Temporal and Spatial Characteristics of Snowstorms in the Contiguous United States

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ABSTRACT

A climatological analysis of snowstorms across the contiguous United States, based on data from 1222 weather stations with data during 1901–2001, defined the spatial and temporal features. The average annual incidence of events creating 15.2 cm or more in 1 or 2 days, which are termed as snowstorms, exhibits great spatial variability. The pattern is latitudinal across most of the eastern half of the United States, averaging 0.1 storm (1 storm per 10 years) in the Deep South, increasing to 2 storms along the Canadian border. This pattern is interrupted by higher averages downwind of the Great Lakes and in the Appalachian Mountains. In the western third of the United States where snow falls, lower-elevation sites average 0.1–2 storms per year, but averages are much higher in the Cascade Range and Rocky Mountains, where 5–30 storms occur per year. Most areas of the United States have had years without snowstorms, but the annual minima are 1 or more storms in high-elevation areas of the West and Northeast. The pattern of annual maxima of storms is similar to the average pattern. The temporal distribution of snowstorms exhibited wide fluctuations during 1901–2000, with downward 100-yr trends in the lower Midwest, South, and West Coast. Upward trends occurred in the upper Midwest, East, and Northeast, and the national trend for 1901–2000 was upward, corresponding to trends in strong cyclonic activity. The peak periods of storm activity in the United States occurred during 1911–20 and 1971–80, and the lowest frequency was in 1931–40. Snowstorms first occur in September in the Rockies, in October in the high plains, in November across most of the United States, and in December in the Deep South. The month with the season's last storms is December in the South and then shifts northward, with April the last month of snowstorms across most of the United States. Storms occur as late as May and June in the Rockies and Cascades. Snowstorms are most frequent in December downwind of the Great Lakes, with the peak of activity in January for most other areas of the United States.

1. Introduction

Snowstorms create a variety of problems and major damages. Foremost is the magnitude of the snowfall, which, by its weight and conversion to ice, damages property and the environment and requires costly removal efforts. The difficulty of its removal also greatly limits surface transportation, stopping or greatly delaying automobile, air, and train travel. Heavy snow also creates slippery surfaces, leading to vehicular accidents, injuries, and loss of life. Heavy snow followed by rapid melting creates another major problem—flooding. Snowstorm-related damaging floods occurred with 42% of the 155 most damaging snowstorms in the United States since 1948 (Changnon and Changnon 2005).

Sizable economic losses from snowstorms during the 1990s drew national attention to the need for information on the nationwide climatological behavior of snowstorms and their impacts. The "superstorm" of March 1993 began a costly trend of losses. This record storm affected 20 states from Louisiana to Maine, caused $1.8 billion (2000 dollars) in insured property losses, led to

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270 deaths, and became labeled as the nation's most widespread winter storm of the past 100 yr (Kocin et al. 1995). It was followed in 1994 by three major snowstorms that also struck the northeastern United States and adjacent regions, causing insured property losses totaling $651 million. Then, in January 1996, three more severe snowstorms struck the northeastern United States, causing $1.1 billion in insured losses (Kocin and Uccellini 2005). During 1993–99, 11 major snowstorms occurred, including two in the western United States, and their insured property losses totaled $4.6 billion, which is 20% of all losses from the 155 most damaging snowstorms in the United States during 1949–2001 (Changnon and Changnon 2005).

The literature is devoid of nationwide climate studies of snowstorms, although storms in the Northeast have been extensively studied (Kocin and Uccellini 2005). Two factors have been central to this void: 1) a lack of quality historical snowstorm data and 2) the regional differences in what snowfall magnitudes equate to a snowstorm. For example, a 10-cm snowfall in Alabama causes numerous problems and would likely be classed locally as a snowstorm, whereas a 10-cm snowfall in Minnesota would have less significance because of the many facilities available to handle snow and frequent public experience with heavy snowfalls.

Efforts to identify and classify snowstorms have followed different directions. One direction has attempted to equate snowfall magnitude to regional impacts. Studies of snowstorms in the Midwest during 1901–65 found that 15.2 cm (6 in.) or more snowfall in 1–2 days created major economic and human impacts (Changnon 1969). Subsequent studies of storms during the 1970s verified this finding (Changnon and Changnon 1978). In a study of significant winter storms during 1982–94, Branick (1997) also identified 15.2 cm or more as the measurement of a heavy snow event across most of the United States. A study of snowstorm impacts in 17 cities across the United States found that 12.5–20 cm in 1 day was the threshold for creating major disruptions in transportation and other urban activities (Rooney 1967). Kocin and Uccellini (2004) identified severe snowstorms in the northeastern United States (from Virginia to Maine) based on those having produced potentially severe impacts. Impacts were defined based on two levels: more than 10 cm (defined as moderate) and 25 cm or more (defined as heavy) of snow in two or more areas of the region and the size of the population in the heavy snow areas. If heavy snow fell where the population was dense, it was considered a worse storm than the same amount having fallen in an area of less dense population. Another approach to snowstorm identification has relied on the type of synoptic weather conditions causing the storms (Zielinski 2002). A third approach employed for identifying damaging storms has involved case studies of individual major events (Mook and Norquest 1956; Sanderson and Mason 1958; Rosenblum and Sanders 1974; Kocin 1983; Sanders and Bosart 1985; Sanders 1986; Wolfsberg et al. 1986).

Determination of comparable spatial and temporal measures of snowstorms across the United States was the aim of our study. We recognize that regional differences exist in levels of snowfall that cause impacts, but we chose one level of snowfall to allow a nationwide assessment of the spatial and temporal variations. Data for snowfalls of 15.2 cm or more in 1 or 2 days was chosen as the basis for developing this national-scale snowstorm climatological analysis. Until recently, National Weather Service forecasts of heavy snow have been based on 10.4 cm or more in 12 h (Goree and Younkin 1966), but now forecast criteria vary regionally. Such a 12-h definition was not usable in this study because the cooperative substation data were essential and their snowfall values are daily, based on once-per-day observations. A newly developed database consisting of all snow events that created 15.2 cm or snowfall in 1 or 2 days during 1901–2001 provided the data for this study. Quality historical data were available for 1222 stations across the 48 contiguous states. This database provided two key ingredients that past studies lacked: 1) highly reliable snowstorm values collected over a long 101-yr period and 2) data from a dense array of stations across the United States. Thus, both the temporal and spatial aspects of snowstorm distributions could be adequately addressed at a uniform level.

2. Data and analysis

Daily snowfall data at approximately 1550 weather stations in the United States were assessed in a recent project to define stations with quality data on snowstorm events for each station (Changnon 2005). Snowfall measurements are not exact values and are influenced by where, how often, and on what type of surface measurements are made (Doesken and Judson 1996). However, many of the measurement problems are less in cases of heavy snowfalls because of the fact that observers are likely to give more attention to big storms (Robinson 1989). Regardless, exact amounts of snowfall should be accepted with a certain degree of caution. In general, comparative evaluation analyses, among adjacent stations, of snowfall from most storms (>15.2 cm) revealed consistent patterns of snowfall among groups of nearby stations (Changnon 2005). This result further indicates that, despite the measurement problems, the measurements of heavy snows were suffi-

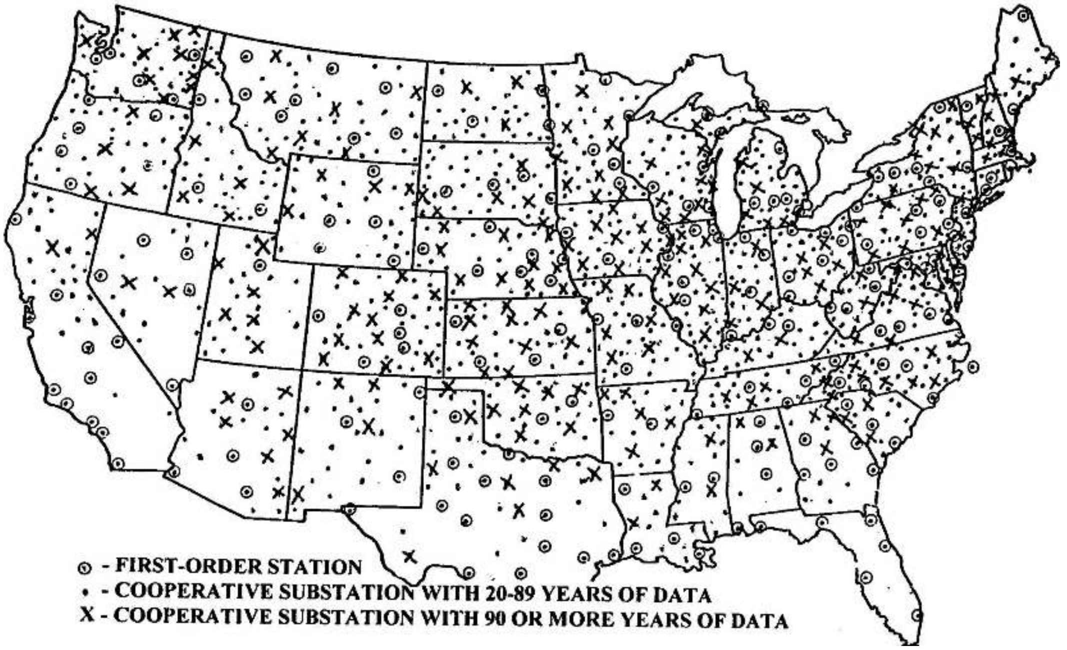

FIG. 1. The distribution of first-order stations and cooperative substations with quality snowstorm data during the 1901–2001 period. Substations with 90 yr or more of data are also indicated.

ciently good to pursue a meaningful climatological analysis.

A snowstorm at a station was defined as an event that produced 15.2 cm or more snowfall in 1 or 2 days, and most storms identified actually occurred in 24 h or less. In an earlier study of snowstorms, data from Midwestern weather stations with daily snowfall records for 1901–65 were analyzed (Changnon 1969). Inspection of the original data forms for the stations revealed that many of the cases of 15.2 cm or more in 2 days were situations in which the total snow had fallen in less than 24 h. However, because of fixed observation times, such as 0800 or 1700 LT, the 1-day (or shorter) snowfall was actually reported on two "observational days," and 84% of all 2-day events were cases in which the total snow fell in less than 24 h.

The approach for assessing quality of snowstorm data involved a two-phase process. First was an assessment of data for 208 "first-order stations" (FOS) to detect any shifts in storm frequency over time associated with station moves, operational changes, or the adoption of the "automated surface observing system" (ASOS). The second phase of the data assessment involved evaluation of the data for 1554 cooperative substations across the United States. These included stations in the U.S. Historical Climate Network plus those found in prior data assessments to have quality historical data on days with weather conditions that included thunderstorms, hail, and freezing rain (Changnon 2001; Changnon and Creech 2003). The evaluation procedure developed in earlier studies of substation data (Changnon 1967) was the basis for examining the snowfall data associated with individual observers at cooperative substations. Station values were compared over time using a double-mass curve approach to detect changing relationships resulting from data discontinuities. The data periods judged initially as being good were then used to calculate annual averages, which were compared with averages at nearby stations with quality data. This step served as the final one in the identification of good storm data periods. Similar evaluations were performed for each FOS with attention to frequencies before and after station moves or observational/operational changes, including the shift to ASOS in the 1990s.

As a result of these data quality assessments, quality data on snowstorms were available for 208 FOS and 1014 cooperative substations, each with quality historical records during all or sizable portions of the 1901–2001 period (Changnon 2005). The distribution of stations with quality records (Fig. 1) shows a good density in all but the southern states. There, snowstorms either did not occur or were extremely infrequent; hence, there was little need for numerous stations. All states except those in the Southeast plus Nevada and Arizona, had more than 20 substations with storm data, and many states in the northern half of the United States

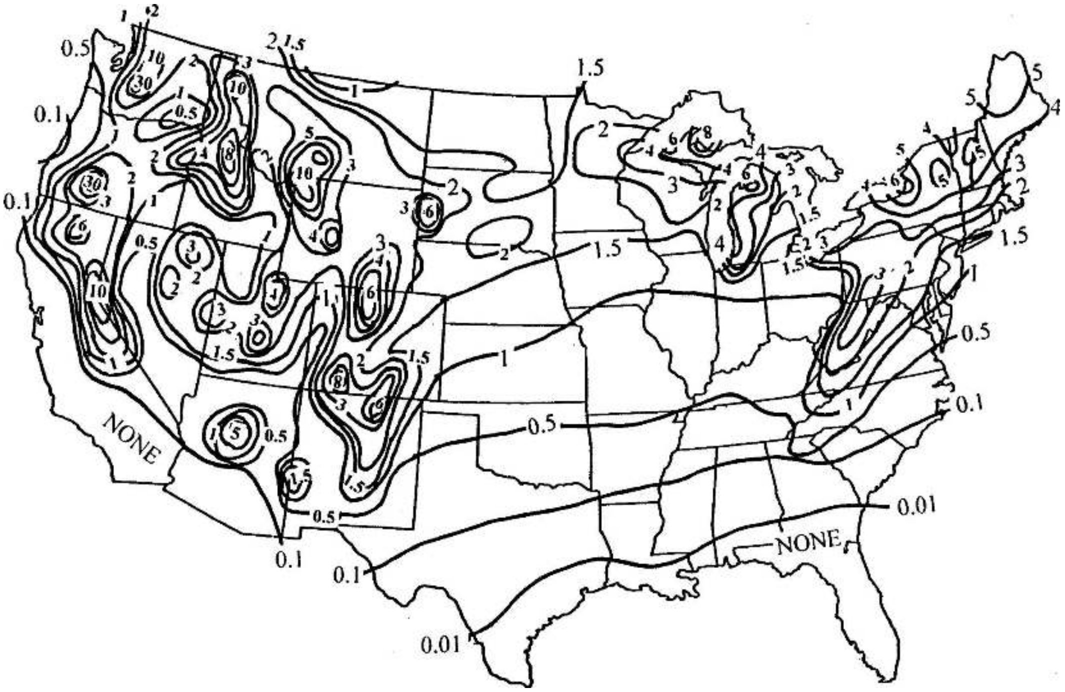

FIG. 2. The annual average number of snowstorms for 1901–2001. A value of 0.5 indicates an average of 5 storms in 10 yr, and an average of 0.1 indicates an average of 1 storm per 10 yr.

had more than 30 substations with quality snowstorm data. The ensuing spatial analysis of storms revealed the need for a good density of stations to define the spatial irregularities in some parts of the United States. The number of stations with 90 yr or more data during 1901–2001 included 247 cooperative substations and 21 FOS. These 247 substations are denoted on Fig. 1, revealing a good density across most of the United States.

The long-term average number of snowstorms was determined for all stations, as was the maximum and minimum annual occurrences of snowstorms. Temporal variability during 1901–2000 was assessed in three ways: 1) comparison of the 1901–50 storm values with those for 1951–2000, 2) comparisons of the time distributions of snowstorm frequencies for eight regions in the United States and for 1901–2000 based on data for all stations in each region, and 3) comparisons nationally of how often each decade between 1901 and 2000 had maximum and minimum decadal values based on data for each station.

The U.S. snowstorm season was delineated by identifying the months in which storms first occurred in the autumn and in which they last occurred in the winter or spring. The months with the greatest frequency of storms at each station also were identified and were used to develop a national pattern denoting the areas and times of peak snowstorm activity.

3. Annual frequencies

a. Average pattern

The national pattern based on the average annual frequency of snowstorms (Fig. 2) reveals that the pattern east of the Rocky Mountains is dominated by a latitudinal distribution. Values along the Gulf Coast average 0.01 snowstorms (1 storm per 100 years), and the frequency increases to 2 or more storms per year along the northern border of the United States. The national peak in blizzards is in the Dakotas and Minnesota with an average of 1 blizzard per year (Schwartz and Schmidlin 2002), and this region is where the average point numbers of heavy snowstorms are 1.5–2 per year.

This latitudinal pattern east of the Rocky Mountains is disrupted by influences of two major surface features—the Appalachian Mountains and the Great Lakes. Both physical features cause more snowstorms in and near their locales. Downwind of Lake Superior in upper Michigan, the point average is six or more snowstorms per year—more than double the averages in northern Wisconsin. Similar lake-induced increases occur east of Lake Michigan and south and east of Lakes Erie and Ontario (Rauber et al. 2002).

The Appalachian Mountains experience considerable storm activity from North Carolina northward through Maine. Surface cyclones that deepen over the Atlantic Ocean east of the Carolinas often create heavy snowfalls over the Northeast (Kocin and Uccellini 2005; Mote et al. 1997). Topographic and latitudinal influences on storm activity are revealed by the 1-storm isoline (Fig. 2) that is oriented east–west across Illinois, Indiana, and Ohio but then shifts southward along the mountains' western edge into North Carolina. The 1-storm isoline then turns northward along the mountains' Piedmont Plateau across Virginia, Maryland, and New Jersey, where it reaches the same latitude as it had in Ohio. Averages in the higher elevations of the Appalachians are 3–5 storms per year.

The average point values for snowstorms in the eastern two-thirds of the United States are essentially representative of values at adjacent locations. However, the averages presented for the mountainous western third of the United States are often not representative of surrounding areas. Most western values are based on data at weather stations located at relatively low elevation sites where communities developed. The values for these lower-elevation locales are representative of nearby low-elevation sites but are not representative of the higher elevations in the nearby hills and mountains where snowstorms are much more frequent than at the lower elevations. For example, in northern California, a weather station at Mount Shasta (elevation 2300 m MSL) averages 6.4 snowstorms per year, whereas nearby stations at lower elevations (720 m) average 1–2 storms per year. Thus, much of the average pattern (Fig. 2) in the West is *only* representative of values found at lower-elevation areas, except along the California coast where no snow occurs. A few high-elevation areas have had long-term weather stations, often isolated, and these create the isolated high-incidence areas shown on Fig. 2.

The lack of snowfall data at many higher-elevation sites makes it impossible to define and portray accurately these local and regional differences related to varying elevations. The amount of increased storm frequency at any given higher elevation is a function of the elevation, slope, and orientation of the hills and mountains. There are isolated locations from north to south along the Rockies with exceptionally high snowstorm frequencies. These areas are surrounded by stations with much lower averages. These high values and those of nearby surrounding stations at lower elevations are listed in Table 1. Similar high averages occur along the Cascade Range. As shown in Fig. 2, notable high-average areas occur in the Sierra Nevada of east-central California (>10 storms per year) and at Mount Shasta (>6 storms per year), in Oregon at Crater Lake (>30 storms per year), and at Stampede Pass in Washington (>30 storms per year), all a result of moist Pacific Ocean air masses rising over the mountains (Rauber et al. 2002).

TABLE 1. Locations in the Rocky Mountains with high annual average frequencies of snowstorms and averages at nearby surrounding stations at lower elevations.

Location/station	High-elevation averages	Low-elevation averages at nearby stations
New Mexico		
Red River	9.5	0.9, 1.4
Bateman Ranch	6.9	2.8, 3.0
Colorado		
Telluride	12.6	1.2, 2.1, 3.9
Steamboat Springs	9.5	1.8, 2.1
Wyoming		
Border	6.1	1.6, 2.4
Lake Yellowstone	7.7	2.0, 2.8
Montana		
Mystic Lake	9.5	2.1, 3.3

The relationship of snowstorm frequency with elevation along the West Coast is well illustrated by comparing elevations and averages of all the Oregon weather stations with quality storm data. Figure 3a shows the annual average snowstorm frequencies plotted as a function of elevation above sea level for the 33 lowest-elevation stations in Oregon. A logarithmic relationship exists, and the correlation coefficient is +0.66. There is a clear indication that snowstorm frequency increases rapidly as elevation increases. Figure 3b presents the Oregon storm–elevation relationship with the 34th station added (Crater Lake), which is located at 2200 m MSL. This height–storm frequency distribution has a distinctive logarithmic relationship, suggesting a rapid increase in storm frequency at elevations above 1300 m.

The American Society of Civil Engineers (2000; ASCE), in assessing design snow values for the United States, recognized the problems of determining regionally representative values for the western and eastern mountainous areas. ASCE's national pattern for design snow loads has a latitudinal distribution in the central United States, ranging from 240 Pa in the Deep South to 3830 Pa in the North, a pattern quite similar to that for snowstorms (Fig. 2). However, in the mountainous areas, ASCE identifies a wide variety of small areas without values and recommends on-site case studies to determine design snow-load values, admitting that elevation differences do not allow definition of a meaningful western pattern. Another factor that affects storm frequencies is the influence of urban heat islands in large cities. Landsberg (1981) defined decreases in urban snowfall, and a recent study of Chicago, Illinois,

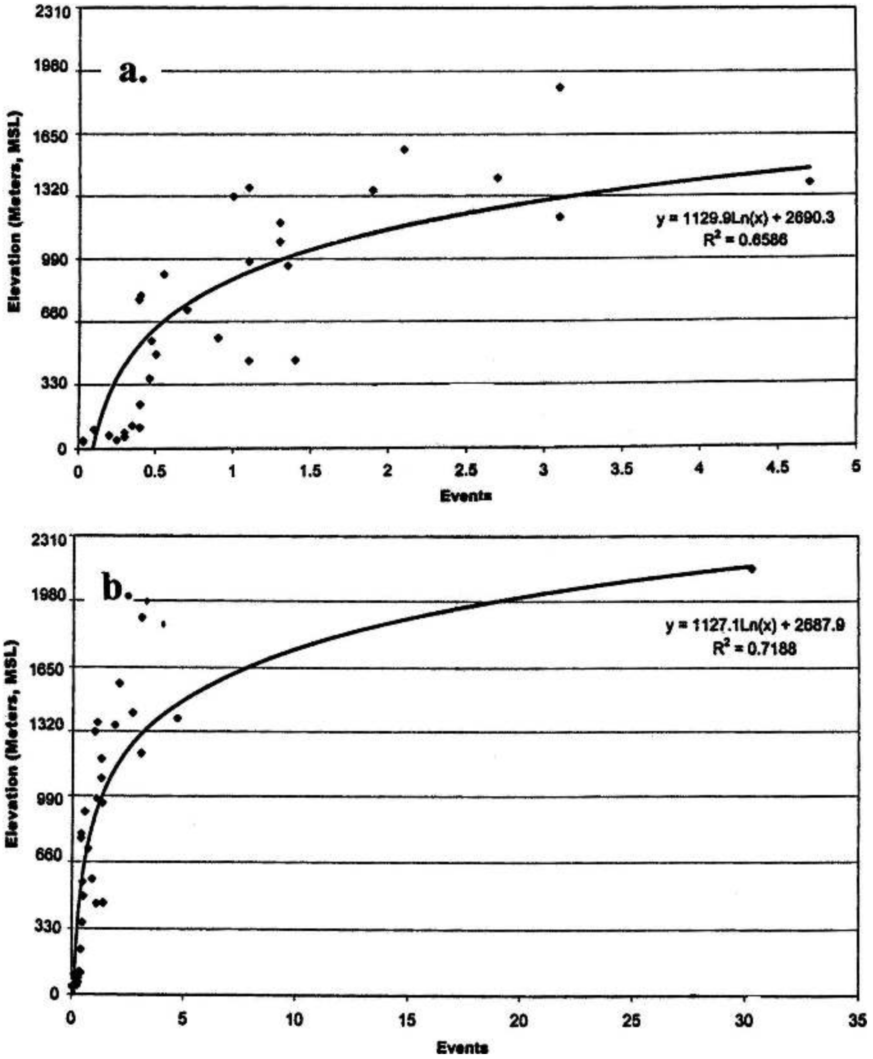

FIG. 3. Relationship of average annual snowstorm occurrences at Oregon stations and their elevation above mean sea level: (a) 33 stations with the lowest elevations and (b) all 34 stations, including the one with the highest elevation in Oregon.

and St. Louis, Missouri, snowfall data found in-city decreases of 25%–40% (Changnon 2004). Thus, stations inside large cities likely experience fewer snowstorms than do surrounding rural areas. However, many urban weather stations were moved from in-city locations to nearby rural airport sites since the 1930s and 1940s, and the urban influence only affected the early values.

b. Patterns based on extremes

The highest annual number of snowstorms experienced during 1901–2001 at each station was used to develop a national pattern (Fig. 4) that is similar to the that of the average (Fig. 2). Ratios of maximum 1-yr values to the average annual averages show differences that shift depending on the magnitude of the average value. Maximum values for stations with low averages, 0.1–0.6 storms per year, averaged 8.0 times the average annual number. The maximum-to-average ratio for stations with annual averages of 0.7–1.5 storms per year was 4.3, for averages of 1.6–2.0 storms per year the ratio was 3.3, for averages of 2.1–5.0 it was 3.0, and for storm averages of greater than 5 per year the ratio was 2.2. Thus, as station averages increased, the ratio decreased, indicating that the maximum 1-yr values are not as relatively great at locations with high averages as at locations with low averages.

The effect of latitude and hence temperature is seen in the central United States. The Great Lakes and the major mountain ranges have a sizable influence on the maximum incidence of storms (Rauber et al. 2002).

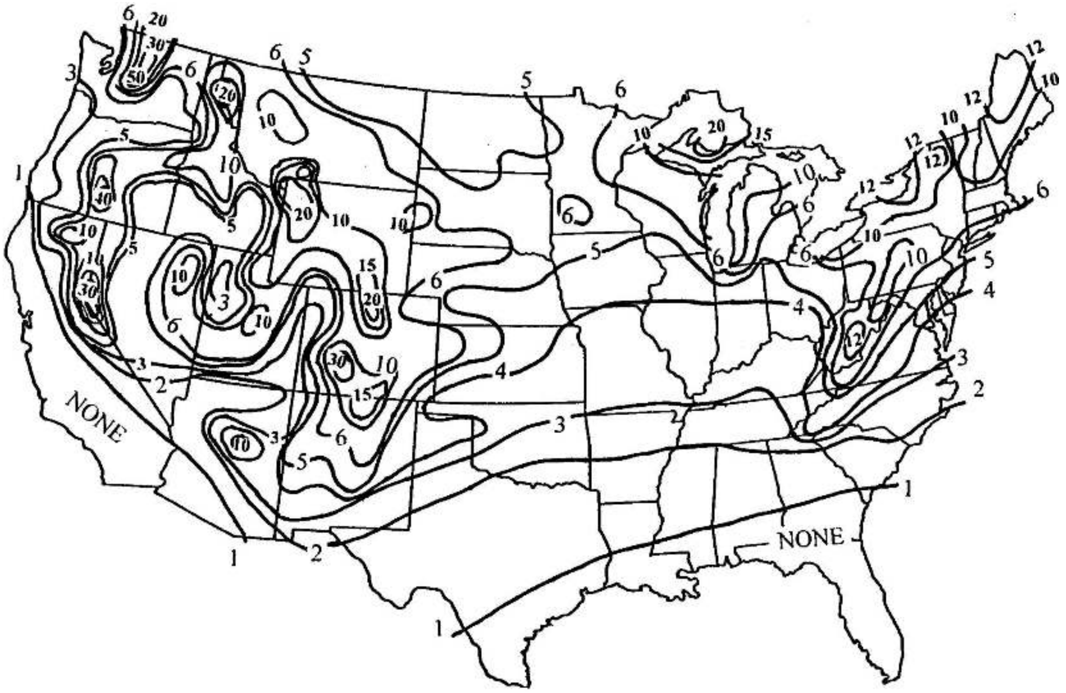

FIG. 4. Pattern based on the maximum number of snowstorms to occur in a single year during 1901–2001.

Downwind of Lake Superior, storm maxima are 20 storms per year, with high yearly values of 10–12 storms east of Lake Michigan and south and east of Lakes Erie and Ontario. The higher-elevation portions if the Appalachian Mountains in West Virginia and Pennsylvania are areas for which 10 or more storms have occurred in a single year. Peak values along the Rockies are much higher, with more than 20 storms in northwest Wyoming and in parts of Colorado. Mountain-generated storms often move eastward (Rauber et al. 2002), which extends the peak incidences eastward into the high plains, as illustrated by the 6-storm isoline found in South Dakota, Nebraska, and Kansas. Peak values in the Cascades exceed 30 storms per year in the higher-elevation areas of central California, southern Oregon, and Washington, where Stampede Pass experienced 53 storms in a single year (1978).

The pattern based on the lowest 1-yr values (Fig. 5) reveals that in most of the United States there have been years with no snowstorms. Only in higher-elevation locales in the western and eastern mountains are there stations that have experienced a low of 1 or more snowstorms. Important is that four isolated areas in which stations have minimums of 2 or more storms exist in the highest-elevation areas of the Cascade Range. Stampede Pass, at an elevation of 1300 m MSL, had a minimum of 17 storms (1989), which makes it the highest national minimum as well as the station with the nation's highest maximum value. Small areas with minima of 1 or 2 storms per year exist downwind of Lakes Superior, Erie, and Ontario, reflecting the importance of lake effects on passing air masses.

c. *Temporal patterns*

A spatially oriented temporal analysis was performed for storm frequencies during the first 50 yr and the last 50 yr of the twentieth century. This division was performed because most structural designs and operations to address heavy snowstorms have been based on data available since 1950 (American Society of Civil Engineers 2000, Changnon and Changnon 2005). This raises the question of the representativeness of the 1951–2000 values for addressing future conditions. Hence, the newly available storm data for 1901–50 were useful for comparing and assessing the 1951–2000 values.

The national totals showed that 103 stations had their highest values in 1901–50, 98 stations peaked during 1951–2000, and 30 had values that were equal. The national pattern based on the peak snowstorm values of the century's early and late 50-yr periods (Fig. 6), as derived from the 231 long-term stations, reveals the spatial distributions of the 50-yr period with the greater number of snowstorms. Several large, regionally coherent regions exist in which many stations peaked either in 1901–50 or in 1951–2000. For example, a region of

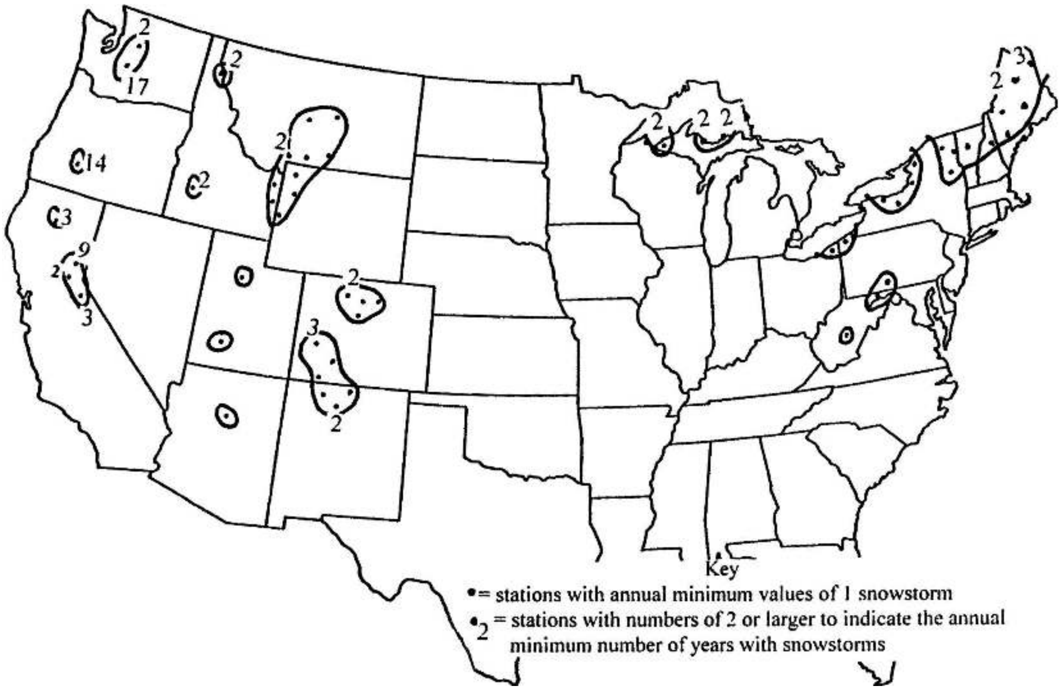

FIG. 5. Pattern based on the minimum number of snowstorms to occur in a single year during 1901–2001.

highest storm frequencies in 1951–2000 exists over New York and most of New England, and these values were statistically significantly different than those there in 1901–50. A large, east–west-oriented area where stations had their highest storm numbers in 1901–50 extends from southeastern Colorado and Oklahoma eastward to Kentucky and Tennessee. Another 1901–50 area exists in parts of Michigan and Ohio and includes

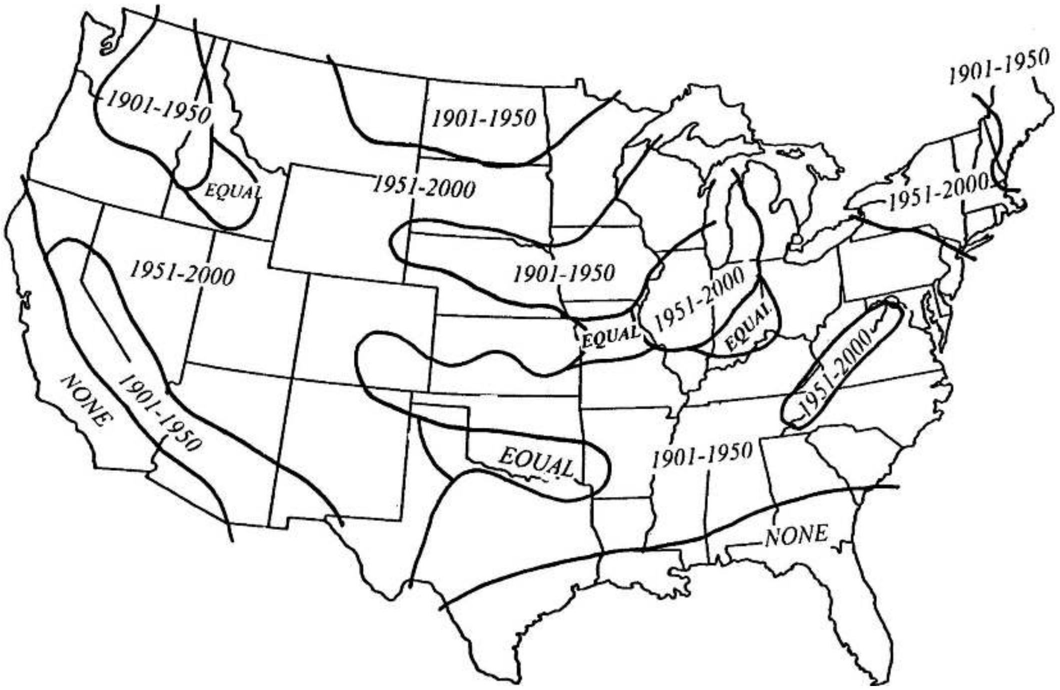

FIG. 6. The areas illustrating differences between the 1901–50 and 1951–2000 snowstorm frequencies. Areas where the two periods had similar values are also denoted.

Pennsylvania, Maryland, Virginia, and the Carolinas. These findings showing fewer storms in 1951–2000 in the central United States and more in the Northeast agree with the temporal distributions of cyclonic activity for these regions (Hayden 1981). Much of the area east of the Rockies, excluding the Deep South where snowstorms are too infrequent to classify their time distributions meaningfully, had more snowstorms in 1901–50 than in 1951–2000, revealing that designs and operations to handle snowstorms based on 1951–2000 data may underestimate the risk. In contrast, most stations in the western United States had their highest 50-yr values during 1951–2000.

Furthermore, the 1951–2000 values may not represent storm conditions under a changed future climate. To assess possible future snowstorm conditions, the relationships of the storm frequencies to seasonal temperature and precipitation conditions, both estimated to undergo future changes, were defined for 1901–2000 using data from 1222 stations across the United States. Results for the November–December period showed that most of the United States had experienced 61%–80% of the storms in warmer-than-normal years. Assessment of the January–February temperature conditions again showed that most of the United States had 71%–80% of their snowstorms in warmer-than-normal years. In the March–April season 61%–80% of all snowstorms in the central and southern United States had occurred in warmer-than-normal years. The relationship of storm incidence to precipitation in all three 2-month periods of the cold season showed that 61%–85% of all storms occurred in wetter-than-normal years. Thus, these comparative results reveal that a future with wetter and warmer winters, which is one outcome expected (National Assessment Synthesis Team 2001), will bring more snowstorms than in 1901–2000. Agee (1991) found that long-term warming trends in the United States were associated with increasing cyclonic activity in North America, further indicating that a warmer future climate will generate more winter storms.

d. *Temporal distributions*

Assessment of shorter-term temporal fluctuations of snowstorms involved analysis of the 231 stations with 100-yr records. The average annual storm pattern (Fig. 2) and seasonal snowstorm patterns were analyzed to delineate regions across the United States, each with notably different snowstorm characteristics. Values of each station within each of the eight regions defined were used to derive decadal average values, and Fig. 7 presents the resulting temporal variations. In general, the regional values of most regions show one or two decades with very high averages and three or four decades with low averages. Considerable temporal variability exists in all regions. Comparison of the regional time distributions reveals that the West Coast and West regional distributions were not alike, and that those of the upper Midwest and lower Midwest also did not agree (Fig. 7). Regional differences exist because the primary synoptic causes of snowstorms shifted regionally over time (Whittaker and Horn 1984). The distribution in the West was similar to that of the high plains, and those of the East, upper Midwest, and Northeast were also similar, revealing where some regional coherence in storm-producing activity has existed. Angel and Isard (1998) assessed strong storm-producing cyclonic activity over the Midwest and Northeast and found significant increases from 1900 to 1990, supportive of the temporal increases in snowstorm activity in these regions. The upward trend of storms in the upper Midwest is also in agreement with trends based on lake-effect snowfall, which occupies large portions of this region (Norton and Bolsenga 1993).

The 100-yr linear trends based on the decadal values of the eight regions showed areas of similarity. The South and lower Midwest had distinct downward trends in snowstorm frequency from 1901 to 2000, statistically significant at the 2% level. The lower Midwest and South had long-term storm decreases, which is an outcome in agreement with the temporal decreases in cyclonic activity in these areas (Hayden 1981). In direct contrast, the Northeast and upper Midwest had statistically significant (1% level) upward linear trends. The recent increase in the Northeast agrees with findings in recent studies of winter storms in this area (Angel and Isard 1998; Kocin and Uccellini 2005). The West region displayed an upward trend from 1901 to the 1970s and then a downward trend to 2000, and this pattern agrees with storm trends in adjacent areas of southern Canada (Zhang et al. 2001). On the national scale, the regionally varying up and down trends resulted in a national storm trend that was slightly upward (5% level of significance) for 1901–2000 (Fig. 8). The long-term increases in strong cyclonic activity in the Midwest and Northeast (Hayden 1981; Angel and Isard 1998) occurred where snowstorms are most frequent (Fig. 2), and thus they had an influence on the upward trend in national snowstorm activity. Reitan (1979) found that cyclonic activity was low in the 1931–50 period—a period of few snowstorms in the United States (Fig. 8).

Nationally, 39 of 231 stations with long-term records had their lowest frequencies of storms during 1931–40, whereas 29 others had their peak of incidences then (Fig. 9). The second-ranked decade with numerous sta-

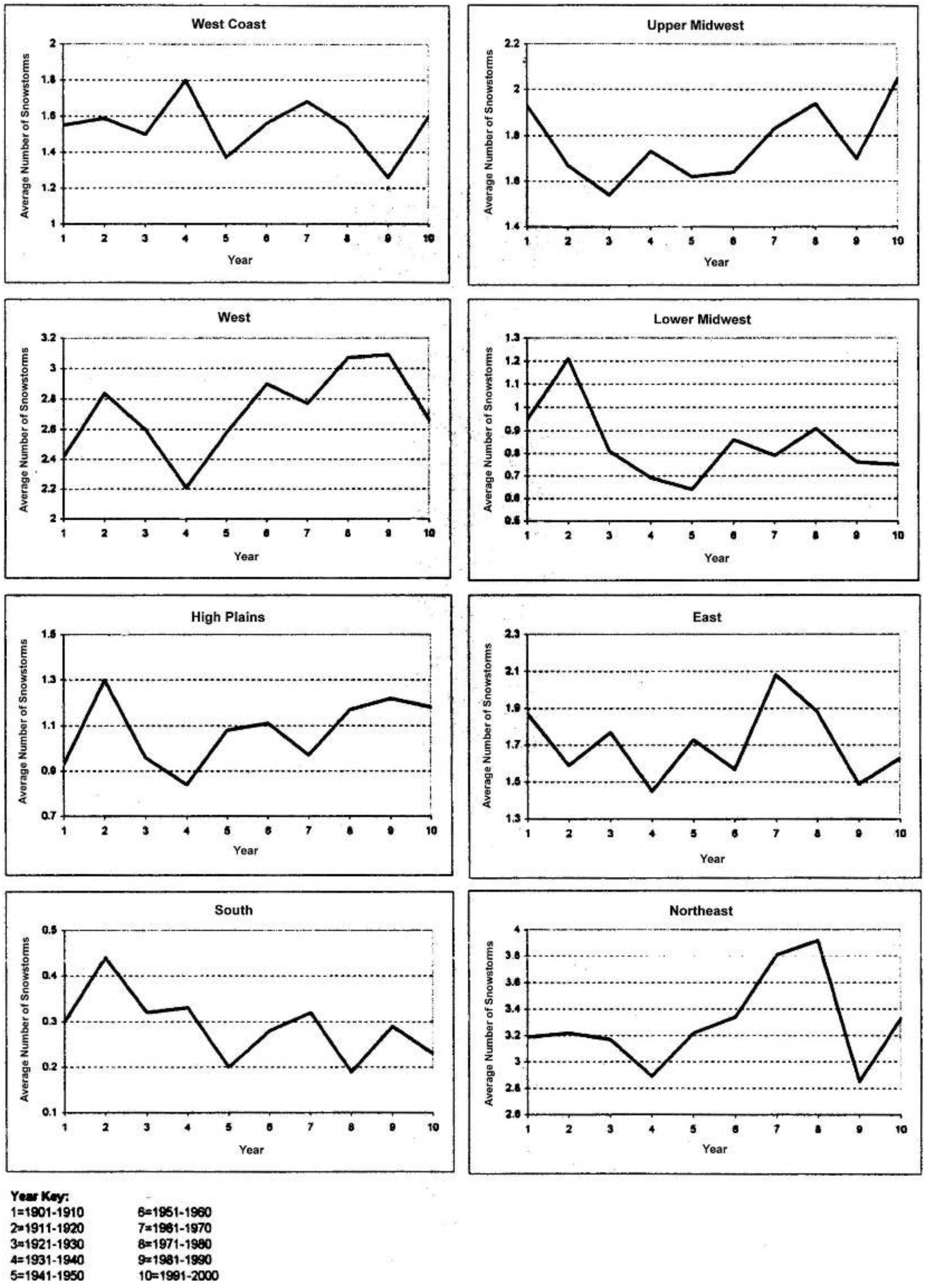

FIG. 7. The temporal distribution of snowstorm occurrences for eight regions based on averages of all stations in each region and for each decade during 1901–2000.

tions having low storm frequencies was 1981–90. Very few low storm occurrences were found during 1911–20 and in the 1961–80 period, times when storms were very frequent (Fig. 9). The 1911–20 decade had the greatest number of high station values with 38 stations. The fewest peak values occurred in the next decade, 1921–30. Comparison of the decades of high and low frequencies of snowstorms (Fig. 9) reveals, as expected, an in-

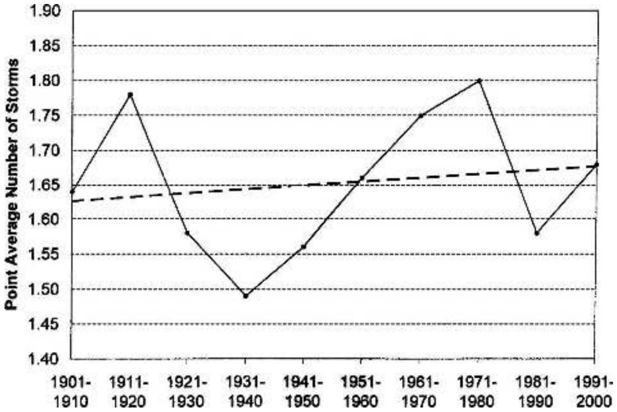

FIG. 8. The national temporal variations of snowstorms, based on point averages for each decade, for 1901–2000.

verse relationship. That is, when many high storm values occurred, there are few low storm frequencies.

4. Monthly frequencies

The national pattern based on the months in which snowstorms first occurred at each station shows wide spatial variations (Fig. 10a). Storms first occur in September in the northern Rockies. October was the first month with snowstorms across the lower Rockies and much of the high plains. Note that there is a lack of stations at high altitudes in the Rockies (Fig. 1), and this affects the patterns of first and last storms in this region. October is also the month with initial storm occurrence in areas downwind of the Great Lakes and in the high-elevation areas of northern New York and in the Cascades. The areas of early storm incidence reveal lake and elevation effects on initiating storm activity (Rauber et al. 2002). The area in which storms start in October in the West is an area of frequent cyclogenesis (Whittaker and Horn 1984) and is also where annual average snowfall amounts are higher than elsewhere in the United States (Harrington et al. 1987).

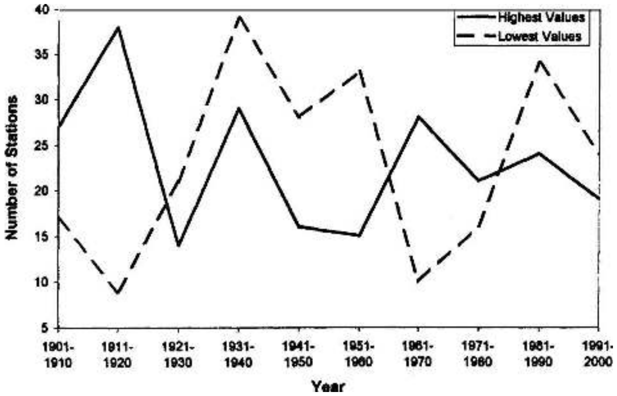

FIG. 9. The temporal distribution of the number of stations per decade experiencing maximum and minimum decadal values during 1901–2000, based on 231 stations with long-term records across the United States.

A latitudinal, temperature-related distribution of initial storm months then shifts southward. November is the first storm month of storm activity across large portions of the United States, extending from the Southwest through the Midwest and into the East. In the southern sections of the United States where snowstorms are infrequent, December is when snowstorms first occur.

The last month of the winter season experiencing snowstorms (Fig. 10b) also reveals a latitudinal effect. In the low-storm-frequency areas of southwest Texas and Arizona, December or January is the last storm month. February ranks as the last month across the Deep South, where December was the first month. A latitudinal shift of storms northward occurs as temperatures increase and storm tracks shift northward. This persists through March, followed by April, which is the last month of snowstorms over much of the area for which November was the first month. May experiences the last storms over the central and northern Rockies. A few high-altitude locations (the Rockies, the Black Hills, and the Cascades in central California and Washington) have their last storms in June. Again, the lack of high-altitude stations makes patterns (Fig. 10b) susceptible to spatial omissions.

The monthly distributions of storm occurrences at all stations were analyzed to determine the month of greatest storm activity during 1901–2001. The resulting national pattern of peak storm months (Fig. 11) reveals considerable spatial variability, reflecting spatially varying conditions causing storms, as well as the influences of the Great Lakes and higher elevations in the major mountain ranges. The influence of the Great Lakes, which are relatively warm in the early winter, leads to the highest storm frequencies in December just downwind of Lakes Superior, Erie, and Ontario. January is the peak storm month over a larger area than any other month, being the peak month in much of the West and over much of the South, Midwest, and East, reflecting a peak in storm-producing conditions across the central-eastern United States (Whittaker and Horn 1984). The areas for which January is the peak storm month also coincide with areas in which the total January snowfall is higher than in any other month (Harrington et al. 1987).

The influence of the Appalachian Mountains leads to maximum storm activity in portions of the mountains during February. The influence of Atlantic moisture on

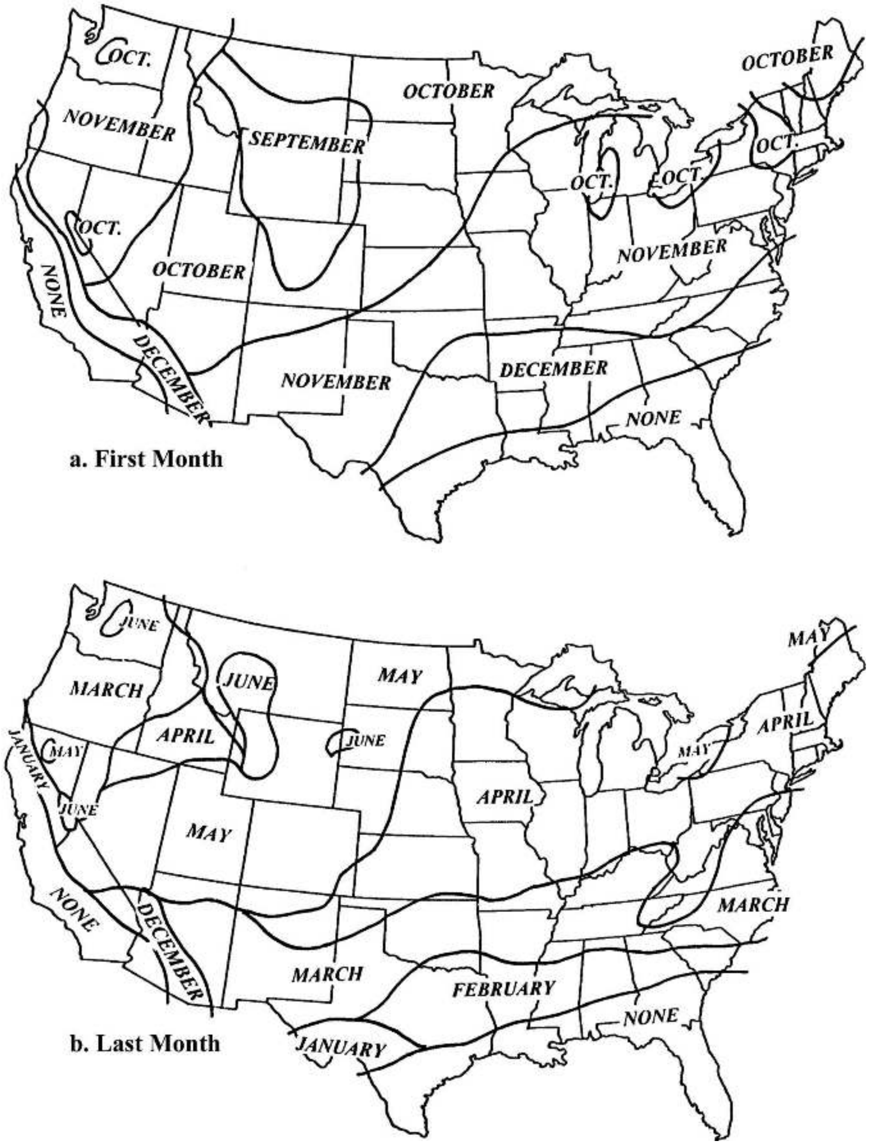

FIG. 10. Patterns based on (a) the first month experiencing snowstorms in each season and (b) the last month with snowstorms during 1901–2001.

storm activity and intensity along the Eastern Coastal Plain from Virginia north to Maine results in the February storm maximum along the coast (Goree and Younkin 1966). Areas for which February had the highest storm frequencies, including the Appalachians and East Coast, also have their highest average monthly snowfall amounts in February (Harrington et al. 1987).

March is the peak month of snowstorms in the southwestern mountains, high plains, and northern Midwest where temperatures are low and storm-producing frontal systems are frequent (Morgan et al. 1975). These areas also experience their highest monthly average snowfall in March (Harrington et al. 1987). The northern Rockies experience their storm maximum in April, and this is also the peak month of total snowfall. Thus, there is a close relationship between peak snowstorm frequencies and total monthly snowfall over most of the United States.

A study of U.S. blizzards that occurred during 1959–2000 found some monthly distributions similar to those of peak snowstorm frequencies (Fig. 11). Schwartz and Schmidlin (2002) identified a January peak in blizzards in Minnesota and the central United States, identical to the January peak in snowstorms. Blizzards peaked in March in the central-northern high plains where snowstorms also peaked. In other months there was not

FIG. 11. The month with the greatest number of snowstorms during 1901–2001.

strong agreement between the patterns of maximum blizzard activity and snowstorm peak frequencies. Cold Canadian air interacts with Colorado lows or Alberta clippers to produce frequent blizzards in the northern plains (Rauber et al. 2002).

5. Summary and conclusions

The geographical distribution of snowstorms in the contiguous United States was determined using a newly available database for storms at 1222 stations during 1901–2001. The resulting findings are considered to be more climatologically representative than prior climatic assessments of storms as a result of two factors: 1) the long duration of data and 2) the great density of point observations. The resulting patterns of average and extreme snowstorm occurrences revealed considerable spatial variability across short distances plus important distributional features that would go undetected if only data from the 208 U.S. FOS had been used in the analysis. Large, short-distance variations exist in the mountainous areas of the western and eastern United States and around the Great Lakes.

The annual average storm distribution across the eastern two-thirds of the United States is largely latitudinal, ranging from 0.1 (south) to 2 storms (north). However, this pattern is interrupted by increased storm activity around the Great Lakes and in the Appalachian Mountains, where averages are 3 or more storms per year. The western third of the United States has wide variations in the average frequency of storms because of major elevation differences in and around the Rocky Mountains and Cascade Range. In the higher-elevation areas, average storm frequencies range from 5 to 30 per year, as compared with 2 or fewer storms in the lower-elevation areas.

The ratios of average storm frequency to the maximum 1-yr values at stations vary from 8 with low point averages (0.1–0.5) to 2.2 where station averages are 5 or more storms per year. This variation results because areas of infrequent snowstorms do experience occasional years with numerous storms. The national pattern based on the maximum 1-yr number of storms during 1901–2001 is similar to the average pattern. Peak values downwind of the Great Lakes are 20 per year, with peak values of 6–10 storms occurring in the Appalachian Mountains. The high-altitude locations along the Cascades have experienced between 30 and 50 snowstorms in a single year. In contrast, most of the United States has had years with no snowstorms. Only isolated areas in the western and eastern mountains, and two areas downwind of Lakes Erie and Ontario, have had minimum annual values of 1–3 storms.

Temporal assessments of the snowstorm incidences during 1901–2000 revealed major regional differences. Comparison of the storm occurrences in 1901–50 with those in 1951–2000 revealed that much of the eastern United States had more storms in the early half of the twentieth century, whereas in the West and New England, the last half of the century had more storms. Over the United States, 103 stations had their peaks in 1901–50 and 98 peaked in 1951–2000.

Assessment of temporal variations in storm activity in eight regions, each with different storm frequencies, revealed that all exhibited considerable variability over time. The temporal distributions of certain adjacent regions were similar, including those for the high plains, upper Great Lakes, East, and Northeast, reflecting upward trends in cyclonic activity. The time distribution of storms along the West Coast was different than those of the intermontane West, and those of the upper and lower Midwest also differed, reflecting different timing of the synoptic causes of storms. Certain regions had 100-yr downward trends, including the lower Midwest, South, and West Coast, areas noted to have decreasing trends in cyclonic activity since 1901. Regions with upward trends for 1901–2000 included the upper Midwest and Northeast. The 100-yr trend for the entire United States was slightly upward. Decades with highest frequency of storms across the United States were 1911–1920 and 1971–80, and decades with few storms nationally were 1931–40 and 1951–60. The regional and national fluctuations and trends in snowstorm activity were in good agreement with temporal behavior of cyclonic activity, as reported in several past publications.

The first months to experience snowstorms included September in the northern Rockies and October in the high plains. November is the first month with snowstorms in areas from the Southwest across the Midwest and East, and December had the first storms in the South. The pattern based on the last month to experience snowstorms has a latitudinal distribution with either December or January being the last storm month in southern areas with few storms. February is the last storm month across the mid-South. March is the end of storm activity in an east–west zone across the central United States, and April has the last storms in an area farther north, including the Midwest and Northeast. This regional shift reflects the movement of zones of frequent cyclonic activity. May is the last month of storms in the north-central Rockies, and a few high-altitude locations of the West have storms as late as June.

Months of greatest storm activity exhibit great spatial variability across the United States. December is the peak month in the lee of the Great Lakes, and January is the peak of storm activity over large parts of the West, South, Midwest, and East. Storm frequencies maximize in February in an east–west area across the south-central United States, in the Appalachians, and along the East Coast. March and April are the peak months in the high plains and the northern Rockies, respectively. Areas with months of peaks of storm activity are also areas in which the highest average total snowfall occurs in that same month.

The geographical patterns of average and peak storm areas are closely linked to seasonal upper-level circulation patterns and the synoptic conditions causing snowstorm events. In the autumn, the start of snowstorm season is marked by storms that affect areas in the northern high plains and the high-elevation areas across the northern tier of states. As the winter season progresses and the circumpolar vortex expands, snowstorms spread southward and eastward across the United States. In addition, areas around the Great Lakes are influenced by lake-effect storms. By midwinter, snowstorm areas and the upper-level westerlies are at their maximum extent. Cyclones tracking up the Atlantic Coast give areas along the East Coast a high proportion of their storm activity. The transition to spring is accompanied by more frequent troughs in the central and western United States, and storms move along the Colorado storm track. As the season ends, late-season storms are restricted to the northern high plains and the higher elevations in the U.S. northern latitudes.

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