



An Atlas of Windstorms in the United States and Their Impacts

Stanley A. Changnon



Illinois State Water Survey
Contract Report 2010-01

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Illinois State Water Survey
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I L L I N O I S

Cover photo: Windblown debris deposited on the side of a house and a fallen tree.

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Abstract

High winds are one of the nation's leading damage-producing storm conditions. They do not come from winter storms, tornadoes, nor hurricanes, but are strong winds generated by deep low pressure centers, thunderstorms, squall lines, or by flow over mountain ranges. The annual average property and crop losses from windstorms total \$379 million, and windstorms over the past 46 years have caused between 6 and 35 deaths each year. Windstorms range in size from a few hundred to a hundred thousand square miles, being largest in the western U.S. where 40 percent of all storms exceed 50,000 square miles. Ten percent of high wind events in summer are 10,000 square miles or larger, whereas 10 percent of winter storms are over 100,000 square miles. In the eastern two-thirds of the nation, windstorms occur at a given location, on average, 1.4 times a year, whereas in the western U.S., point averages are 1.9 storms per year. Midwestern states average between 15 and 20 windstorms annually; states in the East average between 10 and 25 storms

per year; and West Coast states experience 26 to 30 storms annually.

Storms causing insured property losses >\$1 million, labeled catastrophes, were assessed, and 176 such windstorms occurred during 1952-2006, an average of 3.2 nationally. Catastrophic windstorms were most frequent in the Central, Northeast, West, and Northwest climate regions, and least often in the High Plains. More than half of the catastrophes (56 percent) occurred in only one state. Catastrophic storm losses were highest in the West and Northwest regions, the only form of severe weather in the U.S. to maximize losses on the West Coast. Most western storms occurred in the winter as a result of Pacific lows, and California has had 31 catastrophes, more damaging windstorms than any other state. The national temporal distribution of the catastrophic windstorms during 1952-2006 has a flat trend, but their losses display a distinct upward trend with time, peaking during 1996-2006.

Introduction

High winds that are not a result of hurricanes nor tornadoes occur all across the United States. If the winds are sufficiently fast, they are identified as windstorms and are often labeled as damaging straight-line winds. They often cause damages to property and the environment, and sometimes to humans. Damages from high winds include downed transmission lines, broken and fallen trees, damaged buildings and homes (roofs, windows, and siding), and damages to aircraft, trains, and vehicles. A Midwestern assessment of damaging winds showed that much damage to power lines and homes occurred as a result of downed trees and poles (Changnon, 1980).

High winds are one of the most damaging forms of weather across the entire nation. They create losses that have an annual average of \$322 million to property and an average of \$68 million to crops. Thus the national total annual average loss from high winds is \$379 million, and damaging winds rank as the nation's sixth highest weather loss. The five higher average annual weather losses (in \$ millions) are \$4,235 produced by hurricanes; \$3,182 by floods; \$1,632 by thunderstorms; \$1,435 by hail; and \$448 by tornadoes (Changnon and Hewings, 2001). Losses due to snowstorms and ice storms are less than those due to high winds. High winds also caused between 6 and 35 deaths each year during 1961-2006, and they also produced injuries to more than 100 persons each year.

Losses attributed to hail exceed wind losses, but damages credited to hail are often enhanced by strong winds which increase the impact energy of hailstones. Nationally, 85 percent of all crop-hail losses come with winds over 40 mph. Most hail-caused losses to property are also a result of windblown hailstones.

Persons and institutions who should find the material herein of use include weather scientists,

ecologists, those in government agencies that help with weather disaster recovery, representatives of the property and crop insurance industry, those involved in structural design and construction, representatives of agricultural agencies, and those in power and communication firms. The definition used herein to define windstorms excludes those winds created by tornadoes or hurricanes. They also are not those occurring in a snowstorm or a blizzard, nor winds inside a heavy rainstorm or with hail. They are strong straight-line winds caused by various other atmospheric conditions.

High winds are often defined by wind speeds over 60 mph. High winds are created by three atmospheric conditions. Most high wind events result from outflows caused by extratropical cyclones that occur in the nation's interior and along the West, East, and Gulf Coasts. The second cause of high wind events is strong thunderstorms. Some storms create microbursts of small-scale high wind speeds at the surface. Lines of thunderstorms, often in squall lines, can create large areas of damaging winds labeled as derechos. A third cause of strong straight-line winds is the major mountain ranges in the western U.S. They can create high winds in the air descending on their lee sides. High damaging wind areas range in size from a few hundred square miles up to hundreds of thousands of square miles. The average size in the Midwest is 2,300 square miles. Studies of very damaging windstorms (those causing >\$1 million in property damages) reveal that 64 percent of such events occurred within a single state (Changnon, 2009).

This report first describes the atmospheric conditions that cause windstorms. Then, eight recent storms, each representing a different type of windstorm and locale, are described in detail. Characteristics defining the climatological

dimensions of windstorms in the nation are then addressed, followed by information about the losses from major damaging windstorms, labeled as catastrophes, each causing >\$1 million in property damages. This includes descriptions of their space and time distributions. The final section of this document summarizes the environmental, economic, and human impacts resulting from damaging windstorms.

Data and Analysis

This study focused on days with high and dangerous winds. The reason for the daily focus was the fact that much of the available high wind data come from records of stations of the National Weather Service (NWS). The NWS has operated hundreds of cooperative substations, operated by volunteers who were asked to record a day with high winds if local wind damage occurred. From 1943 to 1980 the weather reporting forms had a line for denoting the dates when high winds occurred, and after 1980 the forms had an area which allowed denoting dates with damaging winds. Since this recording of winds was a voluntary effort, the records have required careful assessments to identify stations and periods when high or damaging wind data were recorded correctly. A technique developed to assess substation records of days with thunderstorms or hail was used to assess

the wind records (Changnon, 1967). Analysis of their records across the nation showed that 942 had quality high/damaging wind records of 20 years or more during 1944-2007. These data were essential for defining the occurrence and general dimensions of windstorms because there were too few first-order stations (FOS) for accurate spatial definitions of storms. Thus, much of the climatological assessment of windstorms was based on daily reports of high or damaging winds during 1948-2007. Since the 1930s, the NWS has also maintained 130 FOS in the continental U.S. that have wind sensors, and the speeds are recorded. The locations of both types of stations with quality wind data are shown in Figure 1. Measurements of wind speeds can be influenced by structures near the wind sensor, but this potential problem had little influence on the definition of

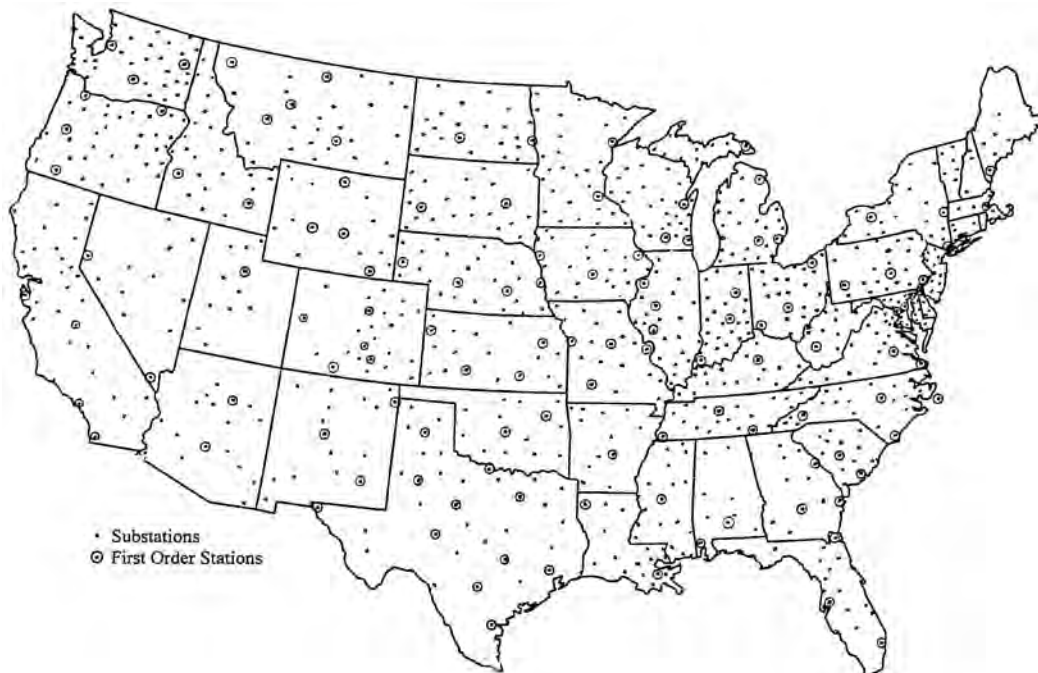


Figure 1. Locations of cooperative substations and first-order stations with quality high wind data.

windstorms since most were defined by cooperative station reports which were not based on sensors.

A detailed assessment of eight windstorms was performed to illustrate their dimensions and regional/meteorological differences. The information was gleaned from data published in *Storm Data*, an annual publication of the National Climatic Data Center based on storm information collected by NWS first-order stations. These documents present information on all forms of damaging weather in the nation, showing dates, times, places of occurrence, and damages caused. Data from NWS weather stations were also used to define the storm locations, and insurance data were used to identify the property and crop losses from each storm. Synoptic weather maps were used to identify the weather conditions that caused each windstorm.

An assessment of the small-scale variations in windstorms used data from an Illinois network that contained 27 wind sensor/recorders distributed evenly within a 900-square mile area, and each sensor was free from nearby structures. The sensor data showed wind speeds for each minute, allowing detailed spatial-temporal assessment of high wind events. This network was operated during the summer months of 1978 and 1979, and storm data were collected on three storms causing winds of 50 mph or higher.

A fourth source of data on windstorms was the loss records of the property insurance industry. Since 1949 the property insurance industry has catalogued all natural hazards in the U.S. that caused \$1 million or more in property losses (Property Claims Service, 2007). These events are named catastrophes, and their losses represent 90 percent of all storm-produced property losses in the U.S. (Roth, 1996). The National Academy of Sciences, in assessing data sources defining losses from natural hazards in the U.S., recognized that the insurance catastrophe data were the best of all forms of historical storm loss data in the nation (National Research Council, 1999). The available data for each catastrophe show the cause of the losses, the amount of loss, the states with losses, and dates of the storm. Catastrophe data for 1952-2006 were available and were used to assess windstorm losses.

Experts at a major property-casualty insurance firm have systematically analyzed in each year since 1952, the historical catastrophe data to update the past catastrophe values to match the current year conditions. This annual assessment resulted in a database allowing the industry to perform at any time unbiased comparisons of current catastrophe losses with those in past years, and thus to assess shifting risk of losses in any parts of the nation. Their adjusted catastrophe data were provided for this research.

This annual loss adjustment effort was a sizable and complex task, requiring assessment of each past event (Changnon and Changnon, 1992). Three adjustment calculations were made to the original loss value for the locations of each catastrophe. One adjustment corrected for time changes in property values and the cost of repairs/replacements, and hence, this also adjusted for inflation. The second adjustment addressed 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 adjusted losses for shifts in the insured property between the year of a given storm's occurrence and the updated year. The third adjustment, 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, was made by using insurance sales records. These adjustments were used to calculate a revised monetary loss value for each catastrophe so as to make it comparable to current year values, 2006 in this study.

None of the available data sets allowed the delineation of a quantitative relationship between various wind speeds and different levels of damage. However, an assessment of all storms producing damages adjacent to wind recorders during 1950-2000 was performed. This analysis revealed the thresholds of speeds when property and crop damages began, showing that damages to property began when speeds were 60 mph or higher, and crop damages occurred when speeds were 45 mph or higher.

Causes of Windstorms

Damaging high winds in the U.S. are created by three different atmospheric processes and phenomena. One is related to cyclones and the outflow generated by their deep low pressure centers. A second source of high winds is the outflow created by strong thunderstorms, and a third source relates to the influence of major mountain ranges which can accelerate passing winds under certain atmospheric conditions.

EXTRATROPICAL STORMS

Extratropical cyclones are large, swirling storm systems. Cyclones are parent storms from which much of the severe weather of the middle latitudes develops, including across the U.S. Cyclones move warm air northward and cold air southward. At the center of a cyclone is a low pressure center, and if

the pressure is quite low, strong winds often result (Rauber et al., 2002). Strong cyclones can create strong straight-line winds. The strongest cyclones form in the winter and spring.

Extratropical cyclones form along the East and Gulf Coasts several times a year during fall, winter, and spring. They also form in and along the front range of the Rocky Mountains in the U.S. or Canada (Alberta) during all months of the year. Cyclones also form in the Gulf of Alaska over the Pacific Ocean, and when they move east and strike the West Coast, strong winds develop. Storms are often enhanced as the cyclonic winds strike the coasts and mountain ranges along the coast. Cyclones in the Pacific Northwest occur at all times of the year, but mostly in the colder months.



A mature thunderstorm over western Kansas that created damaging winds and hail.

THUNDERSTORMS

Thunderstorms can create high winds in two different ways. First, are the strong winds produced by individual storms. A downburst can be created in a strong downdraft that originates within the lower part of a thunderstorm and descends to the ground. When the air in a downburst reaches the ground, it spreads rapidly outward, creating strong straight-line winds. Winds from downbursts can exceed 100 mph. Small and intense portions of downbursts are labeled as microbursts and are often 3 miles or less in diameter (Rauber et al., 2002). Field studies in the Midwest and High Plains have found that microbursts occur often, and a county-sized area can experience 50 to 100 microbursts per year (Rauber et al., 2002). Studies have found two types of microbursts, related to whether precipitation accompanies storm downdrafts. First, when a large amount of rain descending from a storm is evaporated due to dry air, the air in the descending dry downdraft often gets cooler and descends very rapidly at 40 to 60 mph. The second type begins when descending rainfall drives air downward, forming downdrafts. If the area of heaviest rainfall and its evaporation are concentrated in a small area, its size will range from 100 yards to a few miles wide, defining the microburst.

The second type of windstorm generated by thunderstorms is those created by a line of storms. Mesoscale convective systems, including squall lines, sometimes develop a bow-like shape along the front of a line of storms. The bow-shaped storms can create a family of downburst clusters. These in turn create a widespread area of straight-line winds labeled as derechos, which are most common in the Midwest.

MOUNTAIN STORMS

Mountain-generated windstorms occur as relatively fast-moving winds descend on the lee (downwind) side of a major mountain range. The winds approaching the mountains are forced up and over the range and an acceleration can occur on the downside. This descent can create a wind speed in excess of 90 mph. These windstorms occur most often along the east sides of the Rocky Mountains, the Cascades, and the Sierra Mountain range. Those east of the Rockies are labeled as Chinook winds, which mainly occur in the late fall and winter, creating gusts of 115 mph close to the Rockies.



A large rain shaft creating a strong downdraft and a microburst in Missouri.

Examples of Different Types of Windstorms

This section presents descriptions of eight different kinds of windstorms occurring in various parts of the nation (Figure 2). They were selected from among the numerous storms in recent years, and each was labeled a catastrophe by the property insurance industry because each storm caused more than \$25 million in property losses.

JUNE 2-3, 1993

This windstorm began 40 miles east of the front range of the Rocky Mountains in Colorado on the afternoon of June 2. The line of thunderstorms creating the high winds moved east across southwestern Kansas and northern Oklahoma where the windstorm ended at 6:00 a.m. on June 3 (Figure 2). This 13-hour windstorm covered 19,270 square

miles. Winds gusted to 80 mph in most of the storm, blowing down wheat crops in all three states. Power poles and many trees were blown down, roofs were blown off farm buildings, many windows were broken, and aircraft at an Oklahoma airport were damaged along with many mobile homes. Property damages totaled \$150 million; 1 person was killed, and 34 were injured.

JANUARY 8-9, 1995

This was a large storm generated by a major low pressure system moving east from the Pacific Ocean and going inland on the West Coast. The area where high winds occurred is shown on Figure 2 and includes northern California and southwestern Oregon. High winds occurred at various locations

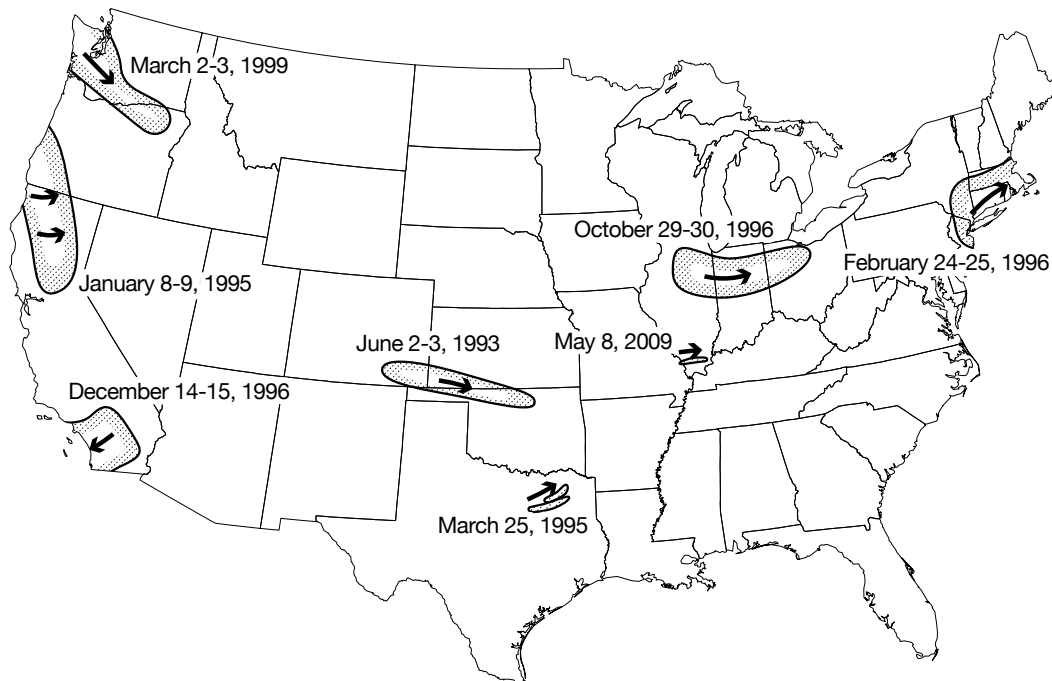


Figure 2. Locations of the eight case study windstorms.

between 6:00 p.m. LST (local standard time) on January 24 and 9:00 a.m. LST on January 25. The areas with winds >60 mph in California included the southern Sacramento Valley, northern San Joaquin Valley, and the northern Sierra Nevada Mountain range, which also created mountain windstorms. The storm also struck the southwestern coast of Oregon and inland hills. Medford, Oregon had gusts of 71 mph. The major impact was to trees with hundreds blown down, resulting in numerous power outages in both states. Two persons were killed by falling trees and more than 50 persons were injured. The property damages amounted to \$235 million. The storm covered 128,600 square miles.

MARCH 25, 1995

This windstorm was due to two microbursts that occurred side-by-side (Figure 3). A line of severe thunderstorms was moving to the east-northeast across northern Texas, and one storm launched a microburst just west of Dallas at 5:45 p.m. LST. It moved to the east-northeast, creating damages along a path that was 4 to 8 miles wide, and traveling 61 miles before ending at 6:50 p.m. Winds were 50 to 60 mph and the primary damages were to trees and power lines. A second microburst began alongside the first at 6:50 p.m. LST northeast of Dallas, and it too moved to the east-northeast and ended at 7:50 p.m. It was 4 to 9 miles wide and traveled 35 miles. It had winds gusting to 70 mph and caused considerable tree damage, plus roof damages to many homes and buildings. The two storms covered 576 square miles, property losses totaled \$68.5 million, and several persons were injured.

FEBRUARY 24-25, 1996

This windstorm occurred in the Northeast, in an area extending from northern New Jersey across Massachusetts (Figure 2). A rapidly deepening low pressure system east off the Atlantic Coast moved inland over New Jersey and then went northeast from New Jersey to Maine on the morning of February 25. The resulting deep low pressure system in Maine created a very tight pressure gradient across New England, causing very powerful and damaging winds from 11:00 p.m. LST on February 24 to 5:00 p.m. LST on February 25. Sustained winds over Connecticut were above

50 mph with gusts to 66 mph. New Jersey and New York had winds ranging from 50 to 70 mph, and gusts in Rhode Island reached 80 mph. The storm affected 14,680 square miles. The storm led to three deaths, all from falling trees. Falling trees and poles also led to many power outages, including power lost to 120,000 residents in Connecticut, 12,000 in Massachusetts, 130,000 in New Jersey, 20,000 in New York, and 13,000 in Rhode Island. Several trucks and rail cars were blown over, and many roofs of homes and buildings were damaged. Property damages amounted to \$365 million.

OCTOBER 29-30, 1996

A large damaging windstorm began in north-central Illinois during the afternoon of October 29, and it then moved east across the northern half of Indiana and reached the northern third of Ohio by the early morning on October 30 (Figure 2). The area experiencing high winds was 96,500 square miles. The windstorm was created by a strong area of low pressure moving east across the northern Midwest. Sustained wind speeds were 50 to 60 mph and gusts often reached 80 mph. At

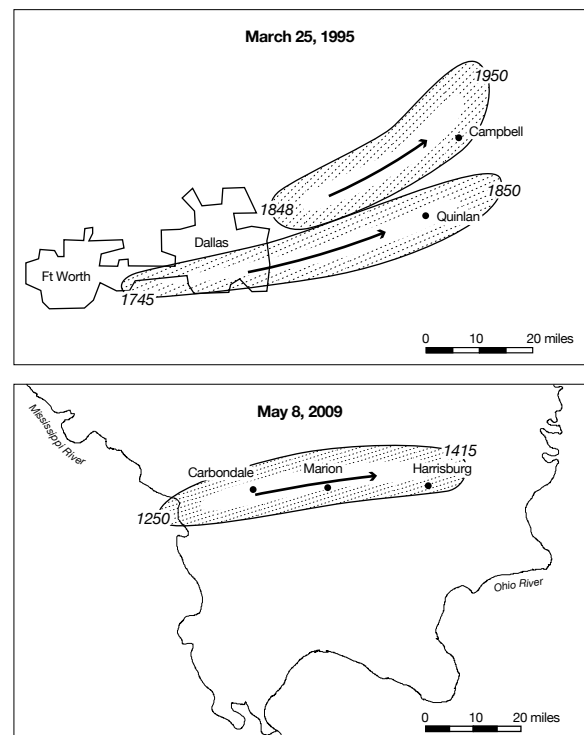


Figure 3. A microburst windstorm in Texas, and a derecho-generated storm in the Midwest. The times of high winds are shown by the numbers.



Downed tree branches from a windstorm in Wisconsin.



A row of rural power poles partially blown down by a windstorm in Illinois.



High winds blew this house trailer over and destroyed a garage.

most locations the high winds lasted 4 to 5 minutes. Damages were extensive and property losses totaled \$86.7 million. Crops awaiting harvest were blown down in many fields in Illinois and Indiana. Many trees were blown down, and falling trees damaged vehicles and homes and knocked power lines down. Power outages in Illinois occurred to 90,000 residents and to 56,000 in Indiana. Trucks were blown over, and one person was killed by a falling tree. More than 40 persons were injured.

DECEMBER 14-15, 1996

A type of windstorm that occurs only in the southwestern U.S. struck southern California during the evening of December 14 and morning of December 15 (Figure 2). This type of storm, labeled as a Santa Ana wind, develops over the hot, dry deserts in Arizona and southern California east of the Sierra Nevada Mountains, and its high winds move to the west, driven by strong pressure gradients from an anticyclone over the Great Basin of the West. These become windstorms as the air descends on the west sides of the San Bernadino Mountains, the Riverside Mountains, and the Santa Ana Mountains. The storm's high Santa Ana winds struck 13,220 square miles in southern California, including San Diego. Much property damage occurred in Orange County where gusts reached

111 mph. Two persons were killed, one electrocuted by a downed power line and another by a falling tree. Many trees and roofs were badly damaged and property losses amounted to \$145 million.

MARCH 2-3, 1999

A Pacific storm brought high winds into western Washington late on March 2. The high winds moved inland across western and southwestern Washington, causing major damages in Tacoma and Seattle. The winds hit the west slopes of the Cascade Mountains and moved along the Columbia River basin and into northeastern Oregon by the morning of March 3 (Figure 2), covering 28,925 square miles. Numerous orchards along the Columbia River Valley were severely damaged. Sustained wind speeds in the storm area were 50 mph with gusts at most locations of 70 to 80 mph. Trees and power lines were blown down, siding and roofs of houses and buildings were blown away, and several buildings were toppled. Power outages affected 200,000 residents in Washington. Property losses totaled \$48 million, and two persons were killed by flying debris.

MAY 8, 2009

An example of a windstorm caused by a derecho from a line of thunderstorms occurred on May 8, 2009 in southern Illinois. The windstorm had a path



House damaged by fallen branches due to a passing windstorm.

that measured 12 to 15 miles wide, and it extended for 68 miles from west to east (Figure 3), covering 893 square miles. Its duration at points along the track ranged from 1 to 4 minutes. The storm began at 12:50 p.m. LST just west of the Mississippi River and ended at 2:15 p.m. LST. Its forward speed was 55 mph. Gusts reached 106 mph near Carbondale and then the wind-measuring tower was blown over. Gusts measured elsewhere were 85 to 90 mph. The storm caused extensive damage to the campus of Southern Illinois University, with losses totaling \$1.5 million. Much tree damage occurred because much of the storm area is heavily forested, and numerous fruit orchards were badly damaged. Along the storm's path large trees with trunks of 3 to 4 feet in diameter were blown over and many uprooted. Several farms had houses and barns destroyed or badly damaged, and several trucks

were blown over. Four persons were killed, one in a truck accident, another by a falling roof, and two in an automobile that caught fire after being hit by a falling tree. Major power outages resulted from damaged power lines, and it took four days to restore power in some areas. Property losses amounted to \$59 million.

SUMMARY

The eight assessed windstorms had damaging winds covering areas ranging from 576 to 128,600 square miles. Sustained wind speeds in all storms were in excess of 50 mph and all gusts were 70 mph or higher. Trees suffered the greatest damages in all storms, and falling trees and branches were the major cause of property damages. The eight storm losses totaled \$1.16 billion. Six storms caused a total of 14 deaths and hundreds were injured.



Windblown debris deposited on the side of a house and a fallen tree.



House damaged by fallen trees in Nebraska.

Windstorm Characteristics

An in-depth analysis of windstorms in the nation was performed based on two data sets covering 1948-2007. First, was the daily data from the NWS cooperative substations. These stations do not have wind sensors, but the observers have been asked since 1943 to report high or damaging winds on days when local damages to property or the environment occur; 942 substations had quality high wind data spanning 25 years or more. The second data set was from the 192 first-order stations of the NWS, and these have wind sensors/recorders.

The atmospheric conditions causing each of the windstorms were determined. Table 1 presents the seasonal and annual values, expressed as percentages of the total high wind events at any point in the area, for thunderstorms and cyclones. Table 1 shows that most windstorms are caused by extratropical cyclones, but in the summer (June-August), thunderstorm-derived windstorms were the most frequent, causing 68 percent of all summer storms. The event totals reveal that winter is the prime season of windstorm activity in the eastern U.S., and summer is the season of lowest frequency. In the western U.S. Pacific lows moving inland from the Pacific Ocean caused 78 percent of the storms, mountain ranges created 18 percent, and thunderstorms produced 4 percent of all storms.

The average incidence of high damaging wind events at a point (weather station) was also

determined. The average for the cooperative weather stations in the eastern two-thirds of the nation was 1.4 windstorms per year. Point averages across the region varied from a low of 0.3 events per year in the Deep South to a high of 2.9 events at locations in New England. The point frequency for high winds in the West averaged 1.9 per year. The highest frequencies were 3.1 at cooperative stations along the coast, and in parts of Utah the average frequency was lowest at 0.8 events per year.

Analysis of annual windstorm frequencies revealed 15 to 20 storms affected each state in the Midwest (Figure 4). Illinois averaged 17 high wind events annually. States in the High Plains averaged between 11 and 20 windstorms annually. Most



Figure 4. Average annual number of high wind events occurring in each state during 1948-2007.

Table 1. Frequency of high wind events at any given location in the eastern two-thirds of the nation expressed as a percentage of the total events, and for the conditions causing the events

<i>Causes</i>	<i>Winter</i>	<i>Spring</i>	<i>Summer</i>	<i>Fall</i>	<i>Annual</i>
Thunderstorms (%)	8	26	68	24	30
Extratropical Cyclones (%)	92	74	32	76	70
Total events (%)	45	21	12	22	100

states along the East Coast experience between 10 and 25 high wind events annually, although there are fewer in the small states of New England and New Jersey, Delaware, and Maryland. States in the Southeast and Gulf Coast experience 8 to 11 high wind events annually (Figure 4). California averages 30 windstorms per year, and Oregon and Washington average 27 storms. Utah averages only 10 storms annually.

Durations of events at a point varied seasonally, as shown in Table 2, based on data from first-order stations. This reveals that most windstorms in the eastern U.S. lasted only a minute at most locales. Winter windstorms tended to last longer than did summer events, reflecting differences in their causes. Summer storms were largely a result of thunderstorms, whereas most winter storms were due to the passage of deep low pressure centers. Analysis of western windstorms revealed that 33 percent had one hour or longer durations.

On some storm days there were two discrete periods of high winds (>60 mph). Data from wind sensors in the Midwest show that when two discrete high wind events occurred in a day, 30 percent were 1 to 5 minutes apart, 21 percent were 6 to 10 minutes apart, 11 percent were separated by 11 to 15 minutes, 24 percent were 16 to 50 minutes apart, and 14 percent were more than 51 minutes apart. The diurnal distribution of all high wind events nationally showed that 20 percent occurred during the 00-06 hour period, 24 percent during 06-12 period, 31 percent during 12-18 period, and 25 percent during 18-24 hour period.

The areal extent of windstorms was quite varied, ranging from a few hundred square miles up to hundreds of thousands of square miles. Their

sizes also varied seasonally. Figure 5 shows the distribution of sizes for winter and summer storms. Each season's values are expressed as a percentage of the total seasonal storms. Winter windstorms are larger at all percentage levels. For example, 50 percent of all winter storms were 3,600 square miles or larger, as compared to 1,650 square miles for summer storms. Ten percent of all summer storms covered areas of 10,000 square miles or more, whereas 10 percent of the winter storms were 100,000 square miles or more. Six percent of all winter storms had areas that exceeded 300,000 square miles, whereas the largest summer storms were only slightly larger than 100,000 square miles. Seventeen percent of all summer storm areas were smaller than 1,000 square miles.

The temporal distributions of windstorm events were assessed for each state. Distributions for six states scattered across the nation are shown in Figure 6. The 60-year distributions of the 48 states, assessed regionally, revealed that most states in the western and southern regions showed high storm values during recent years, after 1990 and up through 2008. This is illustrated by the curves

Table 2. Point durations of windstorms in the eastern two-thirds of the nation with values expressed as a percentage of the total events

<i>Duration</i>	<i>Winter (%)</i>	<i>Summer (%)</i>	<i>Annual (%)</i>
1 minute	59	80	69
2 minutes	4	11	7
3 minutes	5	9	3
4 to 9 minutes	10	0	12
>10 minutes	22	0	9

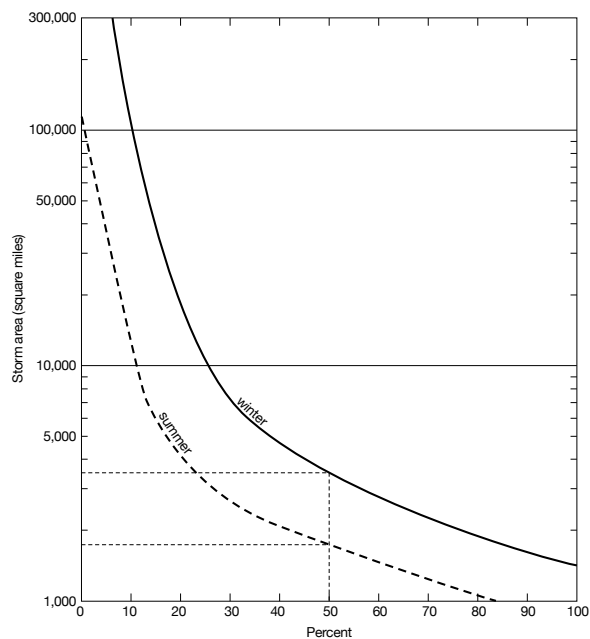


Figure 5. The spatial dimension distributions for all winter storms and all summer storms in the nation. The distributions are based on their seasonal frequency expressed as a percentage of the total storms in each season.

for California, Oklahoma, and Illinois, shown in Figure 6. States in the northern and northeastern areas, including North Dakota, Michigan, and New York (Figure 6), did not experience recent increases in windstorms. The temporal increases in the frequency of windstorms may have some relevance to the issue of global climate change.

SMALL-SCALE VARIATIONS IN WINDSTORMS

The operation of a dense network of wind sensors in central Illinois during the summers of 1978-1979 provided data to assess the spatial variations within high wind events. There were 27 wind recorders located at sites evenly distributed within a 900-square mile area. This allowed examination of the small-scale spatial patterns of high winds. Figure 7 shows the patterns based on speeds of >60 mph that occurred on three dates, and the minutes of occurrence are shown for each wind sensor. If the times at a site differed by more than 2 minutes, this is noted by a line drawn between the time periods.

The event on July 13, 1978, came from a group of thunderstorms moving to the east, which produced rainfall totals of 0.30 up to 1.1 inches in the

study area. The windstorm had two areas with high winds, and the area in the northwest sector had two periods of high winds, one from 3:13 p.m. LST to 3:21 p.m. and the other from 3:26 p.m. LST to 3:33 p.m. High winds on this day covered 273 square miles. Durations of the high winds at points in the network varied from 1 to 5 minutes and averaged 2 minutes. The highest wind speeds at the other sensors in the study area ranged from 30 to 38 mph.

The high wind areas on July 30, 1979 (Figure 7) are three separate areas, each with high winds moving from the north-northwest. These were generated by a group of thunderstorms moving from the northwest, and rainfall amounts in the study area ranged from 0.21 to 0.86 inch. The high winds covered 410 square miles of the network. High winds at the sensors lasted from 1 to 8 minutes, with a network average of 3.5 minutes. Two of the windstorm areas were close and parallel, but they occurred at slightly different times. One began at 7:08 p.m. LST, and at that time the earlier event (which had begun at 7:04 p.m.) had moved farther south.

An event on August 6, 1979 produced winds of 60 mph or higher at three isolated locations

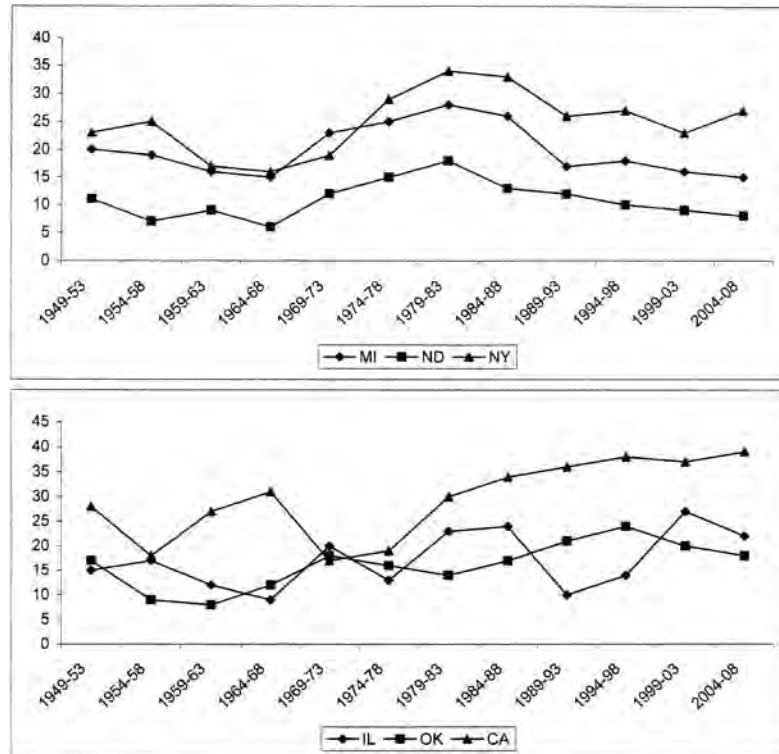


Figure 6. Temporal distributions of windstorms in six states for 1949-2008.

(Figure 7), each lasting only 1 minute. These high winds resulted from a rapidly moving squall line from the west, and rain amounts in the area were from 0.14 to 0.35 inch. The other 21 wind sensors had gusts that ranged from 25 to 42 mph.

The two July storms produced damages to local corn and soybean crops, particularly those planted with their rows at right angles to the high

wind directions. One gust on August 6 removed a roof on a rural farm building and caused a few trees to fall. Windstorm movement in two events was oriented 30 to 45 degrees to the right of the thunderstorm movement directions. These three windstorm examples reveal that various small-scale differences occur within microbursts.

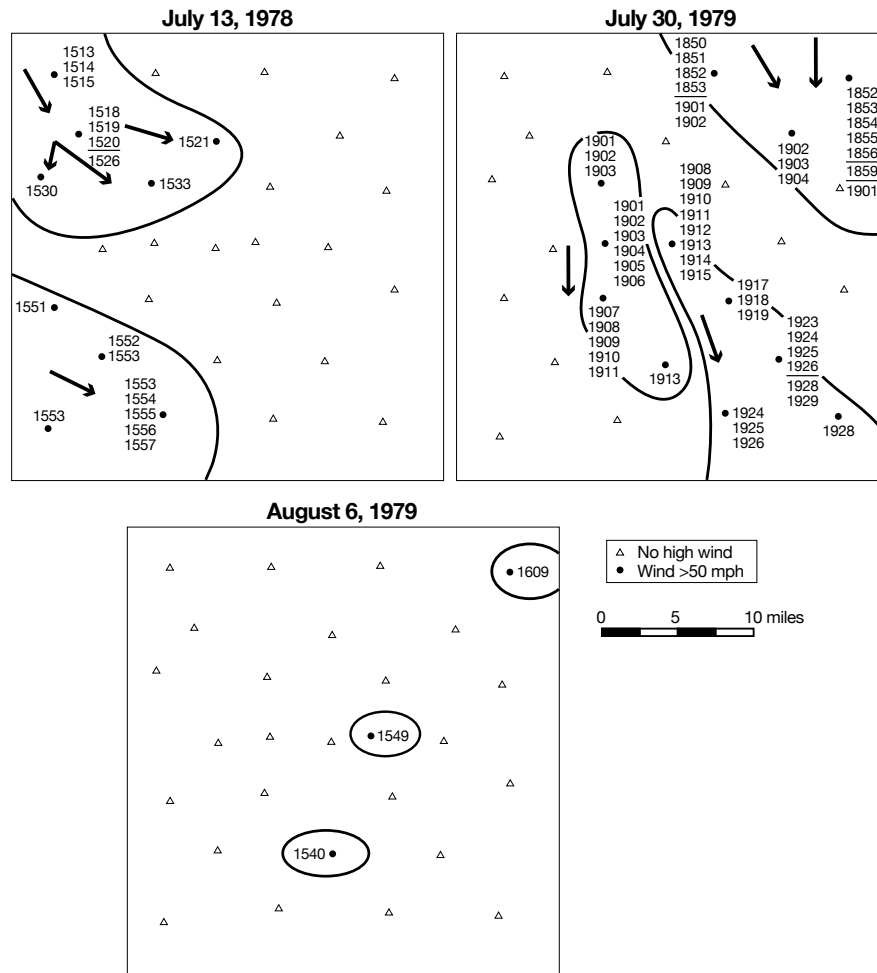


Figure 7. Areas of high winds, >50 mph, in a network of 27 wind sensors in a 900-square mile area in central Illinois during 1978-1979. Times are shown in CST, and periods of two or more minutes between gusts have a line separating them.

MAJOR WINDSTORMS

Since 1949 the property insurance industry has catalogued all natural hazards in the U.S. that caused \$1 million or more in property losses. These events are named catastrophes, and their losses represent 90 percent of all storm-produced property losses in the U.S. The available data for each catastrophe show the cause of losses, the amount of loss, the states with losses, and dates of the storm. Catastrophe data were available for the 1952-2006 period, and were used to assess losses due to major windstorms across the nation.

DIMENSION OF LOSSES

During 1952 to 2006, there were 176 catastrophes that listed high winds as the primary weather peril causing the event. The total amount of high wind produced losses during 1952 to 2006 was \$15.578 billion. The average high wind catastrophe loss was \$90.6 million. The annual average loss from wind damages to property in the U.S. is \$283.3 million. Insurance losses from lesser storms not classed as catastrophes have an annual average that is 10 percent of the catastrophe losses (Roth, 1996; Lecomte, 1993). Thus, the total national property losses from high winds are 10 percent higher than

the catastrophe losses. This means the national wind damages to property, on average, are \$311 million yearly. Crop losses from wind damages for 1949 to 1998, as measured by crop insurance data, averaged \$68 million (2000 dollars) per year (Changnon and Hewings, 2001). Thus, the national average annual losses from high wind damages to property and crops are \$379 million.

The annual average property loss due to high winds was compared with property losses due to other storm conditions (Winstanley and Changnon, 2004). The ranks of the annual average property losses of all the conditions in the U.S. are as follows (dollars in millions): 1) hurricanes (\$4,235), 2) floods (\$3,182), 3) thunderstorms (\$1,632), 4) hail (\$1,435), 5) tornadoes (\$448), 6) windstorms (\$379), 7) snowstorms (\$262), and 8) freezing rainstorms (\$186).

SPATIAL DISTRIBUTION OF STORMS

The catastrophe data list the states with losses for each catastrophe, offering a measure of the general size of the loss areas across the nation. Table 3 shows for each season the distribution of windstorm catastrophes per number of states with losses. The national totals show 99 of the 176 catastrophes, or

Table 3. Distribution of high wind catastrophes during 1972-2006 by number of states with loss in each catastrophe

<i>Number of states</i>	<i>Winter</i>	<i>Spring</i>	<i>Summer</i>	<i>Fall</i>	<i>Total</i>
1	32	21	30	16	99
2	8	2	4	3	17
3	5	2	1	3	11
4	3	3	3	3	12
5	2	1	3	2	8
6	3	1	0	3	7
7 to 11	16	1	1	4	22
Totals:	69	31	42	34	176

56 percent of the total, had losses that occurred in only one state. One-state occurrences were the highest values in all four seasons. Spring (21 of 31 total) and summer (30 of 42) showed relatively high frequencies of one-state losses, but in winter and fall, a greater percentage of the loss areas were larger than one state. Sixteen of the 69 winter catastrophes had wind losses existing over 7 to 11 states, and 37 winter events, 53 percent of the total, produced losses in two or more states.

The distribution of windstorm catastrophes across the nation and their losses were both assessed for the nation's nine climate regions; Figure 8 presents the regional values. The frequencies of catastrophes were highest in the Northeast and Central regions, with moderately high values in the two westernmost regions. Windstorm catastrophes were least frequent in the West North-Central and East North-Central regions. The magnitude of losses per catastrophe (Figure 8) had a regional distribution that differs from that of catastrophe incidences. The highest loss values were in the Northwest and West regions, and values were relatively high in the Northeast and Central regions.

The East North-Central region had a high loss value, but a low incidence of catastrophes. The western mountains, northern plains, and Southeast region all had low frequencies of catastrophes and low loss values.

The incidence of catastrophes in each state was assessed, and the 16 states with the highest frequencies are listed in Table 4. California had the highest number of catastrophes, 31, which is 18 percent of the total high wind catastrophes. Assessment of the locations of the 16 top-ranked states (Table 4) reveals three regional clusters: 1) the West Coast (CA, OR, WA), 2) the Midwest (IL, IN, IA, MO, OH, and MI), and 3) the Northeast (NY, NJ, PA, CT, and MA).

TEMPORAL DISTRIBUTION OF STORMS

During 1952-2006 there were 176 windstorm catastrophes, an average of 3.2 per year. The nationwide distribution over time (Figure 9) shows low frequencies occurred in the early years (1952-1966), and incidences peaked during 1977-1991. The fit of a linear trend to the annual data showed no upward or downward trend over time.

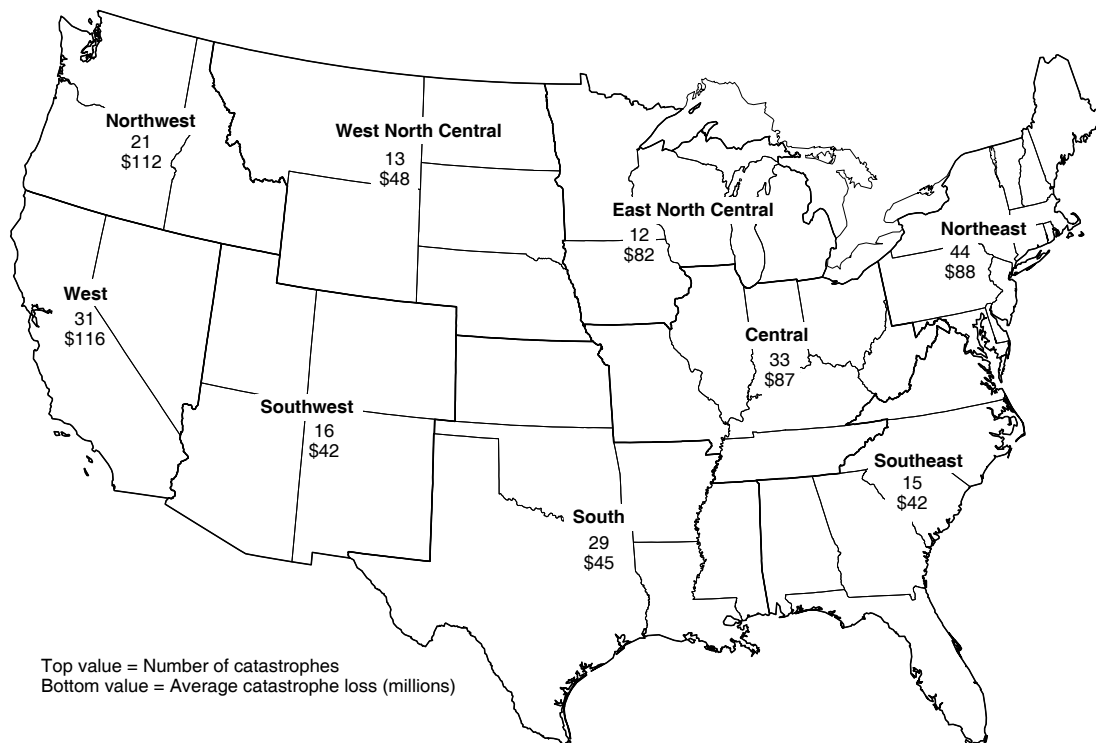


Figure 8. The frequency of high wind catastrophes in each climate region and the average loss (\$ millions) created by a catastrophe in each region (Changnon, 2009).

The average losses per catastrophe over time (Figure 9) show two periods of high losses (1962-1966 and 1997-2006). The losses had an upward linear trend over time, statistically significant at the 2 percent level. The recent increase in losses occurred when the number of storms was low, reflecting that recent storms were strong and that society had become more vulnerable to wind damages.

Figure 10 presents the regional time distributions of the number of catastrophes. The two westernmost climate regions have similar temporal distributions with high values during 1997-2006. Losses in these two regions also showed a significant upward time trend for 1972-2006. The Southwest and West North-Central regions (Figure 10) had similar distributions with upward time trends similar to the adjacent western regional distributions. The Southern region's distribution had high values in 1992-1996 and low values in 1952-1966. The Northeast and Southeast regions had similar distributions with major high values in 1977-1981 and low values in the early and late years of the 55-year period.

Table 4. The 16 states with the highest frequencies of high wind catastrophes during 1972-2006

<i>Rank</i>	<i>Catastrophe State</i>	<i>Frequency</i>
1	California	31
2	New York	29
3	New Jersey	27
4	Pennsylvania	24
5	Connecticut	22
6	Washington	19
7	Ohio	19
8	Texas	19
9	Illinois	18
10	Oregon	18
11	Massachusetts	17
12	Michigan	14
13	Indiana	13
14	Iowa	12
15	Missouri	12
16	Colorado	12



A fallen power pole, downed by high winds in Illinois.

Losses in the two westernmost regions (W and NW) had upward time trends, peaking in 1995-2006. However, in the Midwest and the two easternmost regions, losses peaked in 1975-1985 and were low in recent years. The regional differences in losses and the frequencies of catastrophes reflect differences in storm-causing conditions over time, and are not changes related to shifts in society.

The seasonal distribution of windstorm catastrophes across the nation shows the greatest frequency is 69 events in winter, which is 40 percent of the total catastrophes. The summer frequency of 42 ranks as the second highest seasonal total, and catastrophes in spring totaled 31, with 34 in fall. The national monthly distribution during the year is depicted in Figure 11. This reveals January and December are the peak months of windstorm catastrophes. The lowest incidences of windstorms occur in April, May, and September.

The two westernmost regions (W and NW) had high values in winter months, reflecting the

high frequency of stormy winters along the West Coast. In contrast, the southern region had frequent catastrophes in spring and summer months. The Northeast region had frequent catastrophes in fall and winter when coastal storms prevailed. The Midwest had catastrophe peaks in summer months, reflecting the regional peak in thunderstorm occurrences.

Table 5 lists the 12 most damaging windstorms that occurred during 1952-2006. Their dates of occurrence ranged from 1955 to 2006 with a peak of four during 1982-1985. Loss values ranged from a high of \$1,939 million to a low of \$226 million, and the total for the 12 storms was \$6.61 billion. Nine of the 12 occurred in winter months, 2 in fall, and 1 in summer. Six of the 12 had losses in only three states or less. Climate areas most often impacted were the West, Northwest, Central, and Northeast.

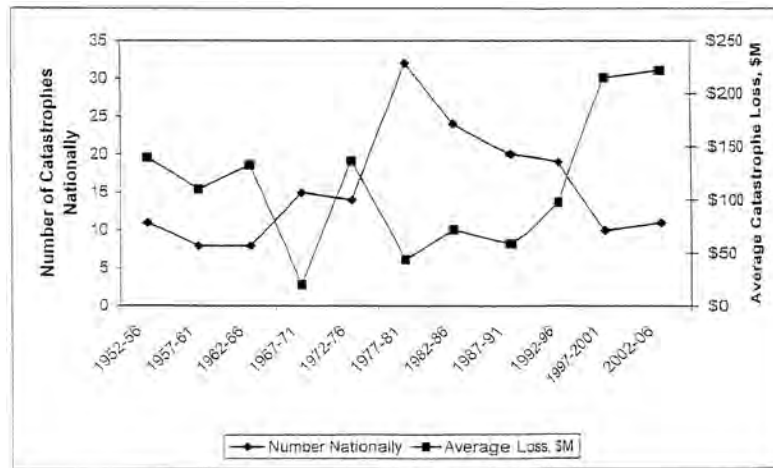


Figure 9. The national frequency of high wind catastrophes and their losses (\$ millions) during 1952-2006 (Changnon, 2009).

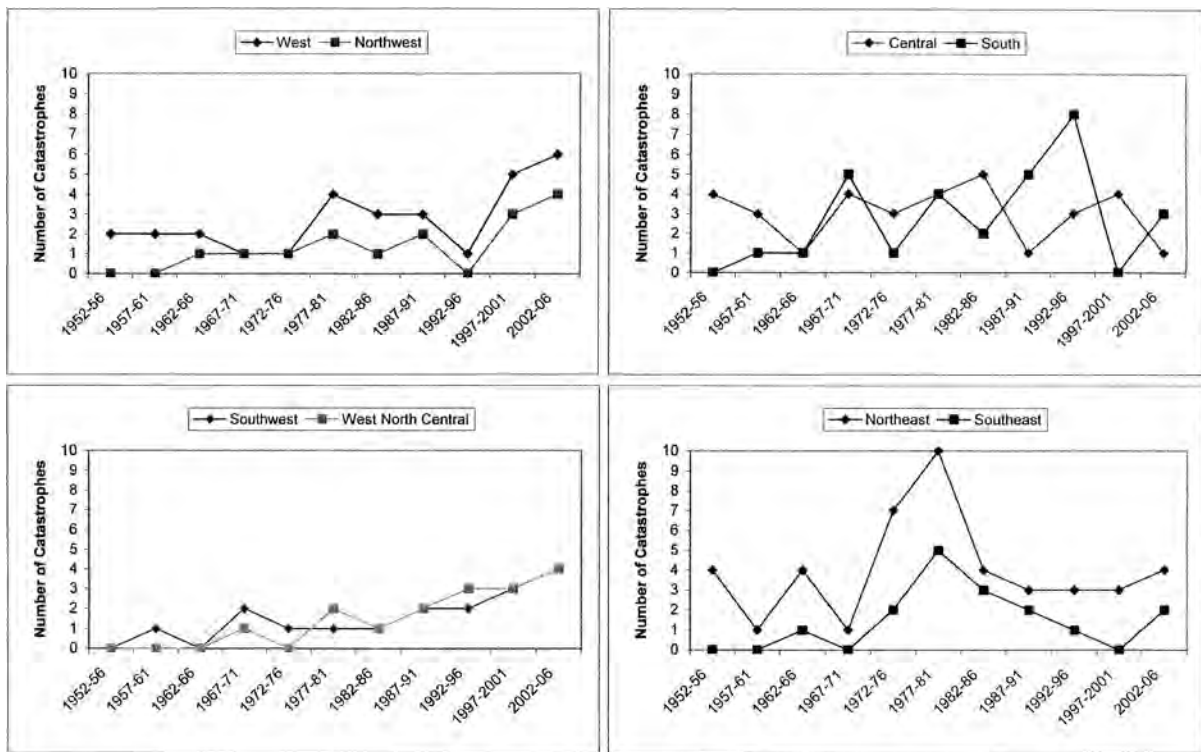


Figure 10. The temporal distribution of high wind catastrophes in eight climate regions, for 1952-2006 (Changnon, 2009).

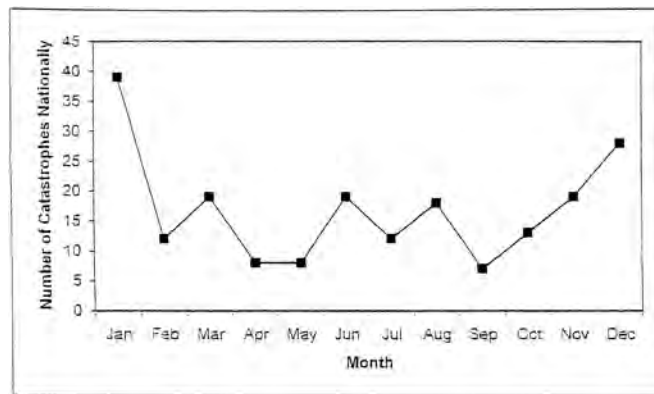


Figure 11. The monthly number of high wind catastrophes across the nation for the 1952-2006 period (Changnon, 2009).

Table 5. The 12 most damaging windstorms during 1952-2006, based on property losses (2006 dollars)

<i>Rank</i>	<i>Loss, \$ millions</i>	<i>Date</i>	<i>States with loss</i>	<i>Climate Regions with loss</i>
1	1,939	Oct. 11, 1962	3	W, NW
2	792	Dec. 18, 1955	1	W
3	776	Jun. 17, 1972	8	C, NE
4	745	Nov. 30, 1974	3	C, ENC
5	429	Jan. 8, 1982	16	C, S, ENC
6	365	Feb. 24-25, 1996	2	W, NW
7	307	Dec. 11, 2000	11	C, NE
8	300	Dec. 29, 1982	3	NE
9	267	Dec. 17, 1983	19	NW, SW, WNC
10	235	Jan. 8-9, 1995	4	NE
11	229	Jan. 19, 1985	11	C, SE
12	226	Dec. 14, 2006	2	NW



A ripe soybean crop blown down and destroyed by high winds in Indiana.

IMPACTS

The information presented about different types of windstorms and the damages they create identified the types of impacts created by windstorms. The average annual losses from windstorms in the U.S. are \$379 million. Below are listed the windstorm impacts in various sectors.

Environment. High winds create serious damage to trees, breaking off limbs, and blowing large trees down, either by uprooting or trunk breakage. In addition to forest damages, windstorms also cause costly losses in planned landscapes and enhance existing woodland fires. The impacts to trees and the environment are greatest in regions that are heavily forested such as the Pacific Northwest.

Power/Communication Provision. High winds create many damages to power and communication (telephone) lines by breaking power poles and/or causing lines to break because of falling trees or large branches. The result is loss of power to large numbers of customers, often lasting several days.

Transportation. High winds occasionally blow large trucks and rail cars over, creating major damages. Falling branches and tree trunks often damage autos and trucks.

Agriculture. High winds blow down certain crops such as corn in its mature stages, and sometimes break stalks. Shorter crops, such as wheat and soybeans, are also damaged by high winds at crop maturity stages. High winds also create damage to orchards by breaking limbs and causing trees to fall. Crop damages are greatest in the Midwest and High Plains. The annual average crop losses from high winds are \$68 million.

Human Health. High winds cause deaths to humans often by falling branches or trees hitting occupied vehicles. Downed power lines also cause deaths. Annual losses during 1961-2006 ranged from 6 to 35 deaths with an annual average of 11. Many windstorms produced numerous injuries to humans.

Property. Buildings and homes are damaged. Roofs and siding are blown away, roofs become damaged from fallen trees, and windows are blown out. The national average annual losses from high wind damages to property is \$311 million.

Government. Local and state agencies often must clean up wind damages, particularly to trees, an unexpected cost.



Badly damaged houses due to high winds in Kansas.

SUMMARY

An assessment of many windstorms revealed that property losses began to occur when winds reached 60 mph and crop losses occurred when winds were 45 mph or higher. Studies of eight recent windstorms in different parts of the nation revealed that extratropical cyclones along the coasts created the largest storms. Microburst storms were the smallest. Sustained high winds causing property damages were 60 mph or higher with gusts typically 70 to 80 mph. Property losses from the eight storms ranged from \$48 million to \$365 million, and the amount of loss was often a function of the density of property in the storm zone. All eight storms created sizable damages to trees that fell, producing damages to property and power lines. Power outages were common in all these storms. Fourteen deaths occurred, either as a result of falling trees or electrocution from downed power lines, and many persons were injured in all eight storms.

Windstorm sizes ranged from 130 up to 477,000 square miles, and winter storms were larger than most summer storms. Some storm characteristics in the eastern two-thirds of the nation were different from those in the western third. Analysis found that 70 percent of the eastern U.S. windstorms were caused by extratropical storms and 30 percent by thunderstorm winds. In the west, 78 percent of all storms were generated by Pacific lows and 18 percent by mountain ranges. Point storm durations were mainly three minutes or less in 85 percent of all the nation's windstorms, whereas 12 percent lasted one hour or longer at a point. Point occurrences in the eastern two-thirds of the U.S. averaged 1.4 storms a year, and the average was 1.9 events in the West. The longest durations in the West came along the Pacific Coast, and the longest average point durations in the East were in the Northeast.

Warm season windstorms generated by convective storms, as measured on a dense network of wind sensors, revealed they often have considerable spatial variability across short distances such as 1 or 2 miles. Some high wind gusts were followed by a second gust in the same locale or in a nearby area. Damaging winds (>60 mph) occurred over a few square miles in one case and over 200 to 400 square miles in the other two cases. The direction of the high wind gusts were not always aligned with the direction of the storm movement that generated the microbursts, and in two cases was 30 to 45 degrees to the right of the storm direction.

Windstorms are the only form of severe weather in the U.S. that cause their maximum damages on the nation's West Coast. For each catastrophic windstorm, the average loss is \$115 million in the West climate region (California and Nevada) and \$112 million in the Northwest region. In contrast, the average storm loss in the adjacent regions, the High Plains, is only \$42 million. Windstorm catastrophes are most frequent in the Northeast, Central, Northwest, and West regions. Nationally, the average catastrophe loss is \$90 million, and annually, the average nationwide loss from windstorm catastrophes is \$283 million. An adjustment of this value for uninsured property losses and those from insured losses from events causing less than catastrophes (\$1 million) raises the annual loss total to an estimated \$311 million. Wind-caused crop losses average \$68 million per year.

Windstorm catastrophe losses occurred most frequently in only one state (58 percent of the total storms), and the largest loss areas occurred in the winter. Spring events occurred in one state in only 68 percent of the cases, and 71 percent of all summer storms caused losses in only one state. States that had the most frequent catastrophes included

California (31), New York (29), and New Jersey (27). States with frequent catastrophes were found in three regions: the West, Midwest, and Northeast.

During 1952-2006 there were 176 windstorm catastrophes in the United States, producing an average of 3.2 per year. Their 55-year time distribution revealed high values had occurred in 1977-1991, and the time trend was neither up nor down. However, the distribution of losses over time showed high values in recent years, 1997-2006, and the 55-year distribution had a statistically significant upward trend over time. The regional temporal

distributions of catastrophes showed notable spatial differences. Events in the four westernmost regions peaked in 1997-2006, whereas the number of events in the South and Central regions was not frequent during recent years.

Monthly incidences of catastrophes were highest in January, December, and November, with moderately high values in summer. Windstorm catastrophes were least in late spring (April-May) and early fall (September-October). Winter is the prime season for windstorm catastrophes with 38 percent of the 55-year total.

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