Data and Approaches for Determining Hail Risk in the Contiguous United States

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(Manuscript received 3 November 1998, in final form 10 March 1999)

ABSTRACT
Rapidly increasing hail damages to property have brought average annual losses to $1.2 billion (in 1997-adjusted dollars) during the 1990s; this rise in loss exposure has created great concern in the insurance industry and has led to efforts to define the hail risk across the nation. Since the property industry has not kept hail loss records, it must rely on available climatological data supplemented by data from field studies to assess hail risk. Hail risk at a point or over an area is a function of the target at risk (property or crop) and the hail frequency and intensity. Newly available climatological data based on historical hail records collected by the National Weather Service since 1900 have enhanced the ability to assess point risk. Some spatial risk assessments have combined point averages of hail-day frequencies with hailstone sizes to define risk, and others also employed hailstone volume (mass of ice) and wind associated with hail, based on data from field projects. Those seeking to define the spatial aspects of risk caused by very large hailstones, greater than 2.5 cm in diameter, have had to use area-based risk assessments since point data are too short to provide reliable frequencies of these rare events. Ongoing research is defining the hail damage characteristics for various structural surfaces and roofing materials for which most damage occurs. Crop insurance risk studies have combined that industry’s existing data on crop losses across the nation with long-term frequencies of hail days to generate crop–hail risk patterns for setting rates, and their data, which began in 1948, have been used to assess temporal variability of risk. These temporal assessments have relied also on long-term records of hail-day incidences, and both datasets show that the magnitudes of major features in average hail risk patterns fluctuate as much as 50% in any given 5- to 20-yr period, but that these features persist over time. Long-term trends of hail reveal increases in the High Plains and Southeast with decreases in the Midwest and West.

1. Introduction
The last 10 years have seen a series of very damaging hailstorms that created major losses in several urban areas. A 1990 hailstorm in Denver caused $0.9 billion in losses to homes, vehicles, and businesses, and a 1995 storm caused property losses of $1.1 billion in Dallas–Ft. Worth [Hill 1996; Institute for Business and Home Safety (IBHS) 1998]. In the 1990s, other sizable losses, each greater than $0.3 billion, have occurred in Orlando, Wichita, Dallas, and Oklahoma City (Changnon 1997a). National property losses from hail, when assessed 25 years ago, represented only one-ninth of the total annual hail loss with most hail loss occurring to crops (Friedman 1976). However, there has been a rapid increase in property losses and they now match crop hail losses, both averaging about $1.2 billion annually (in 1997-adjusted dollars) during the 1990s (Changnon 1998a).

These increased property losses have created great concern about hail risk within the property–casualty insurance industry. This concern has led to efforts by the IBHS, an organization sponsored by many insurance firms, to find ways to assess the risk and to reduce hail losses (Cook 1995). Since most property hail damage occurs to roofs, the IBHS and others have conducted studies of roofing materials and ways to mitigate hail losses in the future (Devlin 1997). These industry-wide concerns over hail damage have led also to various corporate efforts to assess the risk of hail damage for setting rates, revising building codes, developing and installing new hail-resistant materials, and general planning for loss potential. The property insurance industry has never established an industry-wide database of losses due to hail (or other types of weather) and hence must rely on climatological data to measure the temporal and spatial risks from hail.

Ascertaining the risk of hail damage to crops or property is a function of 1) the target under consideration (corn plant, a roof, etc.), as reflected in the interests of those who utilize risk values for insurance or other structural design applications, and 2) the data available to assess the specified hail risk. For most applications, hail risk is the threat of damage at a point, such as a farm field, a house or building, or a group of vehicles in a parking lot. In some instances, risk also has been as-
esessed for larger-scale areas, such as townships or counties, using various hail loss statistics and point-area relationships (Changnon 1977).

Studies of hail damage to crops and to property reveal that the amount of damage is a function of two factors: the frequency and the intensity of hailfalls (Changnon 1997b). The relationship of these two factors to damage varies according to the type of target. Hence, there is no single unique mix of frequency–intensity values that can address all forms of hail damage and measure all risks.

The frequency of hail typically is represented by the number of days with hail, the only existing nationwide measure with extensive historical data. The hail-day frequencies based on weather station data typically are expressed as the average value or extreme value per year or for the growing season of threatened crops. The intensity of hail during a given hailfall event is a function of three variables, depending on the type of target, including 1) the maximum and/or average hailstone size that falls, 2) the number of hailstones that fall (volume or mass of ice), and 3) the wind with the hail that causes the hailstones to fall at inclined angles. For crops like tobacco or tea, which have delicate leaves, the volume of ice and not hailstone size is the most critical intensity variable (Changnon and Stout 1967), whereas the key variable for a florist’s greenhouse or the roof of a convertible is the maximum hailstone size that occurs (Collins and Howe 1964). Most crops and the sides of structures are damaged when winds are strong enough to blow hailstones at angles away from the vertical.

Various assessments of hail risk have investigated each of these hailfall values to address their specific needs. For example, studies done for the crop–hail insurance interests have used a mix of hail-day frequencies (seasonal averages and/or extremes) and average loss statistics (the target’s susceptibility) to define risk areas, and these measures were used to help to establish rates (Changnon and Fosse 1981). Unlike the property insurance industry, the crop–hail insurance industry in 1948 established an industry-wide association at which all loss data have been archived. In some field experiments, instrumental measures of the total kinetic energy imparted by the volume of hail that fell were collected and compared to the damages to various crops to develop a better concept of what parameters to use in assessing risk (Changnon 1971a).

Efforts to provide measures of hail risk to property have varied but generally have used some mixture of climatological data such as the average hail frequency coupled with some measure of hailstone sizes considered to be critical to the property being insured. Recent concerns in the property insurance industry about hail losses have led to ongoing studies to define better the parameters that cause damage to various property materials and surfaces (Devlin 1996).

In summary, one key factor in assessing hail risk values is the determination of the hail conditions that cause damage, that is, the target susceptibility, which is a factor to be defined by the users of the risk information. The other key aspect is the hail data available to measure the key hail characteristics at various locations of concern. The types of hail data available to compute hail risks are reviewed and assessed herein. Then approaches used for determining risk spatially and temporally are reviewed, and examples of how the crop and property insurance interests have addressed and defined risks are provided.

2. Available hail data

The determination of hail risk in the United States is limited by the types and duration of the data available, and hence it is important to assess and to understand the existing sources of hail data that pertain to calculating hail risk at the ground. Hail data can be obtained from three basic types of sources (Changnon 1997b). First are the historical records of hail incidence collected by the National Weather Service (NWS). Second are the widely varying data on hail that have been collected in field studies. Third are the data generated from theoretical calculations, simulations, and laboratory studies of hail. United States hail data, more limited than could be desired for certain risk analysis, are considered to be as good or better than those found in other nations. Most European nations, Canada, Australia, South Africa, and Russia have quality historical hail occurrence data and some damage-prone nations such as Italy, Russia, and France have crop–hail insurance data, but few have databases that can match the length, areal extent, and quality of the insurance database in the United States.

a. Historical hail data

A critically important record of hail is the counts of days when it hailed as noted at NWS stations for all or portions of the twentieth century. These data are available for the nation’s 145 first-order stations; data for hundreds of cooperative weather stations also exist but must be extracted from paper records and be carefully screened for quality (Changnon 1967). The historical hail-day data for 6200 NWS cooperative substations spread across the higher hail incidence areas of the United States have been screened. Quality hail data were defined for all or portions of the 1901–96 period at 924 stations with 25–50 stations per state in the 27 states with the highest risk of hail damage (Changnon 1998b).

Historical measurements of hailstone sizes in three categories were made during the 1920–50 period by weather observers at cooperative substations of the U.S. Weather Bureau. These data are in paper formats and until recently had not been assessed to determine which stations had quality records of hail sizes. A recent assessment of these hail data identified 465 cooperative substations across the United States each with quality historical hailstone data in three size/intensity classes...
The stations have 12–30 years of quality size data. A third form of historical data comes from the reports of large hail published in Storm Data by the NWS. These data come from volunteer reports of 1.9-cm (0.75-in.) or larger hailstones, collected by the NWS since 1955 to verify their severe hail forecasts. This database lists the date and location (typically a county) where hailstones of 1.9 cm or larger occurred. The data have major drawbacks for many hail risk assessments and have been misleading in certain insurance applications. For example, a recent insurance study used these data to calculate a national pattern of “average” hailstone sizes that showed incorrectly that most of the United States had average hailstone sizes greater than 3 cm (Cook 1995). The data in Storm Data cannot be considered to be representative of a point record of large hail because the events reported are those that some untrained person happened to see and chose to report to a weather office. The data serve as proof that a hailstone of 1.9 cm in diameter (plus or minus some error in observer judgment) fell in place X on date Z, but the data do not contain reports of many large hailfalls (either no one saw them, or those who saw them did not report them to the NWS). These data offer no way to assess the long-term incidences of large hailstones for a specific point that serve as the basis for many insurance applications of risk, but can be used for some forms of area assessment of large hail (Kelly et al. 1985).

b. Field studies of hail

Field studies of hail have been pursued for several purposes, including concerns over hail damage to aircraft, hail suppression research–evaluation efforts, detection of hail by radar for improved storm warnings, remote sensing of crop–hail damage, and investigations of degrees of hail damage to property and crops. These field investigations included detailed studies of individual storms and studies of hail using data from dense networks of hail-sensing instruments and/or hail observers, complemented with data from weather radars.

These special field studies of hail, which have been conducted in a few areas of the United States, provide a source of useful hail data. Unfortunately, data collection in most areas covered short periods of time, projects that usually lasted 3–5 years. Data from dense networks exist for only 10 sites across the United States. The networks ranged in size from 2 to 7000 km². In the Midwest there have been three projects with dense hail networks: 1) in northeastern Illinois–southwestern Michigan, operated from 1976–79; 2) in central Illinois, operated in 1958–62 and again during 1967–72; and 3) in eastern Missouri–southern Illinois in 1971–75 (Changnon 1975). These networks were all greater than 5000 km² in size and used many hail sensors and observers (about one per 15 kilometers squared) to measure, for each hailfall, the number and sizes of all of the hailstones. Adjacent recording rain gauges were modified to measure the time and duration of the hail and the rain associated with the hail (Towery et al. 1976). From these data, the hail momentum and kinetic energy of each hailfall were calculated. On two networks, data were collected on the wind associated with hail, and the angles of incidence of hailstones were measured using special sensors (Changnon 1973; Morgan and Towery 1976).

The other seven hail networks were operated in New England, central Oklahoma, northeastern Colorado, the Denver area, eastern Colorado, western South Dakota, and central–western North Dakota (Changnon 1997b). Data collected by observers and passive sensors typically included hailstone sizes (largest and average), number of stones, and times of occurrence. Some of these projects also collected data on crop damages, on the number of hailstones per unit area (e.g., m²), and the wind and rain that fell with the hail.

Detailed field studies of individual hailstorms have been pursued as part of meteorological field studies of hailstorms (Morgan 1982), for insurance purposes such as testing the use of aerial photography to detect hail damage (Changnon and Barron 1971), or to define hail-damage functions for various types of property (Friedman and Shortell 1967). These studies provide extremely detailed information on the structure of hailstorms. During the 1960s, highly detailed field studies were made of 16 major hailstorms in the Illinois–Missouri area (Changnon 1968a) and for 23 storms in South Dakota (Changnon 1970). In the early 1970s several storms in northeast Colorado were defined in great detail (Morgan 1982). Point measurements in these storm areas typically included hailstone sizes and numbers from local witnesses, evidence of winds with hail in the damaged crops and property, the amount of damage, and associated rainfall amounts. Most of these data provide very detailed time-referenced definitions of the various hailstorm conditions as they developed and moved (Changnon and Wilson 1971).

Several meteorological studies since the 1950s have investigated the relationship between echo reflectivities and polarization measurements from weather radars and the incidence of surface hail or hailstones sizes aloft (Wilk 1961; Heymsfield et al. 1980; Knight et al. 1982; Hubbert et al. 1998). These studies largely relied on case studies of individual hailstorms. The new Weather Surveillance Radar–1988 Doppler (WSR-88D) radars of the NWS hold promise for detecting and defining areas that have experienced hail, but, to date, there has been no systematic effort to collect and archive such hail data.

c. Laboratory research and simulation of hail damage

Field and laboratory studies to measure damage as a function of the impact of hailstones using ice propelled against a selected surface (such as a roof tile), or a crop’s...
leaf and stem, provide guidance on the various hail characteristics that create damage. Simulated damage studies to relate crop damages at a given stage of crop growth against ultimate yield loss have used field crops and applied different degrees of defoliation and stem damage manually accomplished at varying crop stages (Changnon and Fosse 1981). Other efforts have used cannonlike devices to propel ice pellets or steel balls at various structural materials and crops to gain information on how hailstone sizes and varying impact energies relate to the amount of damage (Morrison 1997; Devlin 1996).

d. Limitations in hail data that affect risk assessment

There are several cautions about the accuracy of certain hail data that greatly affect risk assessment. One relates to reported hailstone sizes. Hailstone measurements, both by observers and by certain field instruments used to sense hail, provide only an approximate range around the true hailstone diameters. Studies of size estimates made by human observers show that errors are typically 3–4 mm for hailstones in the 6- to 13-mm diameter category; errors are 6 mm for stones 1.9–2.5 cm in diameter; and become 6–9 mm for measurements of hailstones greater than 2.5 cm in diameter (Changnon 1971b).

Most available point hail data are not adequate to calculate a meaningful frequency analysis of large (greater than 2.5 cm) hailstones. Hailstones greater than 2.5 cm in diameter are extremely rare events, even in the highest frequency hail areas of the United States (Changnon 1971b). For example, a 3-yr field project in northeastern Colorado, which is in the nation’s peak area of hail activity, had 612 hail sensors distributed across an 11 000-km² network. The network experienced 33 hailstorms (with 10 000 point hail occurrences and measurements of 344 000 hailstones) and yet no stone larger than 3.5 cm in diameter fell, and only 3% of the point occurrences experienced stones larger than 2.5 cm (Morgan 1982). Most large areas of the United States experience less than 3 hail days per year at a given point, on average, and hailstones of 2.5-cm diameter have point likelihoods (based largely on hail network data) of about 2% of all sampled hailfalls in these climatic zones. This probability means that, on average, a location that averages 2 hail days per year would experience a 2.5-cm hailstone once every 50 years. Accurate point frequencies for larger hailstones simply cannot be achieved because of the lack of long-term hailstone measurements and, hence, inadequate sampling of these sizes.

As explained in the data section, the hail-day data, the basis of most property risk assessments, have undergone vigorous testing to ensure that hail incidences have not been missed (Changnon 1967). It is hoped that this evaluation technique detects most cases of missed hail events and eliminates the stations with questionable data. The crop–hail loss data have been adjusted for shifting liability in an area to ensure temporal compatibility and that significant hail events are not omitted. It is likely that both types of evaluation employed do not detect a few instances of hail, but they serve as the best possible measures of hail for risk analysis.

3. Approaches for assessing spatial hail risk

a. Crop risk

The risk of hail damage to crops has been defined in various ways but always uses a mix of historical hail data and insurance loss data. The insurance data had a much shorter record than the climate hail data and gained reliability by being statistically mixed with the long-term hail-day values (Changnon and Changnon 1997).

The approach employed in assessments done for all states used the relatively short records of daily insured losses, generally 10–15 yr, in a given state to calculate a monthly median storm loss value for the growing season months (Stout 1967). The loss values were normalized to allow between-month and -year comparisons by dividing the annual losses by annual liability and multiplying the ratio by $100, resulting in a value labeled as “loss costs.” For example, the monthly intensity values determined for wheat in Nebraska were 3 for April, 41 for May, 90 for June, 42 for July, and 2 for August (Changnon and Stout 1967). These loss cost-based values measure in-season changes in a crop’s susceptibility to damage, or target at risk, as well as integrating any seasonal shifts in storm intensities. At each weather station, these monthly loss values were multiplied by the climatologically determined monthly average hail days during the crop’s growing season months. The resulting monthly values were summed to obtain a “seasonal sensitivity value” for each station and for each major crop grown in the state under study (Changnon and Fosse 1981).

To measure possible regional differences in storm intensity and crop susceptibilities across a state, the township insurance loss cost values in each crop-reporting district were averaged, and these became “regional sensitivity values” (Stout 1967). For example, in northeastern Nebraska the regional value was 2.9, as opposed to 9.9 in southwestern Nebraska. The station-based seasonal sensitivity values were multiplied by the regional value, and the resulting product was the station’s “crop risk value.” An example of a hail risk map based on the calculated wheat risk values, as determined for 49 stations with hail-day records in Nebraska, appears in Fig. 1. This map reveals that risk values in the west were more than 10 times those in northeastern Nebraska. These patterns, done for each major crop and for each state, were used to establish the crop–hail insurance rates developed in each state (Changnon and Fosse 1981).
Fig. 1. The pattern of hail risk for the wheat crop in Nebraska with risk index values ranging from 1 (lowest) up to 13. These indices are based on hail-day values for 1901–80 at 49 stations and daily storm insurance loss data for 1951–67, which were used to create seasonal and regional intensity indices. These indices and average monthly hail-day values were combined to develop the hail risk indices shown.

**b. Property risk**

Several techniques have been used to assess hail risk to property, but the approaches fall into two general classes: point risk and regional risk. The point-based risk approach usually is based on point values of hail incidence and hailstone sizes of selected diameters, and, in some instances, other hail factors are employed to define the risk of concern to the user. The average point values are plotted on a map to develop a pattern based on the calculated risk indices.

Commonly, the approach begins by using data at all points in the United States with long records of hail incidence, and one or more other hail factors are combined mathematically. In some studies, these factors have included the point average annual hail-day frequency, the average point frequency of hailstones for the size under consideration, the regional estimate of the point average frequency of hailstones, and the point frequency for the wind speeds that are required to produce windblown hailstones for the size under consideration. The wind and hailstone values, as derived from points across the United States, are typically each set to a common base value (based on the lowest value) and all higher values are keyed to this base. These values become weighted and used as input for calculating the final risk index. The resulting combined index values for all data points in the United States then are adjusted to form “risk values.”

Figure 2 presents a map of risk determined using two criteria selected by a national insurance firm: the average point frequency of hail days, and the average hailstone size at a point. In this analysis, the firm set the risk parameters (frequency and size) and asked that the points in the nation’s lowest risk areas be set at a value of 1 and all other locations be scaled linearly up from 1. Further, the user established that frequency and hailstone size be given approximately equal weight in establishing the risk values. Given these conditions, the hail-day annual average values were used, and, in areas where the annual averages were less than 1 day (such as the Gulf Coast), the average, such as 0.4 day per year (equivalent to 4 days in 10 years), was used. Points in areas with average hailstone sizes less than 6 mm (0.25 in.) in diameter were assigned a base value of 0.5 and scaled upward. The categories assigned to the sizes began with 0.5 for stones less than 6 mm, followed by 1 for 6 mm stones, 2 for 9 mm, 3 for 13 mm, 4 for 16 mm, 5 for 19 mm, and 6 for stones greater than 22 mm, the nation’s highest average size. Two regional maps were prepared, one based on the annual average number of hail days (values of 0.1 upward to the highest), and the other based on the assigned values of hailstone sizes. The values on the two maps then were combined to create one map that integrates both values (Fig. 2). For example, a point in southern Alabama with a frequency of 0.6 and a stone size of 0.5 had a risk value of 1.1, whereas a point in central Iowa with a frequency of 3 and a size value of 2 had a risk value of 5. The risk pattern shows major regional differences, with index values ranging from a low of 1 in the deep South to more than 10 in the Colorado–Wyoming area. Note that this index does not incorporate regional differences in the target(s) at risk.

Another example of the point risk approach involved use of two newly developed hail databases. One database is for the point frequency of hailfalls for three hailstone size classes, and the other is the average point frequencies of hail-day occurrences (Changnon 1998b).
These two sets of values were combined to compute point likelihoods, or frequencies of hailfalls, of hailstones in the three hailstone size classes. An insurance firm desired maps that define hail risk patterns for various durations of years and various hailstone sizes. The pattern showing the area where, during any given 5-yr period, one or more hail days will have hailstones of 2.5 cm (1 in.) or larger appears on Fig. 3. Calculations at each point (weather station) were done using the average hail days over 5 years and the percent of hail days with hailstones greater than 2.5 cm. For example, points in central Kansas, for which the 5-yr average is 15 hail days and the incidence of greater than 2.5 cm is greater than 7% (0.07 × 15 = 1.05 hail days), qualified for inclusion in the risk region, as did points in western North Dakota, for which hail days averaged 12 (in 5 yr) and the percent of large stones was 10% (12 × 0.1 = 1.2 days).

Another approach that has been employed for assessing property risk is based on area occurrences of hail. Area risk specifies an expected hail outcome within a prescribed region and is often used when point data are not available or when regional risk is desired, whereas point risk is commonly used as a basis for establishing rates. Several studies have defined point-versus-area risk relationships for hail days (Changnon 1969, 1971c) and for crop-hail loss areas (Changnon 1968b, 1977). Area-based approaches are necessary to examine the risk of very large damaging hailstones greater than 2.5 cm because of their infrequency at a point and the lack of long records of stone sizes. By use of an area composed of hundreds of square kilometers, the incidence of very large hailstones is sufficiently frequent, at least in parts of the United States, to examine the area frequency and to determine the regional risk. The records of reported incidences of large hailstones since 1955 found in Storm Data are the source of such data.

A version of this approach was used by a major insurance company to assess risk and to develop rates for extended coverage of property (Collins and Howe
The pattern of property hail risk based on values for areas of 1° lat and 1° long. The risk is expressed as a percent of the residential property value in each area, and was calculated using large hailstone values (1948–63 data), values of hailfall areas (1948–63 data), and the average fraction of the area that can be damaged as of 1964 (Collins and Howe 1964).

1964). Their analysis was based on conditions within areas of 1° latitude × 1° longitude. The risk index they computed was the product of the incidence of large hail from Storm Data, the areal extent of damaging hailstorms (as determined using data from field studies), and the amount of property value at risk within each area, divided by the area in each rectangle. The resulting pattern (Fig. 4) shows a peak of high risk, with values greater than 30%, in the High Plains. Note that this risk index incorporates the target at risk (property value) with climatological and field data.

4. Temporal assessment of hail risk

Uncertainty tied to the hail risk patterns (Figs. 1–4), which are based largely on long-term averages, is mainly a result of temporal variability. That is, would the major features like the highs and lows in Nebraska (Fig. 1) persist over time, and, second, how much fluctuation around the average risk values can one expect in a few years or decades? Hail risk varies temporally and insurance-motivated studies have been done, particularly in recent years as property–hail losses grew, to measure the temporal variability of risk (Changnon et al. 1997). Unfortunately, the only quality data available with adequate length are the hail-day point frequencies, based on the 946 NWS stations with quality records during the 1901–97 period, and the crop–hail insurance loss cost data for the 1948–97 period. No other data exist to measure shifts in hail intensity over time. A problem with a temporal assessment of hail risk is that the target, in the form of property (not crops), has been changing continuously over time (Roth 1996). Recent studies have shown that weather damages to property have increased with time but that most of the national increase in losses has been due to four nonweather factors: 1) major demographic shifts to coastal and other storm-prone regions, 2) rapid growth and extension of metropolitan areas where small-scale yet intense events like hailstorms wreak havoc, 3) increased wealth and property value at risk, and 4) use of construction materials and methods susceptible to damage (Changnon 1999a).

Recent research found good state-level relationships between the annual crop–hail loss cost values and the amount of state area experiencing excessive numbers of hail days during the growing season (Changnon and Changnon 1997). Figure 5 presents the annual values of both datasets for Nebraska, and these graphs illustrate several key features found in hail incidence and hail loss over time. The strong statistical relationship between loss and hail days found in test studies of Nebraska, Illinois, and Texas has been used by the insurance industry to estimate the annual losses for the 1901–47 period (Changnon 1995; Changnon and Changnon 1996; Changnon et al. 1996). These pre-1948 loss cost values have been sought by the insurance industry to obtain a better concept of the range of risk values apt to occur for use in long-term planning of risk (Changnon and Changnon 1997), and further relationship investigations are under way for other states (Changnon 1998b).

The hail-day and crop–hail loss datasets for locations across the nation reveal highly skewed temporal variations, particularly at points and for areas ranging from county size (500 km²) up to state scales. Typically, a few years have many hail days (or high losses) and most years have little hail. For example, the annual hail-day values for 1901–97 at Des Moines, Iowa, show that 9
hail days occurred in 1 year, 8 hail days in another year, 7 hail days each for 3 years, 6 hail days each for 5 years, 5 hail days each for 13 years, and 4 or fewer hail days per year in the other 74 yr (with no hail in 12 years).

Most temporal studies of hail have found three other types of commonly occurring temporal variations that affect hail risk. One important characteristic found in long records is a mix of a few short periods (1–3 yr in length) with high hail values (days or losses) interspersed between periods of low hail, each lasting 3–15 yr (Changnon et al. 1977). These features are evident in the curves on Fig. 5. This distributional characteristic has caused major problems for the insurance industry. For example, low crop–hail losses persisted from 1981 to 1991 in many states, causing the insurance industry to lower rates, a move seen as necessary to remain competitive. However, rates eventually were lowered below levels that long-term loss records would indicate as necessary, and, when high crop–hail losses occurred in 1992, 1993, and 1994 (one of those occasional runs of high hail years), loss payments greatly exceeded premiums, causing major problems for the industry (Fosse 1996).

A second common temporal feature found in the time distributions that pertains to hail risk is that areas of major highs and lows in hail incidence and loss, as defined by long-term averages, are sustained over time and do not disappear. However, their magnitude in any given 5-, 10-, 20-, or 30-yr period differ between 5% and 55% from the long-term (80-yr or longer) average value (Stout and Changnon 1968; Changnon 1984). For example, a high hail-day incidence area in southwestern Montana with a 20-yr average of 97 hail days, experienced 117 hail days in 1901–20, 78 days in 1921–40, 93 days in 1941–60, and 101 hail days in 1961–80. These shorter-term differences have been measured and defined against long-term averages based on periods of 80 years or longer. The hail risk patterns in Figs. 1, 2, and 3 were all based on hail-day records 96 years in length, and they represent the best estimate of the long-term risk pattern. The cited studies of 5- to 30-yr hail values define the range of possible future differences (5%–55%) apt to occur in the magnitude of risk. Furthermore, these studies have shown that the major features of the long-term patterns (the areas of high and low hail incidences) always are present in any 10-yr or longer periods.

The third temporal feature pertinent to hail risk relates to long-term trends in state values. These trends have been found to be similar across large regions. For example, trends for 1948–97 in crop–hail loss cost values in the High Plains states (Texas to North Dakota) and

![Fig. 5. The annual areal extent where hail days during the growing season achieved the 10-yr or greater frequency level, expressed as a percent of the state, and the annual crop–hail loss costs values for Nebraska during the 1948–94 period.](image-url)
southeastern states (Georgia and the Carolinas) all show statistically significant increases with time, peaking in the 1990s (Changnon 1999b). However, all states in the Midwest and the West show a sharp downward trend in losses. The national loss cost distribution since 1948 has high values in the late 1950s–early 1960s, followed by a general decline to the present (Kunkel et al. 1999).

5. Summary

Assessing hail risk to property in the United States has received considerable attention since several major multimillion dollar property losses have occurred in recent years. The crop–hail insurance industry, which has kept excellent hail loss records since 1948, has used a mixture of its insured loss data combined with longer-term climatological hail data to define spatial risk across the primary loss states. However, a recent case of ignoring the historical behavior of hail risk values caused the industry to incur major losses.

The property insurance industry has not kept comparable hail loss records and, to assess its spatial hail risk, must estimate what hail factors cause damage and must rely entirely on available climatological data and/or data from field studies of hail conducted for other purposes to provide the hail characteristics needed. The available hail data limit the approaches that can be used for defining spatial risk and limit the risks that can be assessed adequately. One approach to property risk assessment seeks to define the point risk and has used long records of point hail frequencies combined with various other measures such as hailstone sizes, volume of hail (mass of ice), and wind associated with hail. The other approach to property risk assessment defines the risk for areas, not points, to address the incidence of very large hailstones, which are extremely rare at a point. The approach chosen in all instances has been based on the desires of the insurance interests, who have selected the data that best fit their needs about property or crops at risk.

Assessment of temporal variations in hail risk for insurance applications must rely totally on either long-term hail-day data (1901–present) or on crop–hail loss data (1948–present). Recent test studies of data in three states have shown that the distributions of the two datasets are related, and further research is in progress. Most studies have found that hail incidences or losses are skewed statistically with a few high hail years interspersed among many low hail years. Major temporal features in regional hail patterns persist over time but their magnitudes in any given 5- to 20-yr period vary widely by as much as 50% around the average. Long-term trends in hail days and losses across the nation exhibit regional differences, with upward trends since 1950 in states in the High Plains and Southeast and downward trends elsewhere in the United States.

Acknowledgments. This paper was funded in part by Grant NA76GP0439 of the Office of Global Programs of the National Oceanic and Atmospheric Administration. The views expressed are those of the author and do not necessarily reflect the views of NOAA or any of its subagencies. The insightful comments and suggestions of the external reviewers greatly improved the paper.

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