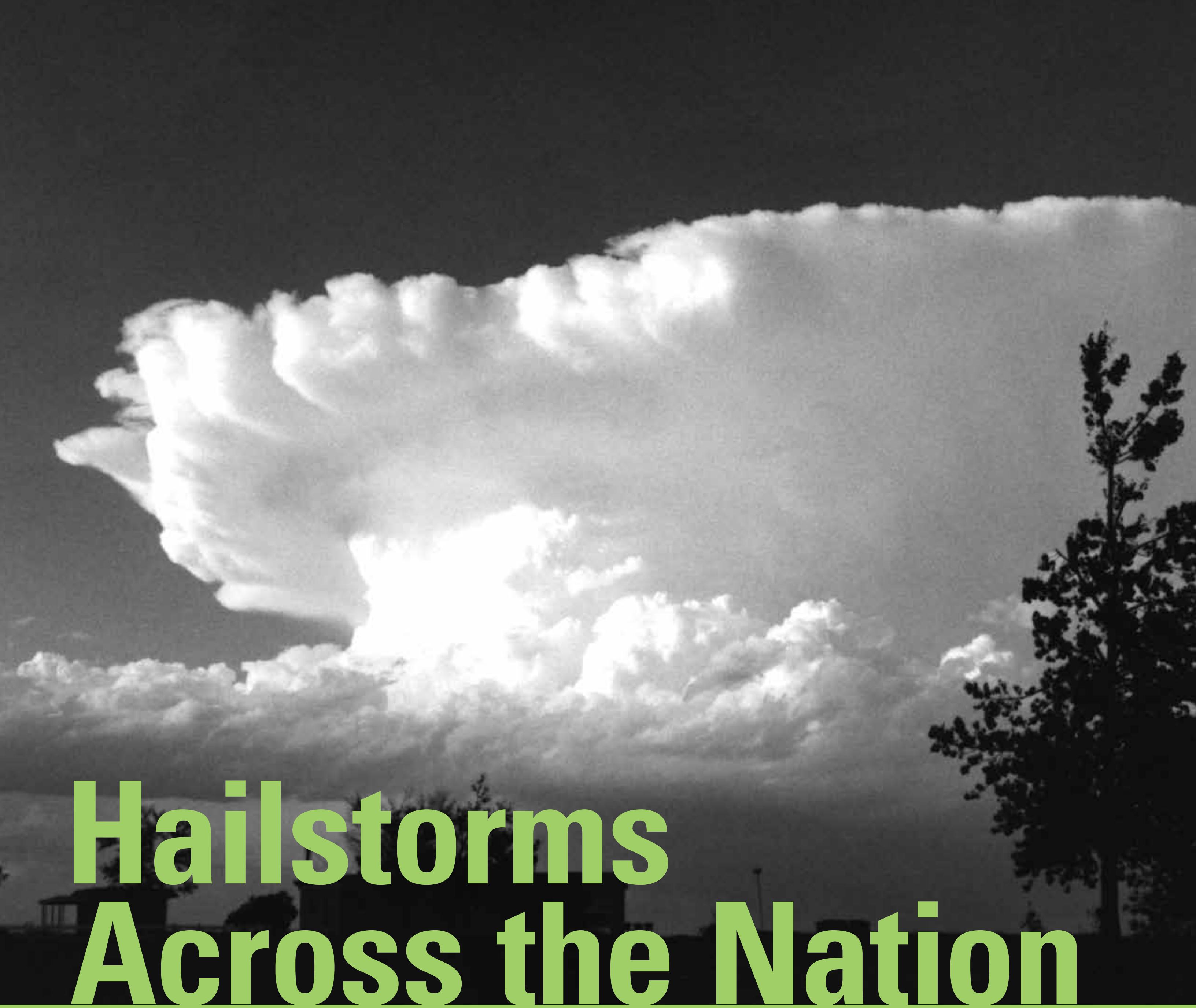

Hailstorms Across the Nation

An Atlas about Hail and Its Damages

Stanley A. Changnon
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Illinois State Water Survey
Contract Report 2009-12

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ILLINOIS

Cover photo: A large hailstorm in Illinois.

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Contents

Abstract

This atlas addresses the climatology of hail in the United States. The information has been assembled from diverse sources from the past 80 years, and includes results of research conducted specifically for this document. Climatological descriptions of the various hail conditions that cause damages to crops and property also are presented, as well as assessments of hail-produced losses.

The nation's areas of greatest hail frequency are along and just east of the central Rocky Mountains where point averages vary between 6 to 12 hail days per year. The lee of the Rocky Mountains has the nation's greatest hail intensity with the largest average stone sizes, the highest average number of hailstones, and the longest hail durations. The nation's lowest hail intensities are found in the southeastern U.S. (Florida) and in the southwest (Arizona and California), areas where hail occurs only once every two or three years. Winds with hail tend to be strongest in the central and southern High Plains, the location where property-hail damage is the nation's highest. Hail risk to crops and property is characterized by enormous variability in both space and time. Exceptionally large hailstones, those exceeding 2 inches in diameter, can occur anywhere it hails in the U.S., but are most frequent in southeastern Wyoming (once every five years) and least frequent in the low hail frequency areas (only once every 100 years or less often at a given point).

The extent of hail damage results from hailstone sizes, the number of hailstones per unit area, and winds with hail. Hail causes considerable damage to U.S. crops and property, occasionally causes death to farm animals, but is only infrequently responsible for loss of human lives. The average annual frequency of days with crop-damaging hail in the U.S. is 158 days, and the average annual crop loss is $580 million. The average annual frequency of days with hail damages to property is 123 days, and the average annual loss total is $850 million. Each year, on average, the nation experiences 15 days with property losses exceeding $1 million and 13 days with crop losses exceeding $1 million. Hail is a threat in most parts of the nation.

The risk of property damage across the nation varies from an index value of 1 in the southeast to a high of 50 (Colorado, Kansas), and the indices of risk of crop damage vary from a low of 1 in the eastern Midwest and East to a high of 20 in the western High Plains (Montana, Wyoming, and Colorado). Hail that is damaging to crops differs from that damaging to property. Various crops can be damaged by small stones, whereas property damage occurs only when hailstones exceed 3/4 inch in diameter. Distributions of hail damage vary considerably with most damages occurring in 5 to 10 percent of all storms, and most losses occurring in only a small portion of an area experiencing hail on a given date.

Hail frequency and crop-hail intensity conditions change significantly over time with a tendency for low hail incidence in 60 to 80 percent of the years, and exceptionally large losses in 5 to 15 percent of the years. The temporal variability of hail loss is greater in the High Plains states than in states in the Midwest, East, or West. The magnitude and frequency of hail shifts up and down randomly over time, but the primary spatial features of hail (areas of extremely high or low incidence of hail in a region) persist from decade to decade. Hailstorms extremely damaging to property show an upward trend with time, and the two most damaging storms in the U.S. have occurred since 2000. Nationwide trends in crop-hail losses, in property-hail losses, and in the number of hail days are either flat or slightly downward for the 1950-2009 period, and do not suggest any climate change influence.

Studies of Hail at the Illinois State Water Survey

Survey scientists in the 1950s began assessment of historical records of thunderstorms and hail in Illinois using records of Weather Bureau volunteer weather observers who were mandated to make daily records of temperatures and rain and only asked to report weather conditions like hail (Changnon, 1967a). The resulting data providing detailed historical information on hail (Changnon, 1962) caught the attention of the expanding crop-hail insurance industry that was trying to assess loss potential and develop better rates for Illinois and all other states. Thus, they began funding the Survey to do research into hail in 24 other states (Changnon and Stout, 1967), and to study the dimensions of severe hailstorms in Illinois (Changnon, 1967b).

The insurance industry also funded extensive Survey studies of small-scale variations in hail, and the Survey established four dense networks of hail-sensing instruments in Illinois (Changnon, 1968). These instruments were designed and built by Survey scientists, and they determined counts of hailstones and their sizes, plus the angles of windblown hail (Changnon, 1973). Another new instrument was designed and it recorded the temporal occurrence of hailstones, the nation's first ever hail-recording device (Changnon and Mueller, 1968).

In the 1960s the Soviet Union reported they had a technique that suppressed hail and reduced hail damages. Therefore the U.S. government pushed to develop hail-suppression methods for use in the U.S. Survey scientists designed a national experiment conducted in Colorado (Schickedanz and Changnon, 1971), and the Survey took numerous surface hail-sensing instruments to Colorado for this project. Survey scientists also designed and built with National Science Foundation (NSF) funds the nation's first dual-wavelength radar designed to detect hailstones in a thunderstorm, and this became a key part of national hail projects (Mueller and Morgan, 1972). Survey scientists were funded to design a major hail-suppression project for Illinois (Changnon and Morgan, 1975). The Survey was also funded by NSF to assemble a national team of scientists of various disciplines to conduct a national study of the economic, environmental, and political consequences if a workable hail-suppression system existed in the U.S. (Changnon et al., 1978).

Survey studies during the 1970-1980 era found that large urban areas, such as Chicago and St. Louis, affected the atmosphere sufficiently to lead to increases in rainfall and hail over and beyond the urban areas (Changnon, 1978b). A scientific study of how Lake Michigan affected weather found that in the fall the warm lake led to more hailstorms east of the lake in Michigan (Changnon, 1966a). A study of the weather effects of a large hilly area in southern Illinois found it led to more hail (Huff et al., 1975).

Survey scientists pursued studies during the 1970s of major damaging hailstorms occurring in Illinois to provide guidance to the insurance industry (Changnon and Wilson, 1971). Also included were field and laboratory studies of the various hail characteristics (stone sizes, number, and winds) that caused crop damages (Changnon, 1971). These studies were followed by a similar study of conditions creating damage to buildings, roofs, and vehicles (Changnon, 1978c). Crop insurance problems and high costs of loss assessment led Survey scientists to propose a project to assess crop losses using aerial photography, and infrared film was found to allow accurate measurements of losses across crop fields, a major breakthrough (Towery et al., 1975).

A study in the 1970-1980s concerned developing a technique that predicted future crop losses, and Survey scientists devised such a method allowing 90 percent accuracy in loss estimation 6 to 12 months before a season (Neill et al., 1979). An in-depth assessment of hail in Illinois was conducted in the 1990s, summarizing the knowledge gathered over time (Changnon, 1995). Recent studies have focused on temporal fluctuations in hail events and losses across the nation, to assess whether ongoing climate change alters hail (Changnon, 2008a). Survey scientists, by 2008, possessed a vast amount of data and knowledge about hail in Illinois and elsewhere in the nation. Many documents from Survey research can be found in the references section of the atlas. This circumstance led to the preparation of this national atlas about hail and its impacts.

SECTION A: OVERVIEW

1. Introduction

This atlas presents information about hail in the United States. The information has been assembled from diverse sources from the past 80 years, and also includes results of research that the authors conducted to provide hail information for this document. Climatological descriptions of the various hail conditions that cause damage to crops and property in the U.S. are presented. For any given location and area these include how often it hails, hailstone sizes, number of hailstones per unit area, and winds with hail.

This atlas should be useful for those involved in structural design, for insurance rate setting and planning for crops and property insurance levels, for reinsurance firms, for loss assessors, and for atmospheric scientists involved in severe weather studies. The building industry and construction regulatory bodies have long been concerned about obtaining hail information for use in building design and proper materials for roofing and siding (Morrison, 1997).

Hail causes considerable damage to U.S. crops and property, and hail losses in the U.S. are the highest of any nation in the world (Hughes and Wood, 1993). Hail occasionally causes death to farm animals, but is only infrequently responsible for loss of human lives. A hail-related death occurred in 1979 when a large hailstone struck a child in the head (Doesken, 1994), and in 2000 a hailstorm killed a person in Ft. Worth, Texas. Hail has caused only eight deaths in the past 70 years, but more than 50 persons were injured by hail in Denver in 1990, and over 200 persons were hurt by hail in Ft. Worth, Texas in 1995 (Hill, 1996).

Hail damages all types of crops. The average annual frequency of days with crop-damaging hail in the U.S. is 158 days, and the average annual crop loss is $580 million. The average annual frequency of days with hail damages to property is 123 days, and the average annual loss totals $850 million. Each year, on average, the nation experiences 15 days with property losses greater than $1 million and 13 days with crop losses greater than $1 million. Hail kills many farm animals including chickens and sheep. Cattle are killed somewhere in the High Plains every year where large hail is common (Changnon, 1999a). Hail is a threat in most parts of the nation.

Different crops are damaged in varying ways by hail. Tea, soybeans, and tobacco leaves are delicate and subject to serious damage even when small 0.25-inch diameter hailstones fall. Windblown hailstones of 0.5-inch diameter or larger cause serious damage to corn stalks and wheat stems. Fruit crops, such as apples and peaches, can be easily bruised by small- to moderate-sized hail and can lose great value because of reduced quality.

Much of the nation's property damage from hail is to shingle roofs that are scarred by hail and must be replaced. Windblown hailstones of 0.5-inch diameter also cause significant damage to siding on houses and break windows of structures and vehicles. Metallic surfaces on vehicles and aircraft are susceptible to denting from hail that is 0.75 inch or larger. Such wide differences in hail conditions that cause crop and property damages require presentation of various types of information to adequately assess the climate of hail.

Finding information about the climatic aspects of hail has been difficult for non-atmospheric scientists, not because there are major unknowns about the hail climate in the United States, but because much of what is known is widely distributed amongst diverse sources published over the past 80 years. Thus, hail information is hard to locate for those seeking a comprehensive description of the hail climatology for the nation. Other publications have addressed the issue of hail climate in other nations including China, France, Italy, Canada, Russia, Argentina, South Africa, and Finland (Zhang et al., 2008; Touvinen et al., 2009; Dessens, 1986; Gokhale, 1975; Morgan, 1973).

The focus of the information presented here is descriptive in nature. The report does not dwell in great detail on the various atmospheric conditions that cause hail. Instead, the emphasis is on providing, in tabular and cartographic formats, information that describes the spatial and temporal variations of hail across the United States over the past 100 years. The information selected also has been chosen with regard to assessing the potential for hail damage, a serious issue across most of the nation.

The climatology of hail has been defined using data from four primary sources. First are the records of hail days, as defined by the weather stations of the National Weather Service since 1895. Second are the impact data on hail damages and their economic losses as derived from crop insurance records, and third are the hail loss data derived from property insurance records since the 1940s. Fourth are the data from special field studies typically focused on hail characteristics in small areas. These studies yielded many measurements but were conducted in only a few years.

In describing the space and time aspects of hail, two basic characteristics that are important to the creation of hail damage are outlined: the *frequency* of the event, and the *intensity* of hail when it occurs. The frequency of hail is usually defined by the number of days with hail or number of hailstorm events at a point or over an area, for a month, season, or year. The intensity of hail is typically determined by the sizes and number of hailstones that fall at a given time and the associated wind speeds. As noted previously, levels of hail intensity that create damage vary greatly with the target.

This atlas also presents considerable information on the impacts of hail, including the physical impacts to crops and property, as well as extensive information on the economic impacts of hail to agriculture and to property in the United States.

A towering hail-producing thunderstorm.

2. Formation of Hail and Hailstorms

Hailstones are pellets of ice created inside convective storms. The development of hailstones typically occurs 3 to 4 miles above the earth's surface where air temperatures are -40 degrees F or lower (Figure 1). There, the moist vapor in the updraft, the air moving upward inside the storm, condenses. The particles freeze and ice crystals, called embryos, form and become the heart of hailstones (Browning, 1977).

Most hail comes from thunderstorms; however, only about 60 percent of all thunderstorms ever generate hailstones aloft (Changnon, 2001). The growth of hailstones sufficiently large to reach the ground requires very strong updrafts, forces creating taller than usual thunderstorms (Brandes et al., 1997). Strong updrafts support the hailstones aloft and allow hailstones to grow, often to 1 inch diameter or larger, before the stones descend. If the falling hailstones enter another strong updraft, they can get carried aloft again in the moist air and grow even larger, and then fall again as a volume of large hail (Hughes and Wood, 1993). This repetitive growth process is reflected in the structure of hailstones that often shows layers of ice around their embryo.

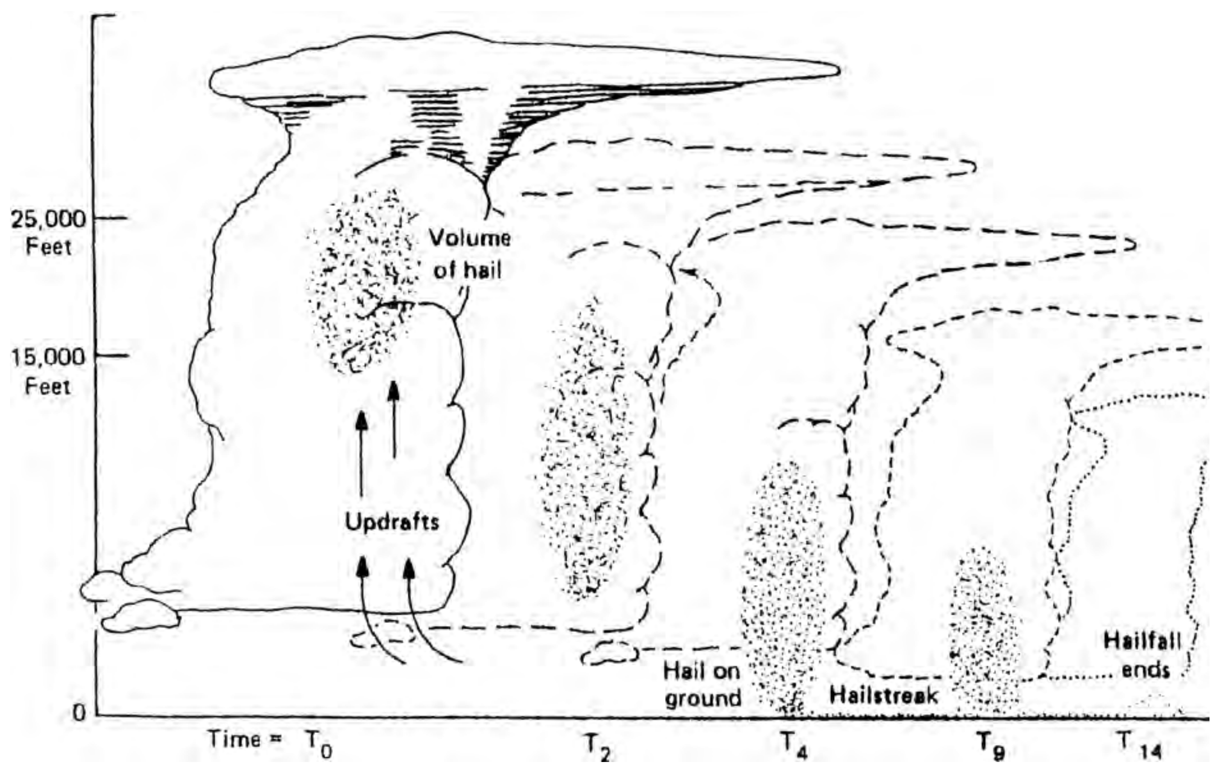


Figure 1. A sequence showing the development of hail inside a thunderstorm, then its descent and arrival at the ground after 4 minutes (T4). Its deposition forms a path of hail labeled as a hailstreak, ending after 14 minutes (T14).

The volume of hail reaching the ground falls at 135 feet per second, and usually is less than 10 percent of the volume of rain produced by a thunderstorm (Gokhale, 1975). Hail produced by many thunderstorms never reaches the ground because it melts as it descends into warmer air near the ground, becoming raindrops. That is why thunderstorms in warmer climate zones seldom produce hail at the ground.

Severe hailstorms produce a large quantity of hailstones, typically more than 1 inch in diameter, and are a result of four atmospheric factors:

1. Strong convective instability creating strong updrafts.
2. Abundant moisture at low levels feeding into the updrafts.
3. Strong wind shear aloft, usually veering with height, enhancing updrafts.
4. Some dynamical mechanisms that can assist the release of instability such as the air flow over mountain ridges.

When a volume of hailstones descending from a storm reaches the surface, the stones often cover an area 1 mile in diameter at the earth's surface. As the hailstorm moves over time, the falling hailstones produce an elongated area of hail called a "hailstreak." Its size and shape depend on how fast the storm is moving and how strong the updrafts are inside the storm. A typical hailstreak is 1 mile wide and 5 miles in length. Most storms that produce hail generate one or two hailstreaks during their lifetime. Some organized lines of thunderstorms produce many hailstreaks with hail covering hundreds of square miles as the storms move across the terrain. Infrequently a thunderstorm becomes a well-organized giant and lasts for three or more hours. These "supercell storms" generate very large hailstreaks. Hailstorms occur in many parts of the world, including most parts of the United States and other mid-latitude nations.

Atmospheric conditions causing hail-producing systems to form vary. Squall lines and low pressure centers at the intersections of warm and cold fronts create 41 percent of all hail systems in the U.S. Cold fronts alone cause 21 percent, warm fronts cause 14 percent, stationary fronts produce 12 percent of all hail systems, and 12 percent are from unstable air mass storms (Changnon, 1978a).

The hailshaft descending from the base of a thunderstorm.

SECTION B: DATA AND ANALYSIS

Four sources of hail data provide most of what is known about the climate of hail in the United States. One primary source of hail information is the historical records of the crop-hail insurance industry kept since 1948 for all areas where insurance has been sold. A second major source of data is the weather records of the many weather stations across the nation operated by the National Weather Service (NWS) since before 1900; another NWS-related data source is *Storm Data*, a publication issued since the 1950s. A third source of hail data is the property insurance records for 1949 to the present for the entire nation. The fourth major source of data is a series of special studies of hail, most of which were conducted during the 1960-1980 period. These were instigated by special needs for hail information in hail-suppression studies, in designs of structures, in property insurance risk assessments, and in aircraft operations.

3. Crop-Hail Insurance Data

The crop-hail insurance database includes records of annual losses, premiums, and liability for each state. These data have been compiled on geographical scales of counties and thus offer considerable spatial information on the patterns of damaging hail. However, they are limited in certain respects: 1) data are available only for the 1948-2009 period; 2) only hail that damages insured crops is recorded (limiting data to the growing season of a given crop); 3) there are major differences in a crop's susceptibility to hail damage during a growing season; and 4) data exist only for areas where insurance is sold (and varying coverage in an area affects how much hail is "sampled"). One example of the problem inherent in these data is that a hailstorm of a certain intensity hitting an Illinois corn field in early June produces much less damage than the same storm hitting the same corn field in mid-July when the plants are much more vulnerable to damage, which greatly reduces yield. Furthermore, hail occurring between October and April (in most locales) is not recorded because there are no insured growing crops at that time. Different crops experience different degrees of loss from hail.

The crop-hail insurance industry has sponsored extensive research dealing with hailstorms, including surface hailfall characteristics and their relationship to crop damages (Changnon and Fosse, 1981). The industry's research program has included field studies relating simulated crop-hail damage to amount of loss as a basis for developing procedures for loss adjustors to quantify field loss assessments. These involved purposeful damage to crops in various growth stages using hail cannons that propel steel balls or spheres of ice to simulate hailstones (Morrison, 1997), or the more commonly used mechanical defoliation and stem damage with hand-held instruments.

The insurance data for 1949-2008 have been adjusted for temporal changing liability (coverage), dollar values, and other factors by use of the "loss cost." The annual loss cost value for a given state (for any crop or all crops) is determined by dividing the annual losses ($) by the annual liability ($), and multiplying the resultant value by 100. Adjusting for liability or coverage is very important for correctly assessing temporal variations in hail losses.

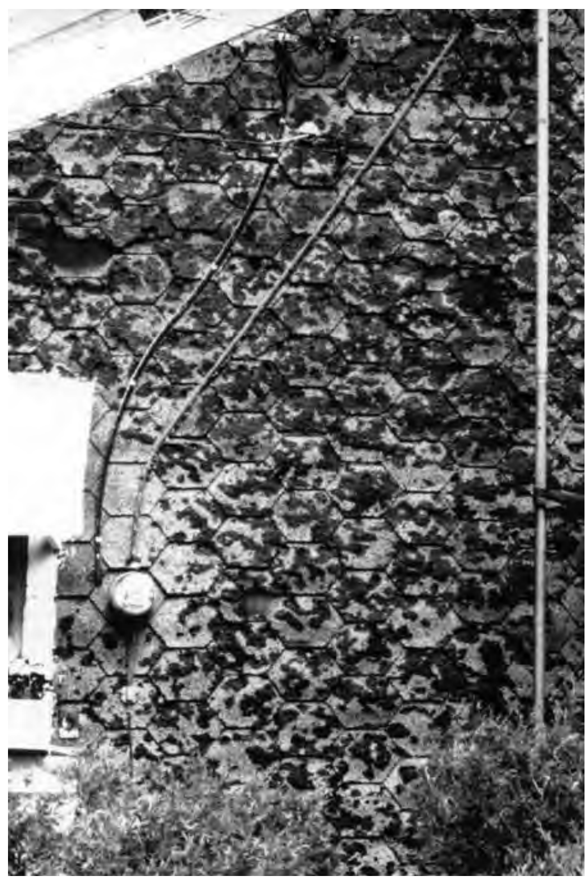
Hailstones in a damaged wheat field.

4. National Weather Service Data

The National Weather Service (NWS) has two types of weather stations that collect hail data: first-order stations manned by trained weather observers, and cooperative substations manned by volunteer observers, whose primary responsibility is to make once-a-day measurements of temperatures and precipitation. The type of hail data collected by both types of stations is a "day with hail." It is a single measure of whether it hailed or not without any other information. The first-order station data are considered of quality because they were collected during assigned observations by trained experts taken 24 hours a day. Unfortunately, there are only 250 such stations distributed across the nation. Conversely, there are nearly 16,000 cooperative substations, which greatly improve the sampling density for a day with hail. But since the observers are asked but do not have to report hail, only a limited number of these substations have been found to possess quality hail-day data.

A technique was developed to assess whether the records of hail at each substation were accurate (Changnon, 1967a). This technique was first used in a series of studies of the hail data for substations in 26 states and conducted during 1961-1985. Typically, 30 to 50 substations in each state analyzed were found to have quality hail-day records lasting 20 years or longer. A recent project assessed the nation's substation data for the 1901-1995 period, examining for quality hail records, and identifying quality data for 1,061 stations in the U.S. (Changnon, 1998). These hail-day data have been extended to include all quality data during the 1996-2006 period.

The value of the NWS hail data is to measure the "frequency of hail days" spatially (on a monthly and annual basis), and to examine for long-term temporal fluctuations in hail days. Fortunately, a few of the thousands of volunteer weather observers have undertaken to report, over a period of years, the sizes of hailstones that fell. Several past climatic studies have been based on analyses of these NWS data (Henry, 1917; Lemons, 1942; Flora, 1956; Changnon, 1967a, 1978a).



The hail-dented wall of a house.

5. Property Insurance Data

In 1948 the nation's property insurance industry formed a group of specialists who had the responsibility of identifying all catastrophes, defined as events causing greater than $1 million in insured property losses. For each such event in 1949 and all following years, they collected data on the date/s of occurrence, the state/s where the insured losses occurred, cause/s of losses, and amount of loss (dollars) of each catastrophe. Catastrophe losses have been found to represent 90 percent of all weather-produced property losses in the U.S. (Roth, 1996; Changnon and Hewings, 2001). Experts in the property-casualty insurance industry have systematically analyzed, in each year since 1949, the historical catastrophe data to update the past catastrophe loss values to match the current year conditions.

This annual loss adjustment effort is a sizable and complex task, requiring assessment of each past event. Three adjustment calculations are made to the original loss value for the year and locations of each catastrophe. One adjustment corrects for time changes in property values and the cost of repairs/replacements; hence, this also adjusts for inflation. The second adjustment addresses the relative change in the size of the property market in the areas affected by the catastrophe using census data, property records, and insurance records. This action adjusts losses for shifts in the insured property between the year of a given storm's occurrence and the updated year. The third adjustment is based on estimates of the relative changes in the share of the total property market that was insured against weather perils in the loss areas, completed by using insurance sales records. These adjustments have been used to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current year values. Thus, adjustments made in a recent year for all past catastrophes dating back to 1949 allow assessment of their losses over time (Changnon and Changnon, 1998). For example, a flood-related loss in Pennsylvania during 1978 was adjusted by insurance experts upwards by a factor of 31.3, whereas a 1978 flood loss in Oregon, where coverage and other conditions differed from those in Pennsylvania, was adjusted by 37.8. In the resulting loss values, the loss from a catastrophe, whether in 1976, 1993, or 2004, could be assessed in terms of the current economic conditions. Insurance data assessed herein were for the 1949-2006 period. An assessment of the insurance catastrophe values using the temporal adjustment method found that demographic changes in various regions of the U.S. since 1949 were well related to the temporal adjustment values used by the insurance industry (Changnon and Changnon, 1998; Changnon and Changnon, 2009). The National Research Council (1999) made a study of all forms of hazard loss data in the nation and found that the property insurance data were the nation's best.

6. Data from Special Studies of Hail

There have been numerous research studies of hail and hailstorms often based on field collections of data for several reasons. Atmospheric scientists extensively investigated the potential for weather modification through cloud seeding during the 1960-1980 period. As part of these studies, capabilities to suppress hail through cloud seeding underwent serious consideration. Several hail suppression experiments led to extensive field measurements of hail in a few locales (Illinois, Colorado, North Dakota, and South Dakota) where research projects were conducted (Schleusener et al., 1965; Changnon et al., 1967; Morgan, 1982). Studies of how large cities (Chicago and St. Louis) modify storms and hail also involved detailed surface measurements of hail during 1968-1980 (Huff and Changnon, 1973; Changnon, 1978b).

Concerns of commercial aviation and the U.S. Air Force about hail damage to parked and flying aircraft led to intensive field studies of surface hail in a few areas (Colorado, New England, and Illinois) during the 1951-1976 period (Beckwith, 1957; Donaldson and Chemla, 1961; Wilk, 1961; Gringorten, 1971). Studies of the nature of severe local storms have also led to the collection of hail data in places such as Oklahoma and New Mexico in the 1970s (Nelson and Young, 1978). Weather modification and aviation studies often included surface hail measurement projects (Beckwith, 1961). Instruments used to sense hail were developed and installed often in dense arrays, which formed networks of varying sizes (Towery and Changnon, 1974). Most instruments used were passive sensors (hail pads, hail stools, or hail cubes),

Two hail sensors. On the left is a hail stool and on the right is a hailpad. The hailpad is a 1-square foot piece of styrofoam wrapped in aluminum foil and supported on a stand made of angle-iron.

since a large number of instruments were needed in a network to capture the large variability of hail falls across short distances. Each of these sensors was covered with aluminum foil which showed the dents from hail. The passive instruments were also inexpensive compared to the hail-recording instruments that were developed. An Illinois hail-recording instrument, the nation's first, consisted of a platform and scale that weighed and recorded each hailstone that landed on the platform and the time of each impact (Changnon, 1973).

These various dense hail networks contained hundreds of hail sensors and sometimes had hail observers distributed over study areas ranging in sizes from 1 to 4,000 square miles (Nicholas, 1977). Such hail sampling networks were operated for 3 to 10 years in New England, Illinois, Missouri, New Mexico, Oklahoma, Colorado, South Dakota, and North Dakota. A few similar field studies have been conducted in France and Italy (Dessens, 1986; Morgan, 1973).

In certain areas, farmers were enlisted as volunteer hail observers to report hail occurrences, hailstone sizes, times, and stone density per unit area. One hail study network in Illinois covered 11,200 square miles with 460 hailpads and 480 hail observers (Changnon and Morgan, 1976).

Data from these field studies offer very detailed and unique information on the small-scale variability of hail, and on all hail characteristics including hailstone sizes and frequencies (per unit area) and winds with hail. However, most such field projects lasted only a few years and thus do not offer information about the longer-term variability of these hail characteristics in a given area.

Efforts to detect and measure hail using weather radars have also been underway for many years. Early attempts using single wavelength radars were not successful. A dual-wavelength doppler radar used to detect hail aloft for research studies was designed by the Illinois State Water Survey and began operations in 1970 (Changnon, 1973). Studies during the 1990s used the then new NWS radars to try to detect hailstones aloft, but failed in most hail cases (Edwards and Thompson, 1998). Later, polametric radars were tested to detect hail aloft (Kennedy et al., 2001). Donovan and Jungbluth (2007) tried detecting large hail aloft using radar reflectivity and echo dimensions with some success. A study using differential reflectivity radar values found that it could detect hail quite well (Depue et al., 2007).

The crop and property insurance industries have also made field investigations of hail to provide data critical to assessing risk and for establishing rates. These efforts included 1) laboratory studies of how hail damaged various roofing and siding materials, 2) a few field studies of damaging hailstorms, 3) study of hail climate data, and 4) assessment of storm loss records (Collins and Howe, 1964; Friedman and Shortell, 1967; Friedman, 1965, 1971). The Insurance Institute for Property Loss Reduction has tested hail-simulation systems that can be used to evaluate the vulnerability of various structural materials to hail damage (Devlin, 1996).

In the left photo is a hailpad, a recording raingage, and a recording hailgage. In the right photo is the sensing platform inside the recording hailgage, a device designed and developed by the Water Survey.

Growing nationwide energy shortages in the early 1970s launched a national effort to assess the potential of alternative energy sources, including solar and wind energy. The large dimensions and fragility of envisioned solar collectors led to concern about potential hail damage. Thus, engineering studies to assess the point risk of hail to solar collectors were initiated (Gonzales, 1977; Cox and Armstrong, 1979).

Some recent studies also explored the potential for using satellite data for measuring hail damages (Peters et al., 2000). One study used satellite data to examine crop and property damages from hail (Klimowsky et al., 1998). Another study assessed the amount of hail damage to vegetation over a 10-year period using satellite imagery and surface hail reports (Henebry and Ratcliffe, 2001). Hailstreaks in the Great Plains were found to produce sizable damages to vegetation.

This document has drawn upon the data and results from many studies of hail and current spatial and temporal information about hail in the United States. Sources of the values presented are documented, and the list of references should prove useful for obtaining more detailed information.

The antenna of the dual-wavelength radar designed and operated by the Illinois State Water Survey to detect hailstones aloft.

SECTION C: FACTORS CAUSING HAIL DAMAGES

Hail damages are a function of two conditions, hail characteristics and the characteristics of the target (property and crops). Hail characteristics that vary and produce varying damages include the size and number of hailstones that fall per unit area, and the strength of winds during a hail fall. The damage also varies according to the target. Some delicate-leaf crops such as tea and tobacco suffer damage from small hailstones, whereas other crops such as corn are not damaged unless hailstones are 3/4 inch or larger. The extent of crop-hail damages also varies during the growing season of a given crop. A specific type of hailstorm may not cause much damage early in the crop's growing season but the same storm in mid-crop season can be very destructive. Property damages vary considerably due to different surfaces and angles of exposure. Some types of wood used on structures are easily damaged as are aluminum and vinyl siding.

Past studies have shown that the nation's annual losses to crops typically exceeded those to property (Changnon, 1972). Studies of crop and property losses in the 1970s found that national crop losses were about 10 times greater than property losses (Friedman, 1976). However, in recent years, annual crop-hail losses have averaged about $580 million (Fosse, 1996), whereas recent property-hail losses averaged $850 million per year. This time-based shift to greater property losses than crop losses reflects the growing sensitivity of ever larger and denser urban areas. A massive 1990 hailstorm caused $625 million in insured losses in Denver; "baseball sized" hailstones hit Wichita in 1992, causing $420 million in damages; and a 1992 hailstorm struck Orlando, causing $575 million in losses (Cook, 1995). Other recent major property-damaging storms appear in Chapter 16.

7. Crop-Damaging Conditions

The amount of crop loss per storm event is an important factor to total crop damages from hail. Most losses are concentrated in a few storms each year. Figure 2 shows the cumulative percentage of total loss created by the 10 most damaging storms each year in Illinois over a 10-year period (Changnon, 1977). There are typically 60 damaging storm days per year, but the graph for 10 years reveals that the 10 worst storms each year caused between 70 and 95 percent of the total annual damage. Table 1 shows the cumulative percentage loss figures for the top 10 damaging storms in several Midwestern states, further revealing the concentration of most hail loss in a few storm days (Hillaker and Waite, 1985).

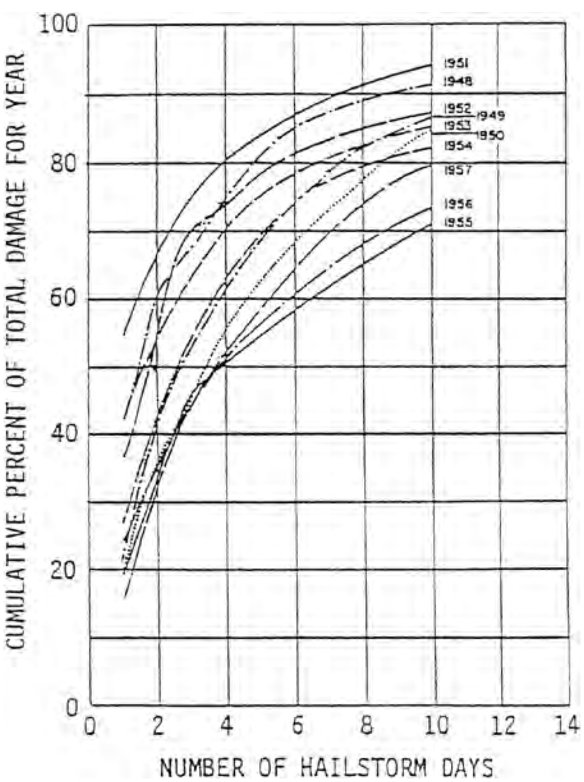


Figure 2. The cumulative percentage of annual crop-hail losses in Illinois produced by the top 10 most damaging hail days in each year, 1948-1957.

The seasonal distribution of the average number of crop-hail loss days across the nation during 1991-2006 is: 1) winter with 22 damage days; 2) spring with 70 days; 3) summer with 86 days; and 4) fall with 62 days. This makes for a national annual average total of 240 days experiencing crop-damaging hail somewhere in the United States. Days with more than $1 million in crop losses average 13 per year. Average annual crop-hail losses are $581 million for the 1949-2006 period.

Studies of windblown hail and crop damages produced several useful findings (Morgan and Towery, 1976, 1977; Towery et al., 1976). First, as shown in Figure 3, the trees near a field intercepted hail and decreased winds speeds, creating a considerable shadowing effect leading to a decrease in losses well beyond the trees. The upper map is for a field with soybeans, and the lower map shows a shadowing effect in a corn field. These studies found that a typical distance-height ratio for such shadowing of windblown hail was 10:1. That is, a decrease in hail extended 10 feet away for every foot of height of the obstacle. This accounts for less hail damage to wheat in the Midwest than in

Table 1. Cumulative Percentage of Annual Crop-Hail Losses Occurring in the 10 Most Damaging Hail Days by State and for the Midwest for 1957-1998

Number of hail days	*IN*	*IA*	*NE*	*SD*	*Midwest*
1	31	29	22	20	26
2	47	42	34	33	40
3	56	52	41	40	47
4	63	59	49	49	54
5	70	65	54	53	61
10	85	81	70	74	77

the High Plains because the rows of Midwestern wheat are planted closer together (due to more available moisture) than wheat in drier regions (Changnon, 1971). The closer rows help shield part of the Midwestern wheat plants from hail damage. Temporal changes in crops such as corn and soybeans since 1990, which have undergone breeding and hybrid changes and planting changes (more dense), may have altered to some extent the crop-hail loss relationships presented herein based on 1960-1990 conditions. The lack of change in crop-hail losses over time (Chapter 17) suggests these crop-hail relationships have not been altered.

The relationship between hail damages to three Illinois crops and two key hail characteristics (hail impact energy and frequency of hailstones) are

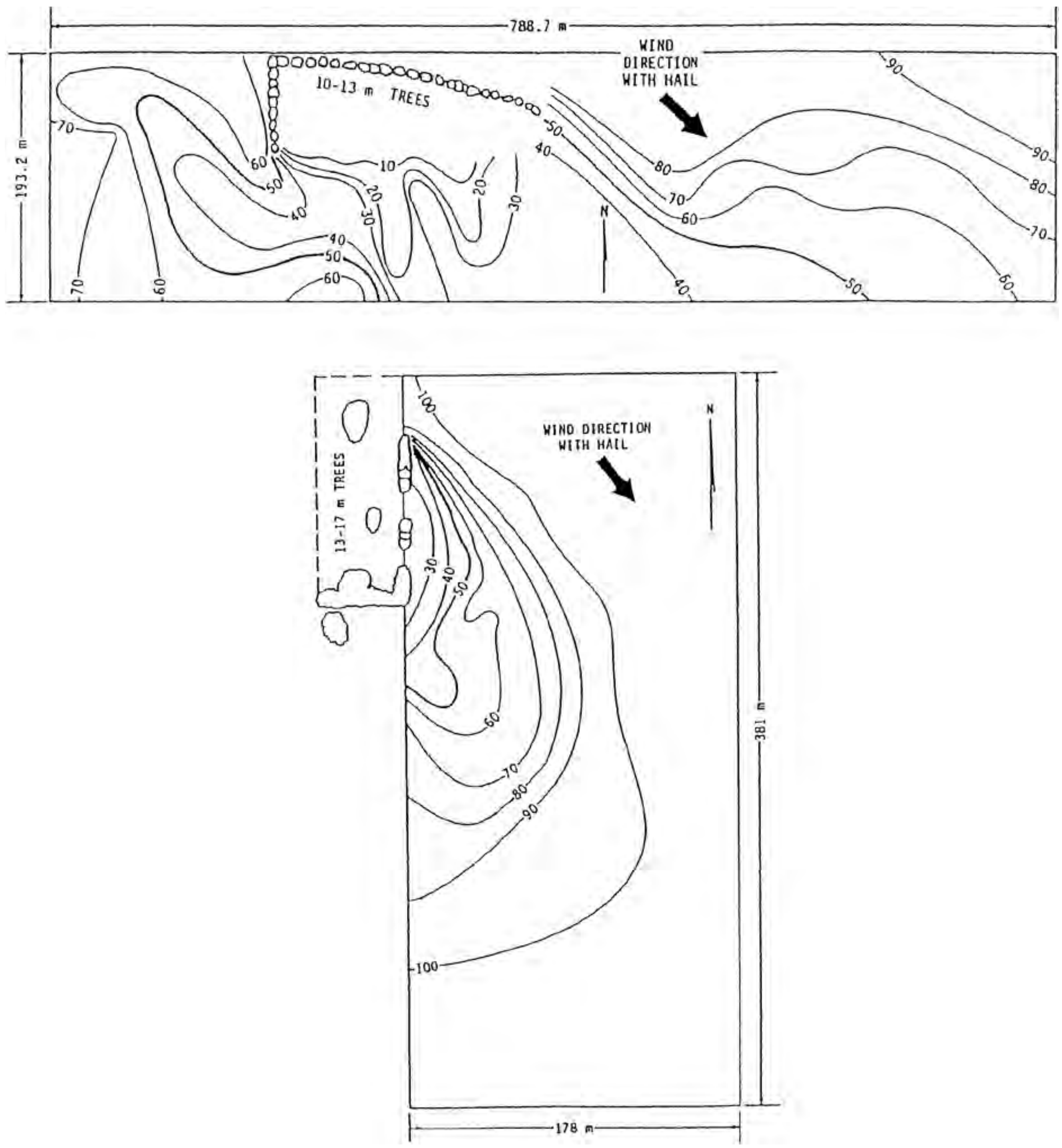


Figure 3. The crop-loss patterns (percent of damage) downwind of trees for soybeans (top) and for a corn crop (lower), showing the shadowing effect of vertical features of windblown hail.

shown in Figure 4. Hailstone frequencies had linear relationships with the degree of crop damage. The results for the impact energy of hailfalls show a curvilinear relationship to losses occurred for corn and soybeans. Losses rapidly increased when energy values exceeded 0.1 foot-pound per square foot. Wheat losses were not well related to energy but were well related to the number of stones that fell, or amount of ice. This is due to the physical nature of the crop and its planting density. Borland (1982) found a similar outcome for wheat damaged by hail in northeast Colorado where the hail mass was the primary factor causing wheat damage. Crop-hail damage studies in Spain found that different crops have different hailstone size thresholds at which damage occurs (Sanchez et al., 1996).

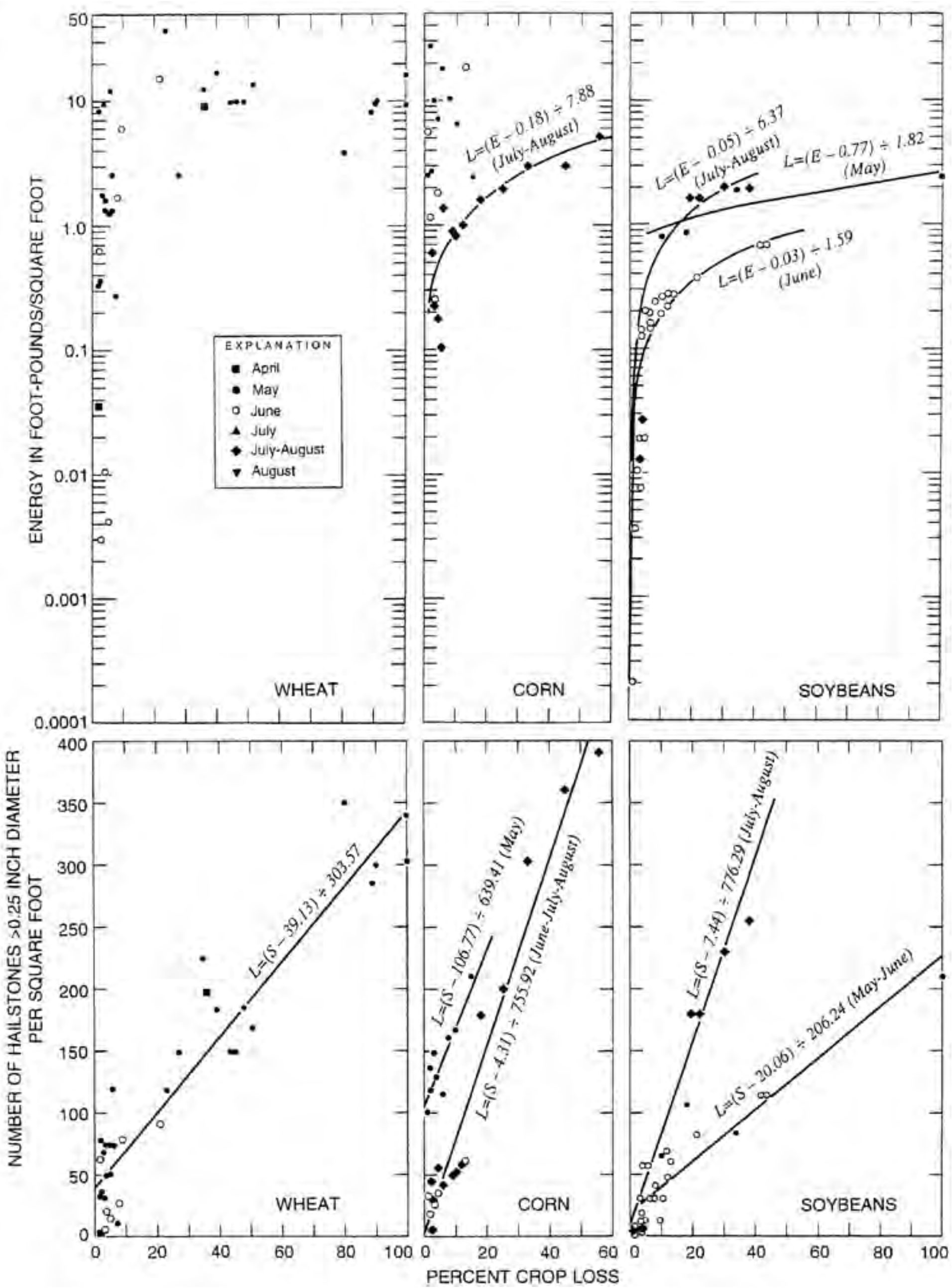


Figure 4. Relation of the amount of crop loss per month with the frequency of hailstones (lower graphs), and the energy of hailfalls (upper graphs).

Crop-hail loss data were used to calculate an "intensity-susceptibility index" for various crops. The *susceptibility* of a crop to hail damage changes dramatically during the growing season such that a hailfall of a given intensity can create much more damage during the middle of the growing season than the same storm at a later or earlier time in the growing season. The *intensity* of hailfalls also changes during the growing season, being greatest during the spring (Changnon, 1967b). To address these in-season changes in crop-hail losses, insurance data on storm average losses (adjusted to liability) during the growing season of various crops were used to calculate a crop intensity value for each month (Changnon and Stout, 1967). The intensity-crop susceptibility values, which essentially represent a point value, for wheat crops in various states are shown in Figure 5. The data for North Dakota show an intensity-susceptibility value of 2 in May, growing to 107 in July, and then diminishing to 3 in September. Figure 6 displays the indices for corn in several Midwestern states. All indices show the expected seasonal variation with the greatest intensity values in July when corn is most susceptible to hail damage. Also noteworthy are the regional differences due largely to varying hail intensities. For example, the July corn index in Nebraska is 80 compared to an index of 8 in Illinois, indicating the corn damage potentials inherent in Nebraska hailfalls are ten times greater than those in Illinois. Inspection of Figures 7 and 8 reveals that the average hailstone size in the corn regions of Nebraska is 0.5 to 0.75 inch, as compared to 0.25 inch in Illinois, and hailstones greater than 0.75 inch occur twice as often in Nebraska (Figure 8).

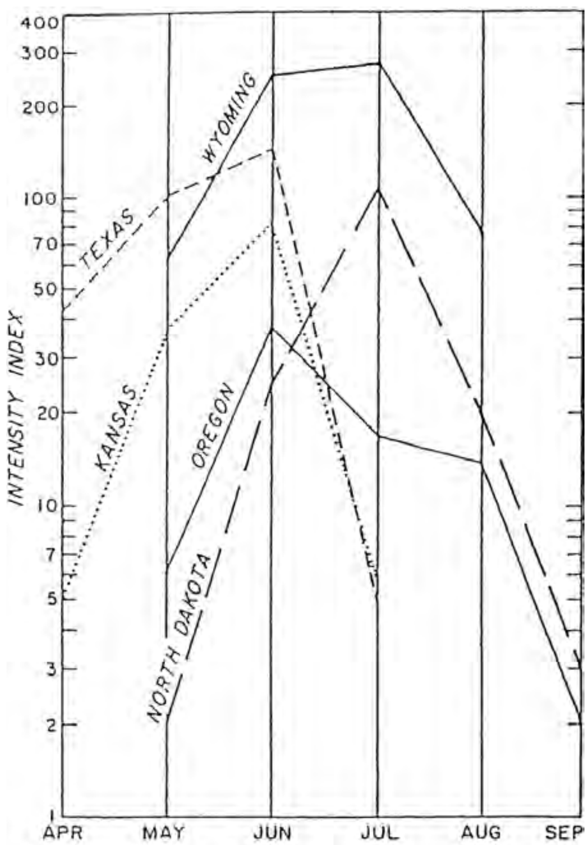


Figure 5. The monthly hail intensity indices for wheat in different states.

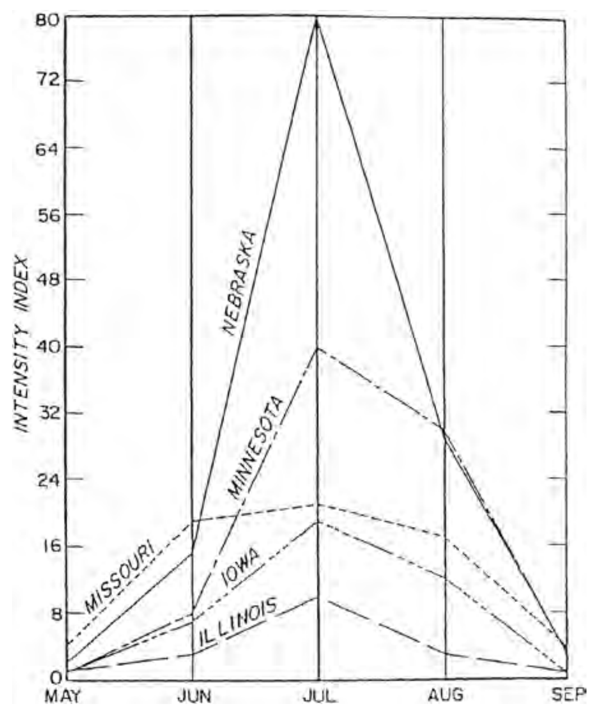


Figure 6. The monthly hail intensity indices for corn in various states.

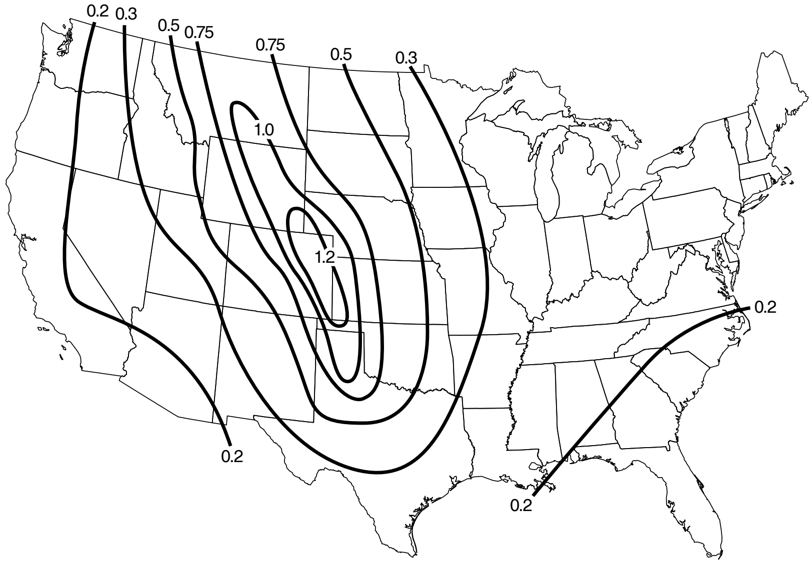


Figure 7. National pattern based on the diameter of average-sized hailstones, in inches.

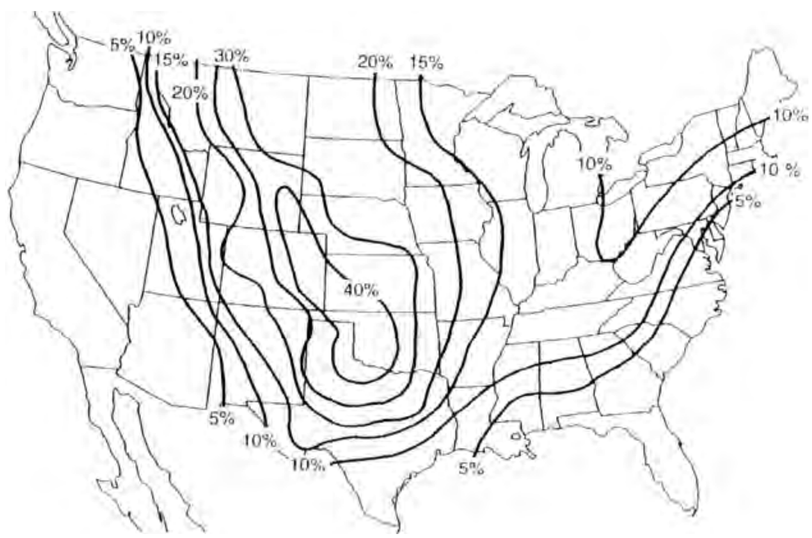
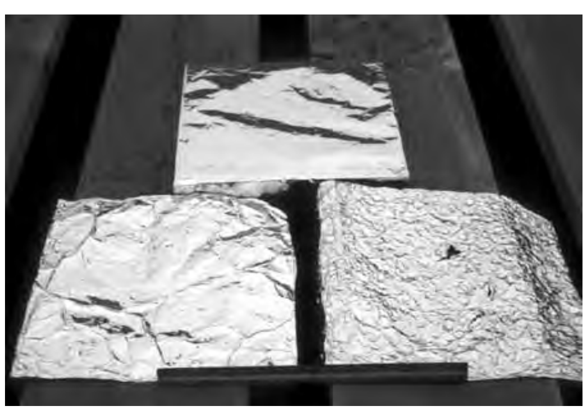


Figure 8. Percentage of hail days that experience hailstones with diameters of 0.75 inch or larger.



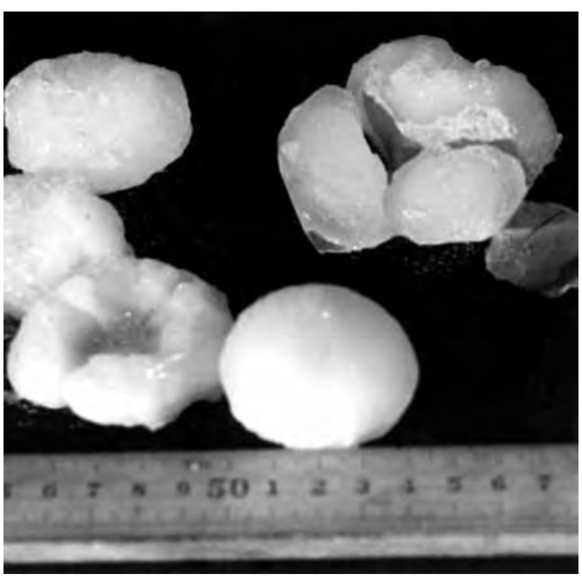
Hail-produced dents in three hailpad aluminum foil covers.

8. Property-Damaging Conditions

Most property losses from hail occur in cities. During the 1990-1994 period, major multi-million dollar property losses occurred when hailstorms struck Denver, Dallas, Ft. Worth, Oklahoma City, Orlando, and Wichita (Changnon, 1996a). However, costly urban storms are not a new phenomena. For example, St. Louis had hail damages creating a $4 million loss in 1950; Wichita lost $14.3 million in 1951 to a hailstorm; hail in Oklahoma City cost $2 million in 1923; Dallas lost $1 million in 1938; Hartford, CT lost $1 million in 1929; and Denver had a $3.8 million hail loss from a storm in 1948 (Flora, 1956).

Construction interests (Greenfield, 1969) and property insurance interests have long been concerned with the incidence of property-damaging hail (Collins and Howe, 1964). Their studies have included calculations of the wind-hailstone size relationship to assess property loss potential. Figure 9 shows the angle of stone fall based on wind speed and stone sizes. The relationship of wind speeds and energy imparted for various hailstone sizes is shown in Figure 10. For example, a 1.5-inch diameter stone falling with a wind speed of 20 mph imparts 10 foot-pounds of energy on impact, whereas a 1.5-inch stone with a 60 mph wind would have 33 foot-pounds of energy on impact.

The construction industry has extensively investigated the relationships between hailstone sizes and different materials (Morrison, 1997). They found that 0.75-inch stones chipped painted



Various types of hailstones collected at an Iowa farm from a hailstorm.

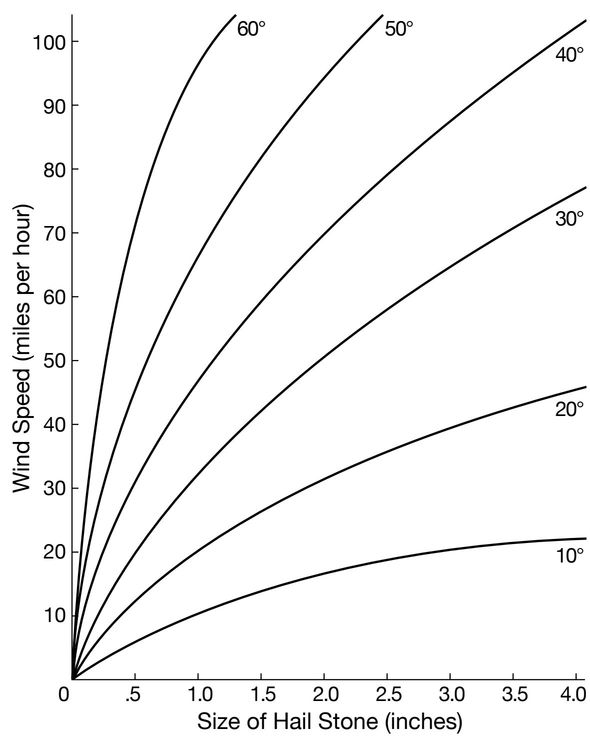


Figure 9. The relationships between wind speeds and hailstone sizes for various angles of hailstone fall from the vertical, expressed in degrees.

wood surfaces and dented all forms of aluminum used in vents and drains. They found that 1-inch stones broke single-pane windows, and that 1.25-inch or larger stones dented vehicle surfaces and broke their windows. Great attention has been given to hail damage to varying roofing materials (Rhodes, 1997). The relation of kinetic energy imparted by hailstones on various construction materials has been determined (Laurie, 1990), and the relationships appear in Figure 11. These results have also been used by the construction industry to estimate indices of hail damage potential, which includes the damage to windows, siding, and roofing materials.

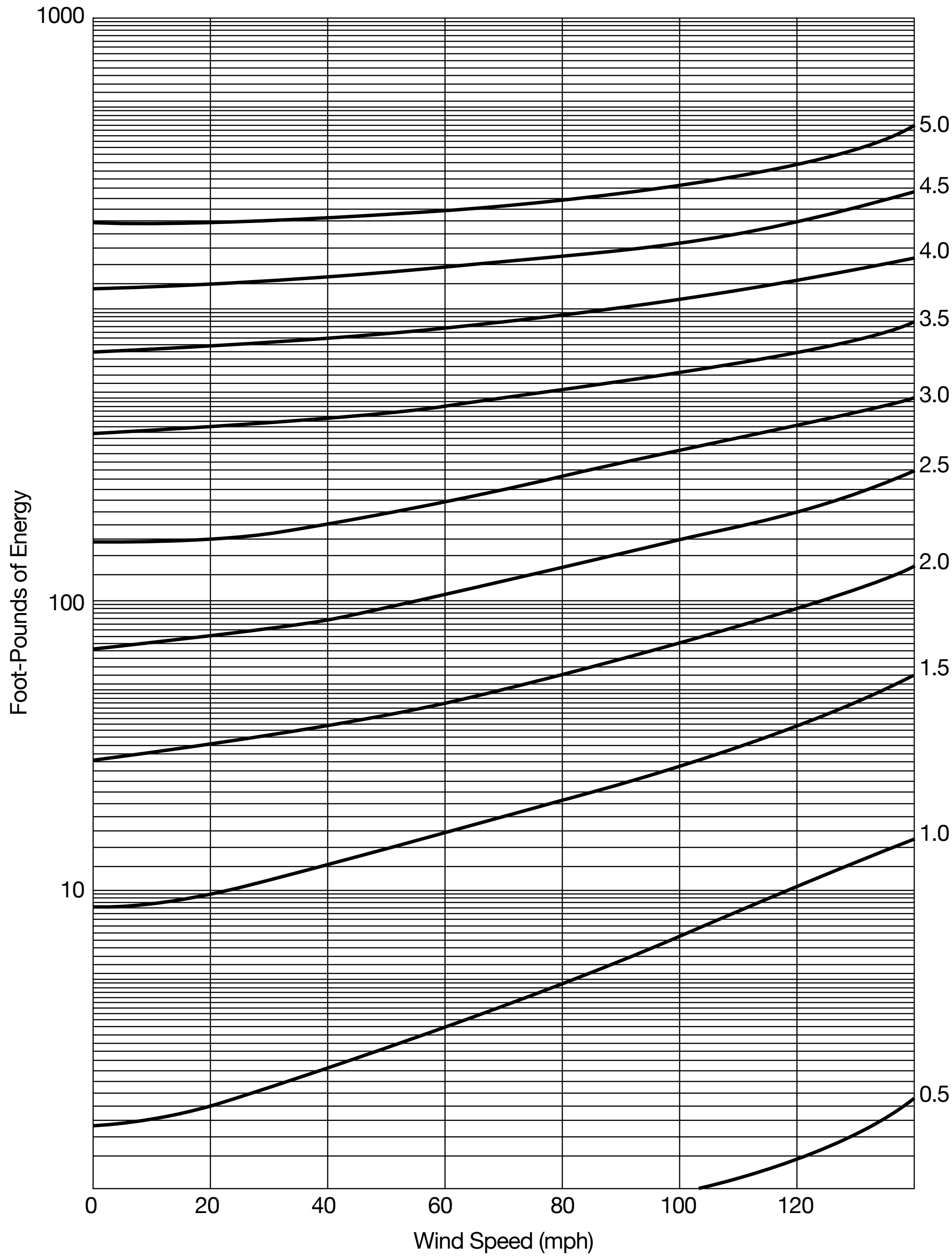


Figure 10. The energy imparted by hailstones of different sizes (right axis shows curves for 0.5 inch up to 5 inches in diameter) for varying wind speeds.

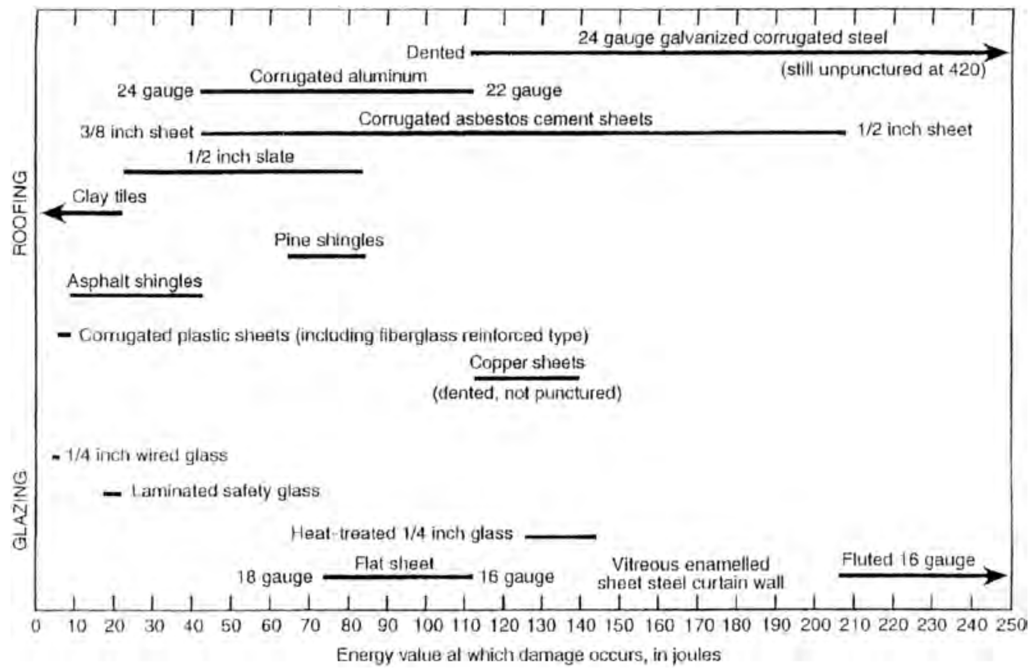


Figure 11. The relative sensitivity of various building materials to the energy levels that can be imparted by hail.

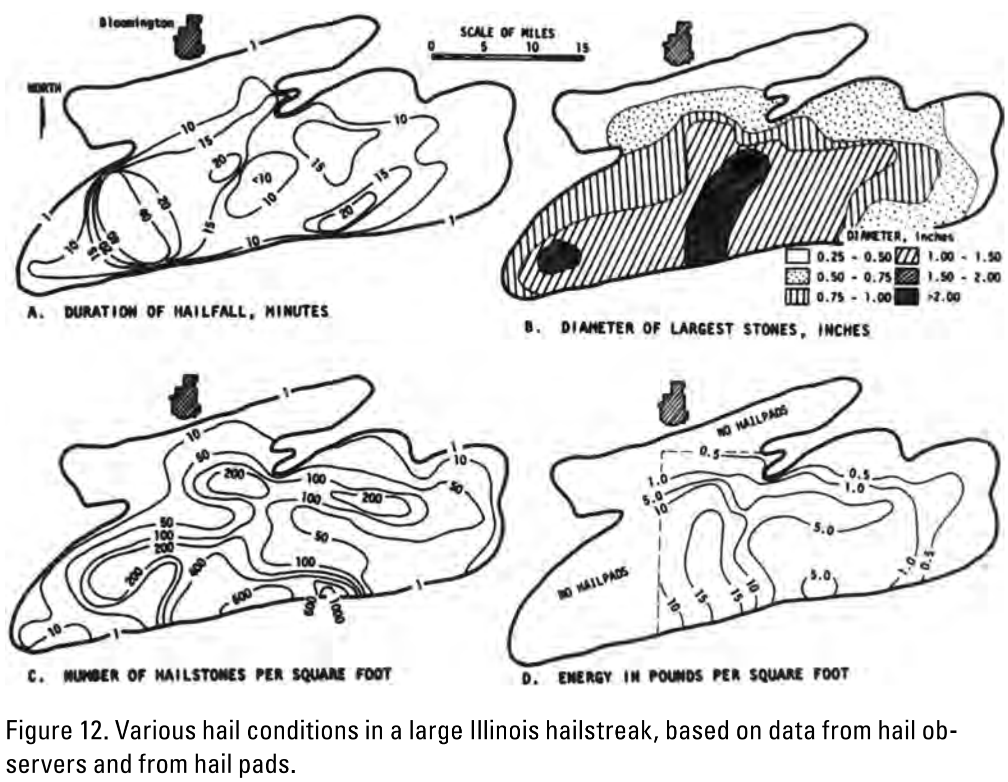


Figure 12. Various hail conditions in a large Illinois hailstreak, based on data from hail observers and from hail pads.

Hailstone size frequencies per unit area, including the sizes (mass of ice) and associated winds, combine to create a kinetic energy that has been measured in various studies using instruments and hail sensors like hailpads and hail stools (Towery and Changnon, 1974). The kinetic energy of various sized hailstones falling without winds is shown in Table 2. Four aspects of hail found in a hailstreak are illustrated in Figure 12. These include hail duration, hail sizes, number of stones, and the energy imparted by the hail.

Loss data from the property insurance industry provides accurate measures of property-hail losses; therefore, these data have been used to define the spatial and temporal dimensions of the nation's hail losses (Changnon, 2008a). Since 1949, the insurance industry has carefully assessed all property losses caused by "catastrophes," defined as events that create losses of $1 million or more. The insurance records of catastrophes list the perils causing each event. Assessment of the causes of catastrophes revealed that some were due just to hail, some due to a tornado and hail occurring on the same day, and some from events with damages due to hail, tornadoes, and flooding. Each of these three types of hail cases has been assessed, and the amounts of loss due just to hail were identified in all cases. This information was used in an assessment of total property losses from hail.

Table 2. Kinetic Energy of Various Sized Hailstones Falling Without Wind

Hailstone size, inches	*Kinetic energy, foot pounds*
1.0	1.7
1.5	8.6
2.0	29.0
2.5	72.5
3.0	160.7
3.5	371.5

Table 3 presents the number of catastrophes by cause, the total financial loss from hail during 1949-2006, and the average annual hail-loss value. During this 58-year period there were 876 catastrophes that listed hail as one of the weather perils causing the event. As shown in Table 3, 202 events were caused by hail alone. Hail with tornadoes were the two perils listed as the cause of 362 catastrophes; and floods with hail and tornadoes caused 312 catastrophes.

For the hail catastrophes with other causes of loss, the amounts of loss due to hail alone have been identified and used in the hail loss assessment. That is, the loss amounts in Table 3 are those just due to hail losses, not to flood or tornado-caused losses. The insurance records showed values of loss for each condition. All losses are in 2007 dollar values. The average catastrophe losses due to hail ranged from $38.2 million to $88.1 million. The greatest average catastrophe loss, $88 million, resulted when hail was the sole cause of loss.

The total amounts of hail loss during 1949-2006 are also listed in Table 3, and the 58-year total was $49.4 billion. The nation's annual average loss from hail damages to property is $852 million, and the average number of hail-related catastrophes is 15 per year. Prior assessments of hail damages

Table 3. Catastrophes during 1949-2006 Caused by Hail and Other Conditions Occurring with Hail. Total and Average Losses Shown are Those Just due to Hail (in 2007 dollars).

Cause of catastrophe	*Number of Catastrophes*	*Total loss, $ million*	*Average event loss, $ million*
Hail-only	202	$17,787	$88.1
Hail & tornado	362	19,843*	54.8*
Hail, tornado & flood	312	11,806*	38.2*
Total	**876**	**$49,436***	**56.4***
Annual average	**15**	**$852**	

** Value due solely to hail.*

to property in the U.S., based on NWS storm reports, revealed an annual average loss of $174 million. These NWS loss data for 1950-1999 had been adjusted for inflation and changes in wealth (UCAR, 2007). The NWS values are based largely on estimates of damages, and users have been cautioned that the loss values may be in error (UCAR, 2007). Loss values presented by the NWS are typically estimates collected from local government officials in damaged areas, made shortly after a storm. NWS officials seldom have actual measured loss data or the expertise to correctly assess losses. In contrast, insurance losses are composed of specific measurements of individual losses (e.g., homes, autos, businesses) made by field adjustors.

The insurance-based value of $852 million is $600 million more than the NWS hail value. Loss values from two recent major hail events further illustrate the data differences. A long-lasting hailstorm in April 2001 began in Kansas and crossed Missouri and most of Illinois (Changnon and Burroughs, 2003). Its losses, as reported in Storm Data (NCDC, 2001), were $1.05 million, and in contrast, the insured property losses totaled $1.5 billion, vastly more. In a two-day storm period in April 2006, damaging hail fell across parts of the Midwest with losses, as reported by the NWS staff, of $163 million, whereas the insured property losses were $1,823 million, 10 times more than the NWS value (Changnon, 2008b). These two storms are assessed in detail in Chapter 16.

Insurance losses from storms causing less than $1 million, and thus not classified as catastrophes, have an annual average that is 10 percent of the catastrophe losses (Roth, 1996). Insurance industry assessments of uninsured property losses from severe storms found losses ranged from 5 to 14 percent of the average catastrophe losses (Lecomte, 1993). Thus, the total national property losses from hail are 5 to 14 percent higher than the catastrophe loss. This means the national hail losses, on average, range between $895 million and $971 million yearly. Crop-hail losses for 1949-1998, as measured by insurance data, averaged $575 million (2000 dollars) per year (Changnon and Hewings, 2001).

SECTION D. SPATIAL CHARACTERISTICS OF HAIL

9. Hail Frequency

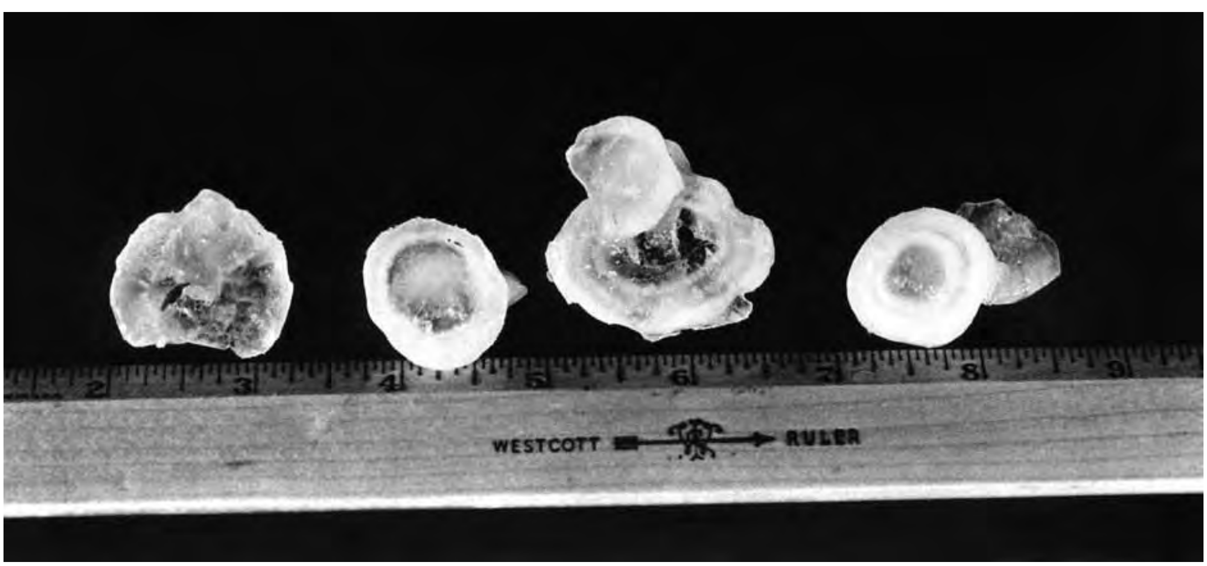
ANNUAL PATTERN

In-depth studies of hail-day frequencies at NWS stations across the nation, based on data for the 1901-2006 period, led to the preparation of the national pattern of average annual hail days shown in Figure 13. The nation's major high hail frequency areas are in the Rocky Mountains and the northwest Pacific Coast, and the lowest frequencies are in the nation's southwest and southeast regions.

The key aspect of the nation's hail pattern is the considerable spatial variability across the nation and in most states. The national frequency varies from less than one hail day per year along most of the East Coast and parts of the desert southwest, to more than five hail days annually in the mountains of Colorado and Wyoming and along the Pacific Northwest Coast. Several relatively high incidence areas are in and along the Rocky Mountains due to orographic effects. The Deep South and Gulf Coast have many thunderstorms but there is very little hail at the surface there because the descending hailstones melt in the high air temperatures below the cloud base and become rain drops.

SEASONAL PATTERNS

The nation's average frequency of hail days during spring (March-May 1901-2005) is depicted in Figure 14. The highest frequencies are in areas extending from eastern Colorado into the Midwest, and in scattered locations in the northern Rockies and in the Pacific Northwest. In summer (June-August) the national pattern (Figure 15) shows that the highest hail averages are in the Rockies, extending from Montana south into New Mexico. Orographically-induced hailstorms often develop along the front range of the Rocky Mountains. Due to the shape of the mountains, some areas are favored for storm development, and these result in paths of hailstorms that stretch eastward into the Dakotas, Nebraska, and Kansas. Summer hail



Inside structures of hailstones that have been cut in half.

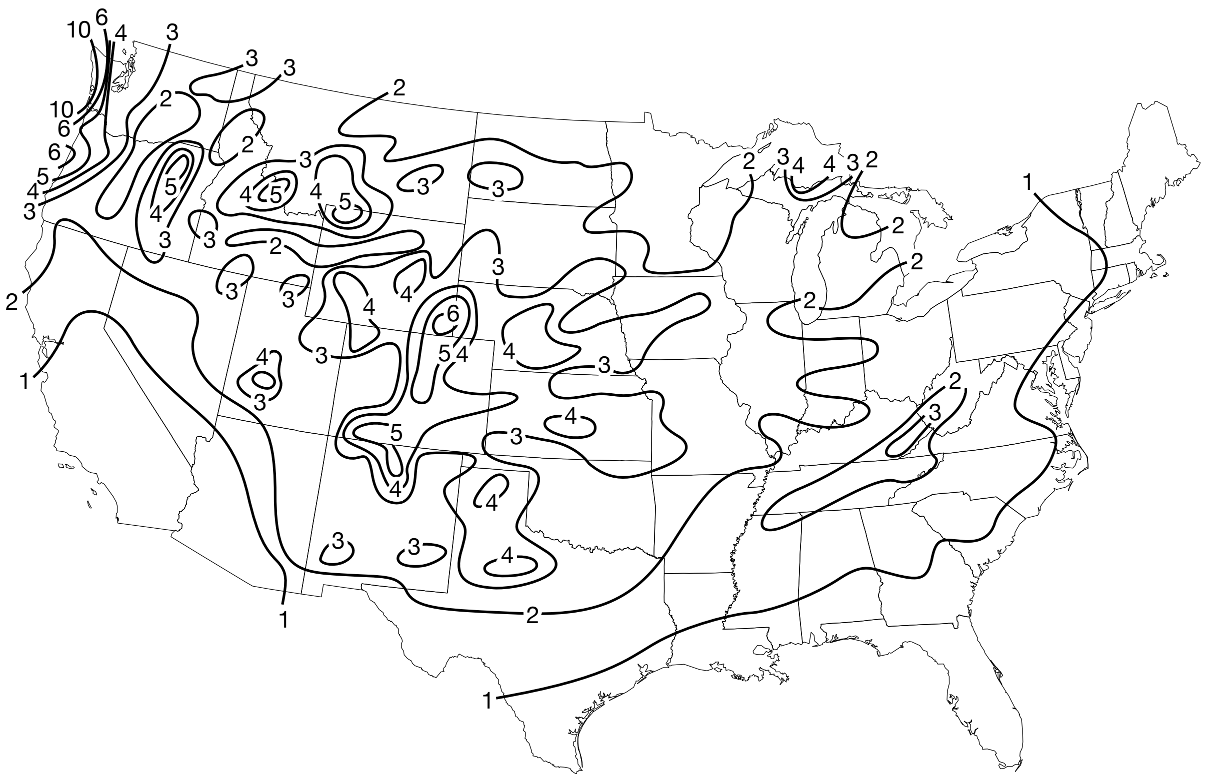


Figure 13. The average annual number of hail days in the U.S.

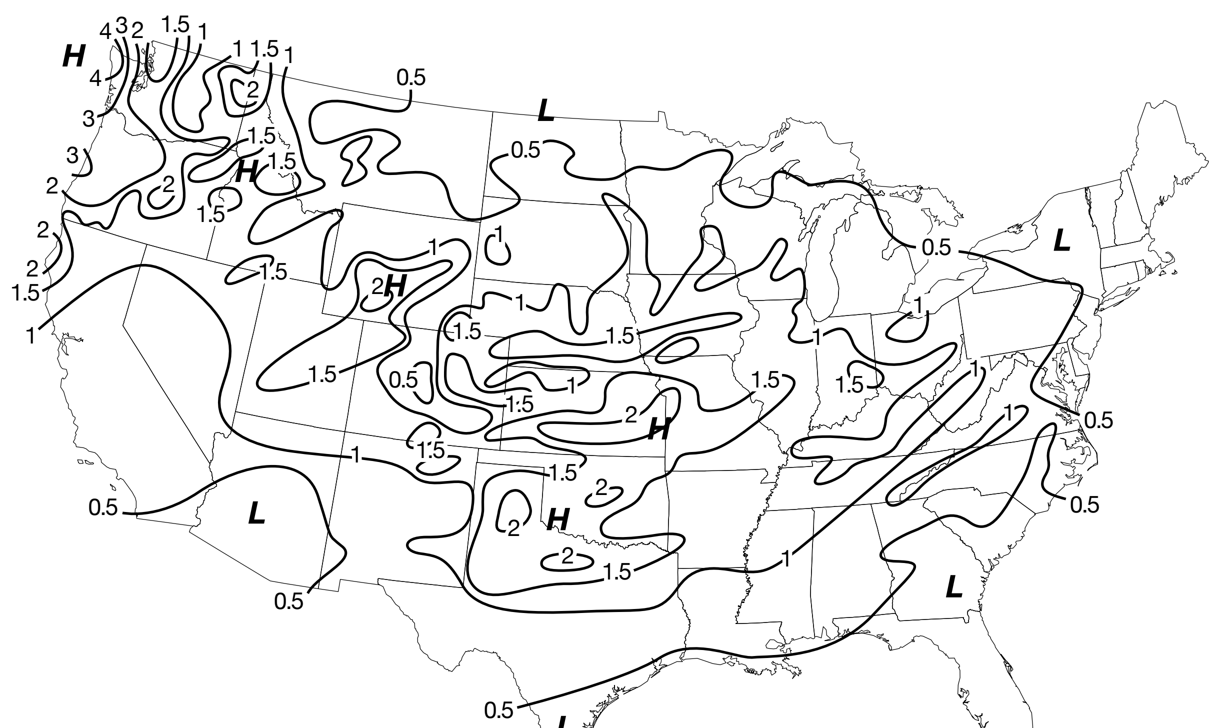


Figure 14. The average number of days with hail in spring (March-May). A value of 0.5 means a hail day once every two years, and 1.5 means three hail days in two years.

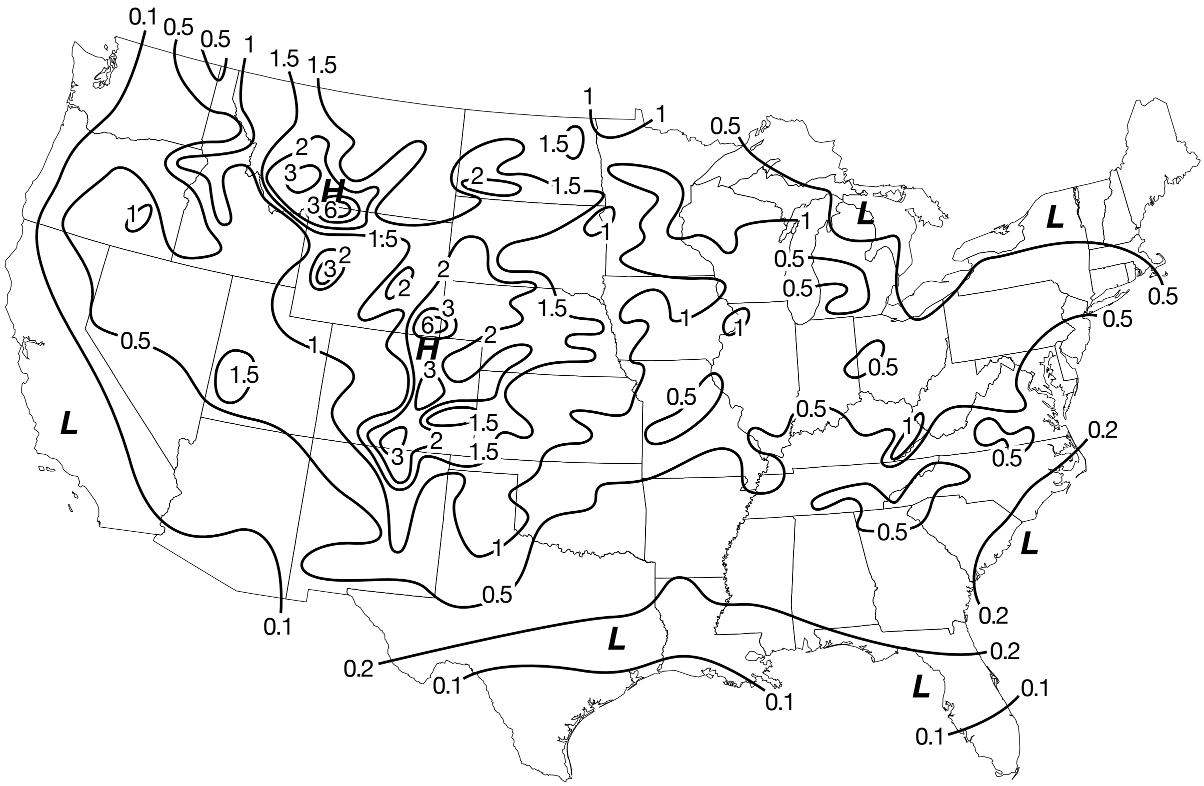


Figure 15. The average number of days with hail in summer (June-August). A value of 0.1 indicates one hail day in 10 years.

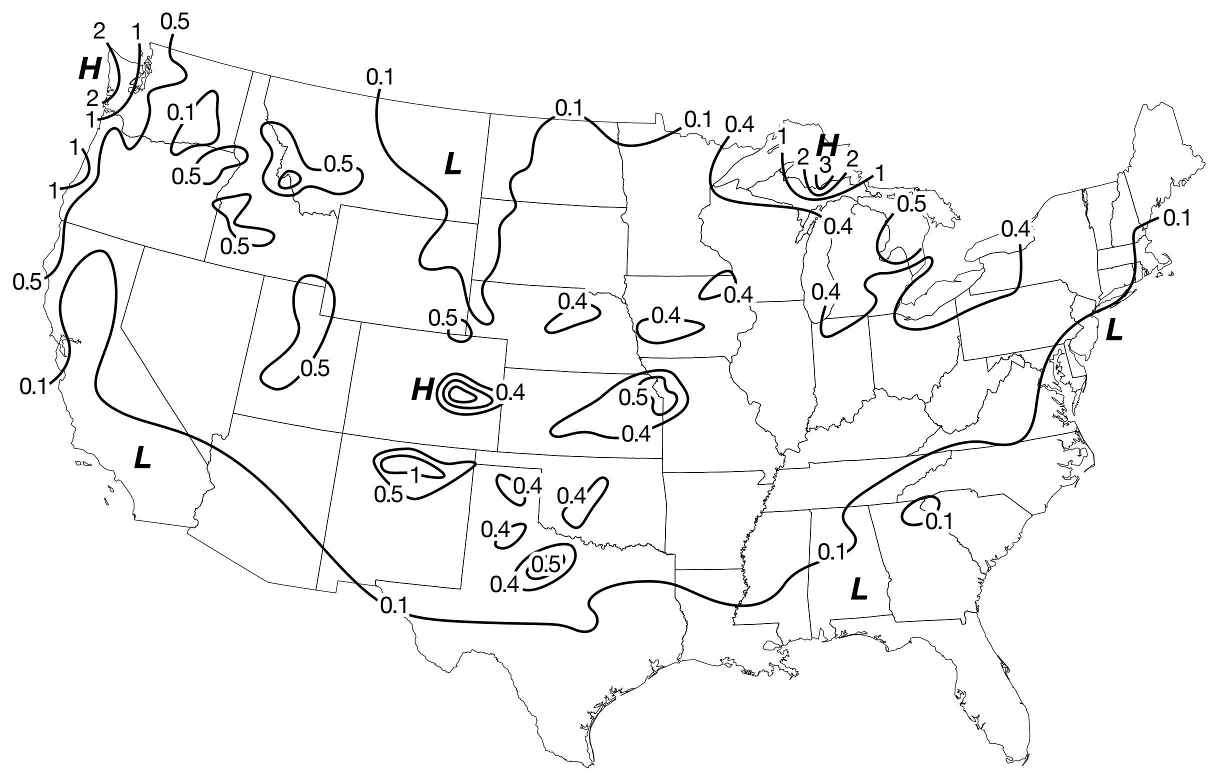


Figure 16. The average number of days with hail in fall (September-November).

is most frequent in June, decreasing in July, and becoming the least frequent in August. Hail in summer is very infrequent (0.1, or once in 10 years) in the Deep South and along the West Coast. The fall average hail-day pattern (Figure 16) shows a few small moderate high hail days along the front range of the Rockies. The largest hail values exist along the Pacific Coast in Washington and Oregon, and in areas downwind of the Great Lakes. Pacific storms in the fall and winter frequently create small hailstones, leading to a 10 hail day annual average (Figure 13) along the Washington coast.

Seasonal patterns reveal that the nation has 22 discrete areas of relatively high hail incidences. These 22 high hail areas are listed in Table 4. The mountain-influenced hail highs occur mainly in the summer (June-August). The highs due to frequent frontal zones occur mainly in spring; those due to the effects of the Great Lakes are in the fall when the lakes are warm relative to the passing cooler air masses and act to induce and strengthen storm activity in the lee of the lakes (Changnon, 1966b).

SMALL-SCALE VARIABILITY

The special hail sampling networks operated in Illinois, South Dakota, and Colorado provided information on the spatial variability of hail across short distances. Figure 17 presents two patterns for the prime hail season, May-September 1968 in central Illinois. The upper map is of hailfalls within a 40- by 40-mile network. It shows that some locations had no hail (northern areas outlined by a 1-value), whereas a few small areas had more than six hail days with up to 10 hail days at one location during this five-month period. The lower map shows another network that is 12 by 12 miles (hail sensors were only a mile apart), and portrays the number of hail days that occurred during May-September 1968. Again, considerable spatial difference is shown with values ranging from no hail days (those inside the 1-line) to more than three hail days across a distance of only 2 miles. These differences clearly illustrate that in any one year, there can be major differences in hail incidences across short distances.

Table 4. Areas of High Hail Incidence in the Central United States

Mountain-influenced Highs and Peak 20-year Average Hail Days at Selected Places in each Area

Cheyenne, WY- 188 hail days, the highest value in the central U.S.
Denver-Southeast CO - 144 hail days
Las Vegas, NM-Southern CO - 130 hail days
West Yellowstone, WY-southern MT - 107 hail days
Dillon, MT- 101 hail days
Rapid City, SD - 97 hail days
Casper, WY - 91 hail days
Sheridan, WY - 90 hail days
Central Montana - 78 hail days
Mara, TX - 59 hail days

Areas of Preferred Storm Activity and Regional Range of Peak Values

Central Texas - 85 to 70 hail days
New Mexico-Ohio Frontal Zone - 70 to 55 hail days
Platte River Valley, NE - 85 to 75 hail days
Kansas City Area - 100 to 80 hail days
Minnesota-Northwestern Iowa - 95 to 80 hail days
Northeastern Iowa-Wisconsin - 90 to 70 hail days
Northeastern South Dakota-Minnesota - 65 to 50 hail days
North Dakota-South Dakota Boundary - 70 to 55 hail days
Western North Dakota - 65 to 55 hail days

Great Lakes Effect Areas and Peak Values

Upper Michigan Peninsula - 100 hail days
Northwest Indiana - 85 hail days
Northwest Lower Michigan - 65 hail days

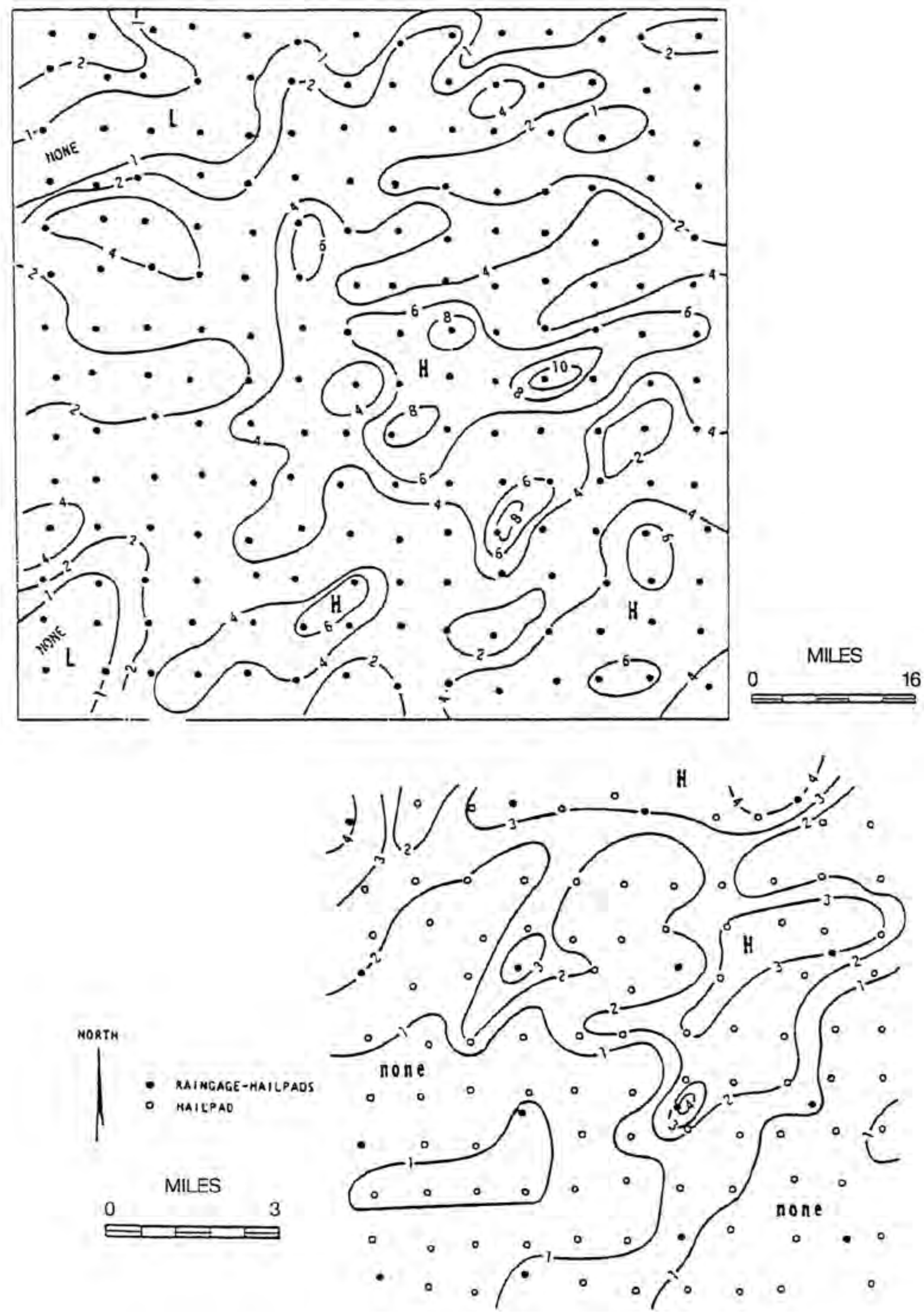


Figure 17. Frequency of hail days in two different sized dense Illinois hailpad networks during May-September 1968.

10. Hail Intensity

The national patterns of annual and seasonal average hail days in Figures 13-16 were developed using values collected during 1901-2005 at a series of points, either by weather observers or by hail sensing instruments. They define the *frequency of hail*, which is one of the four elements that combine to form *hail intensity*.

The intensity of hail at a point (or over an area) is a function of four variables:

- the frequency of hail
- the size of the hailstones that fall
- the number of hailstones (volume of ice) that fall when it hails
- the speed of the wind when it hails

This section discusses each of these four conditions that when combined form the hailfall intensity and the conditions that create damage to crops and property.

HAILSTONE SIZES

One of the more important aspects of hail intensity is the size of the hailstones that occur. During most hailfalls there is a range of stone sizes. Most data that have been collected defined the *average sizes* of stones that fell and often the *maximum size*. The size of a hailstone matters considerably when accounting for damage. Studies have concluded that most property damage begins when hailstone diameters are 0.75 inch or greater. The larger the stones, typically the greater the property damage (Morrison, 1997). However, most crop loss is not linearly related to stone sizes. For example, some crops at certain stages of development are most susceptible to damage from small 0.25-inch stones, and other crops (and growth stages) are susceptible only when stones exceed 0.5 inch in diameter. Hail mass is often the most critical factor causing crop damage.

Hailstones are seldom perfectly circular and most have unusual shapes as a result of the different atmospheric conditions where they formed (Figure 1). Most hailstones have oblate shapes and some have knobs of ice radiating outwards. A recent Colorado storm produced large disc-shaped stones (Knight et al., 2008).

Figure 18 presents a series of bar graphs based on hailstone size measurements from various locations. The most important finding is the considerable difference in the hailstone size distributions. Some locales such as Arizona and Illinois are dominated by small stones, but other locations such as Colorado show a wider distribution with a large number of stones (35 percent) having diameters greater than 0.75 inch. Among the three field projects measuring hail in Colorado, one network operated in Denver found stones averaging 0.5-inch in diameter (Beckwith, 1961), whereas two projects conducted at different times in northeastern Colorado found different averages with 0.65-inch diameters in one project (Morgan, 1982), and an average of 0.75-inch hailstones in another project (Schleusener et al., 1965).

The pattern of average hailstone sizes for the nation appears in Figure 7. It is based on an analysis of all available information in 1960-2000 on average hailstone sizes. Data came from 67 locations in the United States. The pattern (Figure 7) shows the largest average stone size is 1.2 inches, which occurs in the lee of the Rockies in Wyoming and Colorado where the hailstorm frequency is also high (Figure 13). Average stone sizes decrease rapidly west and east of this high. Over much of the United States, the average hailstone size is 0.3 inch or less. Figure 19 presents the national patterns for small-, moderate-, and large-sized hailstones, based on data for 1948-2002. The frequencies of each size are expressed as a percentage of the total hailfalls during the 55-year period. Small hailstones (0.25 to 0.5 inch) are most frequent along the West and East Coasts and in the South. Moderately sized stones (0.5 to 1 inch) are most common along the Rockies from Montana to Texas. Large hailstones (more than 1 inch) are most common in the central Rockies and central High Plains.

Data from 256 first-order stations for 1948-2002 were used to compute the percentage of all hailfalls with stone sizes of 0.75 inch or larger (Figure 8). This pattern shows a peak of 40 percent in the lee of the Rockies, and the area extends southward into central Oklahoma. Over most of the United States, hailstones of this size (or larger) occur in less than 15 percent of all hail events. For a location in Illinois where the annual average is two hail days, or 20 hail days in 10 years, two of the 20 hail days (10 percent) will have stones of 0.75-inch diameter or larger.

Table 5 presents the relationship between the annual average number of hail days and hailstone size distributions. This shows that areas with fewer hail days (on average) experience fewer large hailstones when it hails. Thus, hail-day frequencies and hailstone sizes are related.

The largest hailstones measured in the U.S. have been 6.5 inches in diameter. A 1928 hailstorm in southwestern Nebraska produced a 6-inch hailstone weighing 1.5 pounds (Blair, 1928). A 1970 storm in southwestern Kansas produced 6.5-inch

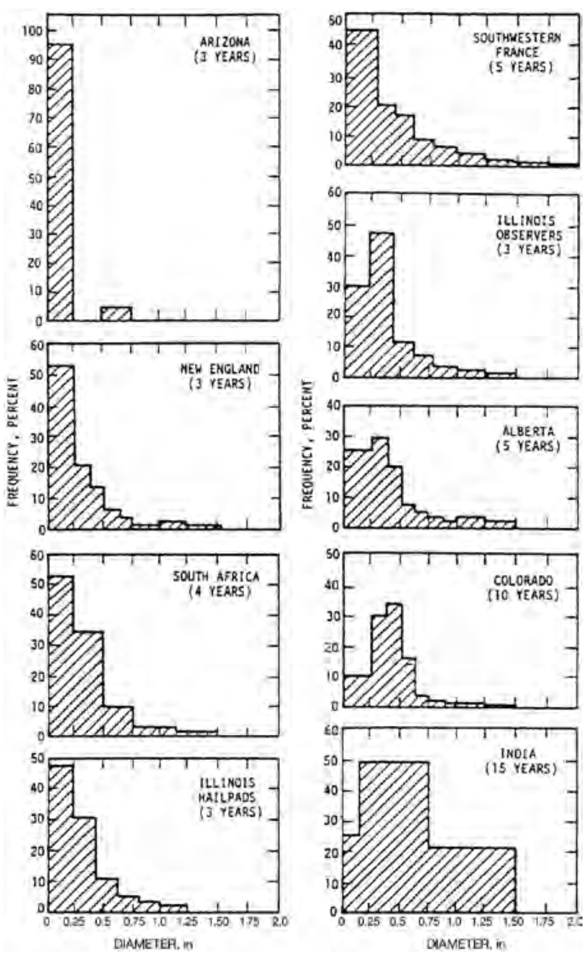


Figure 18. The frequency distributions of hailstone sizes for various locations.

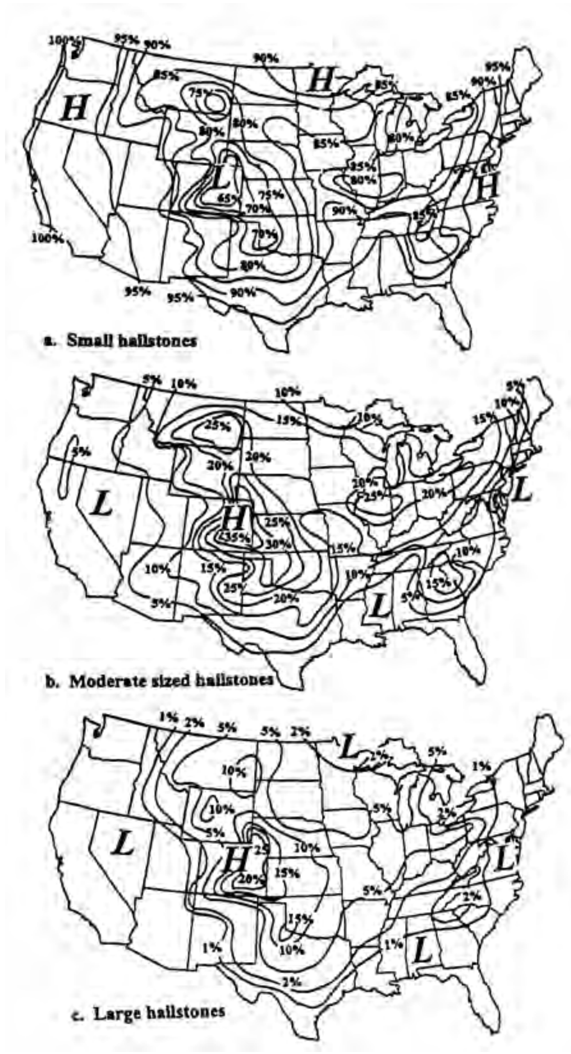


Figure 19. Frequencies of different sized hailstones expressed as a percentage of the total hailfalls during 1920-1950. (Small=0.25-0.5 inch, moderate=0.55-1.0 inch, and large=>1.0 inch).

diameter stones, as did a 2003 storm in western Nebraska. Other reports of exceptionally large hailstones have come from widely separate locales. For example, 5-inch hailstones fell in Chicago in 1938, and 4-inch diameter hailstones fell in Washington, D.C., in 1953 (Flora, 1956). The point is that practically every part of the nation has experienced hailstones of 3 or more inches in diameter at one time or another. The cause for regional differences relates to the hailstone *frequency*; that is, extremely large stones occur much less frequently in low incidence areas than in those near mountain regions of the west. For example, in Florida, a 3-inch hailstone can occur, but the estimated frequency at a point is once every 100 to 125 years. In the high hail frequency area of southeastern Wyoming, 3-inch or larger hailstones occur somewhere every two or three years with a point frequency of once in 7 to 12 years.

An Illinois field project that obtained measurements of 96,614 hailstones over a two-year period with 400 sensors distributed within a 1,600 square-mile area found that the maximum hailstone that occurred was 2.7 inches. Further, only 0.5 percent of the total stones had sizes greater than 1 inch (Changnon, 1970). The four-year National Hail Research Experiment (NHRE) in northeastern Colorado, which sampled more than 180,000

Table 5. The Probability of Various Hailstone Sizes as a Function of the Average Annual Days with Hail

Average annual	*Hailstone sizes, inches*						
number of hail days	*<0.5*	*0.5-1.0*	*1.0-1.5*	*1.5-2.0*	*2.0-2.5*	*2.5-3.0*	*>3.0*
2 to 3	62	28	4	3	2	1	<1
4 to 5	44	43	5	4	2	1	1
6 to 7	25	57	6	5	3	2	2

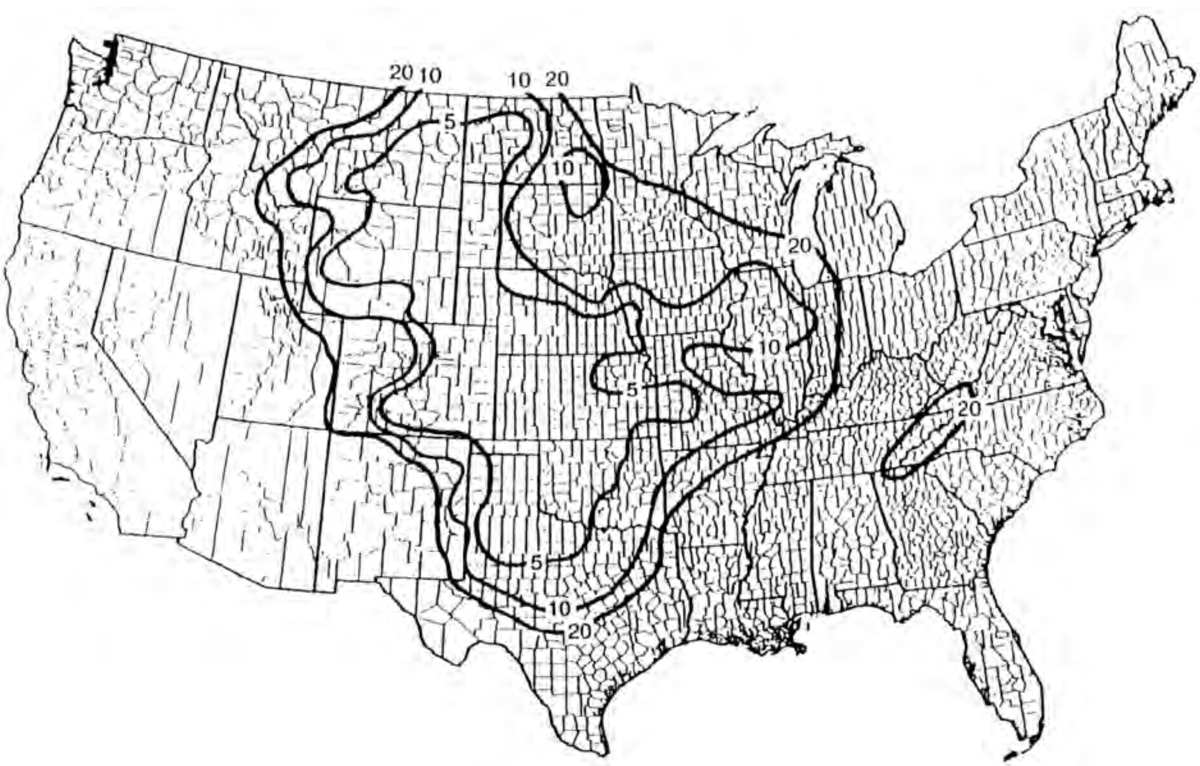


Figure 20. Pattern of the risk of a 1-inch (or larger) hailstone at a point. Shown are areas with a 50 percent chance of a 1-inch or larger hailstone occurring at least once during a 5-year, 10-year, or 20-year period.

hailstones, found the largest was 1.8 inches in diameter (Morgan, 1982), much less than the maximum sizes that have occurred in the region. The key point is that almost any location in the United States that has hail can experience very large hailstones, but any short sampling period may not experience any exceptionally large hailstones.

Figure 20 shows areas with a 50 percent chance of a 1-inch or larger hailstone occurring at least once in a 5-year, 10-year, or 20-year period. The Rockies and High Plains have five-year periods of occurrence, but most of the nation has a once in 20-year or longer period between occurrences.

FREQUENCY OF HAILSTONES

The third component of hail intensity is the number of hailstones at a given site. Measurements of the frequency of stones per hail event are limited to studies in five locations in the nation. The average stone frequency at these locations appears in Table 6.

These values reveal major regional variations with a ten-fold difference between the Colorado value (202) and the Illinois (24) and New England (18) values. Comparison of hailstone frequency (per unit area) with the average hailstone sizes (Table 6) shows they are well related so that the larger the average size, the greater the frequency of stones when it hails. The stone frequencies are also well related to differences in hail-day frequencies (Figure 13). These relationships mean that *the amount of ice that falls when it hails is generally proportional to the average stone frequency and average size of hail.* That is, the more often it hails at a point, the larger the stone sizes (on average), and the greater the number of stones per unit area. Hence, hail intensity is greatest in the lee of the Rockies. The mix of stone sizes and number of stones combine to form the mass of hail, often the key factor in the damage created.

Table 6. The Average Number of Hailstones per Square Foot, and the Average Diameter of Hailstones at Each Location, based on 2- to 4-year Samples Collected during the 1970s

New England	18 (average stone size = 0.25 inch)
Illinois	24 (average stones size = 0.25 inch)
Missouri	54 (average stone size = 0.3 inch)
South Dakota	183 (average stone size = 0.5 inch)
Colorado	202 (average stone size = 0.7 inch)

The small-scale variability of hailstone frequencies and hail mass in a single Colorado storm is portrayed in Figure 21. This pattern is for the number of hailstones (left map) and the areal distribution of the mass of hail that fell (right map) on a dense network in Colorado in a single storm (Morgan and Towery, 1974). The network is small, 1 mile by 1 mile, with 144 samplers (hailpads). Stone values ranged from more than 1,000 hailstones (per square foot) to less than 100 stones just a 0.5 mile away. The mass of the hail measured ranged from 50 up to 2,000 stones per square yard. Most of the seasonal mass of ice that falls in Northeast Colorado is confined to a few storms (Morgan, 1982).

It is worth noting that the number of stones that can fall during a storm is much greater than the averages shown in Table 7. Three years of measurements from the dense hail networks in Illinois gave the following maximum number of stones from a single point (1 square foot) hail occurrence: 1,424 stones of 0.25 inch size, 258 stones of 0.5 inch, 108 of 0.75 inch, 25 of 1 inch, and 11 in excess of 1 inch. This created a total of 1,726 stones on 1 square foot during a 16-minute hailfall (Changnon, 1973). The Colorado point averages were 202 stones per square foot, and Figure 21 shows that in one sampled storm, totals exceeded 1,000 hailstones at one sample site.

WIND WITH HAIL

The fourth factor in the intensity of hail is the force of the wind that exists during the period that hail falls. Few historical measurements of the winds with hailfalls exist since hail is infrequent at a point and is of short duration at a location with a wind recorder. The *average point duration of hail* varies regionally. The median and maximum duration values for three regions are: 3 and 25 minutes in New England, 4 and 35 minutes in Illinois, and 8 and 47 minutes in northeastern Colorado (Morgan, 1982).

Studies of winds with hail in Colorado and Illinois, using hail cubes and hail stools, found that wind speeds were often high (>30 mph), and their magnitudes varied widely across storm areas and between storms (Morgan and Towery, 1976 and 1977). Peak winds with hail in Colorado storms were from 31 to 53 mph (lowest to highest value) across the hail network during one hailstorm, and from 42 to 61 mph at various network locations on another storm day. In Illinois, peak gusts with hailfalls ranged from 12 mph up to 58 mph, as measured in 37 hailfalls. The average peak gust with Illinois hailfalls is 42 mph.

Measurements of windblown hail in northeastern Colorado revealed that 92 percent of all point hailfalls occurred with winds sufficiently strong to blow hailstones at an angle greater than 15 degrees off the vertical (Morgan and Towery, 1976). A special hail sensor was used to measure the occurrence of windblown hailstones during 41 hail events in Illinois (Changnon, 1973), and Table 7 shows the number of hail events with the percentage frequencies of windblown stones. For example, in six hailstorms between 1 and 20 percent of the stones fell at windblown angles (>15 degrees). The median of the 41 hail events was 77 percent. The Illinois results indicate that 1) 98 percent of all hailfalls at a point included windblown hailstones, and 2) nearly 80 percent of all hailstones were windblown (falling at more than 15 degrees from the vertical).

Table 7. The Frequency of Windblown Hailstones During 41 Hail Events in Illinois, 1970-1971

Percent of stones that were windblown	1-20%	21-40%	41-60%	61%-80%	81-100%
Number of hailfalls	6	7	4	10	14

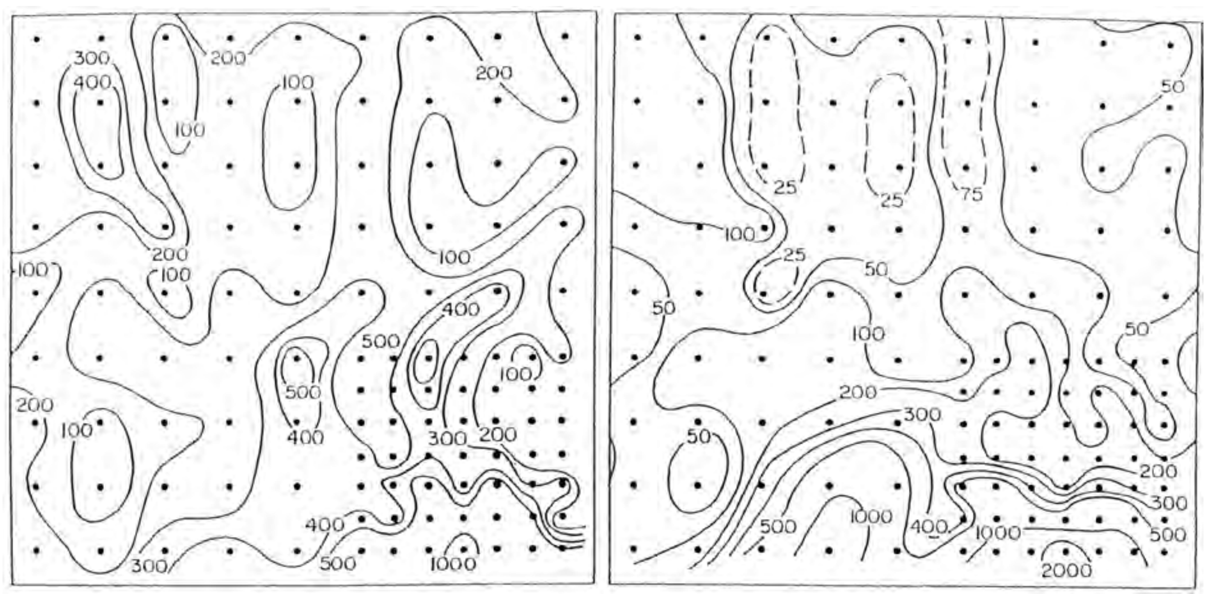


Figure 21. Hail from a single hailstorm in Colorado measured over a 1 square-mile dense hailpad network. The left pattern is based on number of hailstones per square yard, and the right pattern is the mass of hail (in cubic grams).

A farm couple in Nebraska hold huge hailstones that fell just a few hours earlier.

11. Areal Extent of Hail

The prior section on hail intensity summarized a variety of hail values relating to hail characteristics at a point. Many concerns about hail are about the areal extent of hail, particularly over areas ranging from a few square miles up to state-sized areas. Figure 17 presented growing season hail-day values found across a small 100-square mile area and a 1,600-square mile area for a growing season. The results show enormous spatial variability. Unfortunately, there have been few studies dealing with the areal extent of hail on a storm, season, or multi-season basis. This section summarizes what is known about the areal extent of hail. It begins with a discussion of individual elements of hailstorms that relate to assessment of damaging hail.

STORM CHARACTERISTICS

Hail events occurring on the storm scale, or per day, have been categorized into five elements. These are presented in descending order by their size at the surface.

- *Hail-producing system* - a mesoscale convective system usually associated with a specific weather condition that contains one or more hailstorms, and the surface hail pattern produced by such a system is illustrated in Figure 22.
- *Hailstorm* - a convective cloud entity that produces hail at the ground and forms one or more hailstreaks.
- *Hailswath* - an area comprising two or more hailstreaks separated by less than 20 miles and occurring within an interval of two hours or less.
- *Hailstreak* - an area of hail that is continuous in space and time and produced by a volume of hail created within a single cloud.
- *Hailstripe* - a narrow area of higher winds and more hailstones found within a hailstreak.

Hailswaths and hailstreaks come in varying sizes, as shown in Figure 23. A large raincell (lower map in Figure 23) included a series of hailstreaks along a wide path of rainfall in what is defined as a hailswath. In contrast, small thundershowers produced individual hailstreaks, as shown in the upper map of Figure 23. Hailstreaks are the basic areal component of surface hail and serve singly, or in combination, to create the spatial extent of hail per

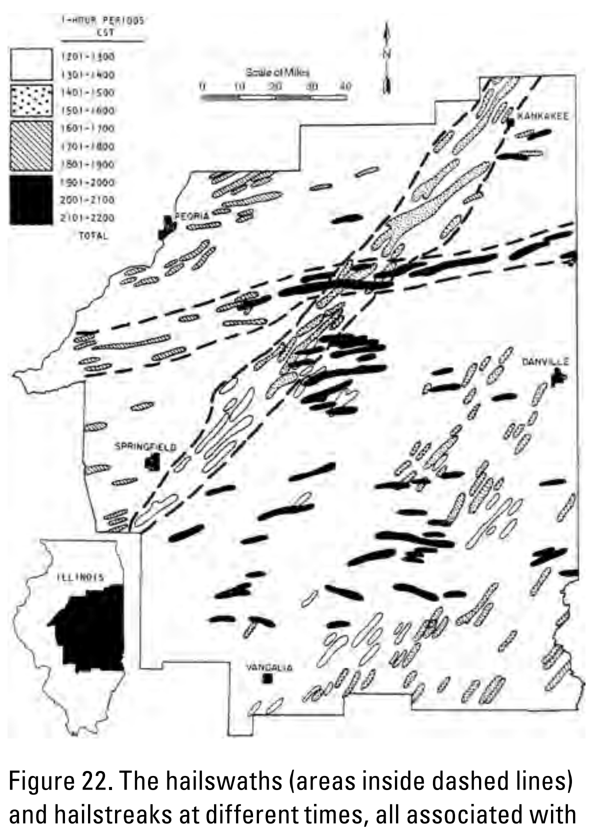


Figure 22. The hailswaths (areas inside dashed lines) and hailstreaks at different times, all associated with a hail system that existed for 10 hours in east-central Illinois.

hour, day, month, or year. They can be large, covering hundreds of square miles, or very small, 1 or 2 square miles. The Illinois field studies of hail during 1967-1969 defined 177 hailstreaks that were produced by 47 hail systems (Changnon, 1970). Statistics describing hailstreaks are presented in Tables 9 and 10.

Most hailstreaks range between 4 and 8 square miles in size, and the median values (Table 8) show that three hailstreaks typically occur in each hail-producing system. Extensive field studies of hail in Illinois and South Dakota allowed calculation of the average dimensions of their hailstreaks (Figure 24). Average hailstreak values showed 1) lengths of 15.3 miles in SD versus 10.8 in IL, 2) widths of 2.3 miles in SD versus 2.7 in IL, and 3) durations of 27 minutes in SD versus 20 in IL. Hail systems typically had 14 streaks in South Dakota versus 3

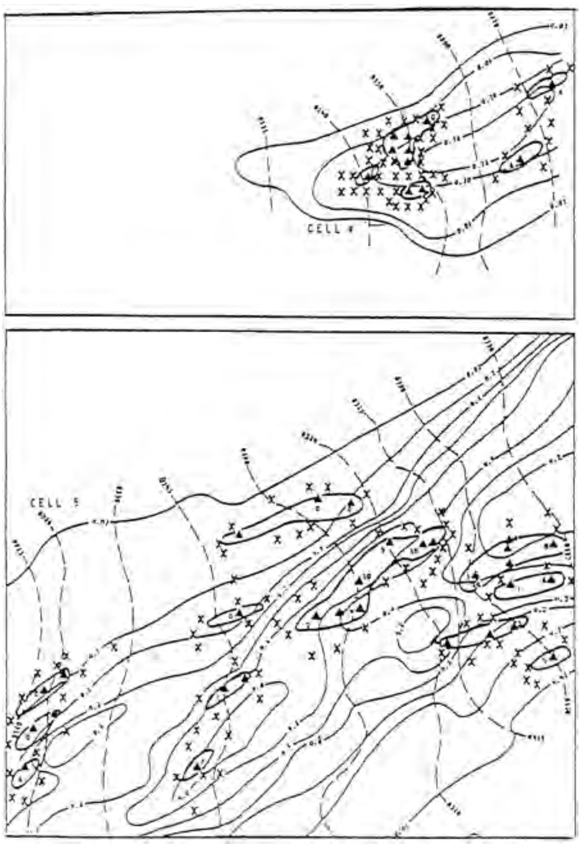


Figure 23. Patterns of hailstreaks (outlined in dark lines) and their associated rainfall patterns in inches (lighter lines) for two storms in central Illinois. Hailfalls are small triangles, and sites with no hail are marked with an X.

A small farm girl holds wheat stems broken by a just ended hailstorm in Kansas.

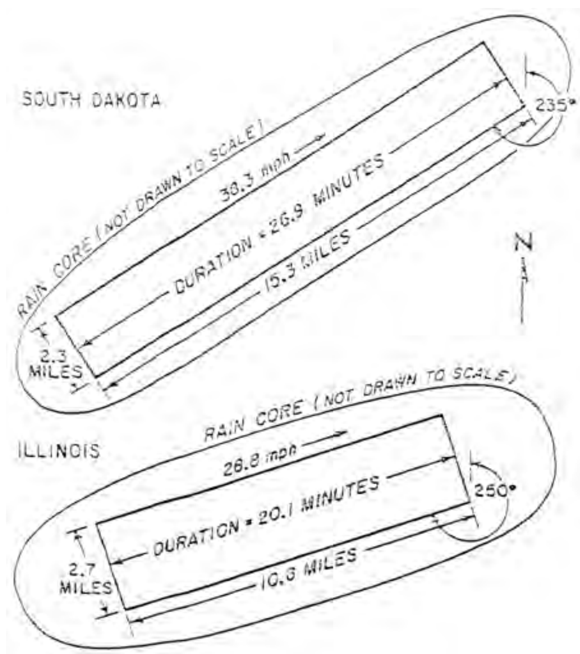


Figure 24. The average values associated with hailstreaks in South Dakota and Illinois.

in Illinois (Changnon et al., 1967). Hailstreaks in South Dakota, considered typical of those in the Great Plains, are much larger than those in Illinois, which are considered typical of Midwestern storms.

Hailstreak mean energy values varied widely with a minimum of less than 0.0001 foot-pounds per square foot up to a maximum of 12.6 with a median value of 0.006 foot-pounds per square foot for all 177 Illinois hailstreaks. The median of the maximum energy values found inside the hail-streaks was 0.022, much higher than the median for the entire hailstreak. These energy values are important since they relate directly to the amount of crop loss (Figure 4) and the amount of property loss expected.

Table 9 presents motion and size characteristics of Illinois hailstreaks. The median duration was 10 minutes with a median speed of 21 to 30 mph. The hail-wind assessment showed that 89 percent of all hailstreaks had windblown hailstones.

Average hailswath sizes in Illinois were 145 square miles (each containing an average of nine hailstreaks). Some Midwestern hailswaths have been measured as being 250 miles in length

Table 8. Hailstreak Frequencies and Their Areal Values in Illinois

	1967	1968	Average	Maximum	Minimum
Number of hail systems	27	20	-	-	-
Number of hailstreaks	77	100	3	22	0
Areal extent hailstreaks, square miles					
0.1-4	23	12	1	4	0
4-8	22	37	1	10	0
8-12	10	19	1	5	0
12-16	7	14	0	4	0
>16	14	18	0	7	0
Average size	**9.7**	**21.6**			
Maximum size	**40.3**	**788.0**			
Minimum size	**0.9**	**1.8**			

Table 9. Hailstreak Characteristics Expressed as a Percentage of 273 Hailstreaks in Illinois during 1967-1968

Duration in minutes

0-1	*2-3*	*4-5*	*6-7*	*8-9*	*10-11*	*12-13*	*14-15*	*>15*
2	4	9	15	13	12	12	6	27

Speed, mph

1-10	*11-20*	*21-30*	*31-40*	*41-50*	*51-60*	*61-70*	*71-80*	*81-90*
2	16	33	22	19	5	2	1	0

Hailstreak width in miles

0.1-0.3	*0.4-1.0*	*1.1-1.5*	*1.6-2.0*	*2.1–2.5*	*2.6-3.0*	*3.1-3.5*	*>3.5*
1	37	38	10	3	4	3	4

Hailstreak length, miles

1-2.9	*3-4.9*	*5-6.9*	*7-8.9*	*9-10.9*	*11-12.9*	*13-14.9*	*>15*
13	17	26	19	9	8	4	4

(Changnon, 1978a). Hailswaths defined from data in the Dakotas were larger, often more than 300 miles long (Frisby, 1963).

Analysis of aerial infrared photographs of damaging hailstreaks in Illinois discovered features within hailstreaks that became labeled as "hailstripes" (Morgan and Towery, 1977). A hailstripe is a narrow line (40 to 80 feet wide and up to 2,000 feet in length) of greater crop damage within a hailstreak. Hailstripes are caused by sudden small-scale bursts of higher winds descending in conjunction with an increased number of hailstones. Large hailstreaks often contain 10 or more hailstripes. These features need to be considered in assessments of crop-hail damage. They also help to explain the often odd patterns of excessive property hail losses found in densely settled areas (Friedman, 1965; Charlton and Kachman, 1996).

POINT VERSUS AREA RELATIONSHIPS

Since there are considerably more data on hail characteristics at a point than over an area, various point-area relationships of hail have been defined using data on both area and point hail incidences to estimate regional hail days. The relationship between point and areal frequencies of hail days in Colorado and Illinois were defined using two data sets, and the resulting curves are shown on Figure 25. The curve labeled "networks" was based on data from 10 dense hail-sensing networks operated in Illinois and Colorado during 1958-1970. It shows how average point values relate to areal averages for areas from 1 to 100,000 square miles. For example, an area of 100 square miles has a network ratio of 4, showing that if a point in this area had an average of two hail days per year, the area average would be eight hail days.

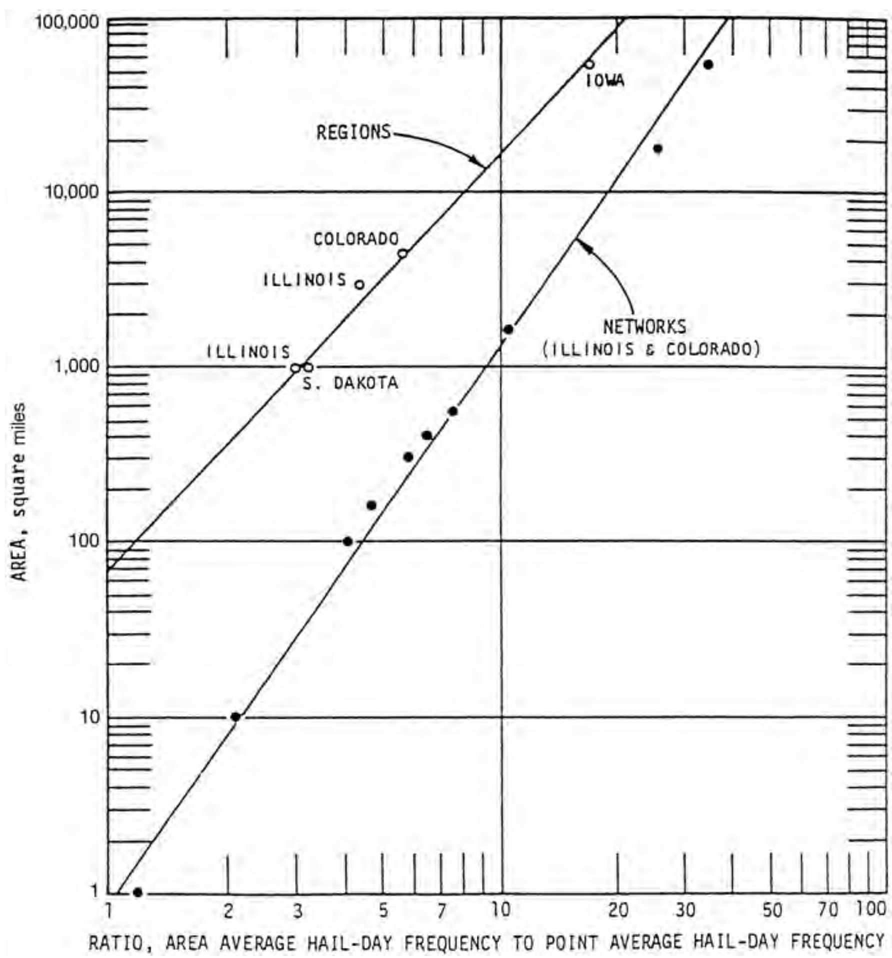


Figure 25. Point-area relationships for hail days based on regional values and on dense hail network values.

The other curve on Figure 25 labeled “regions” is based on hail-day data from NWS stations (less dense sampling than in the hail networks), and is offered for comparison with the hail network curve to reveal the differences inherent in using less dense sampling of hail. The network data are from different hail climate zones, and the good relationship (fit) of the data boosts confidence in using the network curve for defining the areal frequency of hail days anywhere in the U.S.

Figure 26 presents the probability relationships defining the summer (June-August) hail days for two different sized areas in Illinois. For example, the 80-percent probability shows up to three hail days in the smaller area and about five in the larger area. Note, there is a 20 percent probability of having no hail days in the 1,000-square mile area. The average annual frequency of potentially damaging hailstorms (hailstones >0.25 inch) per 1000-square-mile areas for the High Plains states is as follows: 12 storms in central Texas, 40 in the Texas panhandle, 60 in central Oklahoma, 45 in Kansas, 45 in southwestern Nebraska, 20 in northern Nebraska, 12 to 20 in South Dakota, and 10 to 12 in North Dakota.

The relationship between the number of sampling points in an area (such as insured properties) and the areal extent of damaging hail on a storm day is displayed in Figure 27. This shows a sizable effect. For a 4,000-square mile area, the average extent of hail damage to crops will be 10 square miles when based on a sampling of 1 point per 3 square miles. However, the damaged area increases to over 30 square miles if the sampling is at a density of 1 point per 0.5 square mile. The depth of hail on the ground has not been defined for most storms. However, reports of depths of 12 to 14 inches have been made for a few storms in the High Plains. A 1972 hailstorm in southern Illinois created a depth of stones ranging from 4 to 6 inches over 8 square miles. In some cases, the rain falling with heavy hail has moved the hail, creating drifts of stones that are 12 to 24 inches high. A New Jersey hailstorm in June 2009 dumped 3 to 4 inches of hail on two suburbs, and the deep hail covered 21 square miles.

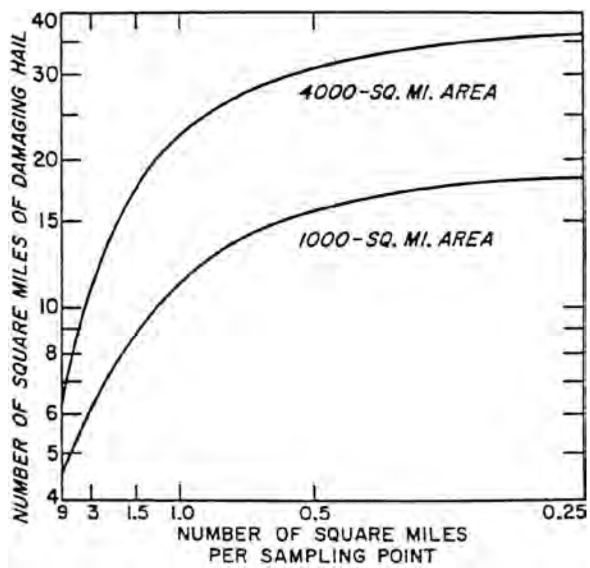


Figure 27. Average areal extent of crop-damaging hail on a hailstorm day in Illinois, based on various densities of sampling points, in 1,000- and 4,000-square mile areas.

An area with hail ranging from 3 to 6 inches in depth after a major hailstorm in southern Missouri in April 1995.

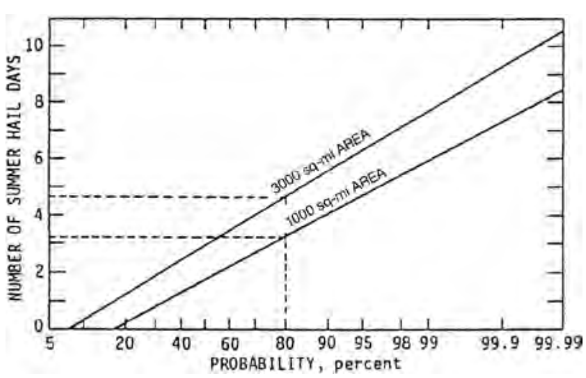


Figure 26. Probabilities for the number of summer hail days in two different sized Illinois areas.

12. Crop and Property Damages from Hail

Most information available about hail risk and damages from hail have come from studies of insurance data. Data available on crop-hail losses exceed that on property losses because the crop-hail insurance industry has systematically collected all loss data since 1948 for insured areas, whereas the property-casualty industry collected loss data only for hail catastrophes (events creating losses >$1 million) since 1949.

CROP-HAIL LOSSES

American farmers have long feared hail for its damages to their crops and have labeled hail as the "white plague" (Hughes and Wood, 1993). The national pattern of crop losses based on insurance values of loss cost during 1949-2007 is presented in Figure 28. This shows a major high of 9 ($9 per acre) in eastern Colorado, and the nation's higher loss values extend along a north-south axis in the Rockies and High Plains. The lowest loss cost values, those less than one, exist in the eastern Midwest, lower Mississippi Valley, and in parts of the East.

The patterns of crop-hail intensity indices for corn and wheat in the four prime months of crop-hail damage are shown in Figure 29. These are based on the intensity-susceptibility indices (see Figures 5 and 6). These reveal the spatial variations in the intensity of hail. Corn loss indices in Illinois and Indiana are the lowest of the Corn Belt states in

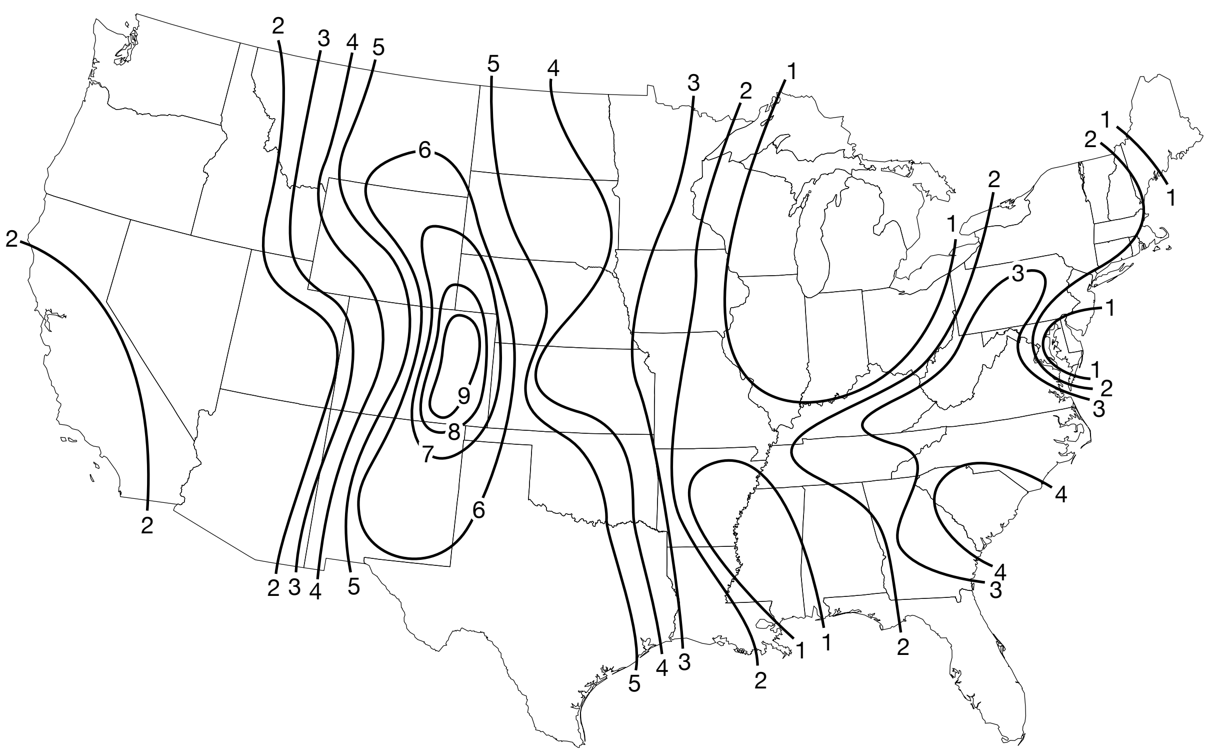


Figure 28. National pattern of the average loss costs (values in dollars per acre).

all four months. The monthly peak value for wheat losses shifts regionally, being 204 in New Mexico in May with a shift northward to a peak of 270 in July in Wyoming, reflecting the maturation of the wheat crop, which shifts northward over time.

Crop loss intensity indices for the peak months were adjusted to the lowest value (Illinois and Indiana with values of 10 were set to 1). These normalized values for the peak months of corn and wheat loss (June or July) were used to develop the map shown in Figure 30. This shows a relative peak of intensity with indices of 18 to 21 in the lee of the central-southern Rockies, decreasing eastward to a value of 1 in Illinois and Indiana, and decreasing westward to indices between 2 and 3 in Oregon and Washington. Dual values are shown in some states where corn and wheat indices were centered. These indices and their pattern shown on Figure 30 are considered the best pattern for assessing spatial variations in crop risk from hail across the United States.

The adjusted crop-loss intensity indices for 19 states were compared with the average number of hail days, as determined for the month of peak intensity. Hail day values were derived from the NWS hail-day data from first-order station records in each state. The resulting values (Figure 31) had a correlation coefficient of +0.89, which indicates a good relationship. For example, the first-order stations in Oklahoma, for the peak month of crop loss (May), produce an average of 10 hail days during that month (based on dates with hail at each station). This relationship allows estimation of the

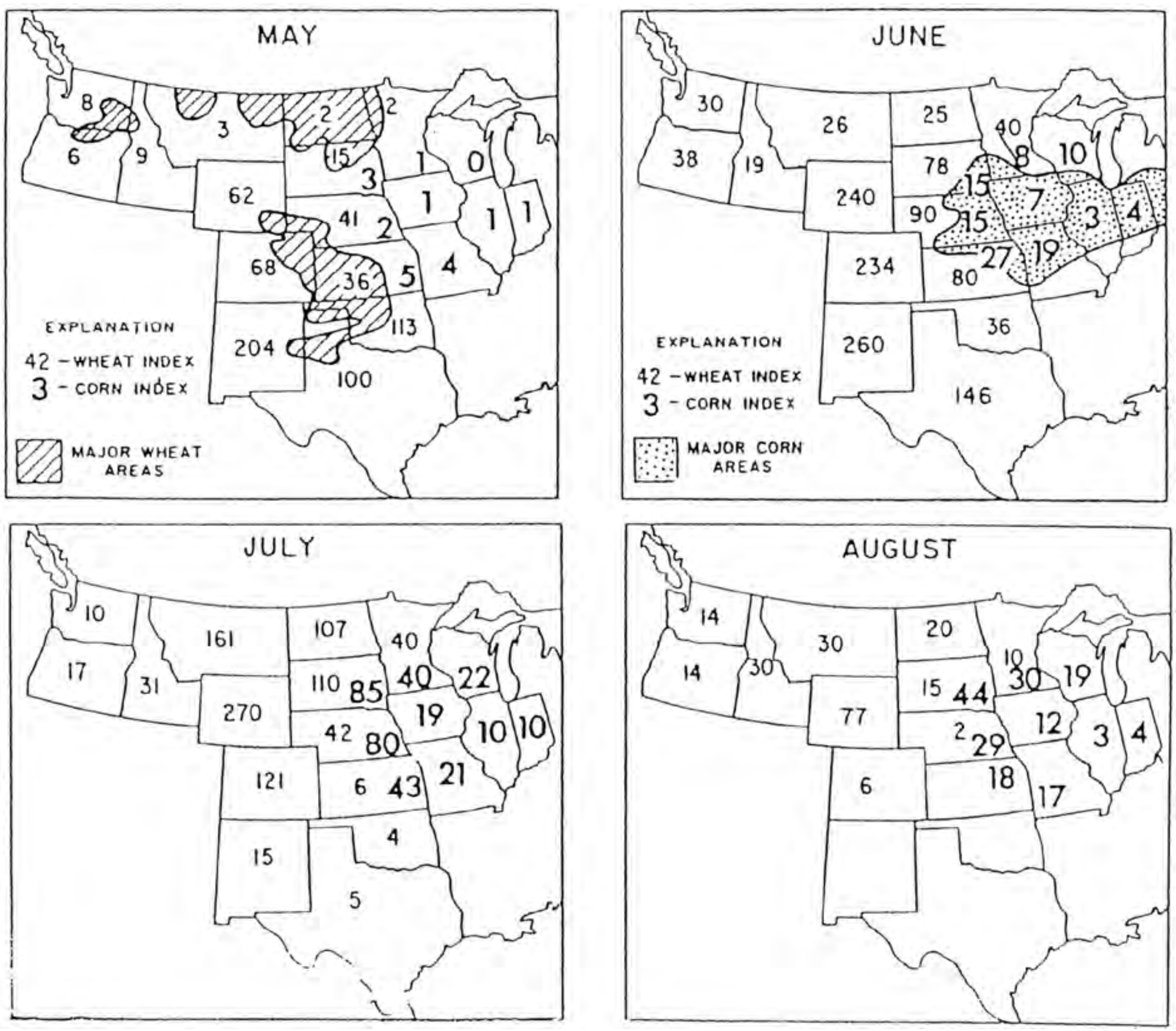


Figure 29. Patterns of hail intensity indices for wheat and corn in the prime loss months.

crop loss intensity indices for states or areas that have no historical crop-loss data.

The areal extent of crop-hail losses has been measured in various ways. The frequencies of hail-loss days per state and by crop are shown in Figure 32. These maps portray the annual averages for the five main U.S. crops damaged by hail (corn, soybeans, cotton, tobacco, and wheat). Texas averages

Corn badly damaged by a hailstorm.

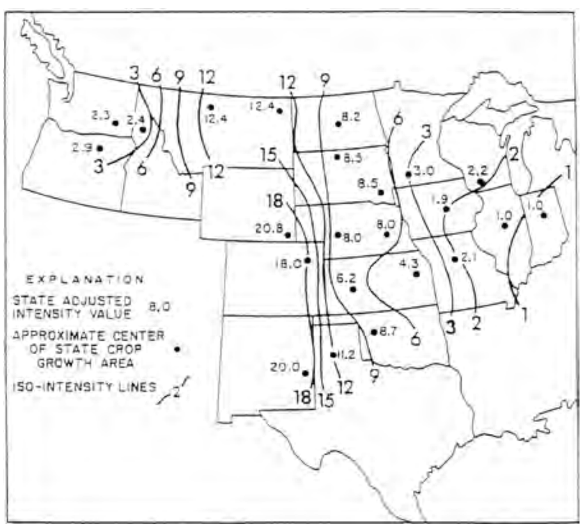


Figure 30. Pattern of crop-hail intensities determined for peak month (June or July) of wheat and corn damages.

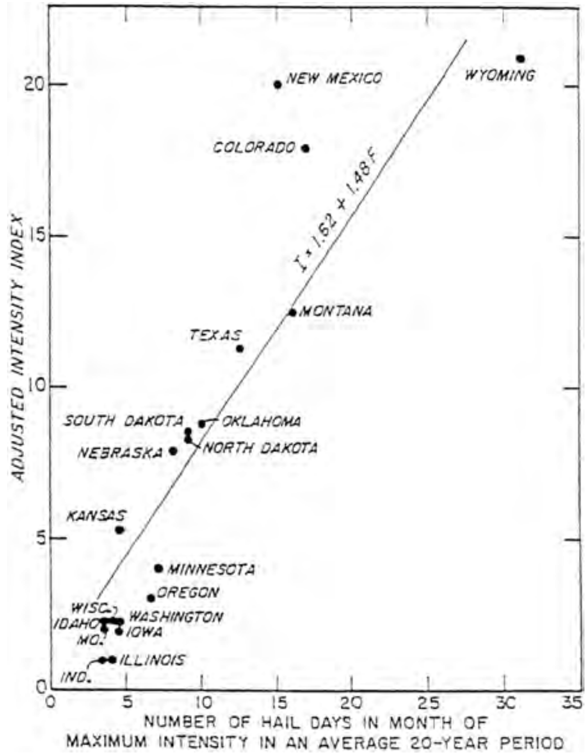


Figure 31. The relationship between state average frequencies of hail days (from first-order station records) for months of maximum crop-hail intensity and the adjusted crop-hail damage (Intensity) index.

Figure 32. Average annual number of crop-damage days in each state for five crops.

111 days per year with cotton-damaging hail, the nation's peak state value. North Dakota averages 87 wheat-damaging days annually to lead for that crop, and Iowa leads the corn states with 90 damaging hail days per year. Crop losses vary by crop type and stage in the growing season. Figure 33 shows the loss patterns for corn and soybeans within a large hailstreak, revealing their different patterns and differing amounts of loss in the same areas.

The areal extent of loss days is further analyzed in Table 10, showing the number of states experiencing losses when storms occur. This shows that most crop-hail loss days involve losses occurring over several states with 68 percent of the storms causing damages in 1 to 15 states. The days with more than $1 million losses nationally are typically very extensive with 88 percent of these days producing losses in 16 to 25 states. Figure 34 shows the widespread crop-hail losses (in 26 states and 190 counties) that occurred on a July day in 1962 with $3.5 million in losses (2000 dollars).

The areal extent of crop-hail losses is further examined in Figure 35, which presents national data for hail loss days expressed on a *county frequency basis*. This shows, for example, that 42 percent of loss days in the U.S. cause damages in 1 to 20 counties with a few loss days extending across 80 or more counties. Also shown in Figure 35 is the distribution for days that experience >$1 million of crop-hail losses. Here, the number of counties with damage typically exceeds 120 counties, and in 5 percent of the days, losses covered between 300 and 320 counties (many Midwestern states each have about 90 to 100 counties). Days

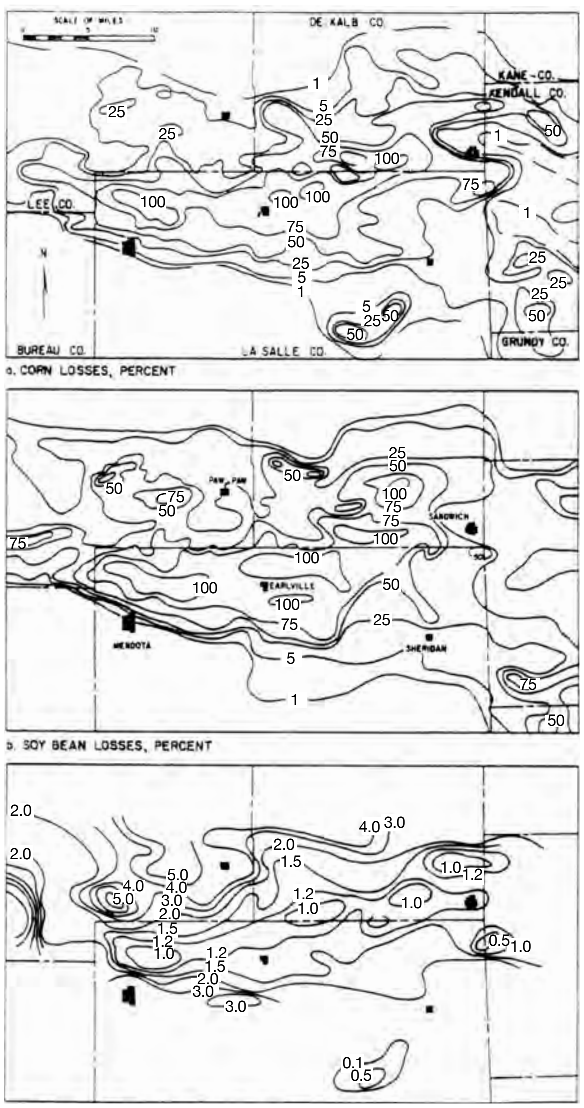


Figure 33. Crop-loss patterns for corn and soybeans (loss in percentage of crop) in a large Illinois hailstreak, and their loss ratios appear in the lower map.

Table 10. Distribution of Number of States with Loss on Crop-Hail Damage Days during 1949-2006

Number of states with hail	*Percent of all hail-loss days*	*Percent of hail days with losses > $1 million*
1-5	39	1
6-10	14	3
11-15	15	4
16-20	22	40
21-25	9	48
26-30	1	4

Apples dented by hailstones.

with more than $1 million in crop-hail losses occur on only 5 percent of the nation's hail-loss days each year, but they cause 40 percent of all crop losses in the United States.

The "big loss days," defined as those when hail causes more than $1 million in property damages, are typically concentrated in the central United States. The five-year average frequencies for the 14 hail areas (see Chapter 13, Figure 38) are shown in Table 11, revealing the Midwest leads with 26 events per five years, or five major storm days per year. The southeast (area 11), which has low hail intensity values, does experience several days with >$1 million hail losses. This results because the area contains very costly structures.

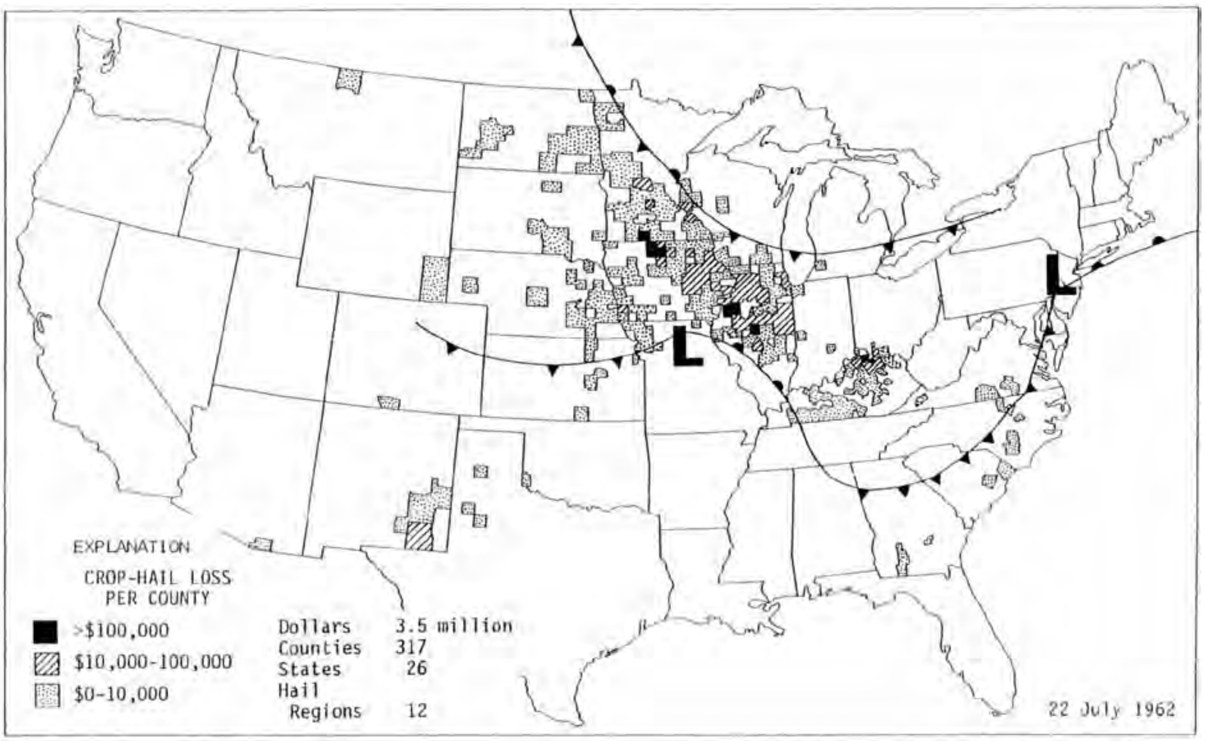


Figure 34. Counties with crop-hail losses on July 22, 1962, and positions of weather fronts causing the storms.

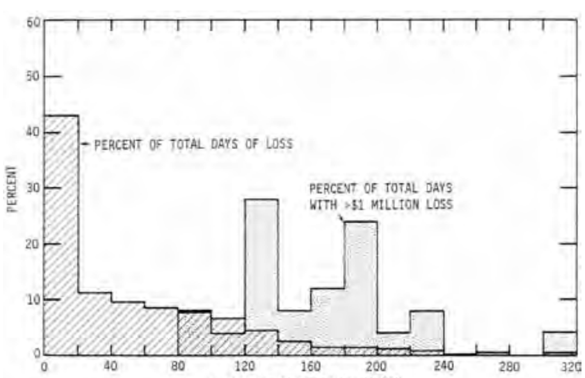


Figure 35. Frequency distributions of U.S. counties experiencing crop-hail losses for all hail days and for days with >$1 million in crop losses.

Youngsters stand in drifts of hailstones from a massive storm in Kansas.

PROPERTY-HAIL LOSSES

Property insurance studies have determined expected loss per risk (an insured property like a home) using hailstone sizes and storm sizes. Results in Table 12 give some measure of the cost and area risk values based on data from a field study of Texas hailstorms. Losses rise quickly after stones reach 1 inch in diameter. Expected losses per hail day can be calculated by using these tabular values and the probability of hailstone sizes. Cook (1995) did a study of the potential property losses across the nation, showing the highest losses were in the Great Plains.

A pattern based on the damage potential to property (Figure 36) reveals indices ranging from a low of 1 in Florida, to 50 in extreme northwestern Kansas (Cook, 1995). This pattern is similar to that developed for crop-hail losses (Figure 28) except that the highest property risk values are located in the High Plains about 50 to 300 miles away from the mountains. This placement of highest risk areas is due to the area's relatively large frequency of larger hailstones (Figure 20) and to higher average wind speeds with storms occurring along the north-south axis of the High Plains (Collins and Howe, 1964). This pattern (Figure 36) is considered an excellent national pattern to assess property-hail risks.

The growing national interest in the development of solar energy during the 1970s brought about the use of solar collectors. The areas of the nation where sunshine was sufficiently frequent to justify economic use of collectors were also subject to hail, and the collectors were found to be very sensitive to hail damage. This led to two studies, each attempting to develop models of the risk of hail damage to solar collectors (Gonzales, 1977; Cox and Armstrong, 1979). Their elaborate mathematical models could not be used in 99 percent of the nation's areas because of the lack of data in many parts of the nation on hailstone sizes, ice volumes, and impact energy needed as input to the models to predict the likelihood of damage. For example, Cox and Armstrong indicated their model to predict the largest hailstone (on a frequency basis) was limited to use only in northeast Colorado where they felt "adequate hail data" existed. Ironically, both studies failed to develop or to utilize regional hail climate studies needed to provide the desired "location-specific" data for many U.S. locations, acts necessary to develop a model-based risk pattern or sets of values for a wide variety of locales. Cox and Armstrong assessed the risk of damage to a solar collector at a given location in northeast Colorado and indicated the probability (based on their model) was 0.5 percent that a 1-inch hailstone or larger would strike a 10-m^3 collector during a 20-year lifetime.

Table 11. Property Losses in Major Storm Days in the 14 Hail Regions of the United States, and Percentage of Annual Total Property Losses per Region for 1950-2006

	Percent of annual property-hail loss	*Average number of hail days with >$1 million in 5-year period*
Area 1 (West Coast)	0	0
Area 2 (Southern CA and AZ)	0	0
Area 3 (NV, interior OR, WA)	0	0
Area 4 (MT)	1.3	1
Area 5 (Rocky Mt: WY, CO, ID)	1.8	1
Area 6 (Intermontain: UT, NM)	0.2	0
Area 7 (Dakotas)	0.3	1
Area 8 (High Plains)	37.8	10
Area 9 (MN and WI)	4.0	4
Area 10 (Midwest: AR, TN, TX)	35.3	26
Area 11 (Southeast)	13.3	16
Area 12 (MI and Great Lakes)	3.8	3
Area 13 (Appalachian Mtn)	1.8	1
Area 14 (New England)	0.8	0

SPATIAL DISTRIBUTION OF PROPERTY CATASTROPHES

The distribution of hail catastrophe occurrences during 1949-2006 in each of the nine climate districts of the U.S. (Figure 37) shows that the peak of hail-only events occurs in the South with the next highest frequencies in the West North-Central and Southwest regions. This spatial distribution agrees with the climatology of hail events for the U.S. The top 10 states of loss based on incidences of hail-only catastrophes (Table 13) reveal the high incidence of hail loss events is in these same High Plains states that are located in the West North-Central and South regions. The frequent catastrophe losses in states in the Central district reflects the region's higher density of wealth and property, and hence greater susceptibility to hail-property damages found in that area (Changnon et al., 2000).

The hail-only spatial incidence pattern is also reflected in the regional distribution of tornado-with-hail catastrophes (Figure 37). These events peaked in the southern Great Plains states (Table 13), as well as in five states in the Central district. Texas was the leading state for hail catastrophe occurrences in both categories. When floods occurred with hail (and tornadoes) to cause catastrophes, the peak area of occurrence was the South (Figure 37), followed by high frequencies in the Central and East North-Central regions.

Table 12. Expected Loss per Risk (assuming $50 deductible) and Percent of Risk with Claims for Hail Damage Related to Hailstone Sizes in Texas

Hailstone size diameter, inches	*Average loss per claim*	*Percent of risks with claims*
<0.5	$0	0
0.5-1.0	$2	1
1.0-1.5	$10	4
1.5-2.0	$60	5
2.0-2.5	$115	6
2.5-3.0	$175	7
3.0-3.5	$255	8
>3.5	$490	10

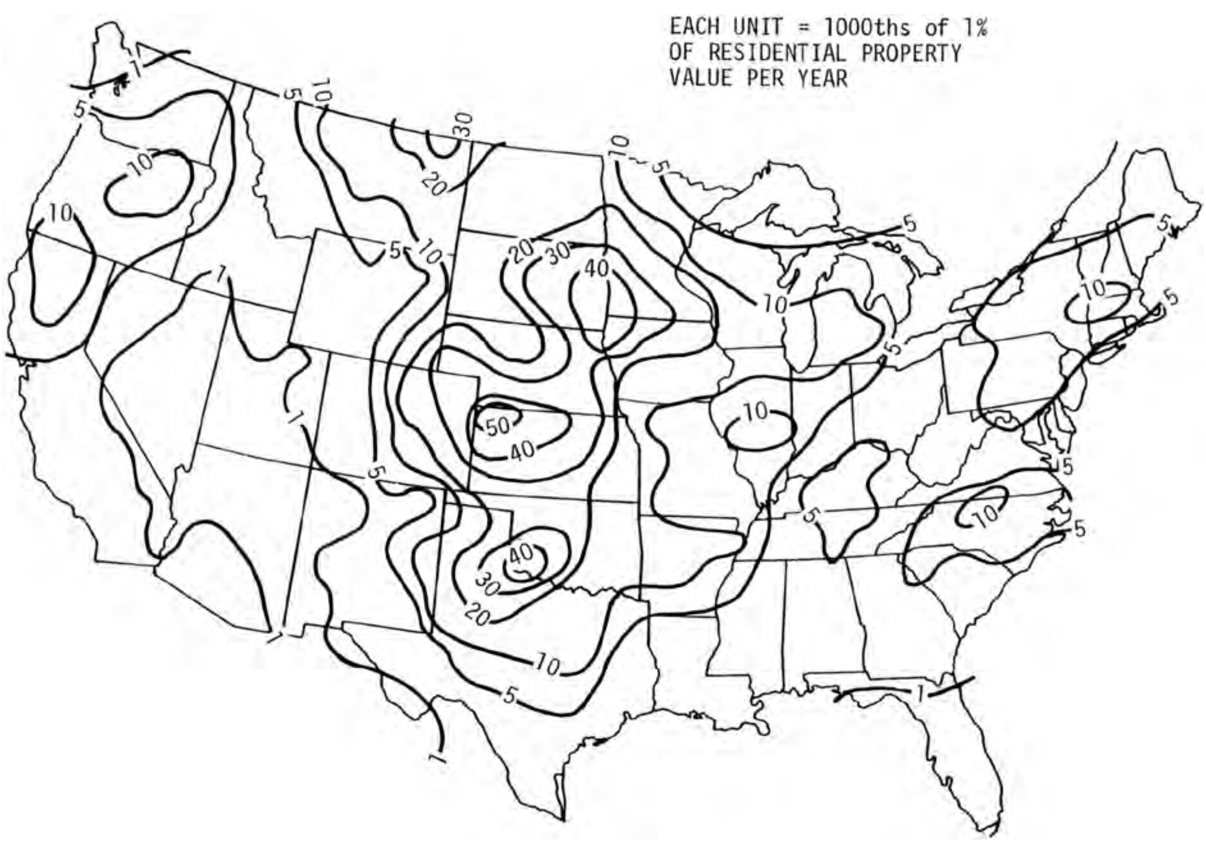


Figure 36. National pattern of the Index of Potential Hail Damage to Residential Property.

The size of property-loss areas has been measured by the frequency of catastrophes according to the number of states with an occurrence (Table 14). All three hail catastrophe types have their highest frequency in the one-state class. The hail-only value of 161 for one-state catastrophes is 80 percent of their total. It is a higher frequency for the one-state size than found in the other two classes of catastrophes. The average number of states per event is one state for hail-only catastrophes; 1.4 states for tornado and hail catastrophes; and the average is 5.5 states for tornado, hail, and floods catastrophes. This larger size with floods (Table 14) is a result of the wider-scale impacts caused by floods, and is not due to a wider extent of hail damages.

In general, hail catastrophe losses peaked in areas of the nation where hail incidences are most frequent, the High Plains (Figure 13). Hail catastrophes were most frequent in Texas, Oklahoma, and Kansas. The relatively high losses in the Midwest, being higher than storm incidences there, result from the high density of property and wealth in the region.

Table 13. The Top Ten States Based on Their Frequencies of Catastrophes During 1949-2006

	Type of catastrophe	
Rank	*Hail-only*	*Hail & tornadoes*
1	Texas	Texas
2	Kansas	Oklahoma
3	Oklahoma	Kansas
4	Colorado	Illinois
5	Missouri	Missouri
6	Nebraska	Iowa
7	Illinois	Arkansas
8	Iowa	Indiana
9	Indiana	Ohio
10	South Dakota	Mississippi

Table 14. Catastrophe Frequencies Associated with Number of States with Loss

Number of states with loss	*Hail-only*	*Tornado-hail*	*Hail, tornado, & floods*
1	161	123	40
2	27	68	33
3	3	52	37
4	6	38	29
5	1	20	38
6 or more	4	61	145

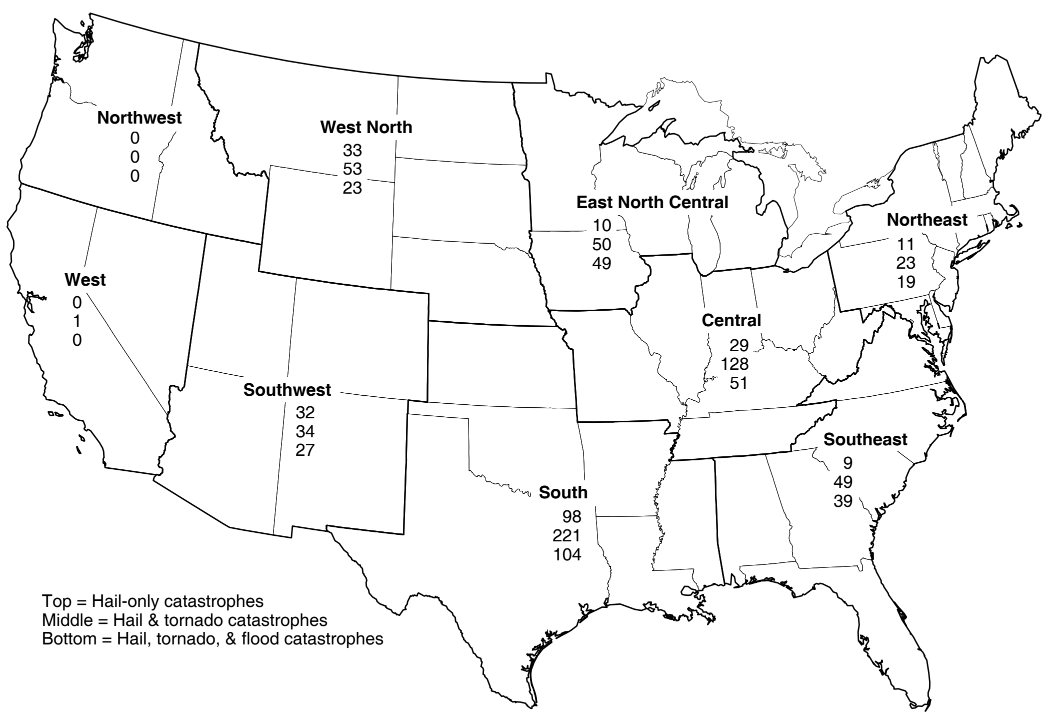


Figure 37. The frequency of hail catastrophes in each of the nation's nine climate regions during 1949-2006.

13. Hail Climate Areas

The various hail characteristics during 1950-2005, as distributed across the United States, were used to develop a national pattern of hail climate areas. The 14 hail regions that have been defined based on their hail climatology are shown in Figure 38. The four key characteristics of hail were used to identify the regions. These characteristics included: 1) its primary cause (in three classes); 2) the average hail-day frequency across the region; 3) the season of peak hail activity; and 4) the relative intensity of hail in three classes. For example, region #8 in the central plains is shown to have hail caused mainly by macroscale weather events (largely frontal activity) with average point frequencies of hail days between three and four days per year. The season of peak hail activity is early summer, and the hail intensity rates as moderate. In contrast is region #5 where storms are largely orographic in nature. Point hail frequencies are high, ranging from three to nine hail days per year. The peak season is late spring (April-May). The region's hail intensity is heavy, and hence often damaging. This map provides an overview of the key aspects of hail in the nation.

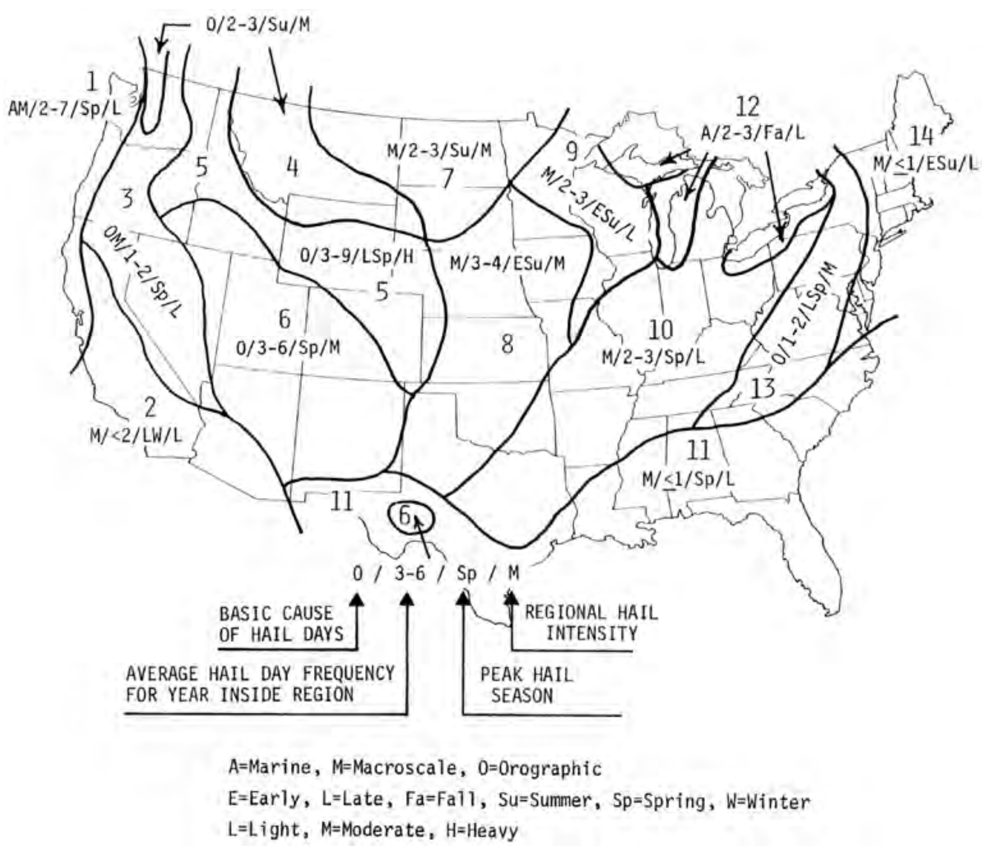


Figure 38. The 14 hail climate areas in the U.S., as defined using four key characteristics of hail.

Hail damage to the roof of an automobile.

SECTION E: TEMPORAL CHARACTERISTICS

14. Hail Frequency

The temporal variability of hail, because of its small nature, is greatly skewed. The typical crop-hail loss history for a county or state shows a few years with extremely high losses interspersed among many years with little loss. A weather station with an average of three hail days a year will, over a number of years, have several years with no hail but a few with double the average value.

Historical variations in hail are first illustrated by the incidence of hail days over time. These variations include time differences found at a point (weather station), those over several states, and that across the nation.

Figure 39 displays the hail-day frequencies during 1921-2000 for seven widely separated weather stations. These show different temporal distributions with time. Peak 10-year periods came at various times during the 80-year period. A few stations showed peak values in 1961-1970, and others had peaks in 1981-1990 or 1941-1950.

Figures 40, 41, 42, 43, 44, and 45 present the annual frequency of hail days during the 1901-1994 period for six states, each representing a different hail climate in the U.S. The distribution in North Dakota (Figure 40) shows a gradual increase in hail days from 1901 to about 1940, and peak values occurred in 1946 and 1976. It is representative of the hail climate of the northern plains (Figure 38). The Colorado distribution (Figure 41), typical of the area of highest hail incidences in the nation, shows its highest values in the 1960s and its lowest values in the 1930s. Ohio's distribution (Figure 42), typical of the Midwest hail region, peaked in the 1950s and then gradually decreased to its lowest values in the 1980s-1990s. The Oklahoma values (Figure 43), typical of the High Plains, display frequent

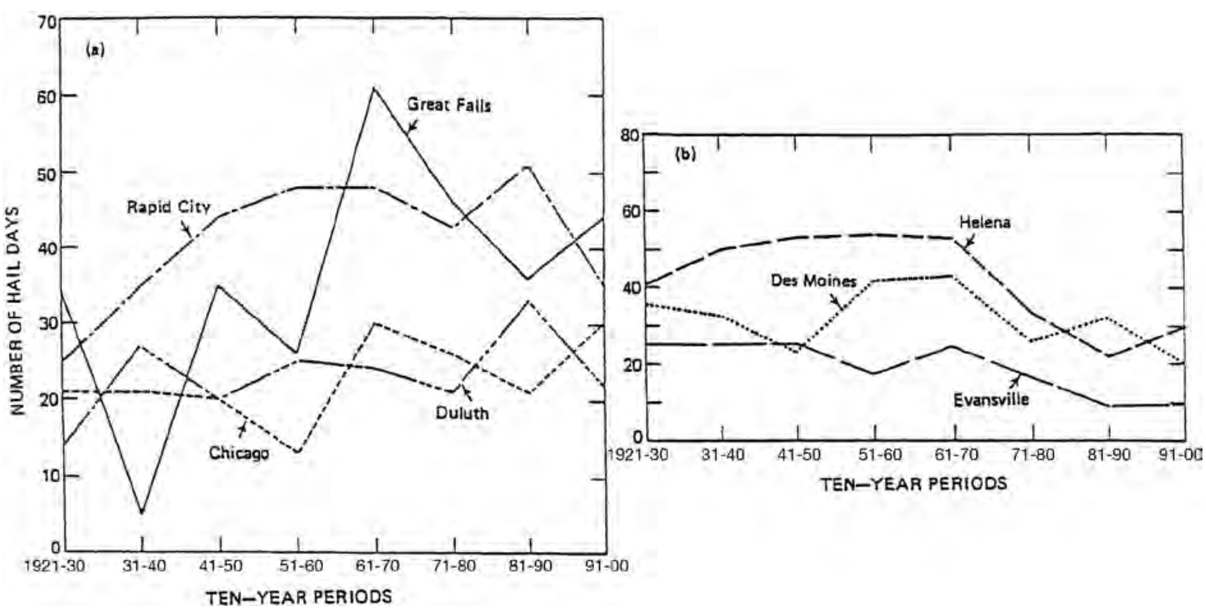


Figure 39. Ten-year frequencies of hail days at seven first-order stations, 1921-2000.

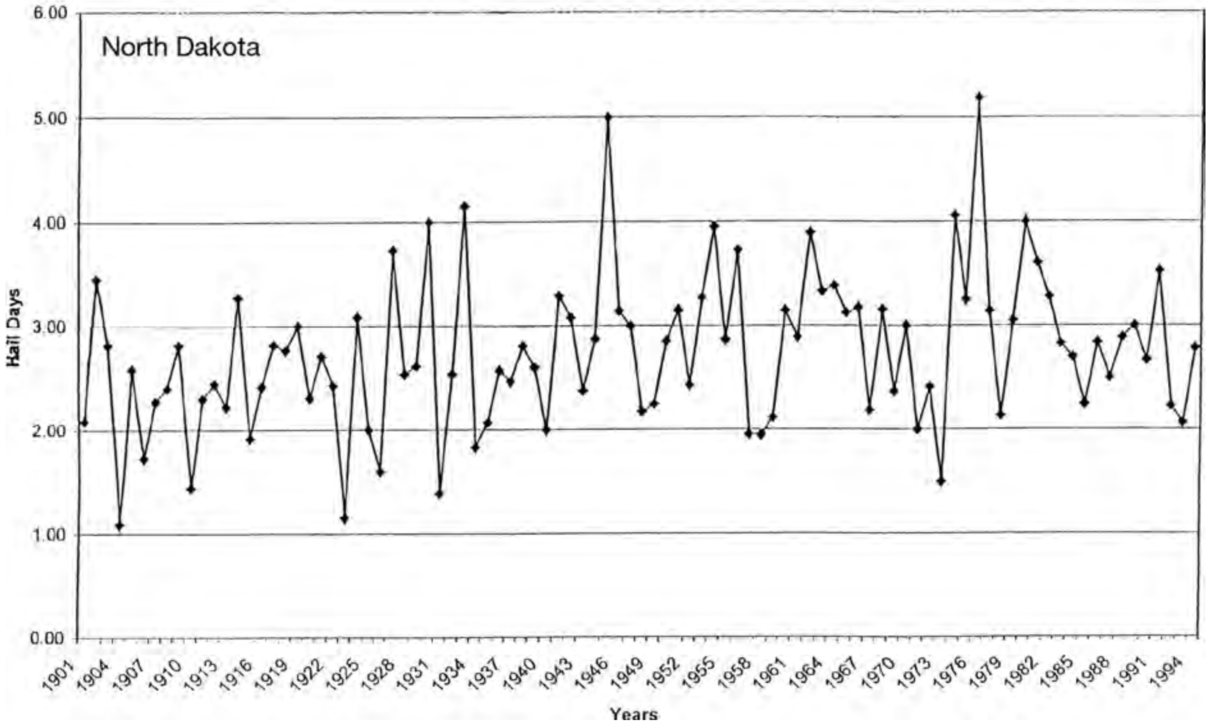


Figure 40. Annual average number of hail days during 1901-1995 in North Dakota (region #7).

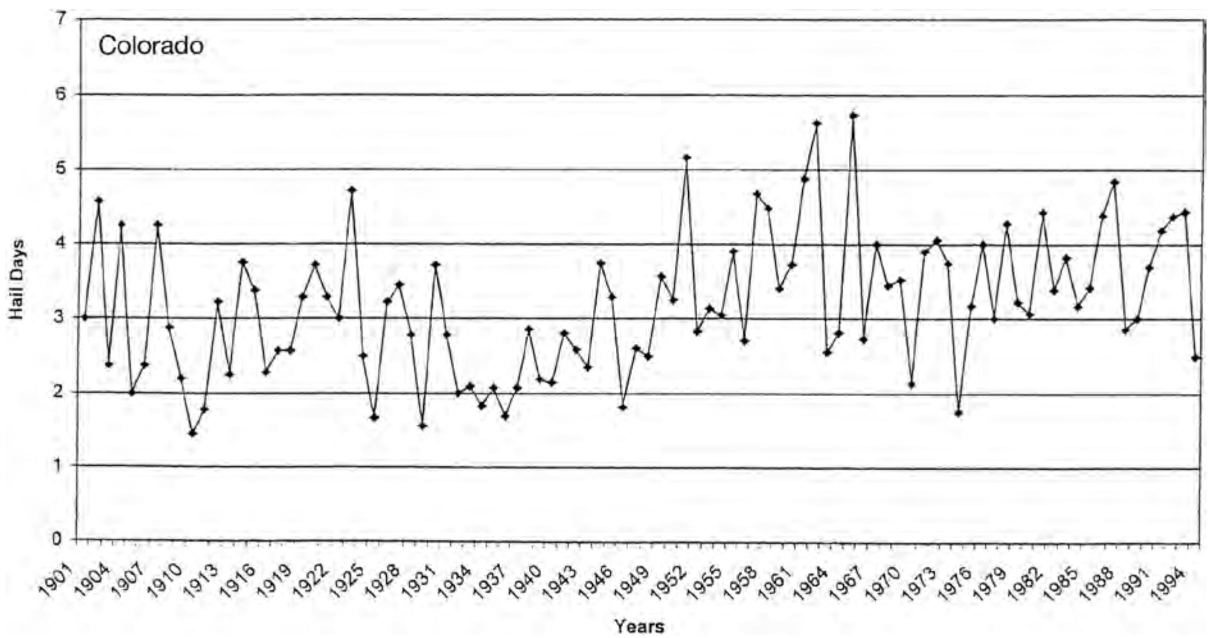


Figure 41. Annual average number of hail days during 1901-1995 in Colorado (regions #5 & 6).

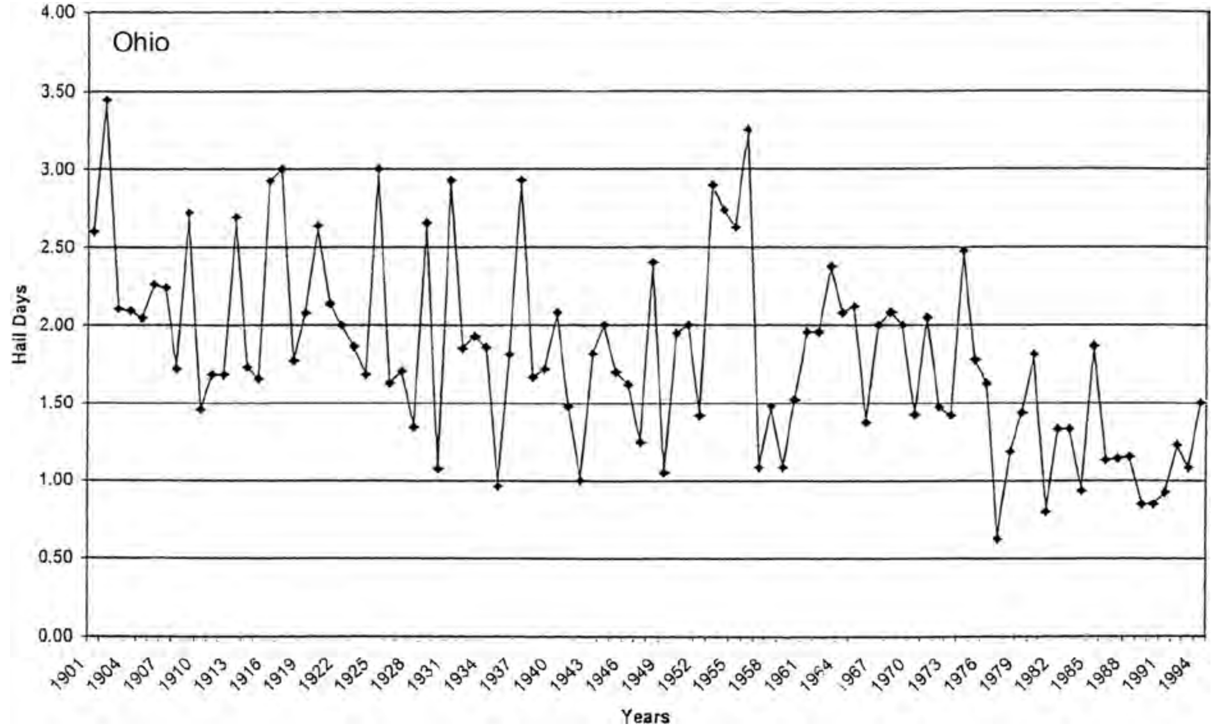


Figure 42. Annual average number of hail days during 1901-1995 in Ohio (region #10).

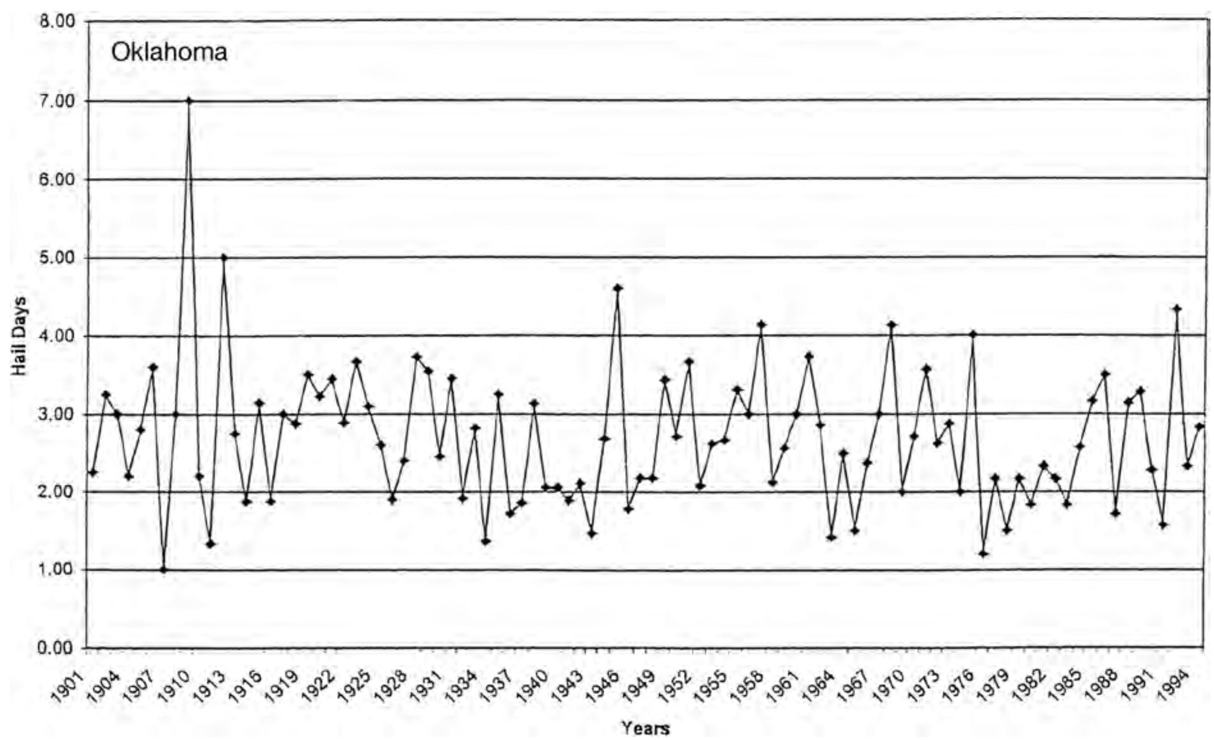


Figure 43. Annual average number of hail days during 1901-1995 in Oklahoma (region #8).

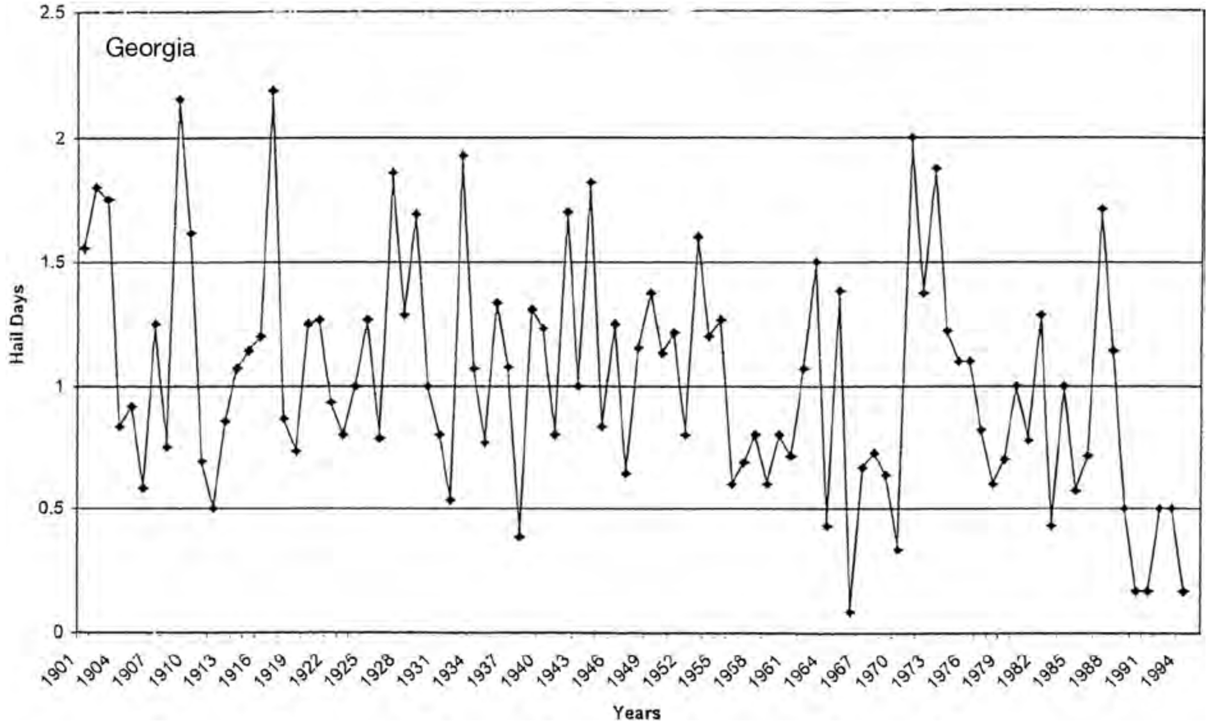


Figure 44. Annual average number of hail days during 1901-1995 in Georgia (region #11).

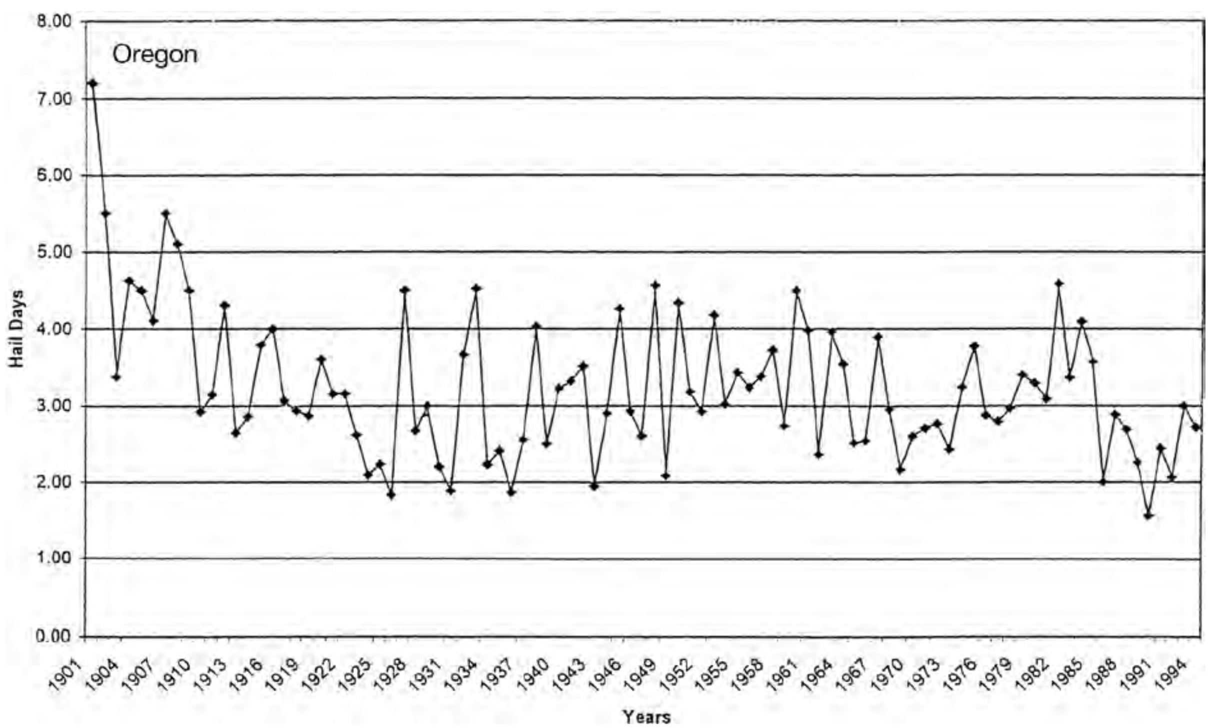


Figure 45. Annual average number of hail days during 1901-1995 in Oregon (regions #1, 3, 5).

fluctuations over time but no temporal trend during 1901-1994. The hail days in Georgia (Figure 44), considered representative of the low hail frequencies of the Southeast, show a slow decline after the 1950s, becoming lowest in the 1990s. The hail days in Oregon (Figure 45), representative of the northwest hail climate, have peaks early in the 20th Century and a flat time trend thereafter.

Figures 46, 47, and 48 are maps of the number of hail days for three decades during 1901-2000 and for the central United States. This is a 17-state area where hail damages and losses are greatest. Hail during 1901-1910 (Figure 46) was more frequent than in any other decade in the 20th Century. Eight states had their highest hail frequencies in this decade, and two very high frequency areas occurred. One ran east from the Wyoming-Colorado area to Lake Michigan, and the other from Kansas to Illinois.

Hail in 1931-1940 was the lowest frequency of all 10 decades, not unexpected since this decade had the nation's greatest drought of the century. A relatively high hail area occurred in the Wisconsin-Michigan area, but hail values were quite low in the Texas-Oklahoma area and in the Nebraska, Missouri, Iowa, and Illinois areas.

Hail during 1981-1990 was moderately frequent, ranking as the second highest decade of the century. Hail incidences were high in the Midwest and lower Great Plains, but relatively low values occurred in the Dakotas and Minnesota.

Table 15 shows the five-year mean values of hail days in seven states during the 1961-1980 period. The highest and lowest values are marked, revealing that the frequency during the 1961-1965 period was the highest in all states, but the lowest values occurred in the various other three pentads. The between-pentad differences are large. Note

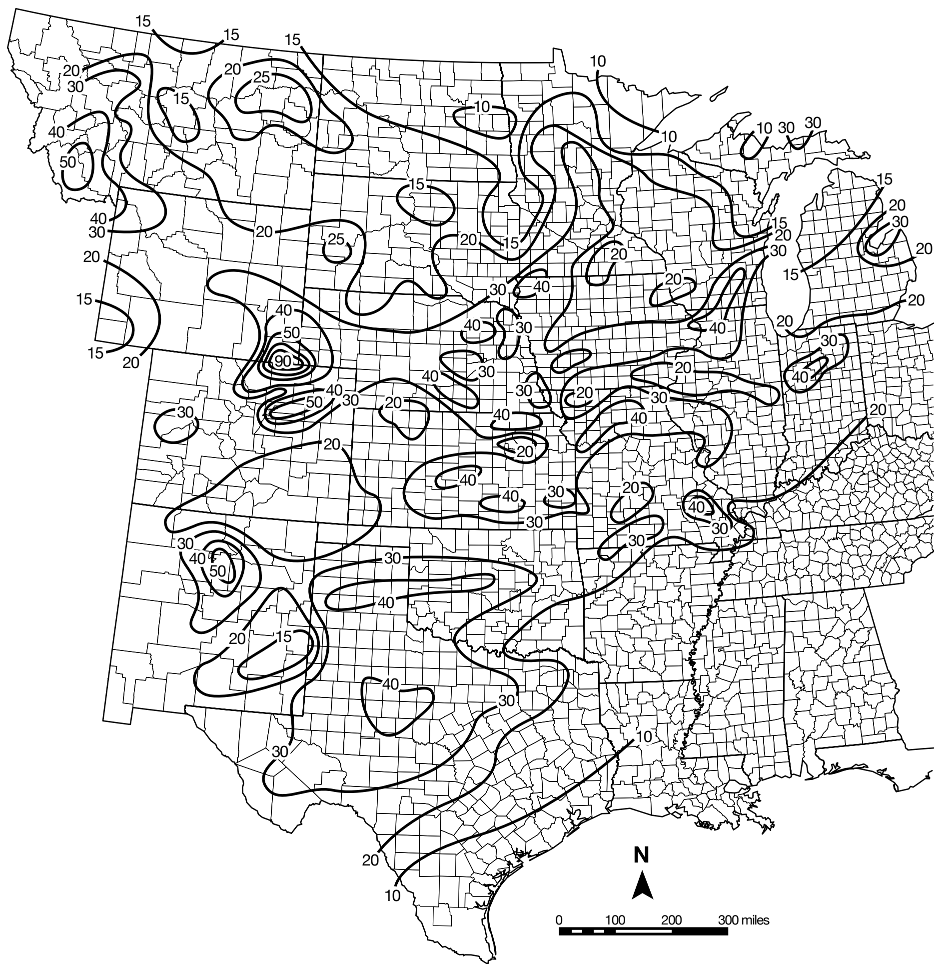


Figure 46. The number of hail days during the 1901-1910 period for 17 states with quality records.

that Illinois and Montana had low five-year values of nine and high five-year values of 14, a difference of five days, which is more than 50 percent of the low value.

The crop-hail insurance industry began a systematic collection of data on hail and wind losses to crops in 1948. These data are based on the crop-hail insurance written in the United States, and for each state (and each crop). The Crop-Hail Insurance Actuarial Association calculated the annual liability, number of premiums, and losses. Loss costs (annual losses divided by annual liability and multiplied by 100) were calculated for each year, and they provide a fair basis for temporal comparisons.

The relationship between summer hail-day temporal frequencies in Illinois (as defined from records of the National Weather Service) and the insurance industry's annual loss costs was assessed. The hypothesis underlying such a relationship was that the number of hail days across Illinois (as reported by the NWS stations) was related to the magnitude of the crop-hail loss. The frequency of NWS hail days for summer (June-August) when 98 percent of all reported crop-hail damage occurs in Illinois (Changnon, 1967b) was chosen for analysis (Changnon, 1995). Measures of the areal frequency of summer hail days were tested against the annual loss cost. The strongest relationship was found to exist between the annual loss cost and the amount of area of Illinois that experienced, in a given summer, hail days matching or exceeding the once in 10-year frequency. That is, the number of hail days expected to occur at a station at least once every 10 years. Statistical analysis was performed involving the 47 values (1948-1994) of annual loss costs (all crops) and the summer values for the percent of Illinois experiencing hail days matching or exceeding the 10-year values, and this yielded

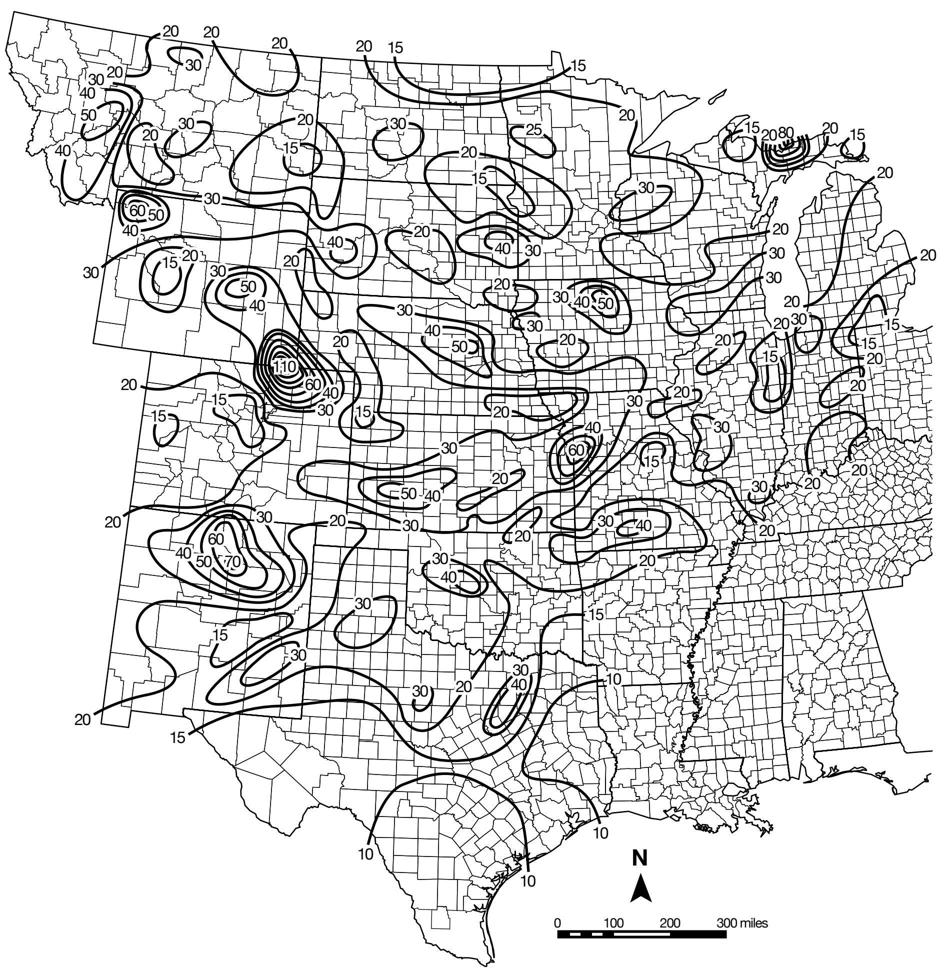


Figure 47. The number of hail days during the 1931-1940 period for 17 states with quality records.

a correlation coefficient of +0.94, indicating an extremely strong relationship.

Similar studies were conducted for Texas and Nebraska involving hail days and annual loss costs for 1958-2004. As in Illinois, good statistical relationships were found between 1) the areal extent of the state with a frequency of hail days equaling or exceeding once in 10-year values, and 2) the annual loss costs. Figures 49 and 50 present the 1958-2004 curves for these two states. The Texas curve shows major highs around 1990 and again in recent years. When the Texas loss costs were exceptionally high (in 1959, 1989, 1992, 1997, 1999, and 2002), the percent of the high liability area of Texas experiencing extreme numbers of hail days was also quite high. The Nebraska hail curves (Figure 50) show a different time distribution, being high in the 1960s and 1970s. The most important findings from these state trend studies are that the areal extent of the

Table 15. State Average Hail-Day Values for 5-year Periods During 1961-1980

State	*1961-65*	*1966-70*	*1971-75*	*1976-80*
Montana	14*	9**	10	11
North Dakota	12*	9**	10	11
South Dakota	15*	13	12**	13
Nebraska	14*	10**	11	12
Iowa	17*	11	9**	11
Minnesota	12*	10	11	9**
Illinois	14*	11	10	9**

** Highest 5-year value*
*** Lowest 5-year value*

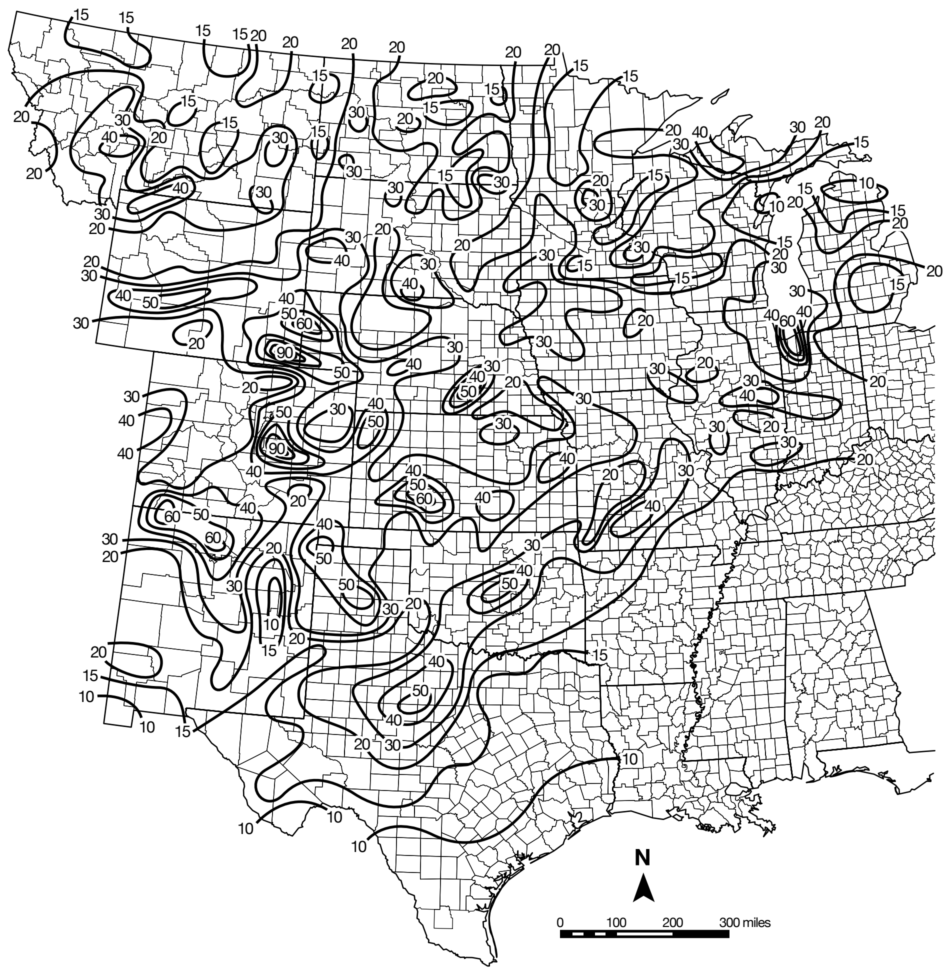


Figure 48. The number of hail days during the 1981-1990 period for 17 states with quality records.

higher frequencies of hail days closely matches the higher insurance-based loss costs. This offers a way to estimate loss functions in areas without a historical record of crop losses.

The national distribution of the average annual number of hail days for 1901-2005 (Figure 51) shows a decline in frequency of days since the 1940s. The highest hail values came during 1936-1950. Values decreased from 2 to 2.5 hail days per year in the 1950s, to 1.5 to 2 hail days in the 1990s. The average was 2.1 days.

Further assessment of the long-term fluctuations and trends in hail days was based on 67 stations in the nation found to have quality hail data for 100 years, 1896-1995. Analysis of the timing of the highest and lowest 20-year values at each station resulted in the distributions shown in Table 16. In each 20-year period, some stations experienced their highest and their lowest 20-year values. However, the values revealed a distinct tendency for the highest values to have occurred in the 1916-1935 or the 1936-1955 period. These two periods accounted for 42 of the 67 highest values. The lowest values were concentrated in the 1976-1995 period. Taken as a measure of the national hail day distributions, the results suggest a peak in the middle part of the century and a decrease thereafter, resulting in low incidences in the most recent years.

Examination of the 20-year distributions at the 67 stations revealed that they defined five types

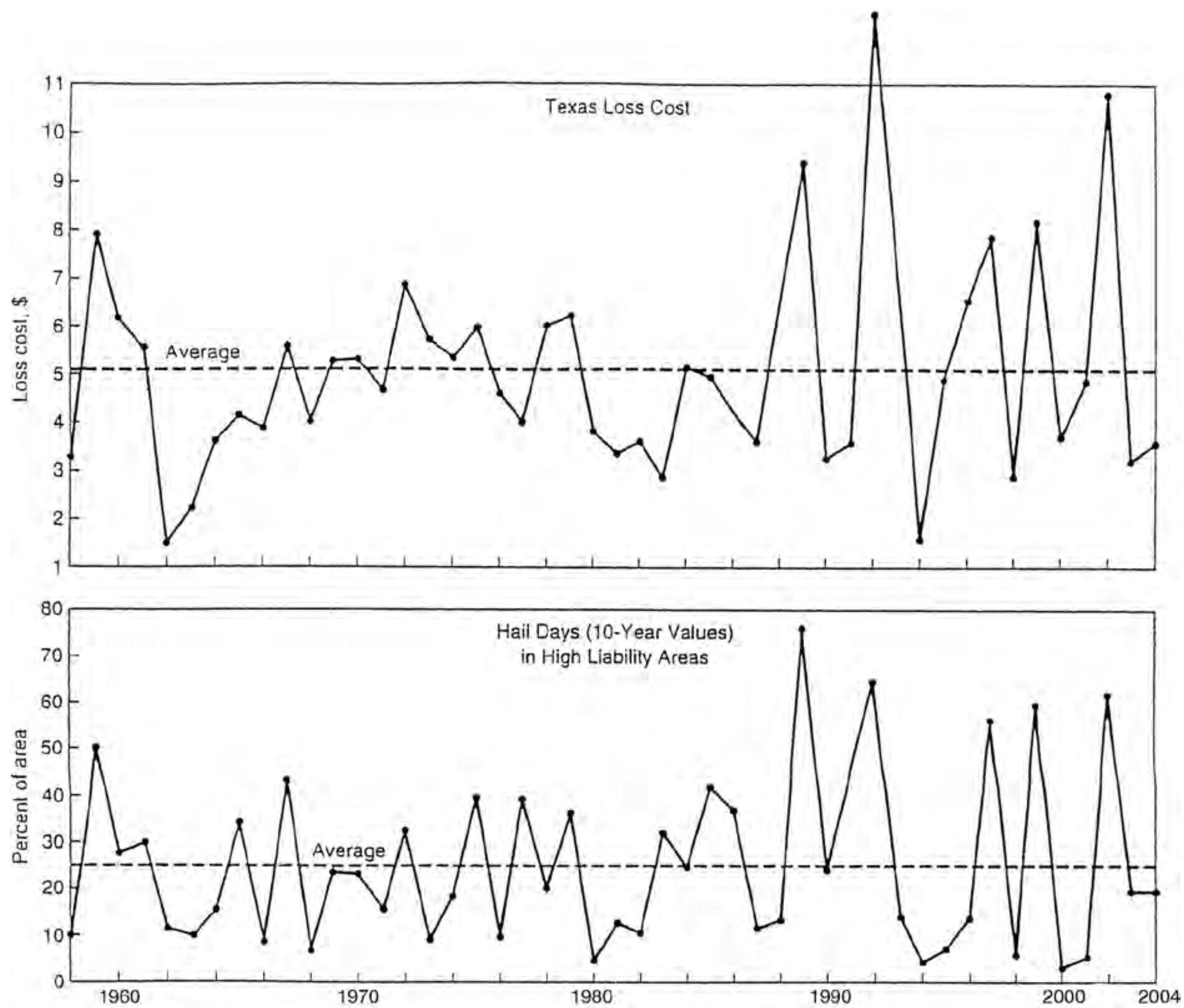


Figure 49. The percent of Texas with high insurance coverage experiencing hail-day values of once in 10-year or greater frequencies (lower curve) for 1958-2004, and the annual crop hail loss cost values for Texas (upper curve).

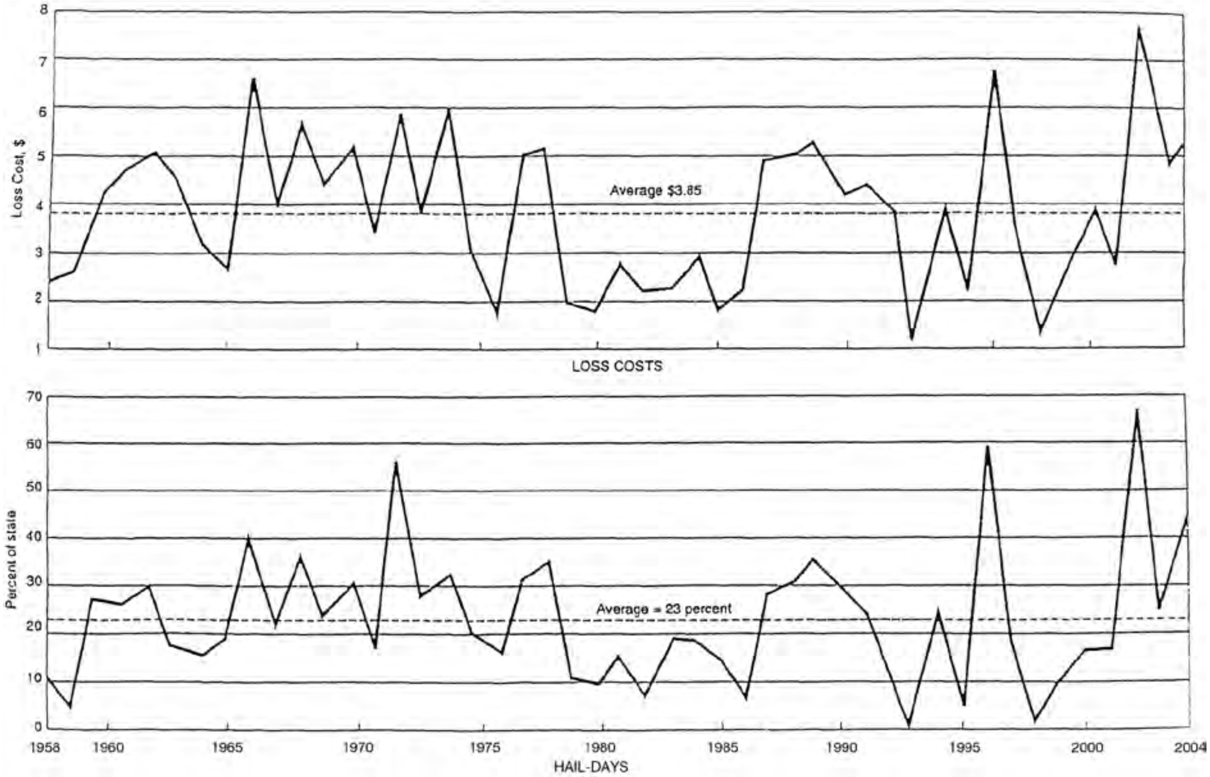


Figure 50. The percent of Nebraska with high insurance coverage experiencing hail-day values of once in 10-year or greater frequencies (lower curve) for 1958-2004, and the annual crop hail loss cost values for Nebraska (upper curve).

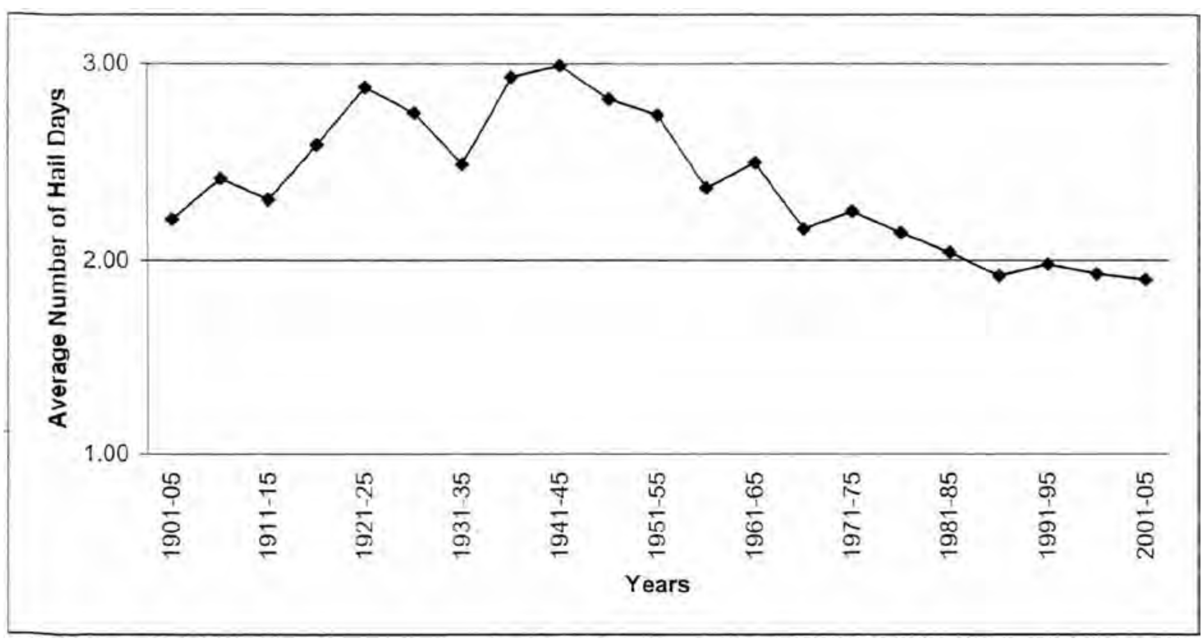


Figure 51. Temporal distribution of annual average hail days in the U.S. for 1901-2005.

of time distributions. The values of the stations in each of these types were used to develop a mean value for each type. The distributions expressed as percentages of the means appear in Figure 52. Each type peaked in a different period. Two were lowest in 1896-1915, and three were lowest in 1976-1995. The types of distributions at each station were plotted on a national map, and analysis revealed several spatially coherent regions (Figure 53). Most of the type 1 distributions were found at 13 stations in the Midwest. The bell-shaped type 2 distribution (Figure 52) was found at 20 stations and these formed three regions. One was along the East Coast, another in the central High Plains, and a third area in the northern Rockies.

The 100-year values of the 67 stations were also used to define linear trends for the 1896-1995 period. This revealed marked differences across the nation, but the trends defined certain large regions, each with different trends. The trends were defined as being upward (statistically significant at the 5 percent level), distinctly downward, or flat. This classification of the trends led to the regional pattern shown in Figure 54. This reveals two regions of upward trends (central area and southeast coast). Two small regions had flat trends, but most of the nation had downward trends.

A national analysis of the hail-day fluctuations based on the 20-year values from all 67 stations resulted in the 100-year curve shown in Figure 55. This shows an increase from early in the century to the highest values in the 1916-1935 and 1936-1955 periods, followed by a decline in hail activity to 1995. A thunderstorm-day distribution based on the same stations is in Figure 55, and it shows a peak in 1916-1935 and a low in 1976-1995. Thus, the distributions are similar, supporting the reality of the hail distribution.

Table 16. The Number of Times the Highest and Lowest 20-year Hail Day Values at 67 Stations Occurred During 1896-1995

Period	*Highest value*	*Lowest value*
1896-1915	7	18
1916-1935	20	1
1936-1955	24	1
1956-1975	10	1
1976-1995	6	42

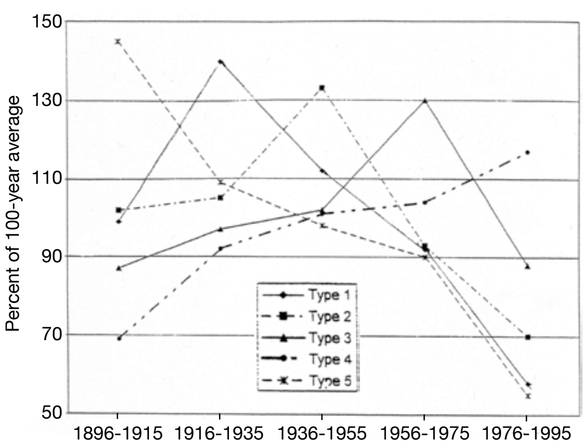


Figure 52. Distributions of hail days in the nation during 1896-1995 fell into five classes, with 20- year frequencies expressed as a percent of the 100-year total.

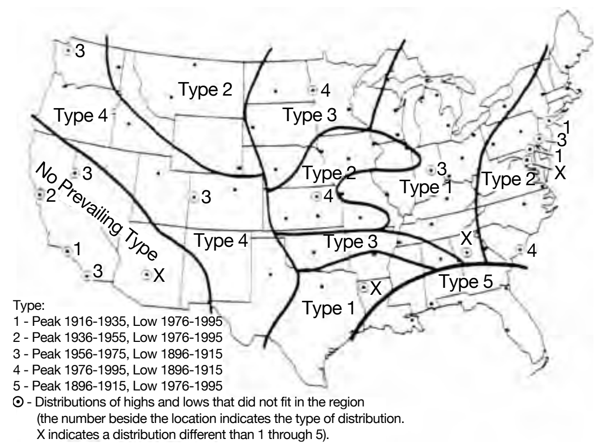


Figure 53. Regions based on the five different types of temporal distributions of hail days during 1896-1995, as depicted in Figure 52.

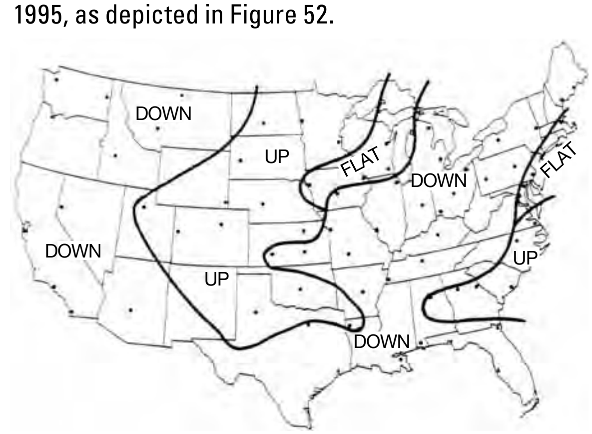


Figure 54. Regions defined by the 100-year linear trends of hail days during 1896-1995.

Another temporal measure of hail is the time of day when hail occurs. Assessment of first-order NWS station data across the nation shows that the occurrence of hail is most likely during the afternoon and is least likely late at night and in the morning. The temporal distribution of hail occurrences reflects the timing of convective instability, and the three-hour values expressed as a percentage of the total events during 1950-1997, is as follows:

Hours, local standard time	*Percent of total hail events*
00-03	12
03-06	3
06-09	2
09-12	5
12-15	12
15-18	38
18-21	15
21-00	13

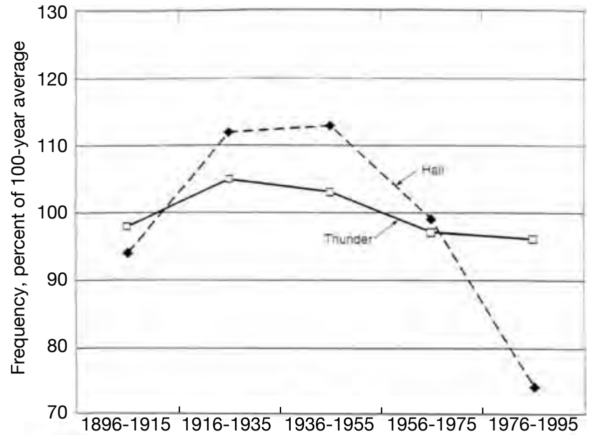


Figure 55. The 100-year distributions of hail days and thunder days for the nation, each expressed as a percentage of the 100-year averages.

Hailstone dents in the metal cover of an outside light at a farm home in Kansas.

15. Temporal Distribution of Catastrophes

The time distributions of various types of hail catastrophes were assessed. The top three losses experienced from hail-only events (in millions of 2006 dollars) were $1,500, $905, and $835. The time distributions of the 10 highest hail-only loss events during 1949-2006 show that five came in early years, 1953-1970, and five in recent years, 1992-2006.

Figure 56a shows the time distribution of hail-only catastrophes during 1949-2006, revealing major peaks in activity in the 1961-1971 period and in the 1979-1981 period. The lowest values were largely in recent years, those since 1995. The annual average is 3.5 events with a maximum of 11 catastrophes in 1962, 1968, and 1980, and none in five years. The annual losses of hail-only events (Figure 56b) peaked in 1961-1968, with generally low values in most other years. The annual average losses were $307 million with a one-year peak of $1,707 million (1962) and none in five years. Losses were not high in 1980 when events were frequent, and all 11 events in 1980 had low losses of $1 to $5 million. Losses peaked in 2002 due to one storm causing $465 million in losses. The temporal trend

A thunderstorm soon to be producing hail is seen over central Illinois.

of the number of hail catastrophes (Figure 56a) is downward over time.

The catastrophes caused by hail and tornadoes occurring together during 1949-2006 (Figure 57a) show a major mid-period maximum centered in the 1970s, but none in losses. Most events in 1971-1981 had low losses. Values in 1949-1965 are low, 5 or less per year, and low values also predominated in the 1995-2006 period. The linear trend for the 58-year period is flat (Figure 57a). The annual average number is 6.2 catastrophes with a peak of 19 (1973) and none in four years.

The time distribution of annual losses of hail plus tornado events (Figure 57b) does not resemble the frequency distribution. The annual average losses were $690 million with a peak value of $3,620 million in 2006 when four major catastrophes had sizable losses. The 58-year distribution shows high losses came in 1953, 1974, and 2006, whereas most other annual values fluctuated between $500 and $700 million. The loss distribution for 1949-2006 has a flat linear time trend.

The temporal distribution of catastrophes resulting from hail plus tornadoes and flooding (Figure 58) shows low values from 1949 to 1974, then ever increasing values, peaking during the 2000-2006 period. The 1949-2006 distribution has a statistically significant (0.1 level) upward trend, and reflects an increase in floods (Changnon and Kunkel, 1995; Pielke and Downton, 2000). Losses also increased with time. These flood increases resulted from an increase in annual precipitation since mid-century (Karl and Knight, 1998) and in heavy rain events (Kunkel et al., 1999), and from rapidly expanding urban areas that increased vulnerability to flood damages (Changnon et al., 2000).

In summary, the temporal distribution of hail-only catastrophes during 1949-2006 revealed considerable interannual variability. Typically, a few years had high frequencies, whereas most years had low incidences. As a result, annual losses from hail catastrophes also had great temporal variability. Hail-only catastrophe losses peaked during 1961-1967 with $1.7 billion in 1962, and no losses occurred in five years.

The 58-year time trends for the number of catastrophes, and for losses of all types of hail catastrophes showed no upward trends with

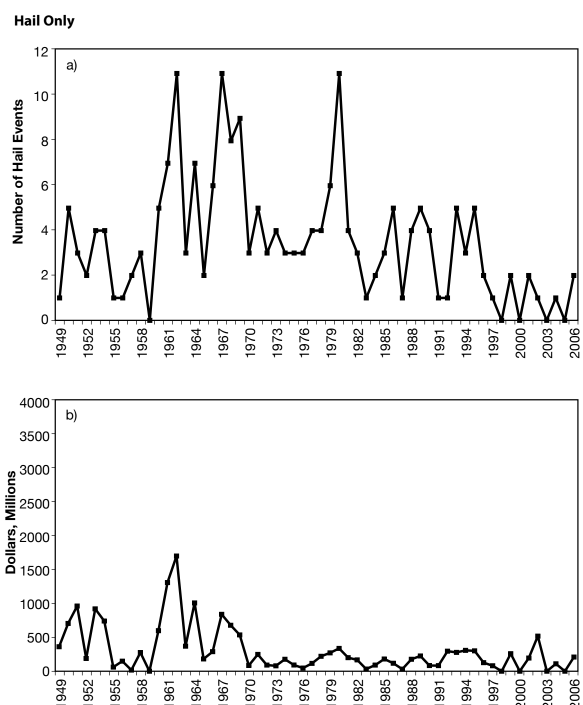


Figure 56. The national temporal distributions of hail-only catastrophic events (a), and their losses (b) during 1949-2006.

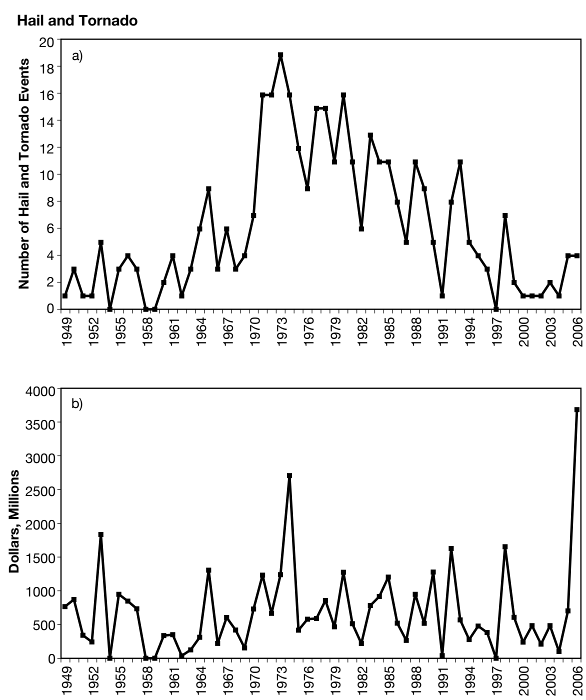


Figure 57. The national temporal distributions of hail with tornado catastrophic events (a), and their losses (b) during 1949-2006.

time. Hail-only catastrophes and their losses had downward time trends, and are not suggestive of increases that some predict to be related to global climate change. The hail plus tornado catastrophes had flat time trends. The hail, tornado, and flood catastrophes had upward time trends, which were due to increases in flooding resulting from upward time trends in heavy rains.

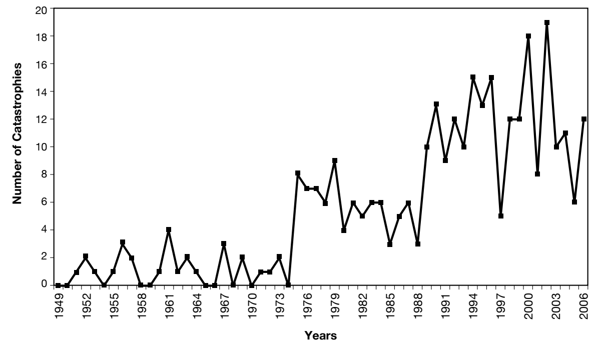


Figure 58. The national temporal distribution of catastrophic events caused by hail, tornadoes, and flooding events during 1949-2006.

16. Major Storms

Two recent hailstorms caused massive property damages, rated as the highest and second highest losses on record since 1949. The most costly storm on record resulted from a series of very severe hailstorms in the central Midwest during a 30-hour period on April 13-14, 2006. It resulted in property losses of $1.822 billion, a new record high hail loss for the nation (Changnon, 2009). The April 2006 hail loss total was also the largest catastrophe loss in the U.S. during 2006 (Property Claims Service, 2006). The second most damaging hailstorm on record occurred in April 2001, creating $1.5 billion in property losses in a three-state area. These and other recent high hail loss events serve as indicators of a strong upward trend in national hail losses.

DIMENSIONS AND LOSSES OF WORST STORM

An unseasonably warm, moist air mass spread over the Midwest on April 13 and 14, 2006. A cold front advanced into the four-state area on April 13, becoming stationary, making the warm air unstable with Lifted Indices in the -5 to -8 range, and CAPE values reached 3500 in the late afternoon. This quickly led to severe thunderstorm developments. An upper-level disturbance combined with a strong low-level jet of 55 knots further enhanced the low-level instability; this plus strong vertical wind shear led to the development of long-lasting supercell thunderstorms that produced large, widespread hail. This unique instability persisted across the Midwest for nearly 30 hours. It led to the development of three large areas of hailstorms, and the resulting storm zones lasted for five to seven hours, each moving more than 200 miles. Figure 59 shows these three large hailswath areas labeled A, B, and C.

Hailswath A began at 1650 LST on April 13 in Iowa, and extended eastward 368 miles, ending in the Milwaukee area. Its width over time ranged from 16 to 35 miles. Radar and surface reports indicated the hail area was created by seven hailstorms. The storms produced considerable hail damage in Madison and Milwaukee, Wisconsin.

Hailswath B began in Iowa at 1815 LST on April 13 and extended to the east-southeast for 323 miles, ending on April 14th in eastern Illinois. Its widths varied from 14 to 39 miles, and during its 6.5-hour lifetime it contained 11 hailstorms. The storms produced considerable hail damage in Iowa City and Cedar Rapids, Iowa, and in the metropolitan areas of Moline, Rock Island, and Peoria, Illinois.

Hailswath C began at 1845 LST on April 14 along the Illinois-Indiana boundary and moved southeast for 221 miles before ending at the Indiana-Ohio boundary (Figure 59). It had varying widths along its path, ranging from 14 to 29 miles, and it consisted of 10 separate hailstorms during its five-hour lifetime. It created major property damages in the Indianapolis metropolitan area.

These three long and wide hailswaths on April 13-14 exceeded average sizes of hailswaths. Historical data show that hailswaths typically have lengths ranging from 48 to 225 miles and widths ranging from 3 to 12 miles (Changnon, 1977).

Figure 59 also shows that there were 10 other smaller hailswaths on April 13-14. Some were single hailstorms and some consisted of two or three hailstorms (hailswaths # 2, 5, 11, and 12). Hailswaths #2, 4, and 12 caused major damages to Chicago and its suburbs. An important aspect of most hailstorms was the production of large hailstones. More than 390 locations reported damaging hail and 286 had hailstones with diameters of 1 to 2 inches. Hailstones with diameters of 3 inches also fell in Illinois at 19 locales. In contrast, the average Midwestern hailstone size is 0.3 inch.

Data on insured property losses in each state revealed 404,000 claims of hail damage. The losses in each state and the types of property damaged are shown in Table 17. This reveals that Indiana, with losses totaling $684 million, had the greatest loss, followed closely by Illinois with $648 million. Personal property (homes) suffered the greatest losses in all four states. The major losses occurred in three large metropolitan areas: Chicago, Indianapolis, and Milwaukee.

DIMENSIONS AND LOSSES OF SECOND WORST STORM

On April 10, 2001, a strong, long-lasting thunderstorm produced numerous hailstreaks that caused major property damages. This record large storm began in Kansas, and ended its west-to-east trek eight hours later in Illinois with large hailstones all along a swath 388 miles long. The insured property losses of this "Tri-State Hailstorm" amounted to $1.5 billion (Changnon and Burroughs, 2003).

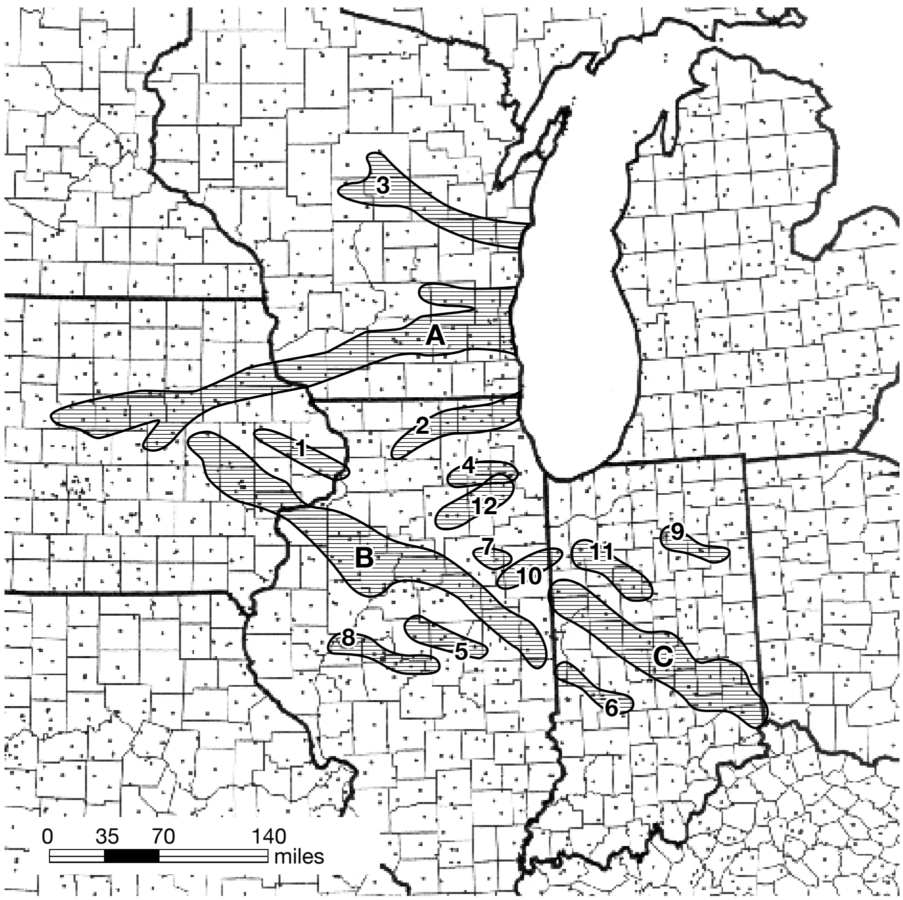


Figure 59. The hailswaths that occurred in the Midwest on April 13-14, 2006.

Table 17. Insured Property Losses from Hail on April 13-14, 2006, Showing Losses for Various Types of Property and for Each State. Amounts are in Millions of 2007 Dollars

Type of property	*Indiana*	*Wisconsin*	*Iowa*	*Illinois*	*Total*
Personal	374	300	37	301	1,012
Commercial	130	50	21	160	361
Vehicles	180	70	12	187	449
Total	**684**	**420**	**70**	**648**	**1,822**

This storm was part of a two-day period when other damaging hailstorms occurred in Nebraska, Oklahoma, Ohio, Indiana, and Iowa, with losses totaling $1.9 billion. This ranked as the ninth most damaging weather catastrophe in the U.S. for the entire 1949-2001 period.

The hail-generating thunderstorm was a long-lived supercell. The first large hail fell 42 miles southwest of Kansas City (Figure 60). In the ensuing eight hours, the supercell storm produced numerous hailstreaks before the hail ended near Effingham, Illinois. The result was a swath of hail that ranged from 9 to 25 miles wide. The 388-mile length of the hailswath exceeded anything previously documented from studies of hail in the High Plains and Midwest (Frisby, 1963; Changnon, 1977). The numerous locations where hailstones of 1 inch or larger in diameter fell are shown in Figure 60. Many locales reported high winds with the large hail, adding to the damage.

Three factors were the cause of the enormous property damage produced by the Tri-State Hailstorm. First was the enormous size of the hailswath. Second was the near continuous production of hailstones ranging in size from 1 to 3 inches, and often associated with high winds. Third was the fact that hail fell over the south suburbs of Kansas City, over portions of Columbia, Missouri, and across the northern portions of the St. Louis metropolitan area. Principal damages were to residences, buildings, and vehicles. Primary targets for the structural damage were windows, roofs, siding, and skylights. Twenty-four jet aircraft at Lambert Field in St. Louis were badly damaged by the hail, and 67 flights were cancelled for up to 24 hours.

MAJOR HAILSTORM LOSSES SINCE 1950

Property damages in major storms often occur when hailstones are 2 inches or larger. Figure 61 shows the temporal differences in the occurrences of 2-inch stones for various regions in the nation. For example, Area #6 expects 2-inch hailstones in a 1,000-square mile area anywhere in the region once every two years, whereas Area #1 expects one only once every 41 years or more. The areas depicted in Figure 61 are a good measure of the risk of property damages from hail.

The 10 largest hail-caused property losses in the United States during 1951-2006 are listed in Table 18. Inspection of the dates of the nation's top ten hail loss events reveals seven occurred during the recent 21-year period, 1986-2006. Figure 62 shows the temporal distribution of the top 10 events and the loss amounts of each. This distribution indicates a major increase in major hail loss events with time and in their losses over time. The top three losses occurred in the 1995-2006 period and two more in 1992. The third ranked event on May 5-6, 1995, created massive losses in Ft. Worth, Texas, with damaging hail extending over 400 square miles. It too was the result of supercell thunderstorms (Hill, 1996). The April 1992 event created

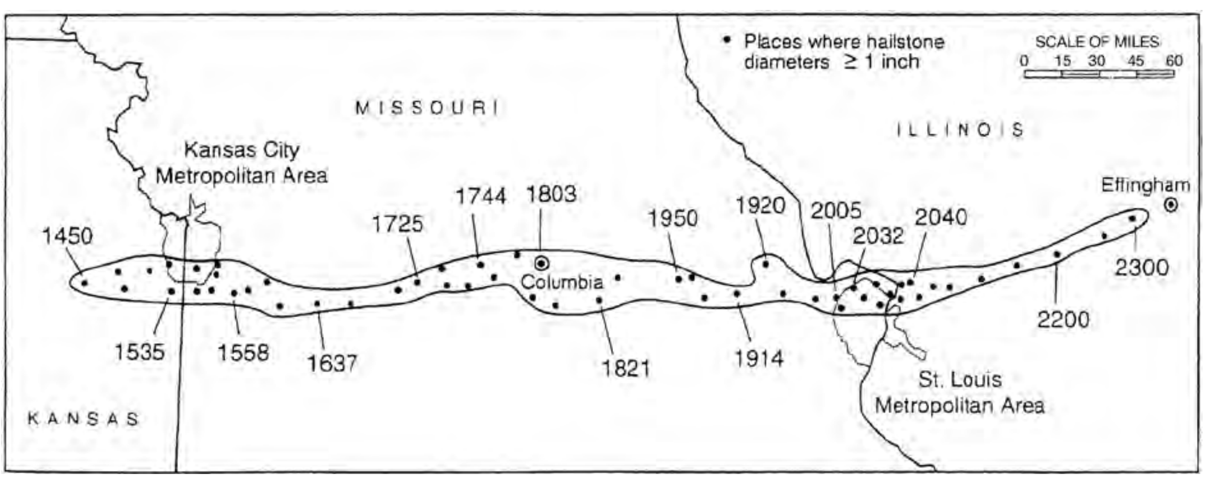


Figure 60. The hailswath of the nation's second most damaging storm since 1949, which occurred on April 10, 2001. Times of hail are LST, and locations with hailstones >1 inch in diameter are shown as dots.

major losses greater than $420 million in Wichita, Kansas (Changnon and Burroughs, 2003).

SUMMARY

Insured property losses in the Midwest due to hail on April 13-14, 2006, totaled $1.8 billion, an amount considerably more than the previous record of $1.5 billion set by the April 2001 hail event. The huge losses during a 30-hour period in April 2006 were largely due to multiple severe storms with frequent large hail. The excessive storm losses occurred because of the damages in the metropolitan areas of Chicago, Indianapolis, and Milwaukee. A highly unstable air mass that developed on April 13 led to a large number of hailstorms in a relatively small region, and several supercell storms formed and produced large hailswaths across portions of Illinois, Indiana, Iowa, and Wisconsin.

Assessment of the 10 greatest property hail losses in the nation reveals an increase over time in frequency and losses with most major events occurring since 1990 (Figure 62). Two factors appear to have affected this increase (Changnon, 1999b). First, is the more frequent occurrence of cases of strong atmospheric instability, leading to the development of supercell thunderstorms capable of persisting for many hours, covering large areas, and producing large hailstones. Second, the expansion of the nation's metropolitan areas has greatly enhanced the target for hail damages to property.

Table 18. Ten Highest Insured Property Losses from Hail Catastrophes during 1951-2006. (Loss Values are in 2007 Dollars)

Rank	*Date*	*Loss, $ millions*	*States with losses*
1	4/13-14/06	1,822	IL, IN, IA, WI
2	4/10/01	1,515	IL, KS, MO
3	5/5-6/95	905	NM, TX
4	4/11/87	835	IL, IN, OH, WI
5	4/28/92	828	TX, OK
6	6/21/53	656	KS
7	6/19-20/92	621	OK, KS
8	8/24/86	611	IL, IN, OH
9	6/8/63	582	MI, OH
10	5/11/70	538	TX

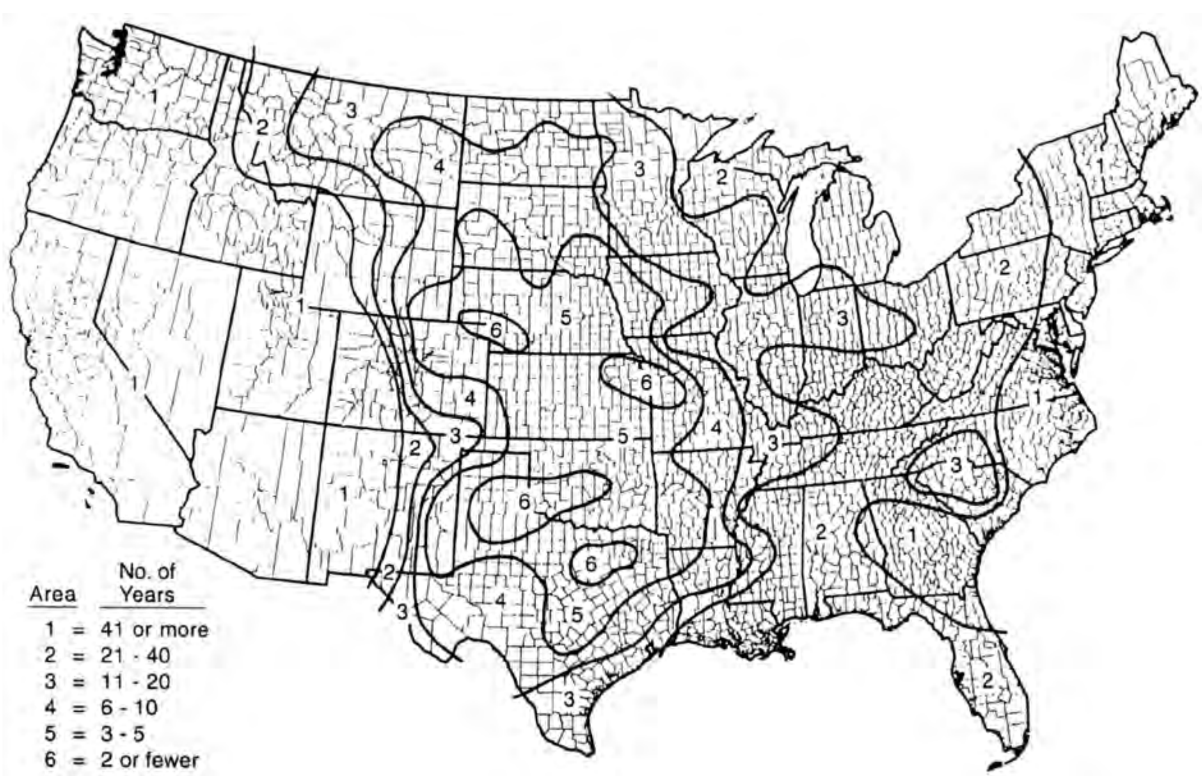


Figure 61. The average number of years between occurrences of hailstones 2 inches or larger within an area of 1,000 square miles in the six areas shown.

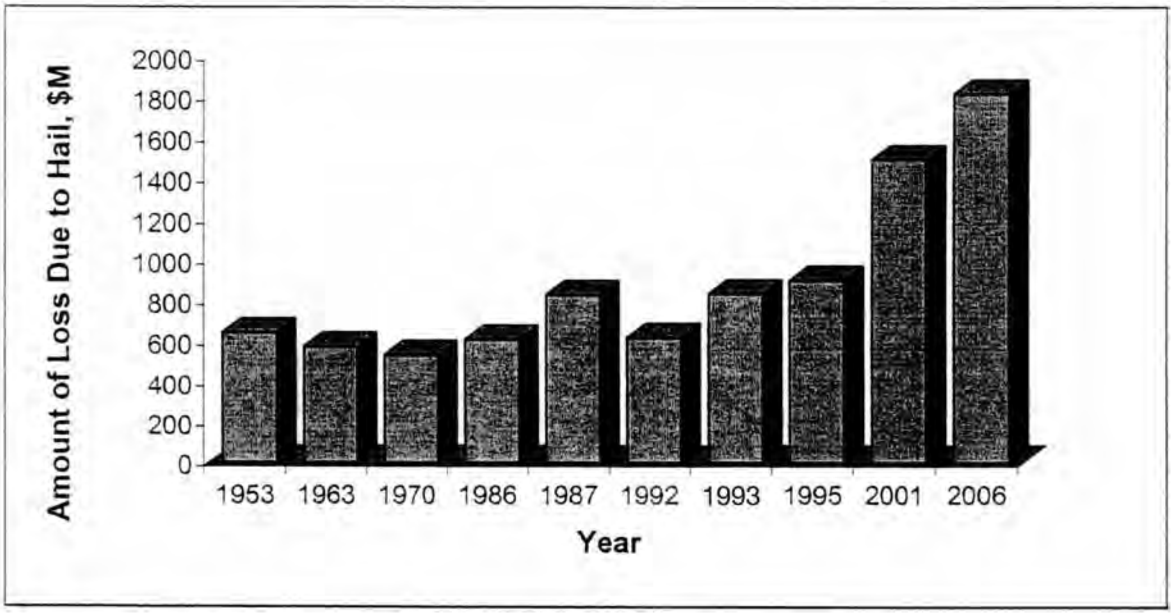


Figure 62. The hail catastrophes causing the 10 highest losses ($ millions) in the nation during 1949-2006 (2006 dollars).

Fog has developed over an area with deep hail that is melting and providing moisture to the atmosphere and lowering temperatures.

17. Temporal Distribution of Hail Losses

Crop-hail loss data are a source of information for examining historical fluctuations in storms since 1948. The national crop-hail loss data for each year since 1948 (Figure 63) were used to create a curve based on annual loss costs for 1948-2008 (National Crop Insurance Services, 2009). Loss cost values (annual loss divided by annual liability and multiplied by 100), which are the best measure for time-series analyses, were relatively high during the 1953-1964 period, and thereafter slowly declined. Singularly high loss cost values occurred in 1980 and again in 1992-1994. The 61-year average loss cost was $2.25, and the coefficient of variation was 0.20.

The nation's annual loss costs for 1948-1994 were ranked and five rank classes were developed (the upper 20 percent, 21 to 40 percent, etc.). Their positions in time were assessed as shown in Table 19. The resulting distributions with time reveal two salient facts. First, most of the higher ranked loss costs (in the top 20 percent and 21-40 percent classes) occurred during 1954-1967. That is, 11 of the 18 top-ranked years occurred in this 14-year period. Second, most of the lowest ranked annual loss costs (in the lowest 20 percent class) occurred during the past 13 years when 6 of the 11 lowest values occurred. The preceding 1968-1981 period had 5 of the 9 values in the next to lowest category, the 61 to 80 percent rank level.

Table 19. The Distribution of Loss Costs, Based on Ranks Which Were Separated into Five 20-Percent Classes, During the 1948-1994 Period

Period	*Top 20%*	*21-40%*	*41-60%*	*61-80%*	*Lowest 20%*
1948-1953	0	1	3	1	1
1954-1960	3	3	0	1	0
1961-1967	3	2	1	1	0
1968-1974	0	1	1	3	0
1975-1981	1	0	2	2	2
1982-1988	0	1	1	1	4
1989-1994	2	1	1	0	2

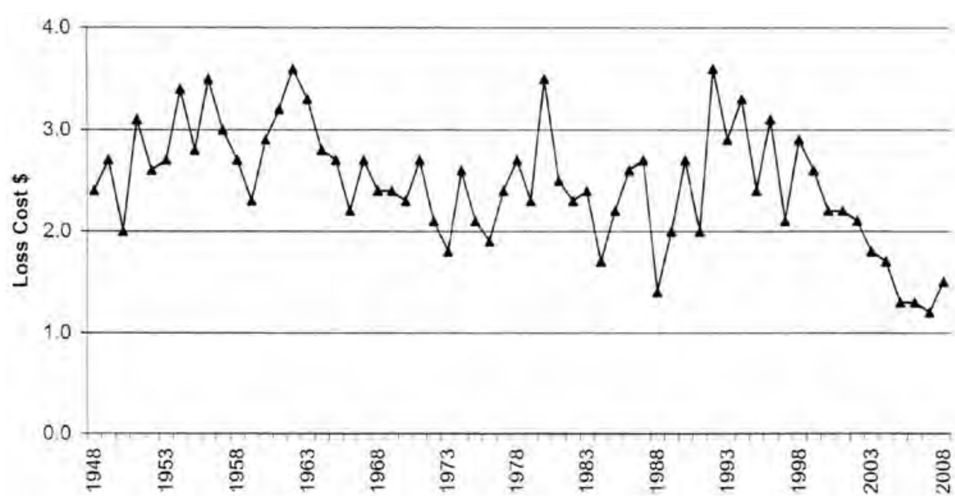


Figure 63. The nation's annual crop-hail loss cost values for 1948-2008.

Assessment of the national crop-hail loss distribution during the 1948-2008 period (Figure 63) reveals that loss costs in 1992-1994 were relatively high. The value for 1992 was $3.79, the highest annual value during the 1948-1994 period. The 1994 value of $3.24 ranked seventh highest, and the 1993 value of $2.83 ranked 14th. Their magnitudes seemed even higher because the loss costs in the preceding 12 years (1981-1991) were unusually low. The incidence of three-year periods of high loss costs matching those of 1992-1994 were assessed, and two comparable periods occurred in the preceding 44 years. The 1992-1994 average loss cost was $3.25. The 1954-1956 average loss cost was $3.27, slightly higher, and the 1961-1963 average loss cost was $3.38, 4 percent higher than 1992-1994.

The temporal variations in the annual loss cost values averaged for the six states in the Great Plains (ND, SD, NE, KS, OK, and TX) appear in Figure 64. The averages and standard deviation values fluctuate in the same directions. The 1993 value is a record high, a very stormy year with record flooding in the Midwest.

The temporal distributions of the annual values of the crop-hail loss cost and liability for 1948-1994 in eight states are shown in Figures 65 and 66. Comparison of their distributions reveals they are considerably different, as illustrated by the dissimilarities between curves of adjacent states, Kansas and Nebraska (Figure 65). Of great importance to the insurance industry is the time distribution and magnitude of losses over time. All state values show a marked tendency for multi-year runs of low values punctuated by occasional single or multi-year periods of high loss costs. For example, Iowa's annual loss cost values (Figure 66) were low from 1948 to 1956 when a high value occurred, followed by a 10-year run of low loss years until highs came in 1968-1970. These high losses were followed by low values for seven years until highs occurred in 1978 and again in 1980, followed by low loss costs from 1982 to 1994. Between 65 and 80 percent of the years have low loss costs, and between 10 and 15 percent of the years have high loss costs.

This type of distribution in losses is also apparent in smaller-sized areas. Figure 67 shows the temporal distributions in crop-hail losses for areas of about 1,000 square miles in Colorado, Illinois, and Texas. There are infrequent big loss years (1979 and 1989) in the Texas area, but the other 28 years sampled had low loss costs. *The time distributions of crop-hail losses, for counties up to state scales, are very skewed.*

Linear trends were fit to the 47 years (1948-1994) of loss cost values of the nation's 25 leading crop-loss states, based on a regression analysis for each state. Examination of the trends indicated three general regions, each with similar trends: 1) the states in the High Plains and mountains (except for Kansas) had flat trends; 2) the Midwestern states, including Kentucky and Tennessee, had downward

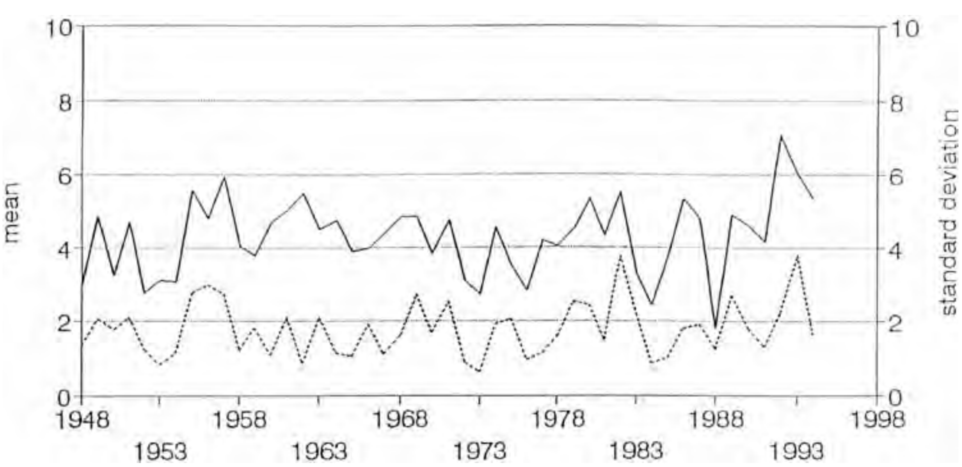


Figure 64. The mean annual crop-hail loss costs (solid line) and their standard deviations (dashed line) for the Great Plains (data from ND, SD, NE, KS, OK, and TX) during 1948-1994.

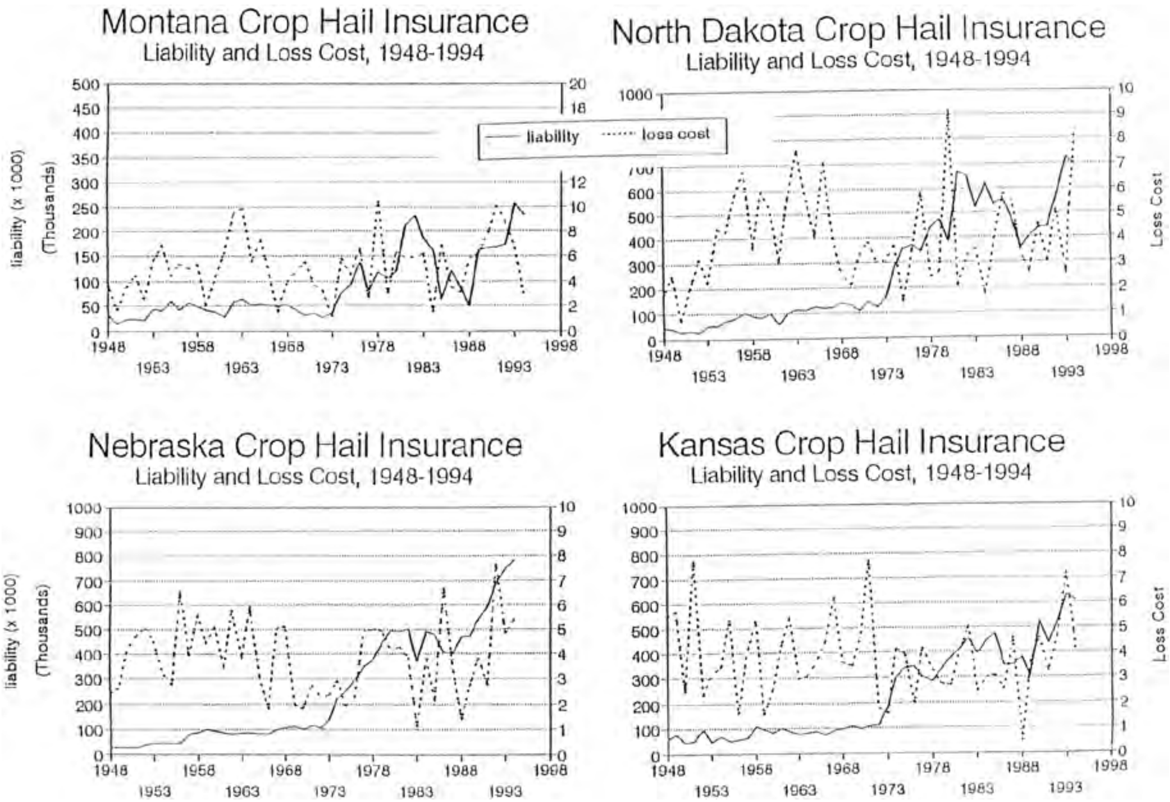


Figure 65. Temporal changes in annual loss costs and liability values for states in the High Plains, 1948-1994.

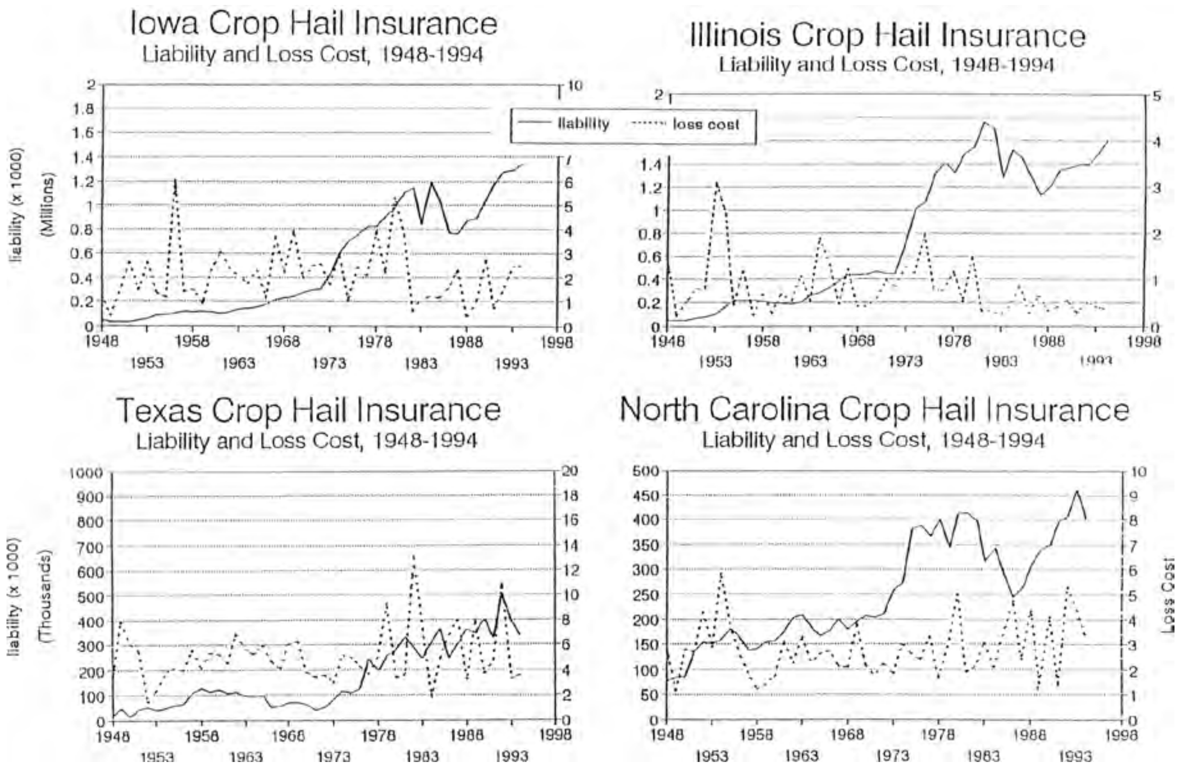


Figure 66. Temporal changes in annual loss costs and liability values for two Midwestern states, Texas, and North Carolina for 1948-1994.

trends in their loss costs; and 3) the southeastern states had upward trends with time.

CLIMATE CHANGE AND HAIL

Recent assessments of a change in climate resulting from global warming, which is an ongoing process, indicate that global warming will lead to more severe storms in North America (Kunkel, et al., 2008; Working Group 1, 2007). The temporal distributions of hail days, property-hail damage events, and crop-hail events and losses during the 1950-2006 period have been presented and are summarized here.

Assessment of hail days during 1950-2004 in several states (Figures 40-45) show no up or down trends over time. In parts of the U.S., including the Southeast, hail days have been increasing, but they have been decreasing over time in most of the eastern parts of the nation. The national frequency of hail days (Figure 51) shows a downward trend over time.

The temporal distribution of property loss catastrophic events (causing losses >$1 million) due to hail during the 1949-2006 period has a flat trend (Changnon, 2008a). Property losses also show a flat trend over time (Figure 56). However, 5 of the nation's 10 most damaging hail events since 1950 occurred during 1992-2006 (Changnon, 2009).

Crop losses due to hail during 1949-2004 also did not show a major up or down trend. The annual number of days with crop-hail losses had a flat time trend over the past 50 years, and the annual amounts of crop-hail losses also had a flat trend (Figure 63).

Thus, the temporal distributions of various hail events and losses do not show upward trends into the 21st Century and do not support an expected outcome of climate change.

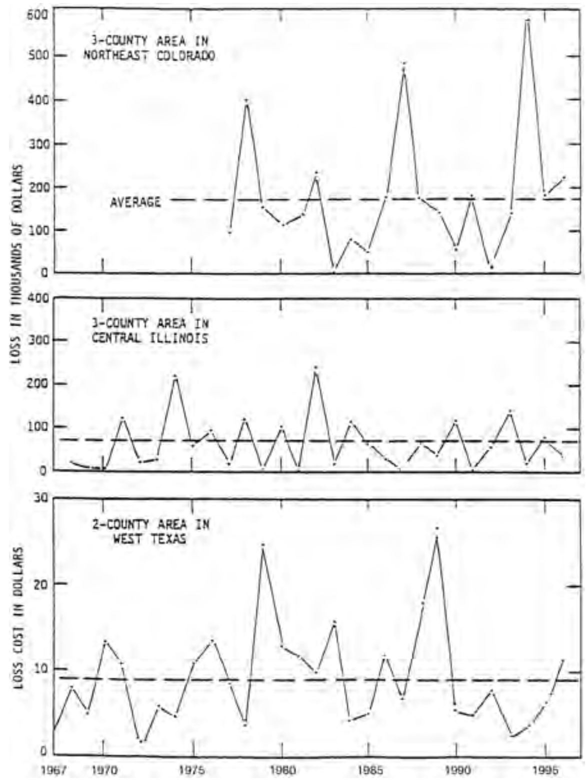


Figure 67. The temporal distribution of annual crop-hail losses in small areas in Colorado and Illinois, and loss cost values in a small Texas area during 1967-1996.

18. Forecasting Hail and Damages

Several studies over the past 60 years have attempted to develop hailstorm forecasts. Gokhale (1975) reviewed the forecast techniques available in the 1970s and concluded they were limited. Brown (1997) devised forecasts to detect different types of hail-producing storms: multicell and supercell storms. Regression techniques using various atmospheric conditions to predict hail sizes had limited success (Billet at al., 1997). One study focused on conditions in the lower atmosphere that act to enhance convection and hail development (Rasmussen, 2003). Another recent study was successful in developing quality predictions of hail severity and hail areas (Brimelow et al., 2006). Horgan et al. (2007) found that elevated severe storms, a result of frontal lifting, were prime hail-producing storms and should be included in forecasting hail.

Research also has been conducted by the crop-hail industry to develop and test statistical techniques for estimating future values of loss and future trends in losses. Testing was done on a crop-reporting district scale and on a state scale (Changnon et al., 1975; Schickedanz et al., 1977). Time series analyses were employed involving first a search for significant periodicities (nonrandom fluctuations) in the historical loss cost data. The significant periods were expressed mathematically as harmonics (sine-cosine waves) and used as predictor variables. Tests were run using two variations, a bandpass method and a filtering method, for predictions of the future annual values, of trends for future three-year and five-year periods, and of possible extremely high or low loss years in the next five years.

Skill with predicting annual values was slightly better than chance. However, the prediction of future three- and five-year trends of crop loss costs, conducted for the 22 states tested, was found to be correct 80 to 90 percent of the time. Figure 68 presents the results for one of the tests of trend prediction. The magnitude of the difference between the predicted and actual values (based on prior year testing) was within 21 percent for the three-year values and 29 percent for the five-year values. Attempts to predict the more extreme high and low annual loss costs failed to provide useful accuracy (Neill et al., 1979).

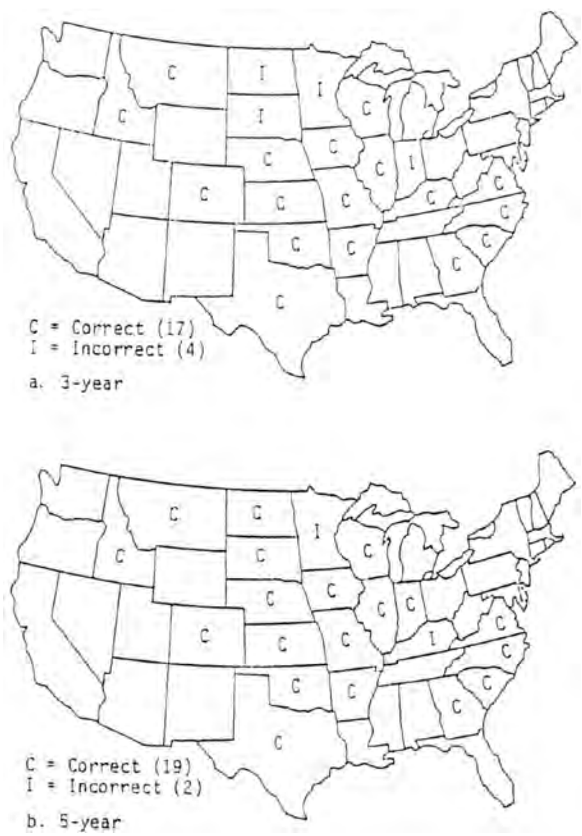


Figure 68. Maps showing the correctness of predictions of future trends in crop-hail losses for various states for a) 3-year periods, and b) 5-year periods.

SECTION F: SUMMARY

SUMMARY

This atlas of hail across the nation has addressed all the key aspects of the climatology of hail. Key findings include:

- The nation's areas of greatest hail frequency are along and just east of the central Rocky Mountains where point averages vary from 6 to 12 hail days per year. Figure 38 portrays regional differences in four important factors: hail frequency, causes of hailstorm, prime season of occurrence, and hail intensity.

- The lee of the central Rocky Mountains has the nation's greatest hail intensity with the largest average stone sizes, the greatest average number of hailstones, and longest hail durations when it hails.

- The nation's lowest hail intensities are found in the southeastern U.S. (Florida), and in the southwest (Arizona and California).

- Winds with hail tend to be strongest in the central and southern High Plains, making property-hail intensity highest in an area including Nebraska, Kansas, Oklahoma, and north Texas.

- Hail risk to crops and property is characterized by enormous variability in both space and time. Figure 30 is an excellent map that assesses hail risk to crops across the nation, and Figure 36 presents a national map showing the hail intensity differences related to creation of property damages.

- The risk of property damage across the nation varies from a low value of 1 in the southeast to a high of 50 (Colorado, Kansas), and the risk of crop damage varies from a low of 1 in the eastern Midwest and East to a high of 20 in the western High Plains (Montana, Wyoming, and Colorado).

- The intensity of hailfalls changes rapidly across short distances, and average intensity values, and risk of hail damage, significantly differ spatially in most states.

- Hail that is damaging to crops differs from that damaging to property, in that various vulnerable crops are damaged by small stones, whereas property damage occurs only when hailstones are 0.75 inch or larger.

- Exceptionally large hailstones, those exceeding 2 inches in diameter, can occur anywhere it hails in the U.S., but are most frequent in southeastern Wyoming (once every five years) and least frequent in the low hail frequency areas (only once every 100 years or less often at a given point).

- There is great variation in the dimensions of hail damage, with most damages occurring in 5 to 10 percent of all storms, and most losses occurring in only a small fraction of an area experiencing hail on a given date.

- Time changes in hail frequency and crop-hail intensity are quite large with a tendency for low hail incidence in 60 to 80 percent of the years, and exceptionally large losses in 5 to 15 percent of the years.

- The temporal variability of hail loss is greater in the High Plains states than in states in the Midwest, East, or West.

- The magnitude and frequency of hail shifts up and down randomly over time, but the primary spatial features of hail (areas of extremely high or low incidence of hail in a region) persist from decade to decade.

- Prediction of future trends in crop-hail losses for individual states, as trending up or down over the following three to five years, is accurate 80 percent of the time.

- Extremely damaging hailstorms to property show an upward trend with time, and the two most damaging storms in the U.S. occurred since 2000. The nationwide trends in crop-hail losses, in property-hail losses, and in the number of hail days all show downward trends for the 1950-present period.

- Average annual hail losses are $852 million for property and $581 million for crops, a national total of $1.433 billion.

On going demographic shifts in the nation's urban areas with rapidly growing metropolitan areas have increased the potential for costly losses from hailstorms. During the 1951-1970 period, property-hail losses represented 46 percent of the nation's total hail losses (54 percent were crop losses). In the 1981–2000 period, property losses grew and exceeded crop-hail losses and had become 61 percent of the national total losses to crops and property.

A storm in a rural area of Illinois is producing 1.5-inch hailstones and heavy rain. A hailstone has just landed in the water in a roadside ditch, creating a large splash (15 inches high), illustrating the force of large hailstones.

ACKNOWLEDGMENTS

Long-term help from E. Ray Fosse, Dick Roth, Don Friedman, and Gary Kerney, all from the weather insurance industry, was essential in being able to prepare a national atlas about hail. Steve Hilberg, Head of the Midwestern Regional Climate Center, supported the development of this atlas. Sara Olson prepared most of the quality illustrations and did the layout, and Eileen Deremiah helped with computer aspects of the atlas. James Angel and David Kristovich provided very helpful scientific reviews, as did Tamara Houston of the National Climatic Data Center. Lisa Sheppard did excellent editing of the manuscript. The atlas is dedicated to E. Ray Fosse who helped the senior author in his hail studies for 50 years, providing data and guidance, and performing joint research with the authors.

The illustrations came from different sources. Many were prepared as a result of recent analyses done for the atlas. Others came from various publications of the Illinois State Water Survey, or from publications of Changnon Climatologist. The photographs were taken by the authors and were done as part of the hail research studies of the Illinois State Water Survey.

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