Long-Term Fluctuations in Hail Incidences in the United States

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ABSTRACT

Hail-day occurrences during a 100-yr period, 1896–1995, derived from carefully screened records of 66 first-order stations distributed across the United States, were assessed for temporal fluctuations and trends. Shorter-term (5- and 10-yr) fluctuations varied greatly and were often dissimilar between adjacent stations reflecting localized differences in hailstorm activity, making temporal interpretations difficult. But temporal fluctuations based on 20-yr and longer periods exhibited regional coherence reflecting the control of large-scale synoptic hail-producing systems on the point distributions over broader areas. Classification of station fluctuations based on 20-yr periods revealed five types of distributions existed across most of the nation. One present in the Midwest had a peak in hail activity in 1916–35 followed by a general decline to 1976–95. Another distribution had a midcentury peak and was found at stations in three areas: the central high plains, northern Rockies, and East Coast. The third distribution peaked during 1956–75 and was found at stations in the northern and south-central high plains. The fourth temporal distribution showed a steady increase during the 100-yr period, peaking in 1976–95, and was found in an area from the Pacific Northwest to the central Rockies and southern plains. The fifth distribution found at stations in the eastern Gulf Coast had a maximum at the beginning of the century and declined thereafter. The 100-yr linear trends defined four regions across the United States with significant up trends in the high plains, central Rockies, and southeast, but with decreasing trends elsewhere in the nation. These up trends have occurred in areas where hail damage is greatest, and the trends matched well with those defined by crop-hail insurance losses and those found in studies of thunderstorm trends. The national average based on all station hail values formed a bell-shaped 100-yr distribution with hail occurrences peaking in midcentury. Thunderstorm data from the 66 stations, also based on screening to ensure quality data, revealed a bell-shaped distribution similar to the hail-day distribution, and national hail insurance loss values have declined since the 1950s, also agreeing with the hail-day decrease since midcentury. The national distribution differs markedly from certain regional distributions illustrating the importance of using regional analysis to assess temporal fluctuations in severe weather conditions.

1. Introduction

Concern over the potential for shifts in weather and climate extremes due to an ongoing or future shift in the nation's climate have led to efforts to measure the long-term distributions of precipitation and temperature extremes (Karl et al. 1996). To assess the temporal behavior of one form of severe storms, a study of 100-yr historical records of hail available in a newly developed hail database (Changnon 1998) was conducted. Analysis of trends and temporal fluctuations in the number of days with hail, as measured at stations screened to define quality records of hail for the 1896–1995 period, was pursued. The 66 stations with quality records were scattered across most of the nation and included all areas where damaging hail is most prevalent including the Pacific Northwest, the high plains, Midwest, and the southeast coast (Changnon 1972).

2. Data and analysis

First-order stations of the National Weather Service having unbroken records of the number of days with hail since 1896 were screened and those found to have high quality data were selected for study. Data at some stations exhibited unusual shifts in hail frequencies after the stations had been relocated and these stations were excluded. The 66 stations found to have quality data are shown in Fig. 1, along with the mean number of hail days per 5-yr period. These values reveal the peak in

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FIG. 1. The locations of the 65 first-order stations with quality hail-day records for the 100-yr period, 1896–1995, and their 5-yr average number of hail days.

hail frequency is along the eastern ranges of the Rocky Mountains. Cheyenne is near the nation's hail maximum (Changnon 1978), averaging 45 hail days (5 yr)$^{-1}$, and mean values greater than 20 hail days (5 yr)$^{-1}$ also exist at Denver, Helena, and Dodge City. The lowest averages occur in the Southwest and East Coast where station mean values are less than 5 hail days (5 yr)$^{-1}$. However, some areas with low hail incidences like the southeastern United States experience considerable crop-hail damage because of the high sensitivity of the region's tobacco and fruit crops to hail damage (Changnon 1972).

Periods of different durations were analyzed to examine for possible varying types of fluctuations in hail occurrences, and because the factors that cause hail at a point, and over a large area, are known to vary on different timescales. The analysis assessed fluctuations found in 5-, 10-, and 20-yr totals of hail days, and values for each period at each station were expressed as a percent of the 100-yr average. Linear trends were also computed based on the annual values. The hail-day distributions of the 66 stations were compared in two ways: (a) the shape of the distribution based on the timing of the maximum 20-yr period and the minimum 20-yr period at each station, and (b) the direction of the linear trend of their 100-yr values.

3. Findings

a. Short- and long-term fluctuations

The temporal distributions of the twenty 5-yr and ten 10-yr values for each station showed considerable variability between adjacent periods. Discrete period values were analyzed since moving averages can produce misleading amplification of the timing of highs and lows in time distributions. The distributions of adjacent stations were compared and most were found to be different and often out of phase for any given period of time. Such short-distance differences are illustrated in Fig. 2, which shows the distributions of the 5-yr values for two stations in Ohio: Columbus and Cleveland. The maximum value at Columbus occurred in 1916–20, whereas that at Cleveland came in 1941–45 and again in 1946–50. The directions of the 19 shifts (up, down, or no change) between the 20 periods were compared for the two stations, and 15 were different with only 4 alike. However, both Ohio stations show a general downward trend in hail days after 1970. The comparative analysis based on the 10-yr values showed results comparable to those for the 5-yr periods.

Analysis of hail frequencies for 20-yr periods, based on the five independent 20-yr periods between 1896 and 1995 (e.g., 1896–1915, 1916–35, etc.), provided results

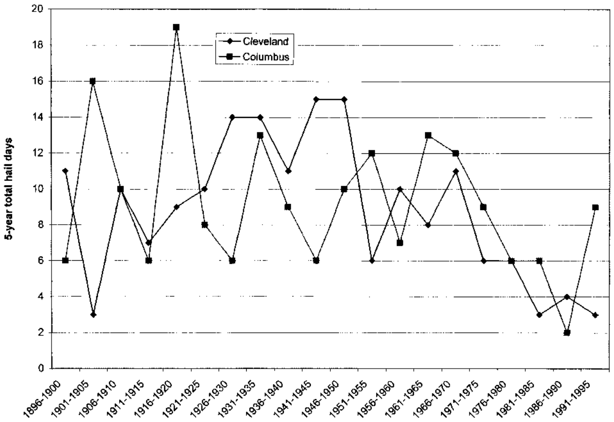

FIG. 2. The temporal distributions of 5-yr hail-day frequencies at Cleveland and Columbus, OH; for the 1896–1995 period.

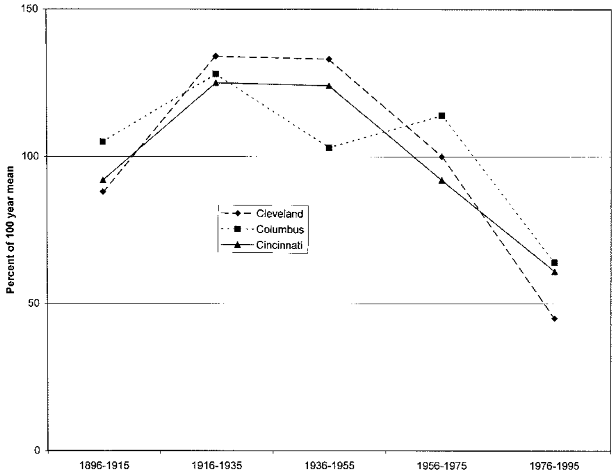

FIG. 3. Temporal hail distributions based on 20-yr values at three Ohio stations for the 1896–1995 period.

quite different than those for the 5- and 10-yr periods. The 20-yr fluctuations were less spatially variable, as shown by the adjacent stations' curves in Fig. 3. Comparison of the distributions of the 66 stations across the nation revealed that adjacent stations in various areas had similar distributions over the 100-yr period.

The differences between the temporal structure of shorter-term fluctuations and that of 20-yr and longer fluctuations at adjacent stations are attributed to the causes of hailstorms. Hail at a point is caused by two general synoptic weather conditions: 1) thunderstorms generated by large-scale mesoscale systems often frontal in nature and widespread, and 2) by localized convective storms resulting from influences due to nearby physiographic features, large water bodies, and/or by localized convection in unstable air masses leading to the development of isolated thunderstorms and hail. Conditions conducive to localized hailstorm development often vary between nearby locations, and as a result, two adjacent locations can experience quite different storm frequencies in any given period of a few years (Changnon and Schickedanz 1969). Larger-scale convective systems that produce most hailstorms generally create storms over wider areas leading to hail occurrences at adjacent locations. These events ultimately predominate in the time distributions for periods longer than 10 yr, creating the longer-term (multidecadal) fluctuations found in the hail records at most locations (Huff 1964). Frontal conditions produced 81% of all hail events in Illinois with 19% due to airmass storms (Huff 1964), results matching those from New England where 75% of all hailstorms were caused by frontal conditions (Donaldson et al. 1960). In eastern Colorado, where weather conditions are similar to those in the high plains, a study of 57 hail events revealed 41 were frontal or postfrontal in nature, and 16 (28%) were due to airmass storms (Fankhauser and Wade 1982). Studies of hailstorms in the lee of the Lake Michigan revealed that 22% of all storms were a result of lake effects active during late summer and fall seasons (Changnon 1966).

Collectively, these results indicate that localized unstable air masses, lake effects, and/or topographic effects in various parts of the United States account for 20%–30% of the hail events at a given point over a long period of years, and that the broader-scale frontal or mesoscale convective complexes, about 75% of all hailstorms. However, in any given short period of 10 yr or less, the percentages can shift at a given locale due to substantial localized increases or decreases in the number of hail events caused by localized influences on storm activity (Huff 1964; Changnon and Schickedanz 1969).

b. Twenty-year fluctuations

Analysis of the timing of the highest and lowest 20-yr values at each of the 66 stations resulted in the distributions shown in Table 1. Each 20-yr period had some stations experiencing their highest and some their lowest 20-yr values. However, the values reveal a distinct tendency for the highest values to have occurred in the 1916–35 period or the 1936–55 period, and these two periods accounted for 41 of the 66 highest values. The lowest values were concentrated in the 1976–95 period. Taken as a measure of the national hail-day distributions, these results suggest a peaking of national hail activity in the early-middle part of the century with a

TABLE 1. The number of times the highest and lowest 20-yr hail-day values at 66 stations occurred in each 20-yr period between 1896 and 1995.

Period	Highest value	Lowest value
1896–1915	7	18
1916–35	19	1
1936–55	22	1
1956–75	10	3
1976–95	8	43

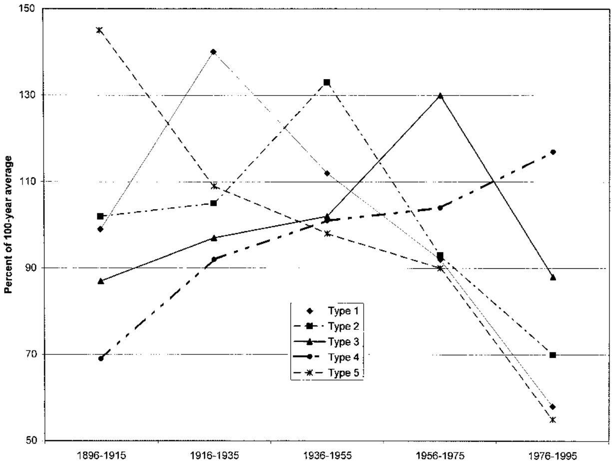

FIG. 4. The temporal distributions, based on 20-yr totals, of the five types of distributions found at the 66 stations and that form major hail regions in the United States. Values are expressed as percent of the 100-yr average.

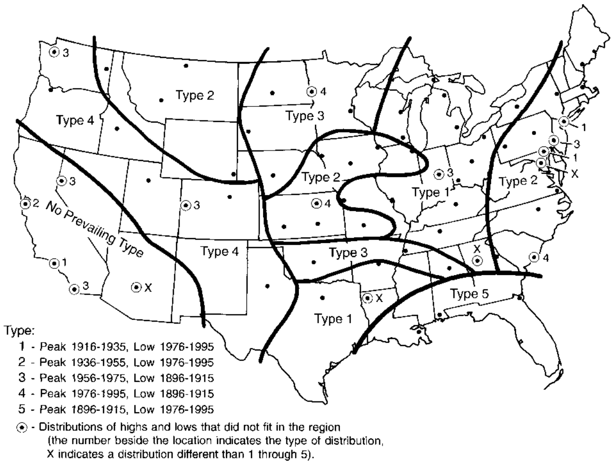

FIG. 5. The regions defined by the different types of 100-yr hail-day distributions, as based on 20-yr values. The distributions are shown in Fig. 4. Stations that have distributions not in agreement with others in a region are marked with a small circle around the dot.

decrease thereafter reaching a low in the most recent 20 yr.

The hail-day distributions of the 66 stations were compared based on when the maximum and minimum 20-yr values occurred. Given there are five discrete 20-yr periods between 1896 and 1995, each with four possible arrangements of high and lows, 20 types of distributions of highs and lows could have existed during the 100-yr period. Interestingly, examination of the 20-yr distributions revealed that those at 62 of the 66 stations fit within five types of time distributions. The other four stations each had dissimilar distributions.

The values of the stations in each of these five types were used to compute a mean value for each type, and the distributions, based on percentages of average values, of the types appear in Fig. 4. Each type peaked in a different period, and two were lowest in 1896–1915 and three were lowest in 1976–95. One class of distribution, labeled type 1, had a long-term, 60-yr down trend from the highest value, an average of 140%, attained during 1916–35. The lowest 20-yr value, 58% of average, occurred in 1976–95. This type of distribution was found at 18 of the 66 stations. The 20 stations with a type 2 distribution had a peak of hail in the 1936–55 period with their lowest value in the 1976–95 period. The type 3 distribution had a later maximum of hail incidences, in 1956–75, but the peak was followed by a sharp decrease in hail to 1976–95 (88% of average), a value only slightly higher than the lowest value in 1896–1915 (86%). This distribution was found at 10 stations. The type 4 distribution found at eight stations was essentially the opposite of type 1 but similar to type 3. Its lowest value occurred in 1896–1915 and its peak was in 1976–95, representing a long-term increase in hail incidence. The fifth distribution (type 5) found at six stations peaked in the initial period (1896–1915) at 145% of the mean in 1896–1915, and then gradually declined to a minimum of 55% in 1976–95 (Fig. 4).

The types of distributions of each station were plotted on a U.S. base map to assess their regional distributions. Analysis revealed several spatially coherent regions existed. These were outlined based on there being three or more adjacent stations with the same distribution. Some of these regions contained a station with a different distribution. These regions are shown in Fig. 5. Stations with distributions that did agree with others in a region are marked in Fig. 5.

Most of the type 1 distributions were found at 13 stations in the Midwest (Fig. 5). This regional outcome is supported by results of a study of hail occurrences during 1901–94 at 35 cooperative substations in Illinois, which revealed all the stations had similar downward trends since midcentury (Changnon 1995). The region of type 1 in the western Gulf Coast is supported by results of a study of hail-day trends in Texas, which found that the cooperative substations in central and southern Texas had downward trends matching that at Dallas (Changnon et al. 1996a). In addition, this time distribution was found at three widely distributed stations including Baltimore, Los Angeles, and New York.

This bell-shaped type 2 distribution was found at 20 stations and 19 of these formed three separate regions (Fig. 5). One was along the East Coast (eight stations), one in the central high plains–Midwest (seven stations), and a third area in the northern Rockies (four stations). An analysis of the temporal fluctuations in hail days at 43 cooperative substations across Nebraska revealed a similar distribution at stations in the eastern half of the state, helping confirm the areal consistency of this type in the central high plains (Changnon and Changnon 1996). San Francisco had a type 2 distribution and was located in an area with several other different types.

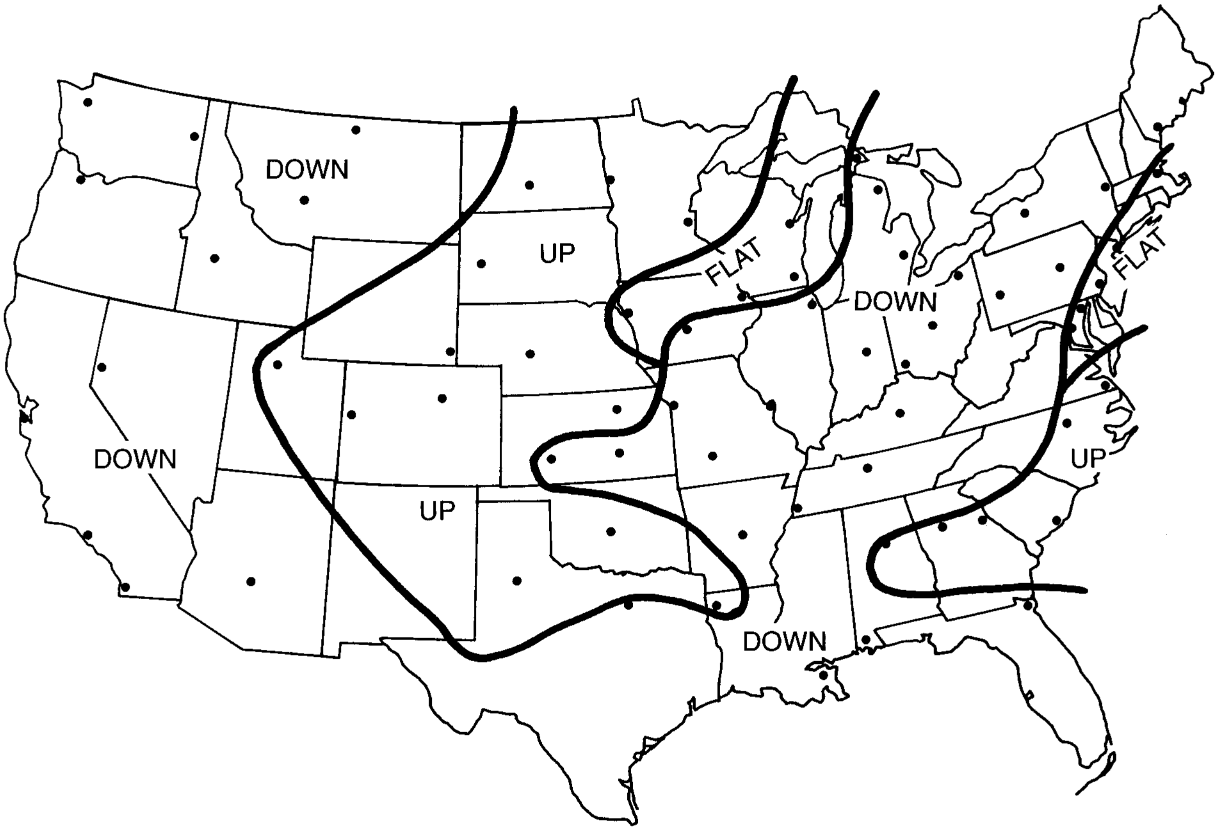

FIG. 6. Regions defined based on linear trends of the 100-yr values. Up is for increasing trend significant at the 5% level, flat is essentially no trend up or down, and down is for decreasing trends significant at the 5% level.

The stations with type 3 distributions formed a region in the northern high plains (based on four stations) and one in the south (three stations). Cooperative substations in western Nebraska also showed this distribution (Changnon and Changnon 1996). This distribution was also found at three distant and isolated sites: Indianapolis, Seattle, and Grand Junction.

The type 4 distributions formed a region based on five stations in an area that extended from the Pacific Northwest to the central-south Rockies. A study of hail-day trends at 47 substations in Texas revealed that those in northwest Texas had similar up trends, indicating that northwest Texas is part of this region (Changnon et al. 1996a). Recent period (1976–95) peaks in hail days were also found at three other isolated locations, including Charleston, Topeka, and Fargo, all in varying climatic regimes. Their hail distributions differed from those of surrounding stations and represent localized peaks of hailstorm activity during the last 20 yr, 1976–95.

Three of the six stations with the type 5 distribution, high to low, formed a region along the eastern Gulf Coast (Fig. 5). The other three stations included Philadelphia, Reno, and San Diego.

Three other time distributions were found at isolated locations and did not form regions. These included Phoenix (a minimum in 1916–35 and a maximum in 1936–55) and Atlanta (highest in 1916–35 and lowest in 1936–55). Two widely separated stations had another type of distribution (peak in 1936–55 and low in 1956–75), and included Shreveport and Washington, D.C. The five stations in the region embracing California, Arizona, and Nevada did not have a predominate time distribution.

4. Trends

Linear trends based on the 100 annual hail-day values at each station revealed there were marked regional differences across the United States, but the trends defined certain large regions with different trends. The regions were defined as having distinct up trends (significant at the 5% level), distinct downward trends with time (significant at the 5% level), or flat (no trend) based on the nonsignificant up or down trends. This classification of the trends at the 66 stations led to the regional pattern shown in Fig. 6. Two regions of long-term increases in hail days exist: (a) one comprising most of the high plains (Texas to North Dakota) and including the central and southern Rockies, and (b) another in the Southeast coastal area. Two relatively small areas without statistically significant up or down trends exist. One is in the northern Midwest and the other is along the East Coast (Washington, D.C., to Boston). The stations in the remaining portions of the United States all had significant downward trends and they included the Far West, Midwest, and Deep South. There were 19 stations with up trends (29%), 9 stations with flat trends (14%), and 38 (57%) with downward trends in hail activity.

These regional trends compared very favorably with trends found in state crop–hail insurance loss costs (Changnon et al. 1996b). The annual loss cost value for a state is the loss divided by the liability (and multiplied by 100), an insurance-based term used to eliminate time changes due to inflation and changing liability, and allows temporal comparisons of loss. The loss cost values for 1948–95, all the historical data available on a state basis, in the major hail loss regions of the United States revealed marked upward trends in the states of the high plains (Texas to North Dakota) where hail-day trends were upward (Fig. 6). The loss cost values in the Midwestern states showed marked downward trends, as did the hail-day trends, and the loss cost values in the Southeastern states (Carolinas and Georgia) were upward as were the hail-day trends.

5. Comparison of hail patterns with patterns of thunderstorms

The areas defined based on the 20-yr maximum–minimum value distributions (Fig. 5) and those based on the linear trends (Fig. 6) were compared with regions previously defined based on temporal fluctuations in the number of thunderstorm days. Gabriel and Changnon (1990) assessed thunder-day trends at 57 first-order stations for the 1901–80 period and found 10 discrete regions, based on a cluster analysis, in the United States. Four of the thunder regions matched moderately well with the hail regions including the thunder region in the Midwest (type 1 hail), the northern high plains (type 3), the Gulf Coast (type 5), and the central high plains (type 2). The major disagreements between the hail and thunder regional fluctuations were in the Far West and East Coast where hail frequencies are low (Fig. 1).

Another study of historical (1900–80) thunder fluctuations at 86 stations defined 11 regions based on thunder-day trends (Changnon 1985). Several of these regions showed good agreement with the hail-trend regions (Fig. 6). Hail and thunder incidences both showed downward trends across the western fourth of the nation, both had up trends in the high plains, and both displayed downward trends in the Midwest and South. Differences existed along the East Coast where thunder-day trends were downward and hail trends were flat or upward. The national time distributions of thunder days for 1901–80 in both studies show an upward trend in storm activity from 1901 to a peak occurring during the 1920–50 period, followed by a decrease in thunderstorm activity.

A national analysis of the hail-day fluctuations based on the 20-yr values from all 66 stations was done, and the resulting 100-yr curve is shown in Fig. 7. This shows an increase from early in the century to the highest values in 1916–35 and 1936–55, followed by a decline in hail activity up to 1995. Thunderstorm-day values available for the same 66 stations for 1896–1995, defined after assessment to ensure the quality of the records, were used to calculate a thunderstorm time series. The values are plotted in Fig. 7. This shows a peak in thunderstorm activity in 1916–35 and a minimum in 1976–95. The hail- and thunder-day distributions are similar, helping to support the reality of the hail distribution.

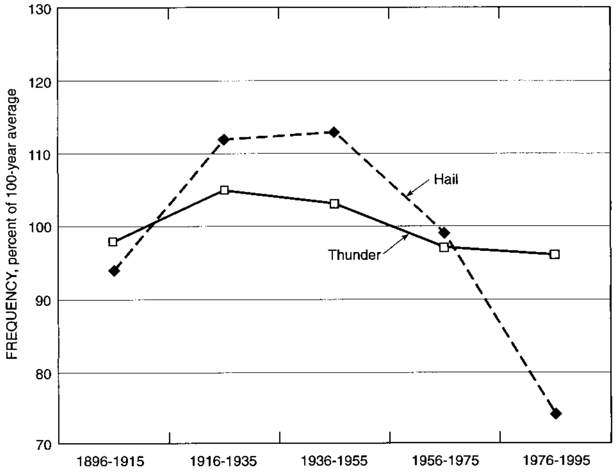

FIG. 7. The 100-yr mean distribution of hail days and thunder days based on values for all 66 first-order stations used in the study.

Analysis of the national crop–hail loss data for 1948 to 1995 showed that the loss cost values peaked in the 1950s and since have declined slowly (Changnon and Changnon 1998). Thus, the loss distribution is also similar to the hail-day distribution found for the 1950–95 period.

6. Summary and conclusions

The temporal analysis of hail frequencies at 66 stations with 100-yr records, based on 20-yr totals, showed that five types of temporal distributions of hail days existed at 62 stations in the United States. Most stations, 43 of the 66 stations (65%), achieved their lowest 20-yr value of the 100-yr period during the last 20 yr (1976–95), but eight other stations had their peaks in the most recent 20 yr. The spatial locations of the temporal distributions of the 66 stations indicated the existence of several large regions each with differing hail distributions based on the timing of their maximum and minimum 20-yr values. The type 1 distribution with a general decline in hail activity over most of the century was present in the Midwest. Type 2 with a peak of hail in midcentury and a low in 1976–95 was found in the central high plains, in the northern Rockies, and along the East Coast. Type 3 had a peak of hail activity in 1956–75 with a minimum in 1896–1915 and occurred at stations in the northern and southern high plains. Type 4 was a long-term increase in hail found at eight stations, forming a region extending from the Pacific Northwest to the central-southern Rockies. Type 5 distribution was a continuing decease from 1915 to 1995 and was found along the Gulf Coast.

The 66 station values for each 20-yr period were combined to form a national hail value, and the resulting time distribution showed a midcentury peaking of hail activity followed by a decline to the lowest value in 1976–95. This is similar to the long-term fluctuations found in thunder-day values for the nation.

The linear trends of the 66 stations defined the existence of upward trends at all stations in the high plains–Rockies and in the Southeast. Downward trends existed in most other areas of the United States. The regions of up and down trends in hail days matched well with regions defined using crop–hail insurance loss data. The hail-day frequencies show an increase with time over the high plains where most of the crop–hail damages occur in the United States. The major regions of increase and decline in hail activity also matched well with regions of increase and decrease in thunderstorm activity for 1901–80.

The regional analysis of fluctuations and trends, when compared with the national distribution, reveals important differences that need to be considered when assessing temporal fluctuations in weather extremes. That is, the 100-yr national distribution, based on all 66 stations, was bell shaped reaching its lowest value in 1976–95, whereas the analysis of trends revealed distinct regions with sharp downward trends and others with sharp upward trends. Furthermore, the major area of increase exists where hail is most frequent and where the greatest crop–hail damages occur.

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