the central and southern Appalachians and the Piedmont. The other situation occurs most often in the northern Appalachians and when eastward-moving cyclones bring warm air over cold air trapped within the Appalachians, particularly in their eastern sector. Thus, the high-frequency FZRA areas in the New York–New England area have all these conditions plus FZRA from occasional frontal overrunning.

The high frequency of FZRA days in the Pacific Northwest lies within the Columbia Plateau, an area typically containing cold air in the winter and protected from the warmer marine air to the west by the Cascade Mountains. When low pressure centers approach the coast, warm, moist air is advected into the plateau ahead of warm or occluded fronts (Bernstein 2000). This often leads to the trapping of the surface cold air in the plateau and in the valleys of mountains that ring the plateau, resulting in FZRA (Steenburgh et al. 1997). Placement of the FZRA events depends on wind directions, and normally the FZRA is short lived because the warm marine air rather quickly modifies the trapped below-freezing air (Steenburgh et al. 1997).

The average FRZA pattern (Fig. 2) exhibits low-frequency areas, values less than 3 days, west of Lake Michigan and Lake Erie, revealing the Great Lakes exert an influence on conditions that produce FZRA. Cortinas (2000) noted that areas to the west of Lake Michigan, and south of Lake Erie and Lake Ontario had fewer FZRA events than locales farther inland, indicating these localized decreases were due to the fact that the relative warm lake waters, particularly in autumn and early winter, acted to warm passing cold air masses sufficiently to stop the formation of freezing rain. Small-scale features not easily discernible on the national average pattern (Fig. 2), but which exist, are lower averages in the metropolitan areas of New York City, New York; Chicago, Illinois; St. Louis, Missouri; and Washington, D.C. These result from the influence of the urban heat islands, which act to modify cold surface air and restrict some cases of FZRA, which occur around but not within the city (Changnon 2003b).

b. Patterns based on extremes

The station records were used to determine the annual maximum and minimum values. The minimum annual values were zero at most stations in the United States. However, in the high-incidence areas of New York and New England where annual averages exceed 5 FZRA days, the minimums were 1 or 2 days. Two stations in Illinois had minima of 1 day for the 1948–2000 period.

Figure 3 presents the pattern of FZRA days based on the maximum number recorded in any year between 1948 and 2000. As might be expected, the shape of the maximum-day pattern is similar to that based on annual averages. In general, the maximum values at a point were 3–5 times as great as their averages. The 5-day isofrequency line on the maximum pattern closely matches the position of the 1-day line on the average pattern (Fig. 2). However, there are some interesting differences between the maximum and average patterns. A high-incidence area with values of 12 or more FZRA days extends across Nebraska and Kansas, where annual averages are 2–3 days yr^{-1}, and eastward through the Midwest and to Maine where 53-yr averages are high.

Parts of Illinois–Missouri had 14 days, which matched the highest values recorded in the New York–Pennsylvania area. Because the Midwest averages were less than those in New York, this finding reflects greater year-to-year variability of FZRA days in the Midwest. The peak in the maximum values in the central and southern Appalachian Mountains, as compared with surrounding lower-elevation values, is relatively less than the mountain's peak average FZRA-day values.

c. Temporal patterns

Patterns were developed based on the averages from the three 17-yr periods during 1948–98 to assess temporal fluctuations over extended periods (Figs. 4a–c). Comparison of these patterns consisted of assessing their pattern shapes and the magnitudes of FZRA days. Their overall shapes, as defined by the 1-day values, and the location of the major areas of high occurrences, reveal considerable similarity. Each pattern has east–west highs in the Midwest, a north–south high along the Alleghenies, and a high in the Northwest. The locations of their three 1-day isolines are amazingly similar. However, the highs in western Iowa and Minnesota were not apparent in the 1948–64 period (Fig. 4a). The lake-related lows in the lee of the Great Lakes (Fig. 2) are also not evident in all three 17-yr periods.

The patterns were similar but the magnitudes of FZRA days varied considerably between periods. The 1948–64 period (Fig. 4a) had relatively high averages, and, as shown in Fig. 4d, most stations east of the Missouri River and in the Northwest had their highest averages in this first period. Values during the 1965–81 period (Fig. 4b) were much lower than those for 1948–64. Several stations in the Northwest and in the upper Midwest (such as South Bend, Indiana, Madison, Wisconsin, and Detroit, Michigan) had averages 50% lower than in the first period. However, averages in the middle 17-yr period did rank as the highest of the three periods at locations in the southeastern United States (Piedmont), southern Texas, and in the upper Great Lakes (Fig. 4d).

Averages in the third period, 1982–98 (Fig. 4c), were generally higher than those in the middle period. The third-period averages that ranked as the highest of the three periods occurred across the High Plains, in the central-southern Rockies, and in parts of the western Appalachians (Fig. 4d).

The FZRA-day magnitudes of the three periods were further compared by measuring the areal extent of areas experiencing averages of different magnitudes. For example, the 1948–64 period had averages of four or more FZRA days over 1 606 800 km^2, and, as shown in Fig. 4a, these areas occurred in the Northwest, the upper Great Lakes, and from Oklahoma eastward across the Midwest and throughout New England. The 1965–81 period experienced 4-day or higher averages over 521 000 km^2, only 32% of the area in the 1948–64 period. Only parts of the Midwest and the Northeast had four or more FZRA-day values. The third period, 1982–98, had 4-day or higher averages across 644 700 km^2, which is 40% of the first period value. Regions with averages of four or more days occurred in the Midwest and covered the Northeast.

The comparative results show major differences in the frequencies of FZRA days between the three periods, but their major pattern features are similar. Their magnitudes suggest a U-shaped national distribution with time, with the right side of the U less than the left. They further illustrate that short-period averages of FZRA occurrences can produce values unrepresentative of the long-term average.

d. Temporal distributions

Assessment of short-term temporal distributions in FZRA days for each climate region was pursued using FZRA frequencies for each 4-yr period beginning in 1949–52 and ending with 1997–2000. The even number of periods (4 yr) led to 48 yr, and we arbitrarily began with 1949, not 1948. The analysis focused on the seven climate regions (Changnon 2003a), as defined by the National Climatic Data Center, that cover the eastern two-thirds of the United States and the Northwest, areas where FZRA occurs at least 1 day yr^{-1} on average. Figure 5 depicts the regional curves for the Northeast (NE), Southeast (SE), and South (S) regions, each revealing numerous fluctuations over time. Also shown for each region are the point-average annual frequencies of FZRA days. Their overall 52-yr distributions are W-shaped with a midperiod peak when all regions had high values during 1977–80. Linear trends for 1949–2000 for these regional values were all downward over time, but only the NE had a trend significant at the 5% level.

The 1949–2000 distributions of FZRA-day values for the central (C), west–north-central (WNC), and east–north-central (ENC) climate regions are alike (Fig. 6). They have high values in 1949–56, followed by lower values through 1988. These three regions had 52-yr linear trends that were downward over time, and those for the C and ENC regions were statistically significant at the 5% level, a result of their high early values. The FZRA distribution for the Northwest (NW) region was similar with high early values and low midperiod values. These findings with high FZRA frequencies during 1949–56 and lower ensuring values, are reflected in the major regional changes shown for the Midwest and Northwest from the 1948–64 pattern (Fig. 4a) to that for 1965–81 (Fig. 4b).

The periods with the highest and lowest 4- and 12-yr values during 1949–2000 were identified for each climate region and are listed in Table 1. This shows that the lowest 4-yr values occurred either in 1965–68 (C, WNC, NW), or during 1973–76 (ENC, SE, S, NE), revealing considerable large-scale coherence in these extremes. The peak 4-yr values came during 1949–52 for five of the seven regions. The regional differences

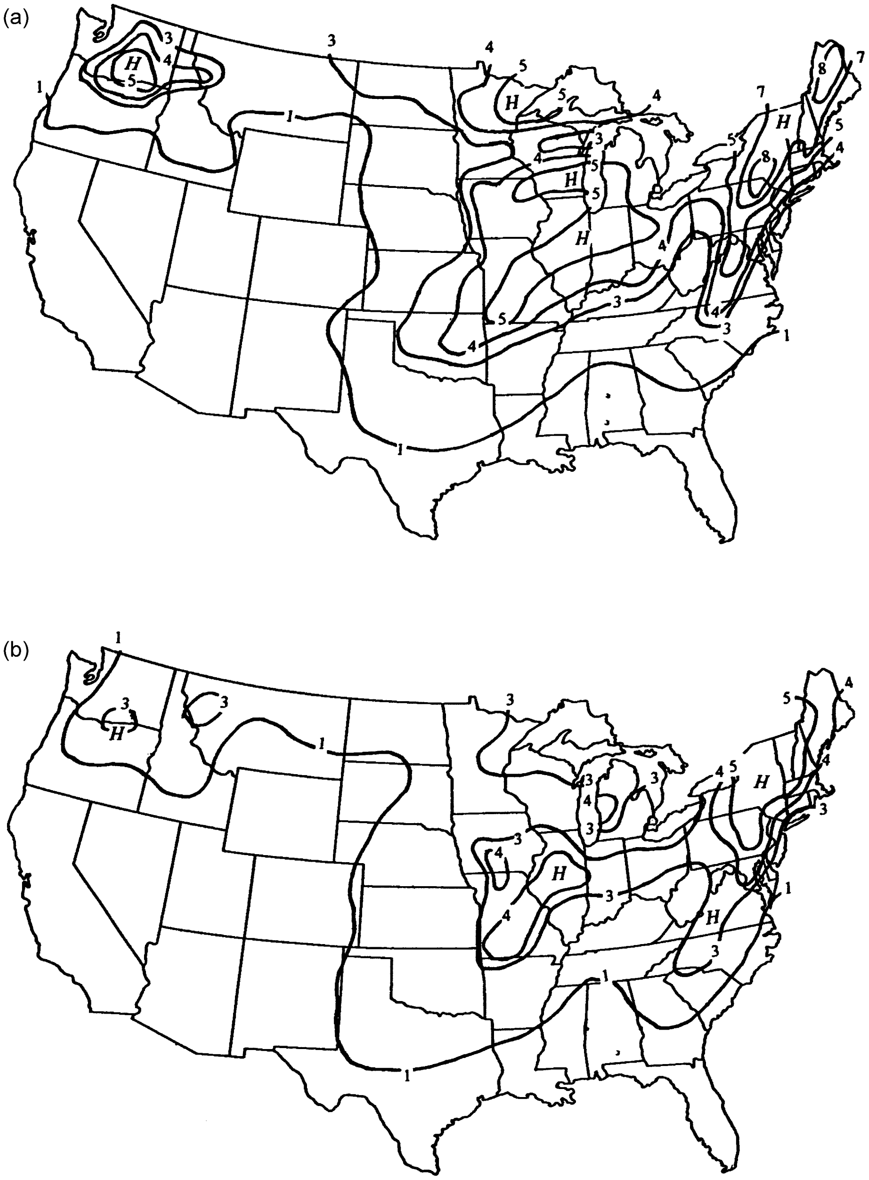

FIG. 4. Patterns of the average number of freezing-rain days for three 17-yr periods: (a) 1948–64, (b) 1965–81, and (c) 1982–98. (d) Pattern based on the 17-yr period with the highest averages.

between the highest and lowest 4-yr values range between 2 and 6 times. The peak 12-yr periods also showed widespread spatial agreement (Table 1). The highest values in the WNC, ENC, C, S, and NE regions occurred during 1949–60 with different peak periods only in the SE and NW. The lowest 12-yr FZRA values occurred during 1965–76 in all regions except the SE where the 1985–96 period rated lowest. The range between the highest and lowest values was varied between 1.6 and 2.2, revealing the considerable temporal differences in FZRA occurrences and risk of damage.

Examination of the 52-yr distributions shown in Figs. 5 and 6 reveals other similar temporal fluctuations among many regions. For example, the 1981–84 period has relatively high values in the SE, NE, and C (most of the eastern half of the United States), and the ensuing 1985–88 period has low frequencies for all regions embracing the eastern two-thirds of the United States. Further, most regions had relatively high FRZA frequencies in the latest two periods embracing 1993–2000.

The findings from this analysis of the short-term fluctuations in FZRA occurrences during 1949–2000 support the findings from the three 17-yr periods. That is, the highest values occurred early and the lowest during the middle years of the 52-yr period. Linear trends of distributions were found to be significantly downward in the NW and Midwest (C, ENC, WNC regions), but trends for the other regions were flat over time. Periods

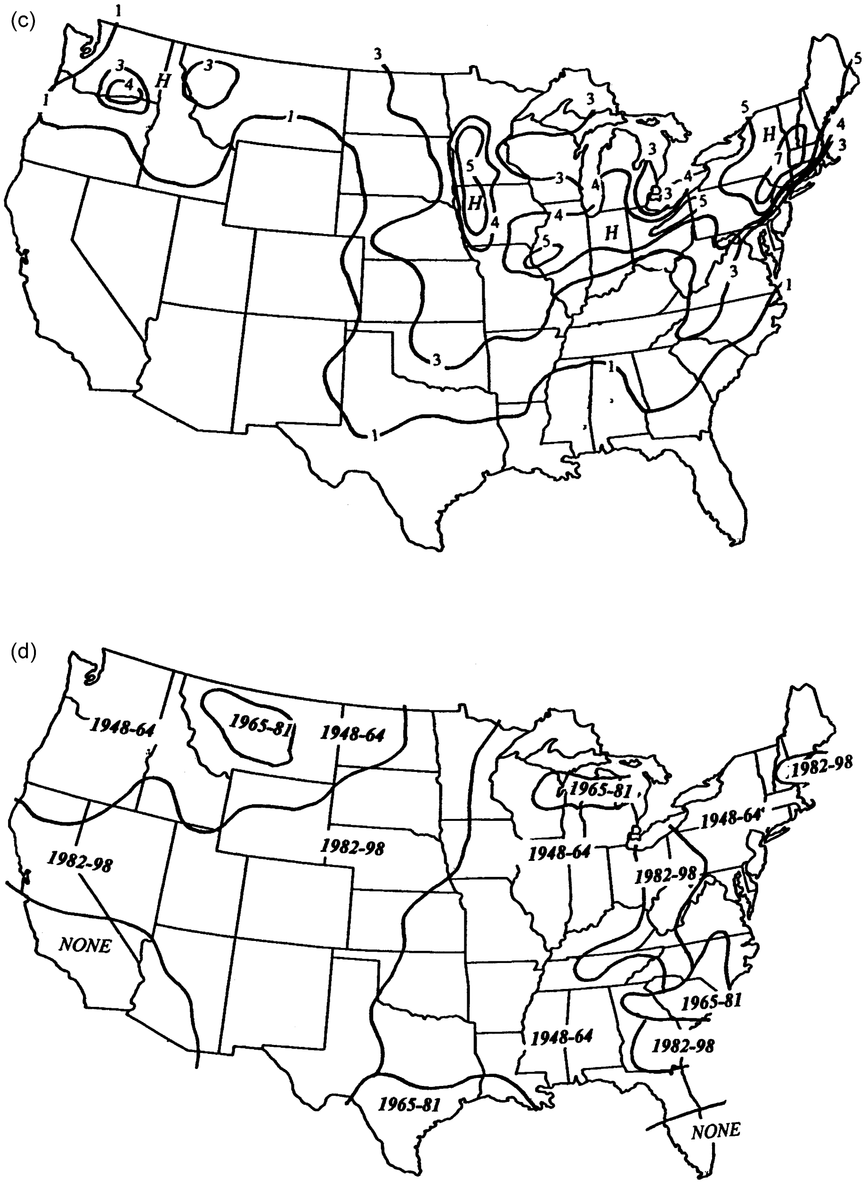

FIG. 4. (*Continued*)

when extremely high and low values occurred revealed widespread spatial agreement, revealing that atmospheric conditions leading to FZRA embrace large sections of the country over periods of years. The 1965–76 period had the lowest frequency of FZRA days in all climate regions except the SE, and the 1949–60 period had the highest frequencies in all regions except the NW (1953–64) and SE (1961–72).

4. Monthly frequencies

The months of the first and last occurrences of FZRA days in the cold season, which define the season of FZRA occurrences, were determined using the 53-yr record for each station. Recall that most of the western fourth of the United States rarely experiences FZRA. Figure 7 presents the pattern based on the first month of the cold season with FZRA occurrences. The autumn season becomes the period when the first FZRA occurs over most of the United States. October is the earliest month of FZRA in a large wedge-shaped area embracing the Great Plains and eastern Rockies, and at few sites in the northern portions of the New England. However, a few stations in isolated locales like Buffalo, New York, and Great Falls, Montana, had their first FZRA in September. Much of the eastern half of the United States experienced its earliest day during November. November is also the earliest month of FZRA in portions of

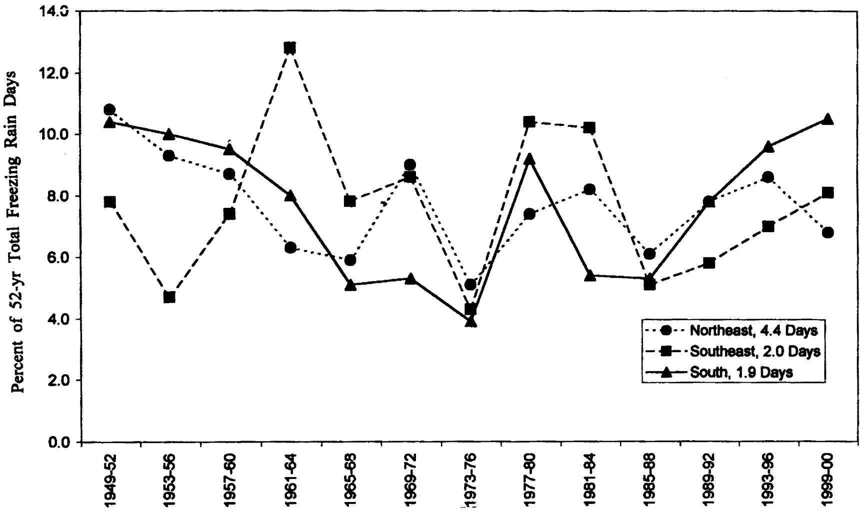

FIG. 5. Curves depicting the temporal fluctuations in frequencies of freezing-rain days in the Northeast, Southeast, and South climate regions. Values for each 4-yr period are percent of the 1949–2000 total number of freezing-rain days for each region. The average annual point frequency of freezing-rain days is listed for each region.

the Pacific Northwest, plus in the western intermontane basin and New Mexico. Many stations in the Southeast had their earliest FZRA a month later, in December. An area centered on Utah and portions of northern California also experienced their first day in December.

The months of latest occurrences of FZRA days (Fig. 8) exhibit a more latitudinal distribution than did the pattern based on the earliest months. January qualifies as the last month in the low-incidence areas of Arizona and New Mexico. February was the last month with FZRA across the southern edge of the United States from Texas to Florida, and also in portions of the west centered on southern Oregon and Idaho and around the Puget Sound. March was the last month of FZRA days in most of the Pacific Northwest, in an area that stretches across the eastern intermontane basin, and in a broad belt from Texas eastward to North Carolina. December had both the first and last FZRA days in northern California, reflecting the fact that FZRA only occurred there in December.

April is the month with the last FZRA occurrences over much of the United States. April as an ending month included those areas with the highest annual average FZRA days, which includes the Midwest and the Northeast. Some FZRA days occurred as late as May

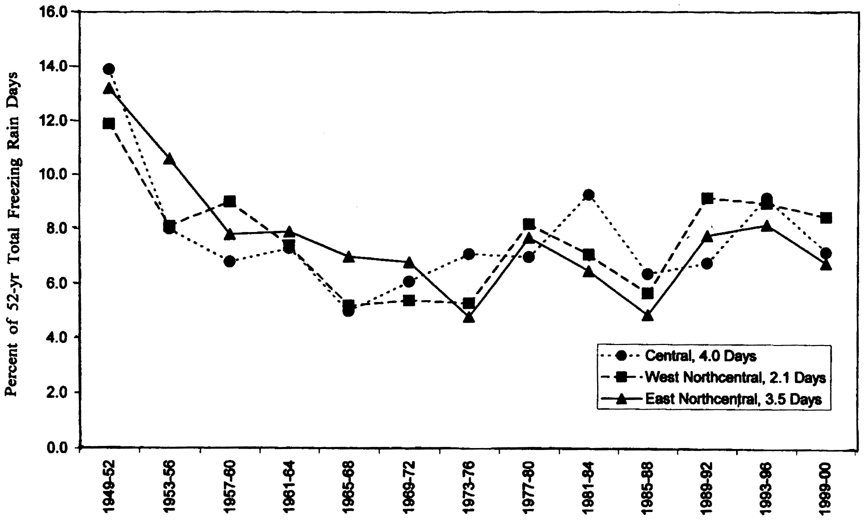

FIG. 6. Curves depicting the temporal fluctuations in frequencies of freezing-rain days in the central, west–north-central, and east–north-central climate regions. Values for each 4-yr period are percent of the 1949–2000 total number of freezing-rain days for each region. The average annual point frequency of freezing-rain days is listed for each region.

TABLE 1. The highest and lowest 4- and 12-yr frequencies of freezing-rain days during the 1949–2000 period for seven climate regions where the average annual frequency of FZRA days is 1 day or more at a point. The frequencies are expressed as percentages of the 1949–2000 total values.

	Highest period and value		Lowest period and value	
Climate region	4-yr*	12-yr**	4-yr*	12-yr**
Northeast	1949–52, 10.8%	1949–60, 28.5%	1973–76, 5.1%	1965–76, 18.2%
Southeast	1961–64, 12.8%	1961–72, 29.1%	1973–76, 4.3%	1985–96, 17.9%
South	1949–52, 10.5%	1949–60, 29.9%	1973–76, 3.9%	1965–76, 14.3%
Central	1949–52, 13.9%	1949–60, 28.7%	1965–68, 5.0%	1965–76, 18.3%
West–north central	1949–52, 11.9%	1949–60, 29.0%	1965–68, 5.2%	1965–76, 18.2%
East–north central	1949–52, 13.2%	1949–60, 31.6%	1973–76, 4.8%	1965–76, 18.6%
Northwest	1957–60, 13.2%	1953–64, 31.9%	1965–68, 2.2%	1965–76, 14.3%

* If 4-yr values were evenly distributed over 1949–2000, 7.7% would occur in each 4-yr period.

** If the 12-yr values were evenly distributed over 1949–2000, 23.1% would occur in each period.

in certain northerly areas and portions of Wyoming and Colorado where late-season winter storms occur. Although the FZRA season in these areas theoretically extends from October to May, FZRA rarely occurs there in most months (Fig. 2). The peak areas of FZRA activity—the Midwest, Northeast, and Appalachians—have FZRA seasons lasting approximately 6 months (November–April), and the Pacific Northwest high has about a 5-month season (November–March). Most of the United States has shorter seasons of freezing rain, revealing that the higher frequencies are usually related to a longer season and the greater opportunity for occurrences.

The average number of FZRA days was assessed for each month to determine each station's peak monthly value. These maximum months were plotted and the resulting pattern (Fig. 9) reveals the January averages are highest over most of the eastern half of the United States and in the Pacific Northwest. The December averages are highest in much of the western half of the United States, although small areas exist that differ with peaks in January or in October (Wyoming). March averages are the highest at stations in the upper Great Lakes.

Figure 10 presents patterns based on the average monthly number of FZRA days for the two top-incidence months, December and January. Patterns for both months are alike in that they have high-incidence areas in the same locations: the Midwest, Appalachians, and Pacific Northwest. The Iowa–Minnesota high-incidence area achieves its peak in December, a time of frequent low passages and Arctic fronts in the plains (Rauber et al. 2001). Otherwise, most areas of high incidence based on the annual averages (Fig. 2), experienced slightly higher monthly averages in January than in December. For example, the 1.5-day area extends from Missouri to Pennsylvania in January, but is small and only found in Illinois–Indiana in December. The area of 2 days or more exists in New York and Pennsylvania in January, but is much smaller in December. The greater frequency of Arctic air masses and their penetrations into the cen-

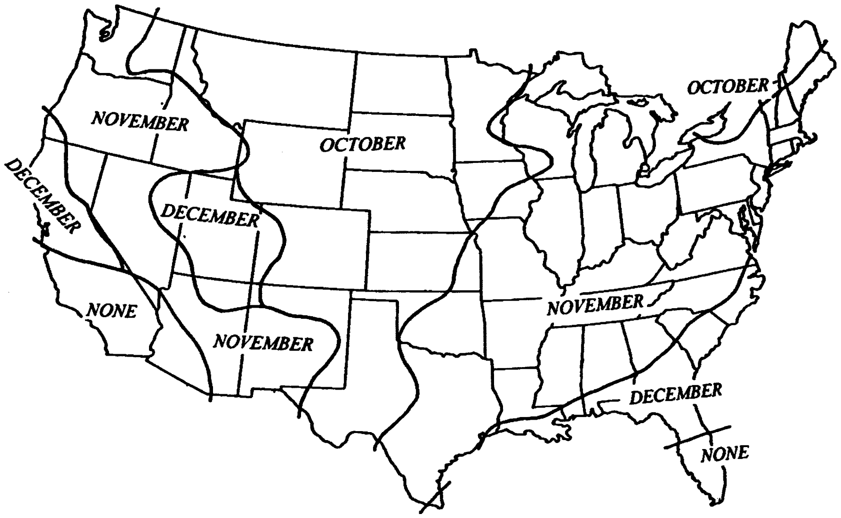

FIG. 7. The pattern based on the month of earliest occurrences of freezing rain during 1948–2000.

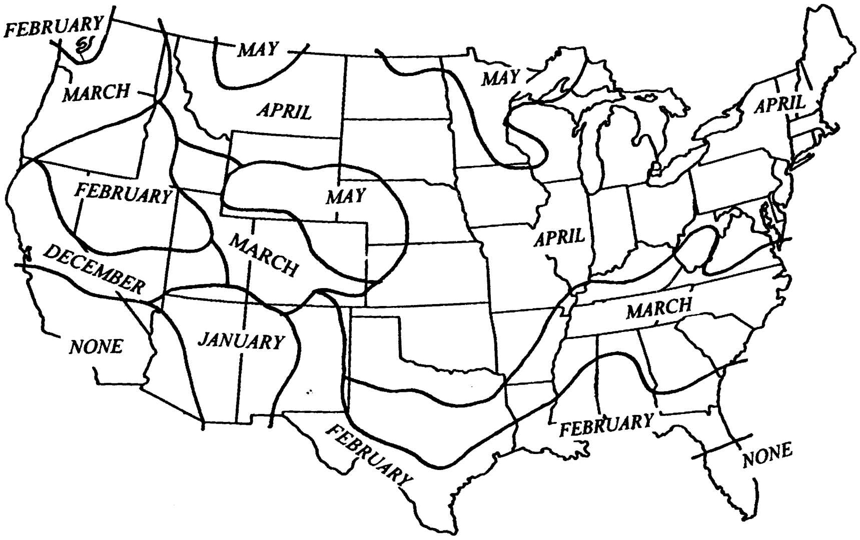

FIG. 8. The pattern based on the month of latest occurrences of freezing rain during 1948–2000.

tral and southern areas of the United States during January help to explain these differences.

The December plus January FZRA days represent a good portion of the total FZRA experienced in the United States. The 2-month values exceed 50% of the seasonal total days in all areas west and south of the northern Great Plains and northern Midwest, as shown in Fig. 9. In most of the Midwest and the Northeast, the December–January total FZRA days are more than 60% of the seasonal totals, and in the Southwest and the southern end of the Appalachians, the 2-month values represent >70% of all FZRA days. The 2-month FZRA-day total was 35%–50% of the yearly total in the area north of the line shown in Fig. 9. The northern plains and Minnesota are where relatively high FZRA occurrences exist in November and March.

The average frequency of FZRA days in February (not shown) ranks as the third highest monthly value in most of the United States. However, in the deep South, from east Texas to eastern North Carolina, February values rank second behind those of January. The prominent FZRA highs in the Pacific Northwest and southern Appalachians in December and January, are much less evident in February.

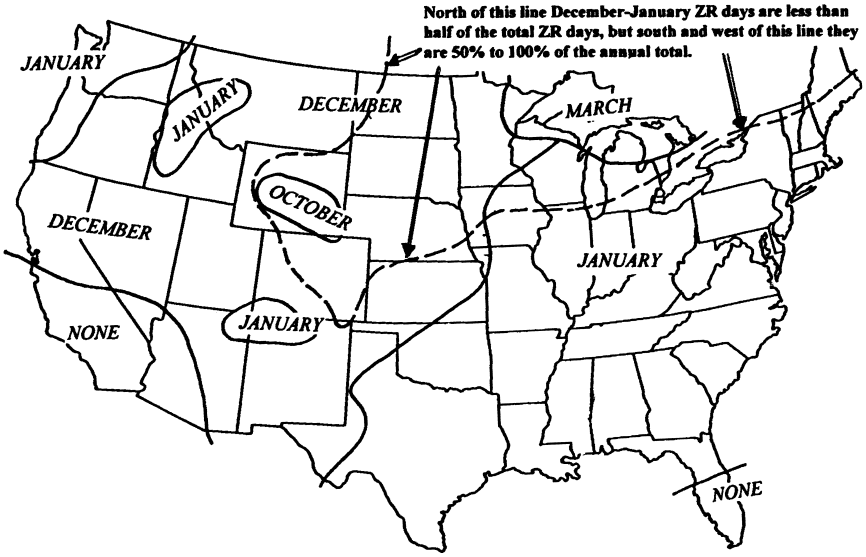
North of this line December-January ZR days are less than half of the total ZR days, but south and west of this line they are 50% to 100% of the annual total.

FIG. 9. The pattern based on the months with the highest monthly average number of freezing-rain days.

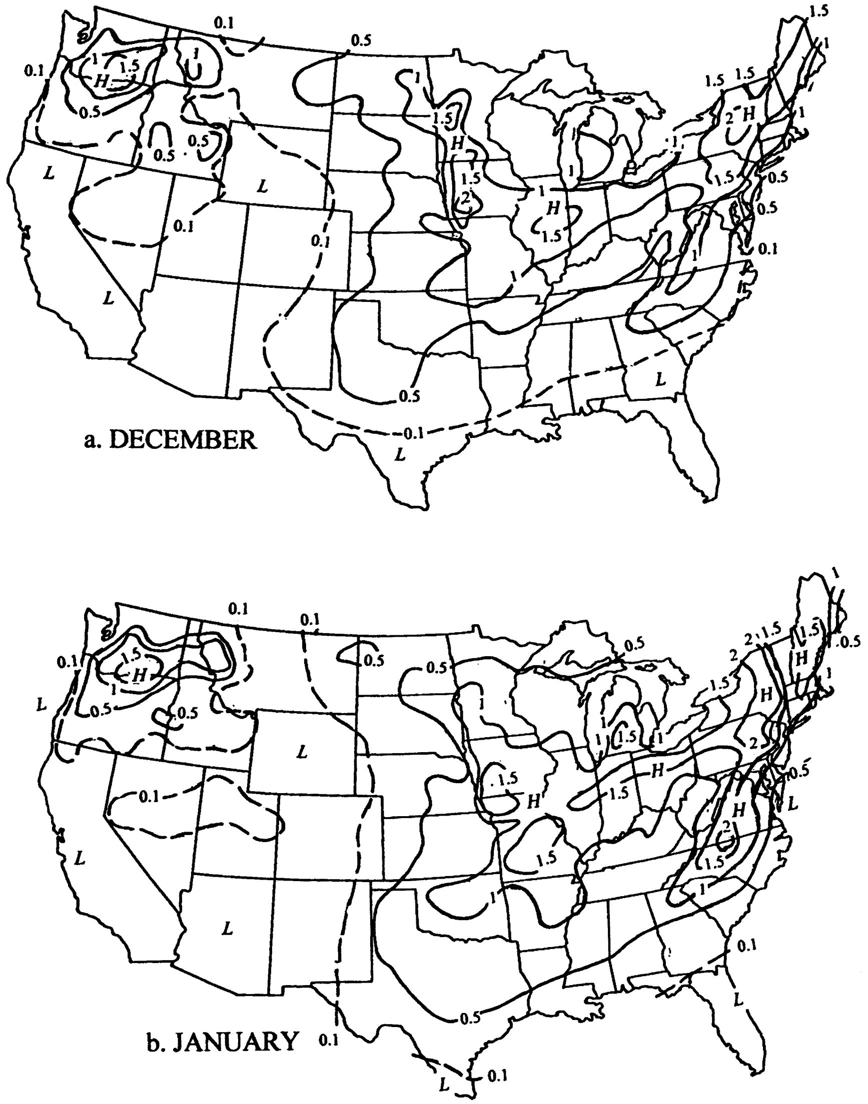

FIG. 10. Patterns of the average monthly number of freezing-rain days for (a) December and (b) January.

5. Summary and conclusions

The national spatial distributions of freezing-rain days were developed using a newly available database for the 1948–2000 period. The resulting findings are considered more climatologically representative than prior climatic assessments of FZRA as a result of two factors: (a) the long duration of data, 53 yr, and b) the greater density of point observations (988) than are available for prior climatological studies of FZRA. The resulting patterns of average and extreme FZRA-day values revealed considerably spatial variability across short distances plus important distributional features that go undetected if only FOS data are used (Bennett 1959; Tattleman and Gringorten 1973; Branick 1997). For example, an elongated zone with annual averages of 5 days or more extends from Missouri to western Pennsylvania, and this maximum was almost totally defined by values from cooperative substations. The >5-FZRA-day averages in western Iowa and Minnesota are based solely on substation data. Hence, past climate studies, like those of Baldwin (1973) and Eagleman (1983), did not detect these and many other important features.

The primary areas of FZRA activity in the United States are in the eastern half and the Pacific Northwest. Weather conditions conducive to FZRA occurrence are very infrequent in the Rocky Mountains, and no FZRA days occurred during 1948–2000 in parts of southern California, Arizona, and southern Florida.

Five distinct areas of high FZRA-day frequency were found in the average pattern, and each high is related to varying combinations of storm-producing synoptic weather conditions identified by Rauber et al. (2001). The most prevalent condition that involves warm air being advected over cold air near frontal zones underlies the two high FZRA areas in the Midwest and is also part of the cause of the area of highest FZRA-day frequencies in the Northeast. High incidences in the Appalachian Mountains (from Georgia to Maine) and in the Pacific Northwest result from cold air being dammed by the mountains as warm, moist air is brought overhead by frontal-low-center activity (Gay and Davis 1993; Steenburgh et al. 1997). All areas of high incidence of FZRA days have long, 6-month seasons of occurrence. Freezing-rain-day incidences decrease dramatically westward across the High Plains because of a lack of conditions producing overrunning of warm, moist air.

The pattern based on the maximum number of FZRA days in a single year is similar to the average FZRA-day pattern, but the peak values ranged from 3 to 5 times as great as the averages. Minimum annual occurrences were zero at 98% of all stations. Extreme high values in the Midwest were 14 days, matching the 1-yr peaks in the 53-yr averages found in the Northeast.

Freezing-rain-day patterns for three independent 17-yr periods revealed similarity in the placement of the high-annual-incidence areas of the eastern United States, and in the placement of the 1-FZRA-day values. However, major differences were found in the frequency of FZRA days among the three periods. The FZRA incidences in the 1948–64 period were considerably greater than those in the ensuing 1965–1981 period, and rated as the highest of the three periods across the eastern half of the United States. The occurrences in 1982–98 were ranked as the highest of the three periods in the western half, and the time trend of three periods was approximately U shaped for all areas.

Analysis of 4-yr fluctuations in FZRA-day occurrences during 1949–2000 supports the findings from the three 17-yr periods. That is, the highest values occurred early (1949–56), and the lowest during the middle years of the 52-yr period. Linear trends of distributions in all climate regions were found to be downward. Those in three adjoining regions (ENC, C, and NE) were significantly downward as was the trend in the NW region. Periods when extremely high and low values for 4- and 12-yr periods occurred show widespread spatial agreement, revealing that atmospheric conditions leading to freezing rain embraced large sections of the United States over periods of years. The 1965–76 period had the lowest frequency of FZRA days in all the climate regions except the SE, and the 1949–60 period had the highest FZRA frequencies in all regions except the NW and SE. The temporal results reveal the risk related to freezing-rain-day occurrences shifts greatly with time, and that 4- and 12-yr periods can experience wide swings in occurrences.

Initial seasonal FZRA occurrences came in October in the High Plains and eastern Rockies, in November in the eastern United States and Pacific Northwest (areas where FZRA is frequent), and as late as December in the Southeast and California. The last FZRA of the cold season was in January in the southern Rockies, in February along the Gulf Coast, and in April over most of the northern half of the United States. May was the last month at some areas along the U.S.–Canadian border.

The months of greatest FZRA-day occurrences included December over most of the western half of the United States, and January in the eastern half and parts of the Pacific Northwest (locations of frequent FZRA). The patterns of average freezing-rain days in these two peak months are similar in most areas except in western Iowa and Minnesota and the western United States.

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REFERENCES

Baldwin, J. L., 1973: *Climate of the U.S.* Department of Commerce, 56 pp.

Bennett, I., 1959: Glaze: Its meteorology and climatology, geographical distribution and economic effects. Quartermaster Research and Engineering Center Tech. Rep. EP-15, 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., 1997: A climatology of significant winter-type weather events in the contiguous United States, 1982–94. *Wea. Forecasting,* **12,** 193–207.

Changnon, S. A., 1967: A method of evaluating substation records of hail and thunder. *Mon. Wea. Rev.,* **95,** 209–212.

——, 1997: Misuse of analytical approaches and data on severe weather. Preprints, *10th Conf. on Applied Climatology,* Reno, NV, Amer. Meteor. Soc., 381–385.

——, 2001: Assessment of the quality of thunderstorm data at first-order stations. *J. Appl. Meteor.,* **40,** 783–794.

——, 2002: Developing data sets for assessing long-term fluctuations in freezing rain and ice storms in the U.S. Changnon Climatologist Tech. Rep. CRR-51, 29 pp. [Available from Illinois State Water Survey 2204 Griffith Dr., Champaign, IL, 61820–7495.]

——, 2003a: Characteristics of ice storms in the United States. *J. Appl. Meteor.,* **42,** 630–639.

——, 2003b: Urban modification of freezing-rain events. *J. Appl. Meteor.,* **42,** 863–870.

Cortinas, J., 2000: A climatology of freezing rain in the Great Lakes region of North America. *Mon. Wea. Rev.,* **128,** 3574–3588.

Eagleman, J. R., 1983: *Severe and Unusual Weather.* Van Nostrand Reinhold, 372 pp.

Easterling, D., and T. Peterson, 1995: A new method for detecting undocumented discontinuities in climatological time series. *Int. J. Climatol.,* **15,** 369–377.

Gay, D. A., and R. E. Davis, 1993: Freezing rain and sleet climatology of the southeastern USA. *Climate Res.,* **3,** 209–220.

Hay, W. W., 1956: *The Effect of Weather Upon Railroad Operation, Maintenance, and Construction.* Civil Engineering Department, University of Illinois, 332 pp.

Jones, K. F., N. Mulherin, and C. Ryerson, 1997: EPRI: Freezing rain mapping project: Region 2. Cold Regions Research and Engineering Laboratory Tech. Rep. CR-00020, 35 pp.

——, R. Thorkildson, and N. Lott, 2002: The development of a U.S. climatology of extreme ice loads. National Climatic Data Center Tech. Rep. 2002–01, 23 pp.

Konrad, C. E., 1998: An empirical approach for delineating fine scaled spatial patterns of freezing rain in the Appalachian region of the USA. *Climate Res.*, **10,** 217–227.

Morgan, G. M., D. Brunkow, and R. C. Beebe, 1975: Climatology of surface fronts. Circular 122, Illinois State Water Survey, 46 pp.

President's Long-Term Recovery Task Force, 1998: A call for collaboration: Final report on the January 1998 ice storm: Maine, Hampshire, New York, and Vermont. Federal Emergency Management Agency, Region 1, 49 pp.

Rauber, R. M., L. S. Olthoff, M. K. Ramamurthy, and K. E. Kunkel, 2000: The relative importance of warm rain and melting processes in freezing-rain events. *J. Appl. Meteor.*, **39,** 1185–1195.

——, ——, ——, D. Miller, and K. Kunkel, 2001: A synoptic weather pattern and sounding-based climatology of freezing precipitation in the United States east of the Rocky Mountains. *J. Appl. Meteor.*, **40,** 1724–1747.

Robbins, C., and J. V. Cortinas, 2002: Local and synoptic environments associated with freezing rain in the contiguous U.S. *Wea. Forecasting*, **17,** 47–65.

Shan, L., and L. Marr, 1996: Ice storm data base and ice severity maps. Jones Power Delivery Tech. Rep. TR-106762, 42 pp.

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

Tattleman, P., and I. I. Gringorten, 1973: Estimated glaze ice and wind loads at the earth's surface for the contiguous U.S. Hanscom Field AFCRL Rep. 11, 35 pp.

Vilcans, J., and D. Burnham, 1989: Climatological study to determine the impact of icing on the low-level windshear alert system. Department of Transportation Tech. Rep. DOT-TSC-FAA-89-2, 45 pp.