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HAZARDOUS WEATHER CLIMATOLOGY FOR ARIZONA

by:
Craig Shoemaker
Jeffrey T. Davis

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Scientific Services Division
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Andy Edman, Chief
Scientific Services Division
Salt Lake City, UT

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By

Craig Shoemaker
and
Jeffrey T. Davis

National Weather Service
Tucson, Arizona

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I. Introduction

Providing expedient severe weather warnings to save lives and property is the most important mission provided by National Weather Service offices in Arizona. This study discusses numerous hazardous weather types including tornadoes, hail, wind, flash floods and floods, lightning, dust storms, dust devils, extreme temperatures, drought, wildfires and winter storms. A comprehensive understanding of the state's hazardous weather climatology will better prepare forecasters in anticipating the timing, strength, location and nature of hazardous weather. This climatological information will also be useful to emergency managers and private citizens in understanding the characteristics of severe weather across Arizona. Therefore, the purpose of this study is to quantitatively describe the hazardous weather climatology for Arizona using reports from 1950 to 2004 for tornadoes and 1955 to 2004 for other events.

II. Methodology

A. Data

This paper is a compilation of nearly five decades of meteorological data formed from multiple hazardous weather data sources. Tornadoes, hail, high winds, lightning, flooding, severe winter-weather cases, extreme heat and cold outbreaks are included. Seven sources of information were used to compile the severe weather information:

- National Weather Service's (NWS) Storm Prediction Center (SPC) Database from 1950 to 2004
- National Climatic Data Center's (NCDC) *Storm Data* (NOAA 1955-2004) NCDC Storm Events Database
- National Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS) from 1994 to 2004
- University of Arizona Storm Database
- Arizona Department of Health Services' (ADHS) Division of Public Health Services Report on Injury Mortality among Arizona residents (1990-2000)
- Arizona Climate: *The First Hundred Years* (Sellers, Hill and Sanderson-Rae, 1985).

Data analysis using ArcView GIS version 3.1 allowed for the plotting of the above mentioned databases to determine trends of events with regards to topography along with seasonal and diurnal frequencies.

B. Data Biases and Discrepancies

The low population density (45.2 people per sq mi) in Arizona (U.S. Census, 2000) has likely resulted in many severe weather events not being reported, especially those which occur away from the high density population centers of the larger cities in Arizona. Additionally, there is a significant bias to reports along roadways in predominantly rural areas. Therefore, it is important to note that the events from which statistics in this study are generated are actually a subset of all significant events which have occurred in Arizona. Figure 1 illustrates the bias of wind events to population centers and along or near roads.

Many database discrepancies were encountered as the study progressed. One example of this is with the Labor Day weekend storm of 1970, which was a flash flood and flood event caused by tropical storm Norma. The official *Storm Data* report shows no deaths or injuries as depicted in Figure 2. However, the Sellers et al. (1985) report shows 23 deaths caused by the system. Further investigation shows that indeed there were 23 deaths. Yet, another discrepancy can be seen in the event reporting methods used in official *Storm Data* entries over the years. When severe weather occurs on a statewide scale, it is often reported in broad terms (central, southern, northern) instead of the preferred county break down (Pima, Yuma, Maricopa). This is especially the case for events prior to the NWS modernization and associated restructuring in the 1990's. The numerous data sources used in this study have sorted out such discrepancies and lead to a more comprehensive dataset which is summarized in this paper.

C. Climate Divisions

Arizona is the sixth largest state in the United States at just over 114,000 sq mi. and elevations varying from under 300 ft to over 12,000 ft (Sellers and Hill, 1974). This topographical variation over a vast spatial area yields an extreme collection of climate regimes with extraordinarily diverse weather. Therefore, for this study Arizona has been broken down into six climate regions, originally developed by Sellers and Hill (1974). Figure 3 shows a map of the six different climate regions used in this study. These climate divisions better highlight the seasonal and diurnal frequencies that would be normally hidden by the typical county or the NWS County Warning Area (CWA) breakdown.

The Northeast region encompasses the area from the Little Colorado River northeast, including the Painted Desert. The Plateau zone stretches the length of the Mogollon rim from the Kaibab Plateau and Grand Canyon to the White Mountains. The Northwest region covers the Colorado River valley over the northwest part of the state. The Central region includes areas along the southern rise to the Mogollon rim. The Southwest region encompasses the lower desert areas including Phoenix and Yuma. The Southeast region covers eastern Pima and Pinal counties, eastward to the New Mexico border. Each of these regions is affected differently by synoptic and meso-scale systems and the resulting monsoonal and winter-time precipitation.

III. Overview of Results

A. Role of Thunderstorms in Hazardous Weather across Arizona

Thunderstorms are responsible for a large percentage of the hazardous weather observed in Arizona. The thunderstorm season, which is driven by the North American Monsoon, encompasses the majority of annual thunderstorm activity. The North American Monsoon is a regional-scale circulation that develops over southwest North America during the months of July through September. It is associated with a dramatic increase in moisture that occurs over what is normally an arid region of North America, as a shift in the mid-level flow from westerly to easterly, occurs (Adams and Comrie, 1997).

The thunderstorm season in Arizona is fairly well defined, although it varies considerably between northern and southeastern sections of the state due to elevation. The thunderstorm season generally begins over the southeast portion of the state in late June to early July (Tucson's average start date is around July 3rd and Douglas is the last week in June). Elevations

above 5,000 feet generally receive their first thunderstorms a week earlier than the above mentioned dates. A gradual decrease in thunderstorm activity occurs in September and October, with some seasonal variability due to tropical activity. In contrast, across northern Arizona (including Flagstaff) the thunderstorm season typically does not become established until mid or late July. Over central Arizona, including the Plateau region and Mogollon rim, the season usually gets started in early July, with the average at Phoenix around the 7th of July.

Thunderstorms also have different characteristics within the state. Across the higher elevations (above 5,000 feet) hail, generally small, and heavy rains are most prevalent. As the thunderstorms progress off the mountains into valley locations, high winds and dust storms become a major concern. This is a result of the elevation change, which allows for a large amount of the rainfall to evaporate before reaching the surface, causing more momentum as rain-cooled air accelerates to the surface. This process can result in numerous micro bursts as these thunderstorms progress into valleys. The drastically warmer temperatures over the valley areas cause the majority of hail stones to melt before reaching the surface. Flash flooding does occur due to heavy rainfall with valley thunderstorms, especially over urban areas. A great flood threat also results when heavy rain falling at higher elevation flows into lower elevation rivers and washes.

B. Ranking of Hazardous Weather in Arizona

Although thunderstorms produce a large percentage of weather hazards, the greatest hazard in Arizona is extreme temperature which is responsible for the largest number of fatalities. Figure 4 shows the frequency of injuries and fatalities in Arizona by weather type for the period of 1955 to 2004. For the extreme heat/cold category, the highest component is extreme heat. It is very likely that heat is an even greater killer than the data depicts. Untold numbers of illegal immigrant deaths go unreported yearly, so the fatalities may be significantly higher (Keim et al, 2006). Available data is only over a ten year period (1990-2000), making it even more impressive compared to other weather events. Extreme heat will not be examined in later sections of this paper due to the unreliability of casualty statistics before 1990, and the vague cause of death reports associated with heat victims.

Floods and flash floods are the next most dangerous hazards when considering injuries and fatalities, followed closely by dust storms. Tornadoes and thunderstorm winds are responsible for a number of injuries across the state, however only three fatalities due to tornadoes have been reported. The greatest number of fatalities outside of extreme heat occurs from May to September, primarily caused by dust storms, flash floods and lightning. Most injuries occur during the months of May through September, with thunderstorm wind in addition to dust storms, flash floods and lightning as the major contributors to the totals.

IV. Severe Thunderstorm Events

A. Tornadoes

Tornadoes are a more common occurrence in Arizona than most people are aware, primarily over the Central valleys and Plateau regions. For the state, the average of reported tornadoes is approximately 4 per year. Figure 5 shows the distribution of reported tornadoes by county from 1950 to 2004. These statistics reveal that the lower valleys of Maricopa, Pinal and Pima

counties, along with the little Colorado River valley, are well-defined maxima for tornadoes. Tornado development in Arizona is often complicated, since they rarely form under textbook conditions. Instead, many Arizona tornadoes are of the non-supercell type; Arizona tornadoes are not associated with low or mid-level mesocyclones, but are formed by thunderstorms interactions with preexisting boundary layer circulations. An example of this would be the stretching of a preexisting dust-devil, gustnado or lesser circulation into the vertical by a thunderstorms updraft. This causes the circulation to tighten and spin faster, allowing for a brief spin up of tornadic wind speeds. Several documented cases of this type have come to light over the past several years, with the onset of digital cameras and camcorders. One such well documented area for non-supercell tornadoes is the region between the Little Colorado River Valley and the Mogollon Rim, known as the Mogollon Rim Convergence Zone (MRCZ) (Blanchard, 2000). This terrain driven convergence is a region of enhanced thunderstorm development and vertical vorticity. Although, MRCZ has been documented by a recent study (Figure 6), many smaller zones of this type exist across the state. As a result tornado detection and verification is often a distorted practice across the state.

Despite the 196 reported tornadoes in Arizona, only 3 fatalities have been reported since 1950, while 139 injuries were documented. The low number of fatalities can be in part explained by the strength of tornadoes found across the state. Wind speeds in tornadoes vary from 40 mph to 318 mph (F0 to F5 on the Fujita scale). Since the mid 1980's, tornado strength has been measured using the Fujita Scale, or F scale (Abbey and Fujita, 1975). This scale ranks tornadoes by damage intensity, with F0 being the weakest and F5 the strongest. This scale was developed to create a relationship between tornado wind strength and the expected structural damage accompanying this wind. Since there is a highly varying degree of structural integrity of buildings across Arizona, the application of the Fujita scale is difficult to apply. In Figure 7, the reported Arizona tornadoes are listed by F scale frequency, and Figure 8 shows the distribution by month and F scale. Certainly, the strength of many tornadoes is not known, but less than 7% of the tornadoes with a known intensity are in the strong category (F2 or F3). Given this information, a high percentage of reported tornadoes in this state are weak, either F0 or F1.

Figure 9 depicts the monthly frequency of all reported tornadoes and Figure 10 shows the distribution by month and region. Over 95% of tornadic storms occur in May through September, with about 60% occurring in July through September. Tornadoes were reported in all months, F2 tornadoes were mainly recorded May through October, except for one occurrence in January. Figure 11 shows the frequency of tornadoes by hour, with the majority of tornadic storms occurring between 11:00 AM and 11:00 PM MST. The number of tornadoes that occur after dark (8:00 PM MST) is very small, with no reports of tornadoes between 2:00 AM and 7:00 AM MST.

Secondary tornado peaks occur for Southwest and Northeast climate regions as shown in Figure 12. In the Southwest region, this secondary peak occurs from January through March in association with strong late winter storm systems. Over the Northeast region two peaks show up outside of the monsoon season: one from April through June, and the other September and October. To further substantiate these peaks, data from the Four Corners region of New Mexico, Colorado and Utah are included in Figure 12 as well. Over the Northeast Arizona zone

this peak is attributed to the interaction of residual monsoonal moisture with late summer-early fall storm systems (Adams and Comrie, 1997). These transitional events are often characterized by high shear and marginally unstable environments (Blanchard, 2006).

B. Hail

The NWS defines a hail event as severe when large hail is at least 0.75 of an inch in diameter. Hail ranks only as the third most frequent hazardous weather type, but is still responsible for a considerable percentage of property and crop damage. The state averages 12 severe hail events per year. Hail is not a major threat for bodily harm in the state; no fatalities and seven injuries have been reported due to hail. These numbers are the lowest of any severe weather type. High freezing levels tend to diminish the threat of large hail across the state, since a significant amount melting occurs as hail stones fall to the surface. High cloud bases also lead to some sublimation of the stones, further reducing the size seen at ground level (Hsin-mu Lin, et al. 2005). Frequent small hail occurrences are seen at higher elevations, but are generally below severe levels, due to weaker updraft strengths with mountain thunderstorms. The percentage of hail events by county for Arizona is depicted in Figure 13.

A significant bias towards population centers is seen with hail reports. This bias should not be a surprise given the visual conformation needed for hail measurements. In unpopulated areas, either the hail melts before a measurement can be made, or the damage from the melted hail is attributed to another severe weather element such as wind. Although these figures show the highest severe hail frequencies over Maricopa, Pinal, Pima and Coconino counties it is likely many of the lower frequency counties such as Graham and Greenlee counties have an equal or greater severe hail frequency.

Figure 14 shows the number of hail reports by month and by size. Damaging or severe hail (0.75 to 1.50 inches) is most common in June through August, as is very large hail (over 1.50 inches); although a significant number of very large hail reports also occur in September. The size of some hail reports are not known, but were included in *Storm Data* because they caused significant crop and/or property damage or had a significant accumulated depth. These reports are included in this study due to their likelihood of being severe hail. Figure 15 reveals damaging hail is most likely to fall in the afternoon and early evening, as is the case with tornadoes. Just over 70% of the reported severe hail events fell between 2:00 PM and 6:00 PM MST. The largest hail stone reported in the state is 4.50 inches, which is softball size. This occurred in Mayer, Yavapai County, on September 28, 1995 (*Storm Data*).

C. Wind

A wind event is considered severe when speeds of 58 mph or greater are measured or estimated, or produce significant damage. Arizona averages 29 severe wind events per year, with the greatest concentration over the southern most climate regions. The number of reported thunderstorm wind events by climate region is shown in Figure 16. Thunderstorms moving off the higher terrain into the hot, dry desert tend to produce stronger downdrafts due to extreme evaporation rates of precipitation and greater descent distance. Therefore, severe downbursts and outflow boundaries are more common over these regions. Additionally, wet microbursts also occur over these areas, especially during the mid and late monsoon season. However, isolated events can occur with strong baroclinic systems outside of the monsoon season. These

events are typically most common over the west and northwest. Dry microbursts occur when rain falls through an extremely dry atmosphere and evaporates, causing rapid cooling of the air. This air rapidly descends and accelerates as it nears the surface. Very little if any rainfall reaches the ground; instead the cooled air spreads out in the form of strong and occasionally damaging winds. Wet microbursts occur during very heavy precipitation, typically in warm and moist atmospheres. They rely on drag of precipitation to accelerate the air towards the surface. The air then spreads out, as it impacts the ground, in the form of strong and occasionally damaging winds.

Arizona thunderstorm wind events are mainly clustered over a two month period: July and August, shown in Figure 17. This should not be a surprise given this is the peak of the monsoon. The slightly higher occurrence rate in September is predominantly over the first half of the month when the monsoon is generally still active. The diurnal cycle of thunderstorm wind events is clustered from 3:00 PM to 9:00 PM MST, with the peak at 7:00 PM MST as shown in Figure 18. This timeframe is to be expected, given the diurnal nature of monsoonal thunderstorms and their dependence on solar heating. Figure 19 shows that hourly events are not uniform over the state. Instead, severe wind events have clearly defined time ranges for each climate region. The time offsets are due to how daily heating and moisture interact with the complex terrain of the state. This diurnal difference is not surprising since thunderstorms form over the higher terrain earlier in the day. Convection then typically shifts into the valleys and lower desert areas in the late afternoon and evening. The most intense and direct solar heating occurs over the mountains during the morning hours. This differential heating produces sufficient buoyancy for earlier thunderstorm development over the mountains. Intense surface heating during the afternoon, allows convection and accompanying damaging winds to transition into valleys and lower deserts by evening, providing adequate moisture is in place. The highest thunderstorm associated wind speed measured in the state is 175 knots. This occurred in Spring Valley which is in Yavapai County on September 6, 1996 at 11:15AM MST (*Storm Data*).

V. Significant Weather Events

A. Flash Floods and Floods

Flash floods are defined by the NWS as a quick response to heavy rainfall in streams, rivers, or any flood prone area, six hours or less after the heavy rain started. Flood events are defined as longer lasting events, with rivers rising above flood stage over 6 hours to many days. For this study flash floods and floods will be combined, due to the broad grouping of numerous flood events with flash floods before NWS modernization in the mid 1990's. A great number of events prior to modernization are simply recorded as statewide flooding, leaving no way to differentiate between flash and river flooding.

In Arizona, the greatest numbers of flood events during the monsoon season are of the flash flood type. Therefore, flood events occurring during the monsoon period (July-September) will be referred to as flash floods for this study. In Arizona, flooding ranks second to extreme temperatures in causing fatalities. Over the period 1959-1999, Arizona ranked tenth in the nation in flooding deaths per million people (NCDC). In the western United States, the monthly distribution of flood events displays a summer maximum due to thunderstorms, and a

secondary winter maximum (January-March) due to winter storms. The monthly distribution of floods in Arizona is shown in Figure 20, and reveals a strong association with the summertime North American Monsoon, with nearly three fourths of floods occurring from July through September. Unlike much of the western United States, the secondary maximum is much smaller during the winter months. Figure 21 shows the distribution of floods by hour. Most of the flash floods occur between 4:00 PM and 7:00 PM similar to the peak hours of severe hail and tornadoes.

Intense rainfall over a short period of time can result in large amounts of water surging through canyons in the mountains of Arizona; however, the valleys receive numerous flash floods as well. Of particular concern in valley locations are normally dry washes, which become raging rivers in a matter of minutes due to intense rainfall. These dry washes are very common over desert terrain and crisscross many urbanized areas, exacerbating flash flood dangers. In Figure 22, the number of reported flash floods and floods for each climate region and the monthly distribution is shown. Flash flood frequencies are greatest over the Southeast followed by the Southwest climate region. These two regions contain the majority of Arizona's population, with the greatest flash flood occurrences in the Tucson and Phoenix metropolitan areas over the July through September period. The Southeast climate zone has a flash flood frequency nearly equal to all other zones combined for the months of July and August. Finally, slight secondary maxima can be seen over the Northwest, Plateau, Central and Southwest climate zones' January through March due to winter storms. Although, these events tend to be less frequent, they are typically more widespread and quite destructive as they usually involve main stem river flooding. Some historically significant aerial flood events and recurrence intervals are shown in Figure 23.

Concealed in the data is flooding associated with tropical systems. Tropical systems are infrequent over the state, occurring only once every five years, as west coast troughs typically lack the amplitude to pull the systems northward. The low proportion of tropical systems impacting the southwestern United States is illustrated in Figure 24.

However, when west coast troughs have the strength to pull tropical systems north; the effects can be devastating. During these events flash flooding and main stem river flooding often occur simultaneously. The deadliest natural disaster in Arizona's history was Tropical Storm Norma on Labor Day 1970. Flooding from Norma resulted in 23 deaths as reported by Sellers et al. (1985).

B. Dust Storms

Dust storms are often underestimated as significant weather events. They rank only behind the extreme heat/cold and flood categories for causing deaths and injuries. Most of these deaths are due to multi-car pileups on roadways and interstates. In Arizona, several different weather regimes are associated with major dust storms. Brazel and Nickling (1986) identified four of them: (1) frontal, (2) thunderstorm, (3) tropical disturbance, and (4) upper level trough and/or cut-off low.

Early season monsoon thunderstorms are the most notorious for producing deadly dust storms. July is clearly the most deadly dust storm month across the state, with nearly double the

fatalities compared to other months depicted in Figure 25. July is the transition month from dry season (March-June) to monsoon season. Thunderstorms during the first few weeks of the monsoon produce very little rainfall, as much of the lower atmosphere remains dry. Much of the rain with early monsoon season thunderstorms evaporates before reaching the surface. This leads to dry downburst winds, which organize into larger and strong outflows. These strong winds pick up the dry soil, dust and sediments pre-conditioned by the dry season, often producing long lasting dust storms with visibilities near zero. Typically, these severe storms frequently referred to as “haboobs” (hə-'büb), affect the Phoenix metropolitan area and surrounding desert areas during the monsoon season.

C. Lightning

Thunderstorms and lightning are a common occurrence in Arizona, mainly during the summer months. Arizona has an annual thunderstorm frequency comparable to many perceived thunderstorm rich Central Plains states. Total thunderstorm days range from fewer than 10 days along the lower Colorado River valley to 80 days over the White Mountains Figure 26. However, the majority of this thunderstorm activity is compacted into a three-month period (July-September). Similarly, thunderstorm lightning flash density shows a favorable comparison to many Plains States; with a maximum over the Mogollon rim and much of southeast Arizona as shown in Figure 27. Arizona lightning fatalities and injuries fall into this timeframe as well (July-September), with August the peak month as shown in Figure 28. The three month period of February-April along with December is devoid of any lightning casualties. Despite the relatively high flash density, Arizona ranks in the middle of the pack nationally for lightning casualties per capita Figure 29 and Figure 30. A major reason for this is the major population centers of Phoenix and Yuma are in lower flash density areas, unlike much of the rest of the state Figure 31 and Figure 32. Of the major population centers Tucson is located in the most lightning flash dense zone (2-8 flashes/sq. km/yr) as depicted in Figure 33. Still, the 80 fatalities and 200 injuries that have occurred over the state are quite significant.

D. Dust Devils and Gustnadoes

Although some may find it odd and even a bit humorous to include dust devils in a hazardous weather climatology, facts point to a destructive side of the often fair weather, benign vortex. Winds of dust devils can reach up to 70 miles per hour, which is certainly strong enough to do minor to moderate damage. Officially, four dust devil reports are listed in *Storm Data*; unfortunately no dust devils have been listed before 1994 or after 1997. Many dust devils in *Storm Data* are cross listed, combined, or misclassified as dust storms, making it nearly impossible to differentiate between the two. Of the four listed, two caused considerable damage in Tucson.

Dust devils are generally small vortexes not associated with thunderstorms, which are made visible by rotating clouds of dust or debris. The key here is that they are not associated with thunderstorms and more specifically do not extend upward to the cloud base of a thunderstorm. Dust devils form due to strong surface heating during hot weather. Strong heating from the sun causes the surface to become much warmer than air above the surface. Additionally, uneven heating of the surface occurs, certain terrain and vegetation type's heat up more and faster than others. As a result, the warm air has a tendency to rise in bubbles. As these bubbles of warm air

rise, cooler air from above and to the sides of the bubble rushes around and below to fill the void. This inrush of air can happen in a somewhat uneven manner, and as it reaches the center of the void filled by the bubble of rising air, can begin to spin (Renno et al. 1998). The combination of lower air pressure and heating causes the air, dust and debris inside the dust devil to rise. Wind speeds near the centers of dust devils can range from just a few miles per hour to perhaps as much as 70 miles per hour.

In Arizona gustnadoes are probably quite common among the strongest thunderstorm-produced gust fronts. Gustnadoes are short-lived, ground-based, shallow, vortexes that develop on a gust front associated with either thunderstorms or showers. They may only extend from 30 to 300 feet above the surface. Again, the key here is there will be no connection with the cloud base. They may be accompanied by rain, but usually are only visible as a debris cloud or dust whirl at or near the ground. Wind speeds can reach 60 to 80 mph, resulting in significant damage, similar to that of a F0 or F1 tornado. However, gustnadoes are not considered tornadoes. Gustnadoes are not associated with storm-scale rotation (they do not extend up into the cloud) that is involved with true tornadoes. They are more likely to be associated visually with a shelf cloud that is found on the forward side of a thunderstorm near strong outflow winds.

VI. Other Weather Related Events

A. Drought

Drought is defined most succinctly as insufficient water to meet needs (Redmond, 2002). Many people are unaware that it is possible to have a drought in the desert; which is an arid environment. Therefore, Arizona droughts seem to take people by surprise, even though they have been worsening for years. The composite Palmer Drought Severity Index (1895-1995 in Figure 34 and 1950-1995 in Figure 35) shows that drought across the state has been steadily worsening over the past several decades. A drought is often looked upon as a long term problem until it affects us in the short term and our everyday life. Figure 36 shows the areal extent of historic droughts and their recurrence interval in years. A federal emergency declaration (allows government aid) was issued for the 1973-77 drought by Federal Emergency Management Agency (FEMA). Figure 37 shows the Arizona statewide water year precipitation from 1896 to 2005. The red highlighted regions are periods of low precipitation. Notice how they correspond favorably to historic droughts. It is difficult to measure state drought effects in monetary or casualty statistics since its effects are subtle, gradual and often linked to some other hazardous event (such as heat and wildfires). However, it is almost certain that when considering a drought's entire duration, its damaging effects are comparable or even greater than other more visible hazardous weather types.

B. Wildfires

Wildfires pose an increasingly significant threat to life, property and the economy of Arizona. High impact wildfires have been far more common over the last decade than previous several decades. In fact, three of the most serious wildfires, Rodeo-Chediski in 2002, Aspen in 2003, and Cave Creek in 2005 have occurred over the past five years. Both the Rodeo-Chediski and Aspen fires were given the dubious distinction of being declared major disasters by FEMA. These are the only two fires to be given this classification in the state's fire history. The increase can be attributed to accumulation of living and dead fuels coupled with extended

drought conditions. Another factor is the population boom of the past several decades as the urban-forest interface merges. Overall, the greatest threat is at higher elevation where fuels are more supportive of extreme fires. Figure 38, Figure 39 and Figure 40 show wildfire hazard severity and risk, notice that the greatest threat is at higher elevation, where fuels are more supportive of extreme fires.

C. Snow and Ice

Arizona winters are highly variable with regards to temperature and snowfall from one year to the next. The impact of any given Arizona winter is highly dependant on the type of storm track that becomes established. Ideally for wet winters, a track from the Pacific Ocean, south to San Diego and across the state develops. Cold, dry winters typically see a storm track along the western Rockies from the Great Basin southeast to New Mexico, although this track can also provide snowfall for northern Arizona. The variability in storm track and subsequent Arizona winters are influenced by ENSO patterns. El Nino is an abnormal warming of the equatorial Pacific Ocean waters and tends to strengthen the southern jet stream. This jet stream develops an orientation from the central Pacific eastward across Arizona. Pacific storm systems and associated moisture follow this track, bringing precipitation, often as heavy snowfall, to the state. Conversely, a La Nina pattern develops when there is abnormal cooling of the ocean waters near the equatorial Pacific. This leads to a northward shift of the jet stream with an orientation over the Northwest United States. Under this pattern Arizona is typically influenced by a ridge of high pressure which blocks moisture and incoming systems leading to warm wintertime temperatures. However, many winters are not easily classified as El Nino or La Nina and show high variability within the winter year itself.

The main time period for winter weather in Arizona is from November through March, with the peak in January and February. The heaviest snow typically occurs along the Mogollon rim where yearly snowfall amounts in excess of 100 inches are common. Figure 41 and Figure 42 shows the yearly snowfall across the state. Notice the extreme snowfall variability, with amounts from zero over the southwest part of the state to up to 200 inches over the Mogollon rim. Figure 43 and Figure 44 depict the mean annual snowfall days over the state, which further illustrates just how different winters are from one part of the state to the next.

Cold temperatures are also quite common over the northern portion of the state and at elevations above 7000 feet in the southeast. In these locations low temperatures fall to well below zero. Exposure to the cold temperatures is a major contributor to the total fatalities statistics in the Heat/Cold hazardous weather category. Cold temperatures often act in unison with heavy snowfall events that can strand and isolate people, allowing exposure to the cold to take hold. This is especially the case for those engaged in outdoor activities from November through March.

Travel in Arizona's diverse terrain can also be hazardous during storms. Many highways that traverse the state see elevation changes of several thousand feet over a short distance. These changes in elevation can lead to rapid changes in visibility and deteriorating road conditions catching motorists off guard. Vehicle accidents during winter storms account for a large percentage of the fatalities that fall in the Snow/Ice hazardous weather category. Figure 45 shows the snow and ice storm frequency by month over the state.

VII. Summary

The results of this study can be summarized in the following:

- The extremely low population density (45.2 people per sq mi) of much of Arizona has likely resulted in many hazardous weather events not being reported, especially those which occur away from population centers. Additionally, there is a significant bias to reports along roadways in rural areas.
- The greatest weather hazard in Arizona is exposure to extreme temperatures (Extreme Heat/Cold category) which is responsible for the largest number of fatalities. The highest component is extreme heat and this is actually an even greater killer than the data depicts.
- Arizona has an annual thunderstorm frequency comparable to many Plains States.
- Tornadoes are a more common occurrence in Arizona than most people are aware, primarily over the central valleys and plateau regions. For the state, the average number of reported tornadoes is approximately 4 per year.
- A high percentage of reported tornadoes in this state are weak, either F0 or F1.
- Hail ranks only as the third most frequent hazardous weather type, but is still responsible for a considerable percentage of property and crop damage. The state averages 12 severe hail events per year.
- Arizona averages 29 severe wind events per year, with the greatest concentration over the southern most climate regions.
- Arizona thunderstorm wind events are mainly clustered over a two month period: July and August.
- In Arizona, flooding ranks second to extreme heat in the number of reported fatalities. Arizona ranks tenth in the nation in flooding deaths per capita. The Southeast climate zone has a flash flood frequency nearly equal to all other zones combined for the months of July and August.
- Dust storms are often underestimated as significant weather events and rank only behind extreme heat/cold and flooding for deaths and injuries.
- Despite a relatively high flash density, Arizona ranks in the middle of the pack nationally for lightning casualties per capita.

- Dust devils in Arizona can have a surprisingly destructive side, with winds up to 70 miles per hour. Dust devils are often cross-listed with dust storms making it hard to obtain accurate information on historically dust devil damage.
- It is difficult to measure state drought effects in monetary or casualty form, since its effects are subtle, gradual, and often linked to some other hazardous event (heat and wildfires).
- High impact wildfires have been far more common over the last decade than previous several decades.
- The main Arizona wintertime hazardous weather aspect is exposure to the cold temperatures and heavy snowfall over the higher terrain of northern and eastern parts of the State.

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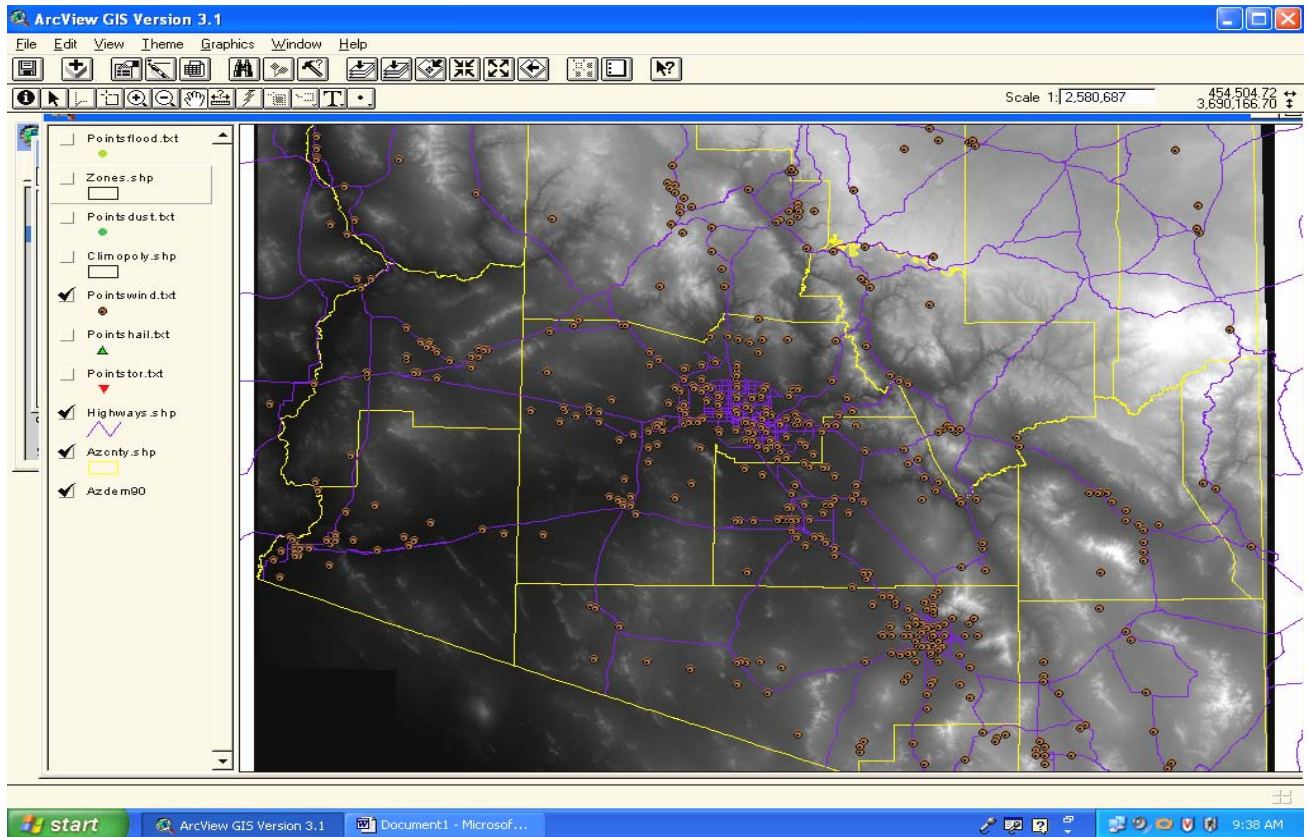


Figure 1. Example of *Storm Data*, historical, and spotter reports skewed toward cities and major highways for wind events.

Arizona Climate Regions

from Sellers and Hill (1974)

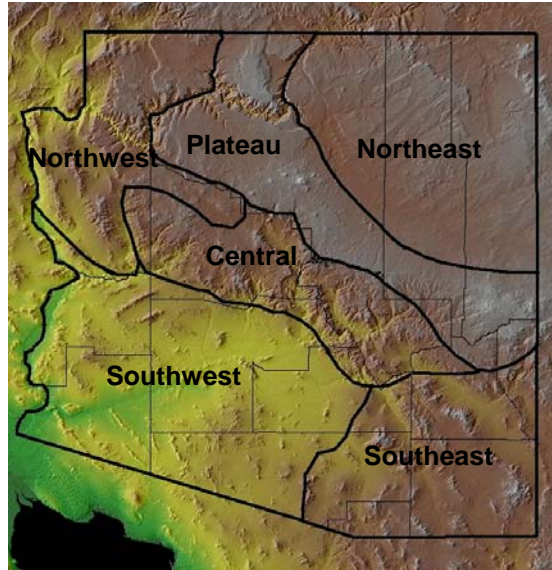
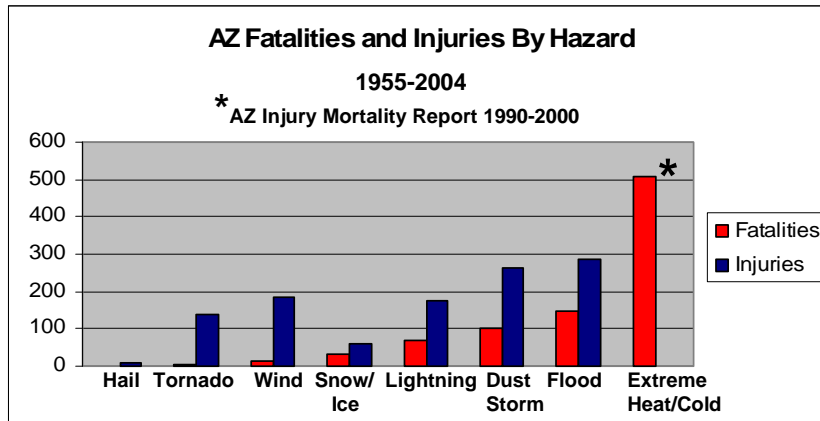


Figure 3. Arizona climate regions used in this study as defined by Sellers and Hill (1974).

Arizona Deaths and Injuries by Hazardous Weather Type



Data Sources:

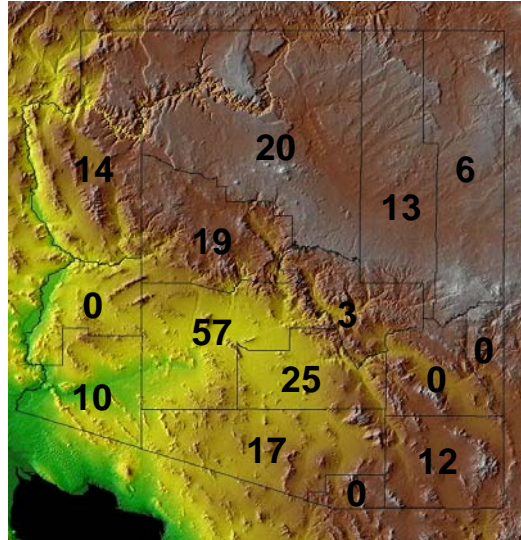
- Arizona Climate- *The First Hundred Years (Sellers, Hill and Sanderson-Rae)*
- NCDC Storm Data 1955-2004
- SPC Events Database 1950-2004
- NCDC Storm Events Database: Online- www4.ncdc.noaa.gov/cgi-win/wwwcgi.dll?wwEvent~Storms
- DOT Fatality Analysis Reporting System: Online- www-fars.nhtsa.dot.gov
- University of Arizona Storm Database: Online- ag2.calsnet.arizona.edu/cgi-bin/storms.cgi
- Injury Mortality Among Arizona Residents, 1990-2000 Report (March 2002)

Figure 4. Injures and fatalities in Arizona sub-divided by weather event for the period of 1955 to 2004

Arizona Tornadoes 1950-2004

Number of Tornadoes Reported By County

Apache:	6
Cochise:	12
Coconino:	20
Gila:	3
Graham:	0
Greenlee:	0
La Paz:	0
Mohave:	14
Maricopa:	57
Navajo:	13
Pima:	17
Pinal:	25
Santa Cruz:	0
Yavapai:	19
Yuma:	10



Arizona Averages 4 Tornadoes per Year

Figure 5. Total tornadoes in each county from 1950 to 2004

Mogollon Rim Convergence Zone (MRCZ)

A region of non-supercell tornadoes

Blanchard (2000)

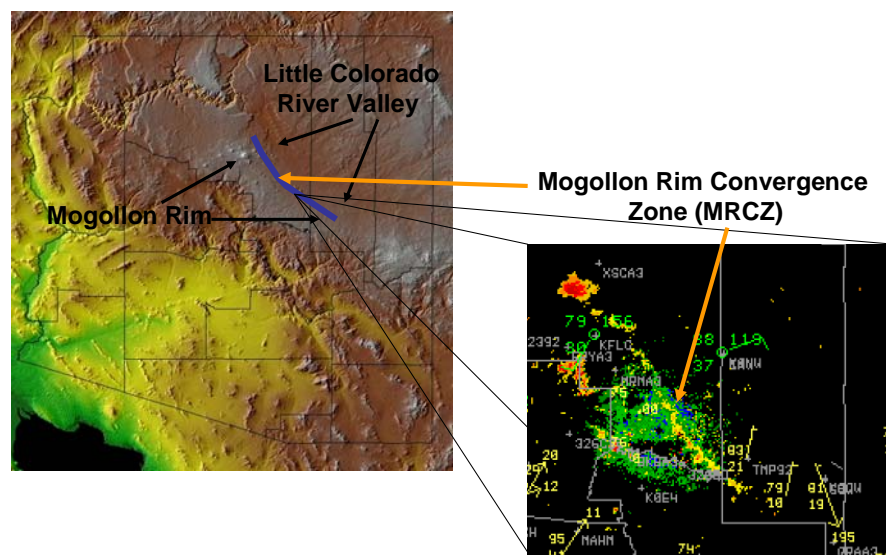


Figure 6. Mogollon Rim Convergence Zone (MRCZ) noted by Blanchard (2000)

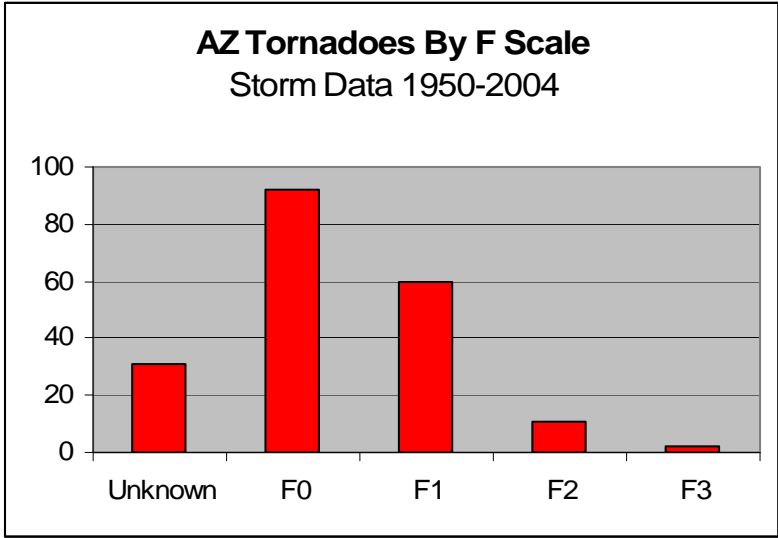


Figure 7. Tornado frequency by F scale from 1950 to 2004

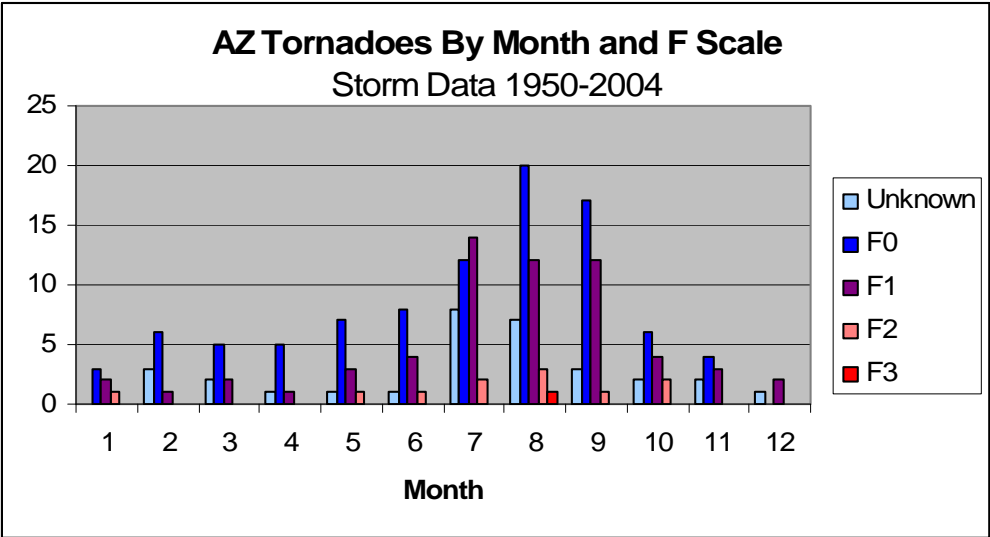


Figure 8. Tornado frequency by month and F scale from 1950 to 2004

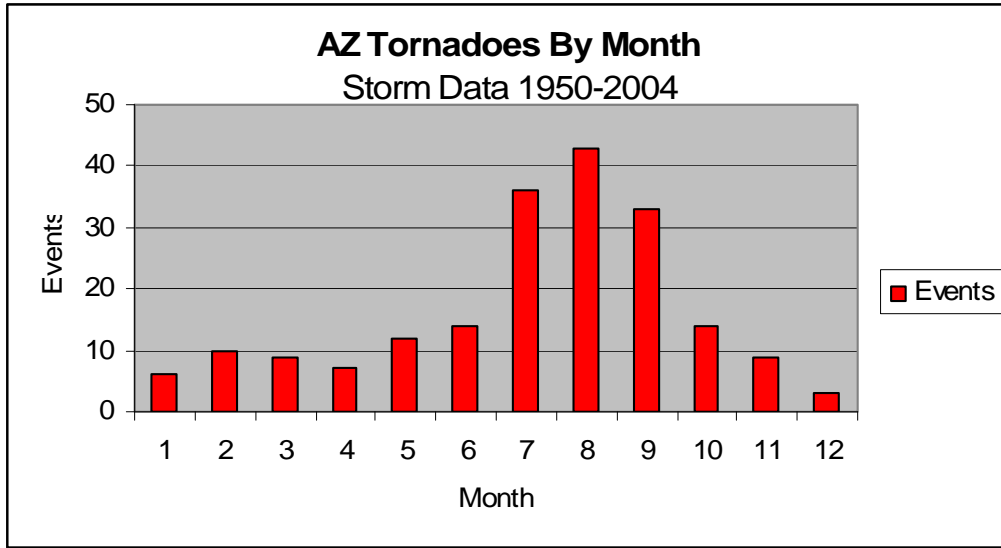


Figure 9. Tornado frequency by month from 1950 to 2004

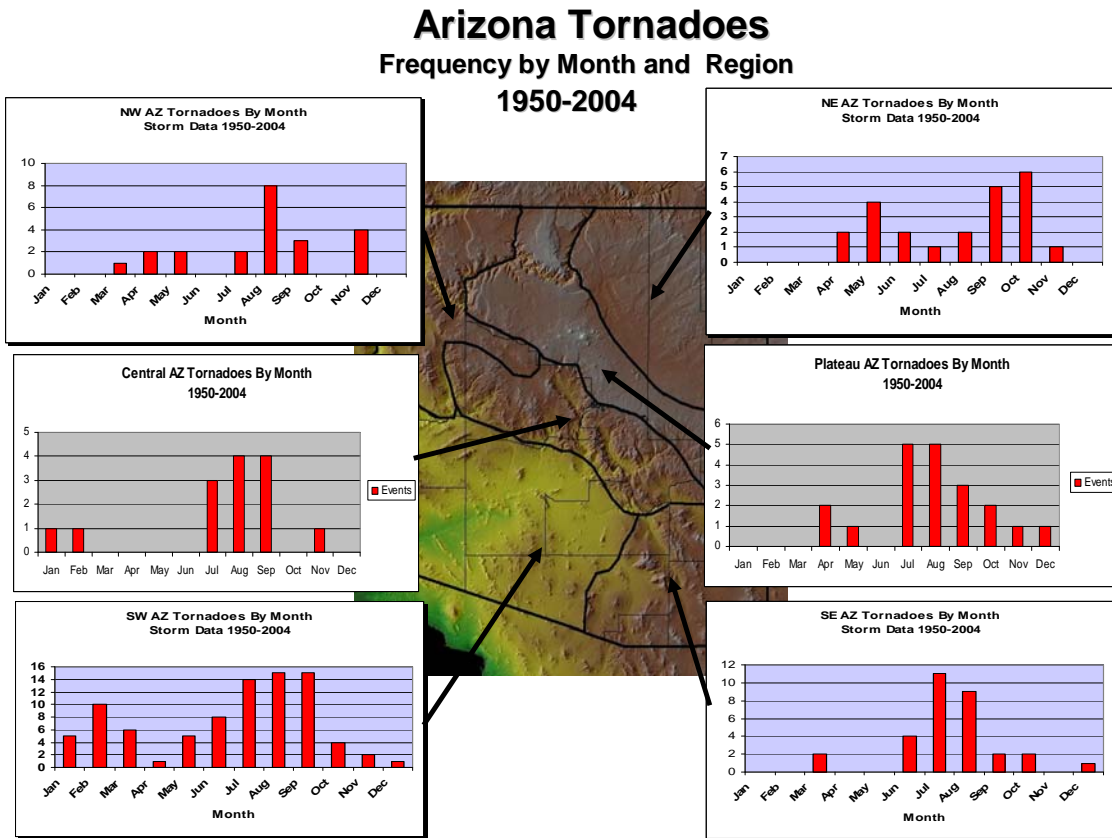


Figure 10. Tornado frequency by month and climate region from 1950 to 2004

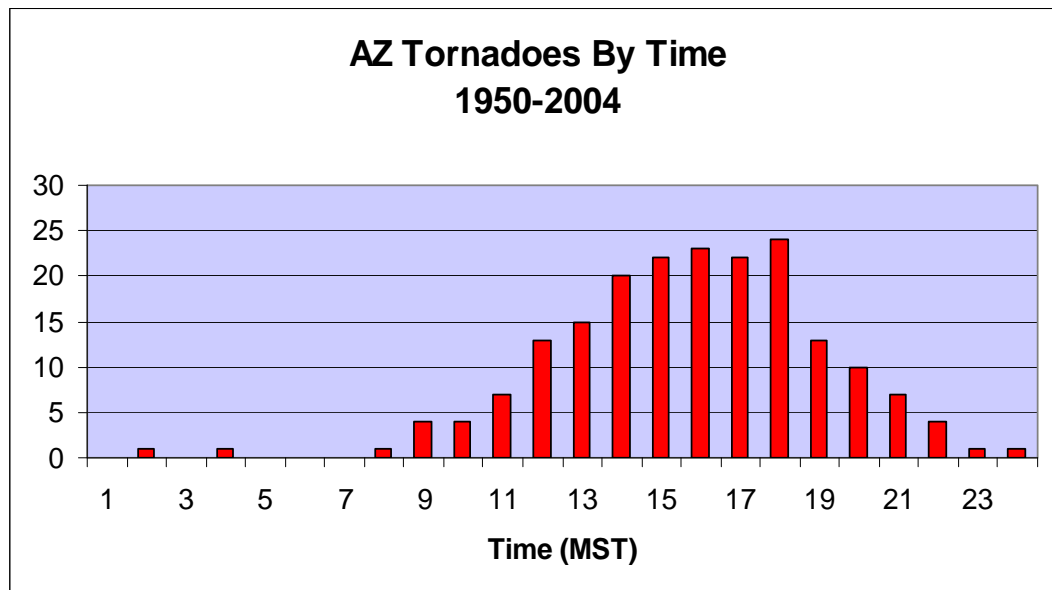


Figure 11. Tornado frequency by hour (Time MST) from 1950 to 2004

Arizona Tornadoes by Month and Region 1950-2004

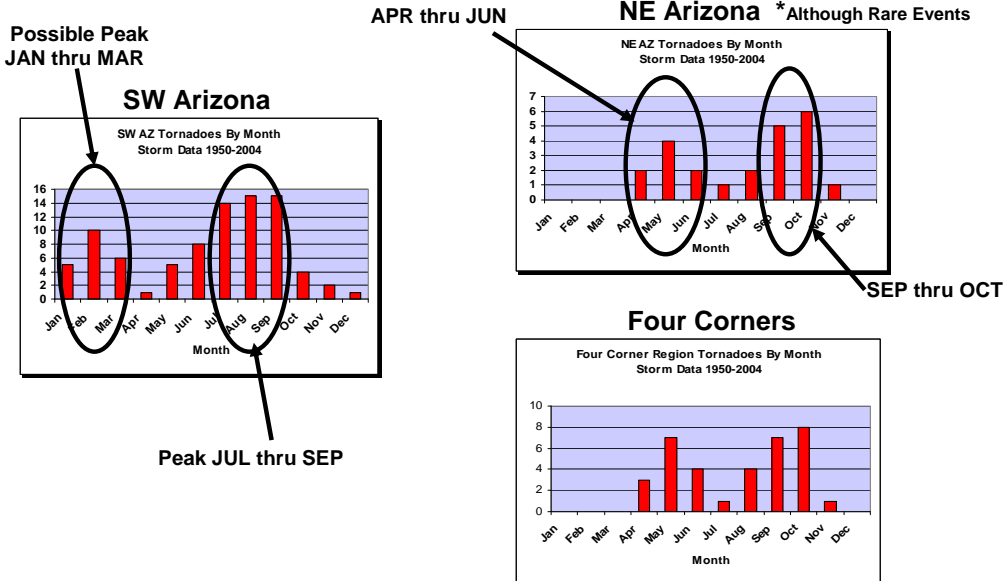
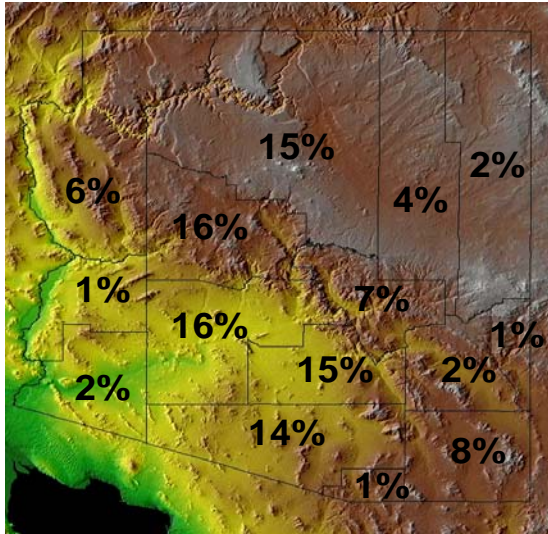


Figure 12. Secondary peak in the annual tornado frequency for the Southwest and Northeast climate regions from 1950 to 2004. The frequency for the four corners region of the United States is included for comparison with the Arizona Northeast climate region.

Arizona Hail

1955-2004

Percentage of Hail Events By County



Arizona Averages 12 Hail Events per Year

Figure 13. The percentage of hail events by County from 1955 to 2004

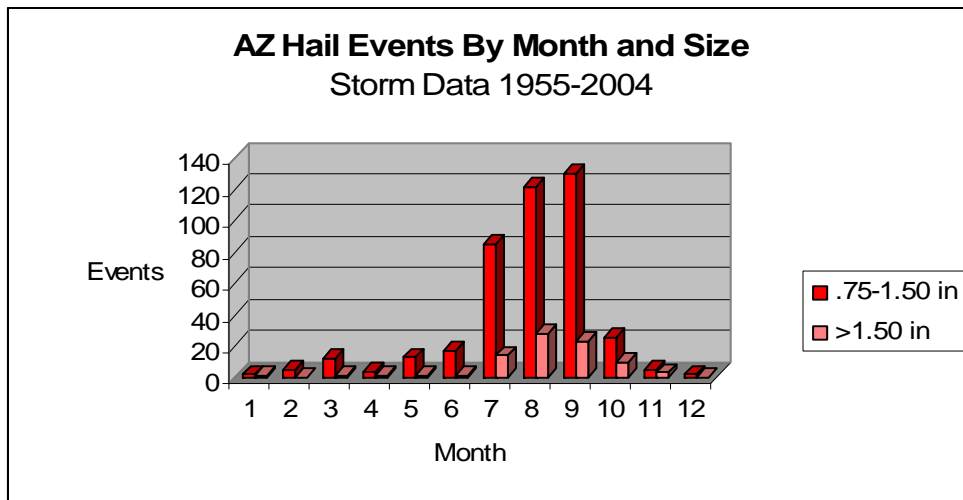


Figure 14. Hail frequency by month and size from 1955 to 2004

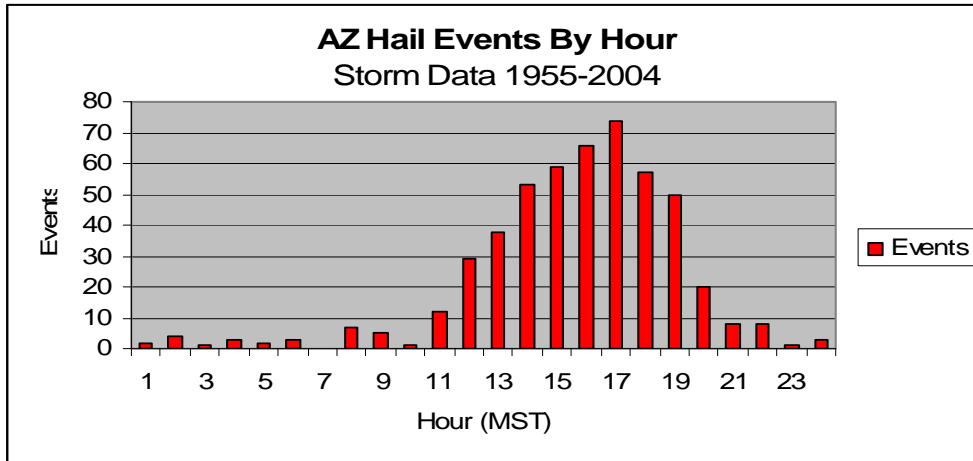
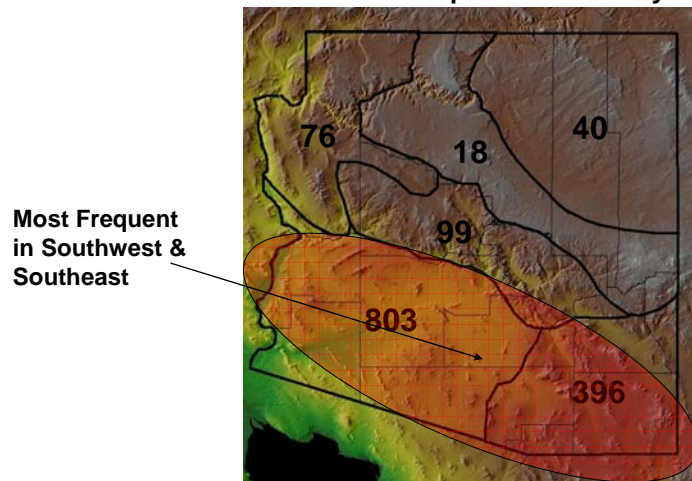


Figure 15. Hail frequency of hour from 1955 to 2004

Arizona Thunderstorm Wind 1955-2004

Total Number of Reported Events by Region



Arizona Averages 29 Thunderstorm Wind Events per Year

Figure 16. Thunderstorm wind events by climate region from 1955 to 2004

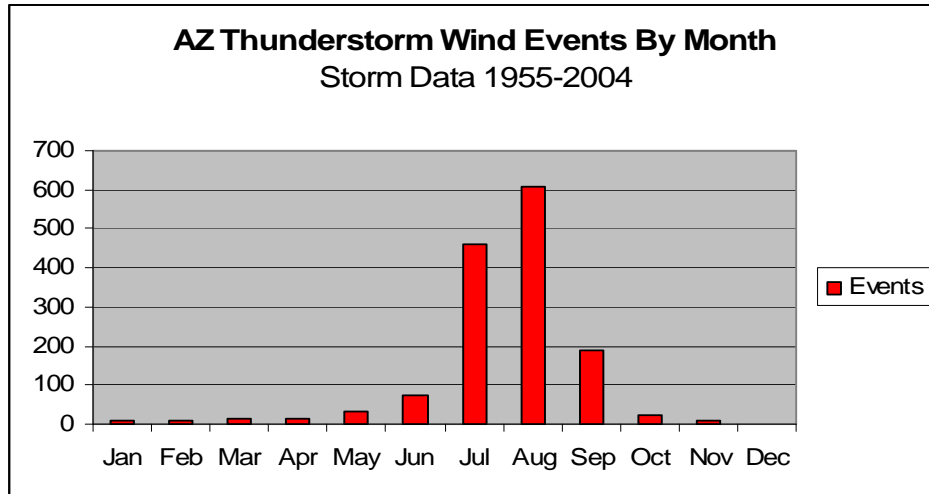


Figure 17. Thunderstorm wind frequency by month from 1955 to 2004

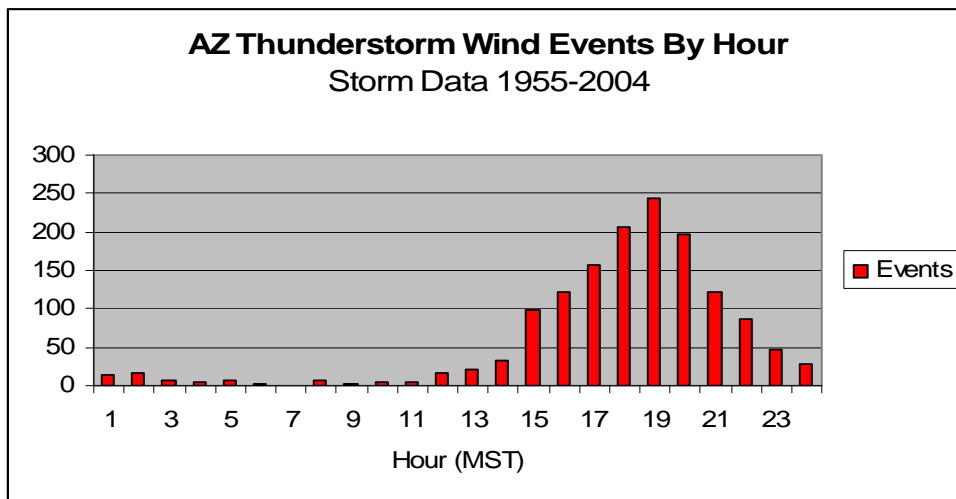


Figure 18. Thunderstorm wind frequency by hour from 1955 to 2004

Arizona Thunderstorm Wind

Frequency by Hour and Region

1955-2004

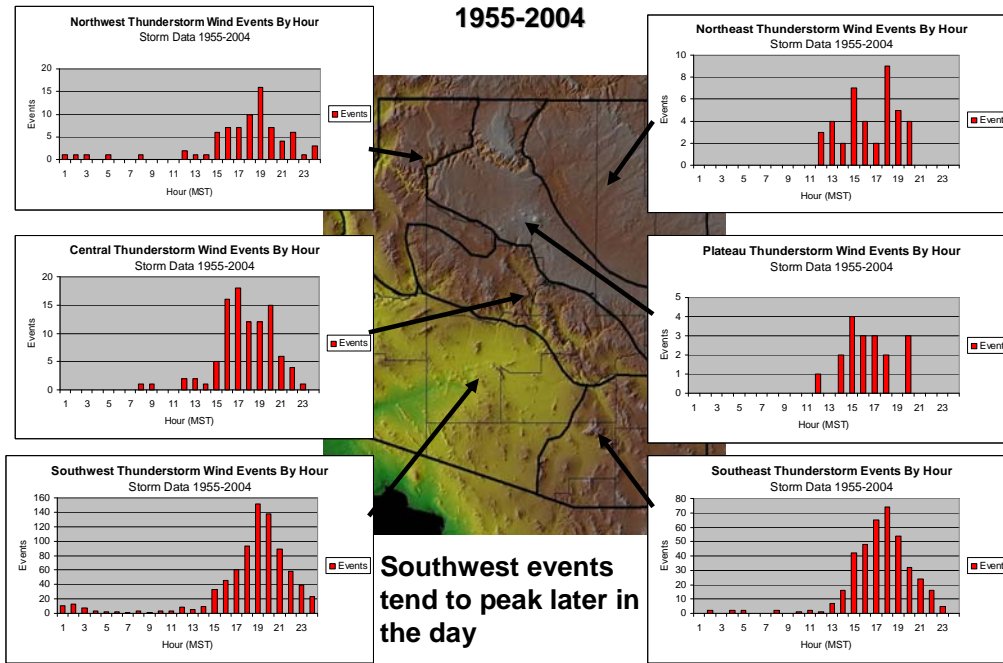


Figure 19. Thunderstorm wind frequency by hour and climate region from 1955 to 2004

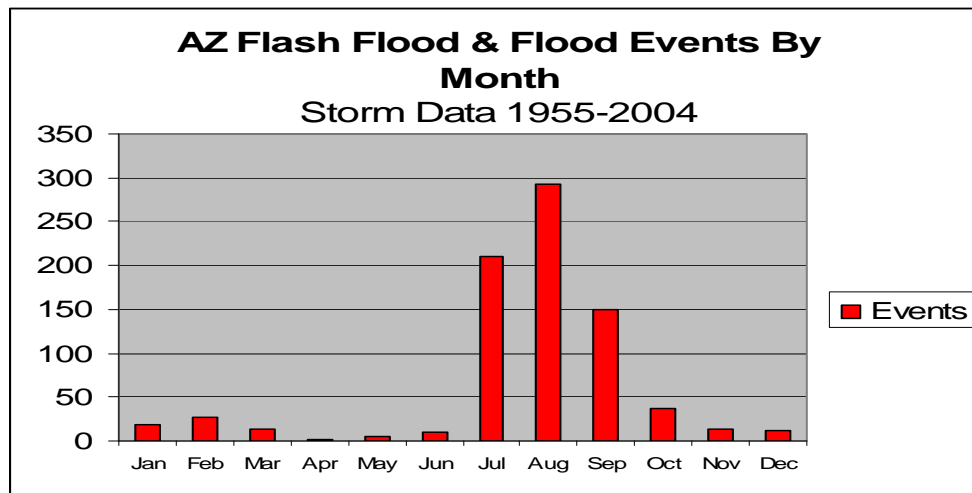


Figure 20. Flash flood and flood frequency by month from 1955 to 2004

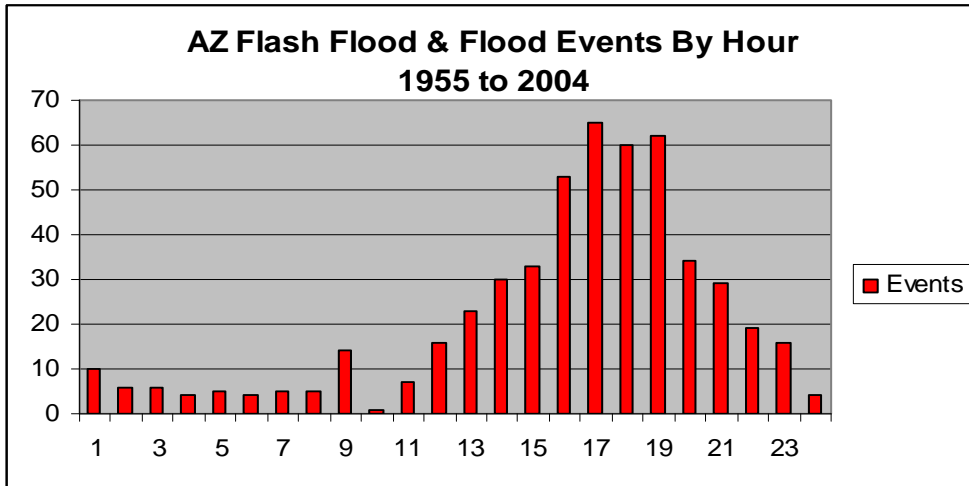


Figure 21. Flash flood and flood frequency by hour from 1955 to 2004

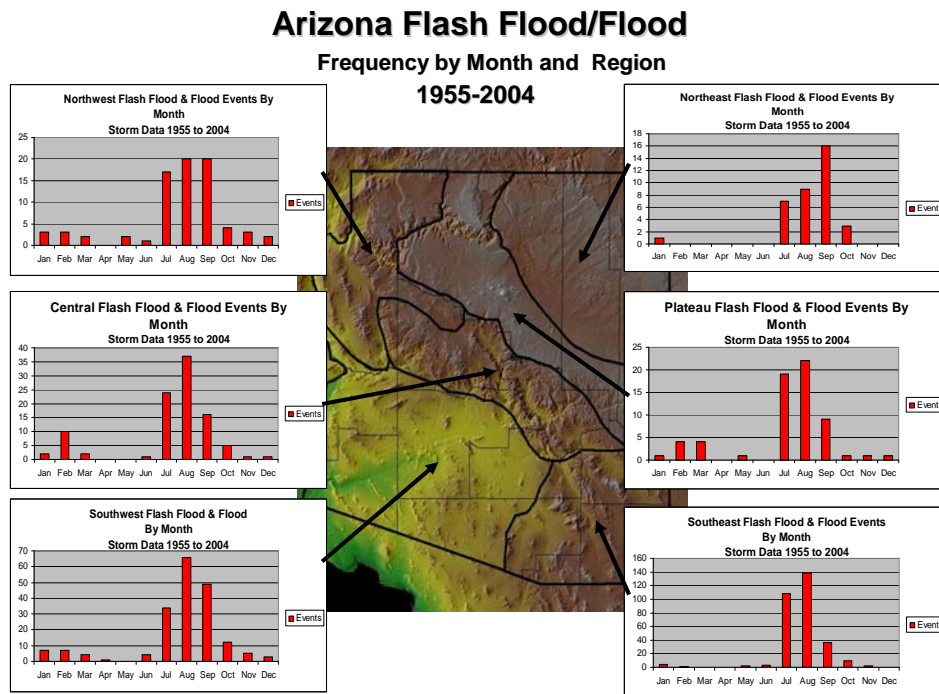


Figure 22. Flash flood and flood frequency by month and climate region from 1955 to 2004

Areal Extent of Floods

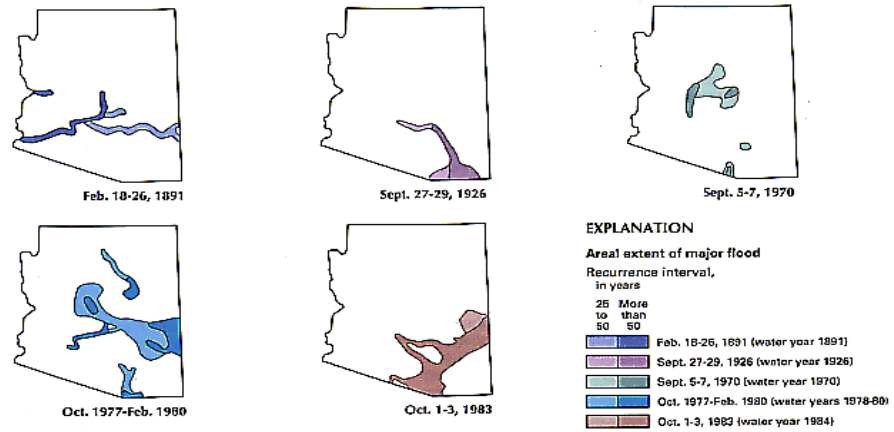


Figure 23. Areal extent of some historical floods in Arizona (U.S Geological Survey)

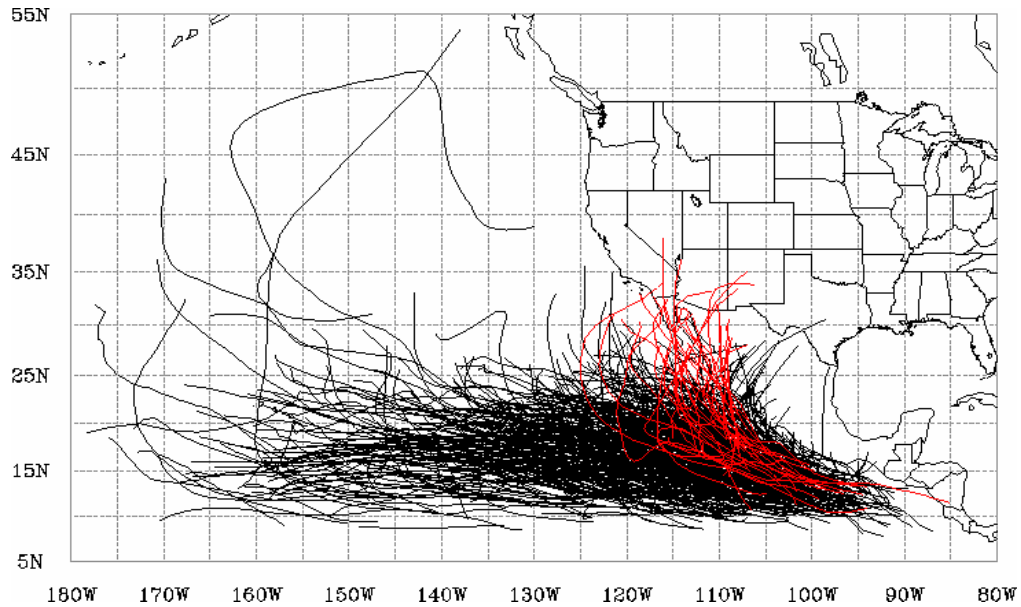


Figure 24. Tropical system tracks over the Pacific and southwest U.S. 1958-2003. Red denotes tracks over the southwest states, black are tracks over the Pacific and dissipation over Mexico. (Corbosiero)

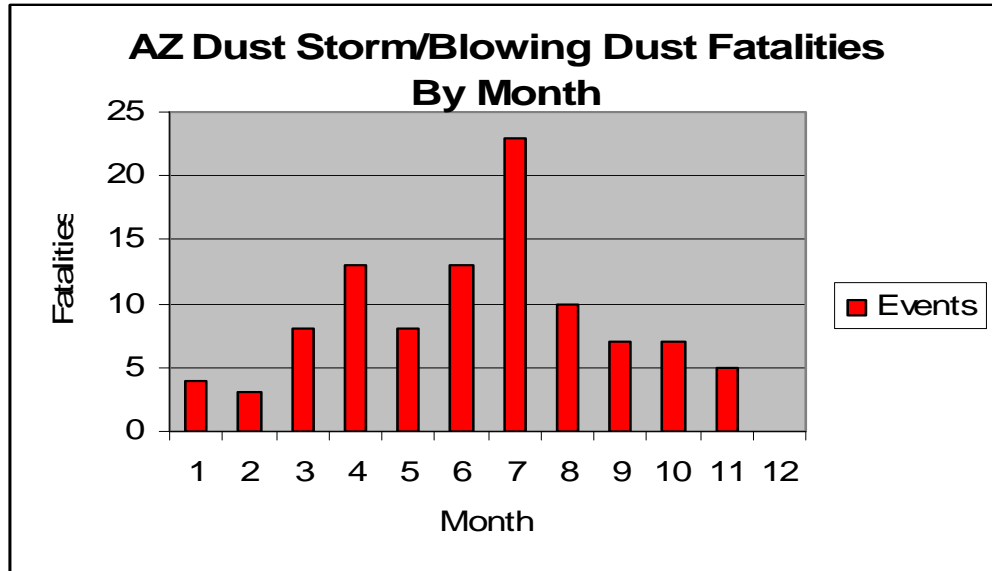


Figure 25. Frequency of dust storm fatalities by month from 1955 to 2004

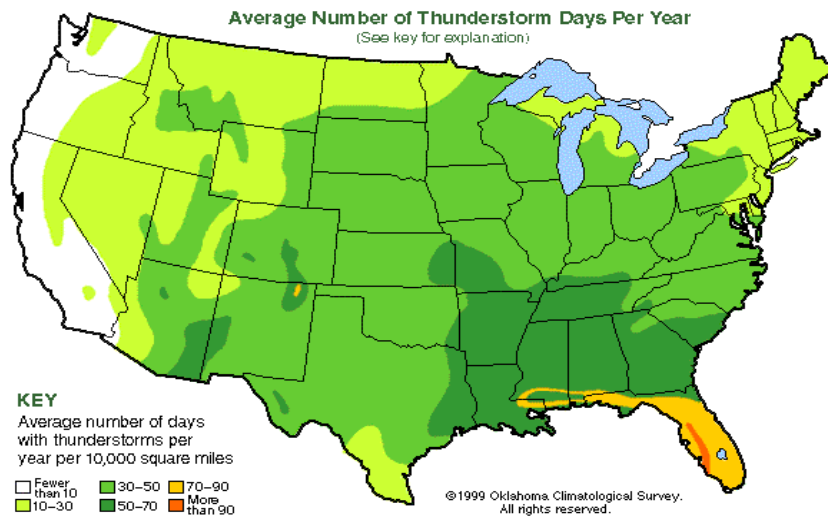


Figure 26. Average number of thunderstorm days (Oklahoma Climatological Survey)

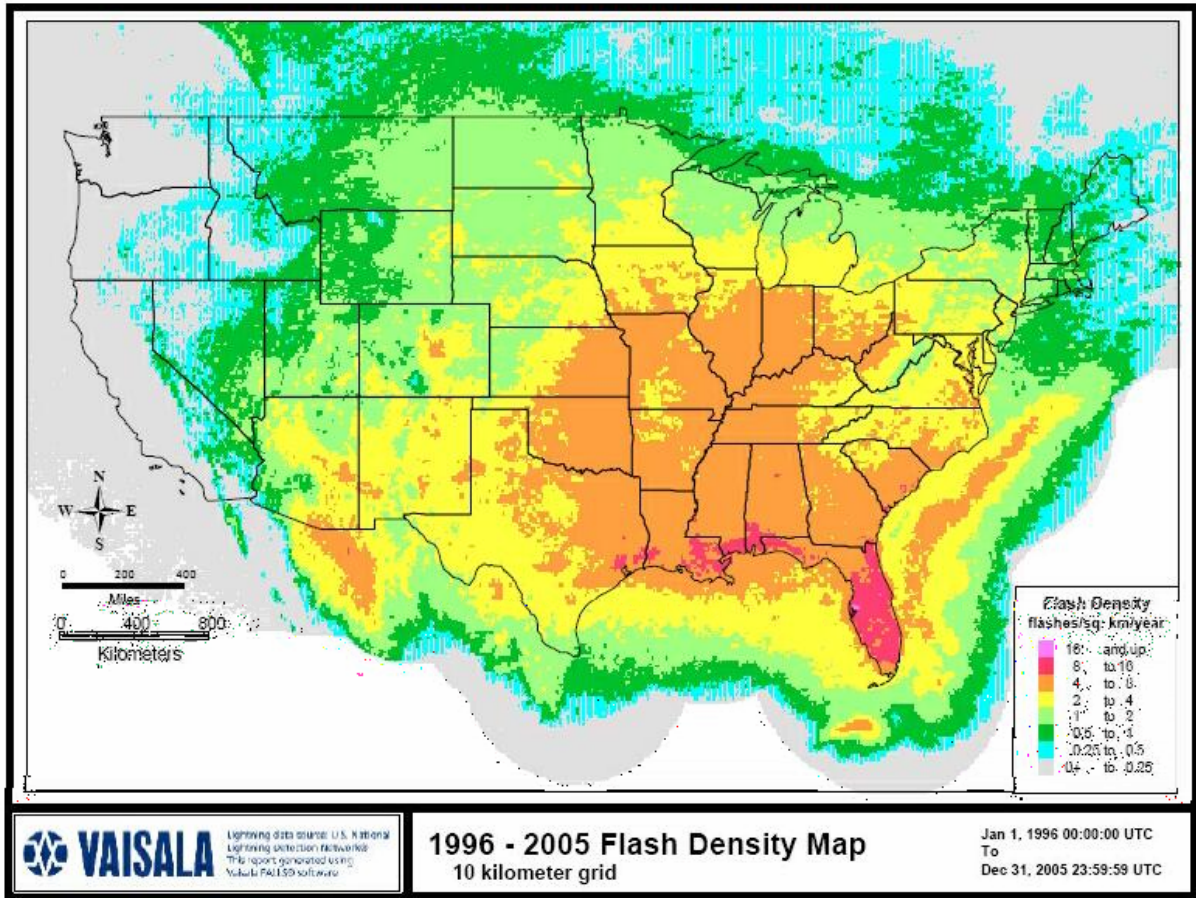


Figure 27. The ten year flash density for the U.S from 1996-2005 (Vaisala Inc.)

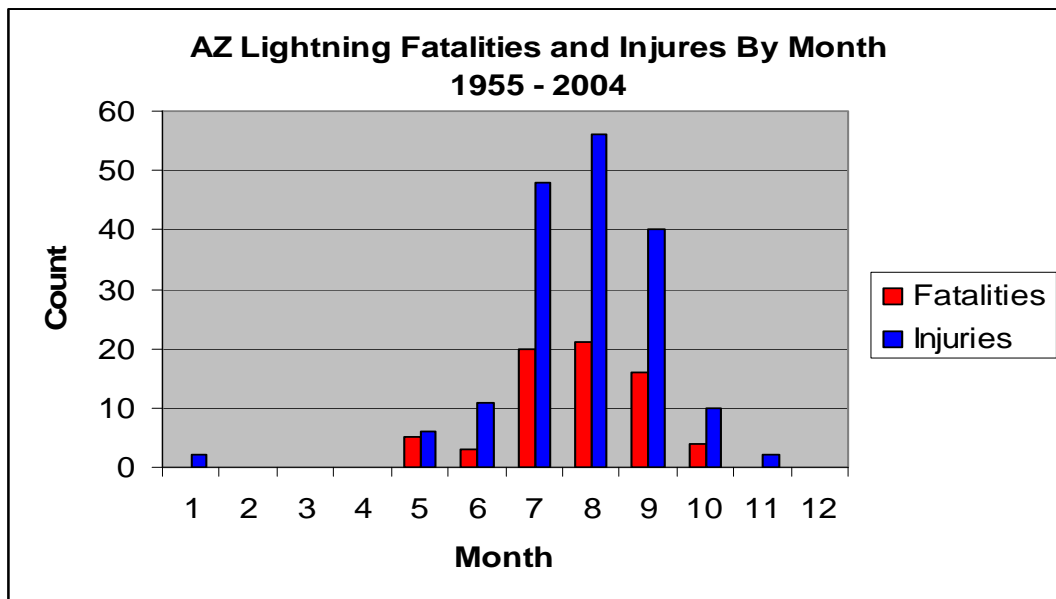


Figure 28. Lightning Fatalities and Injuries by month from 1955 to 2004

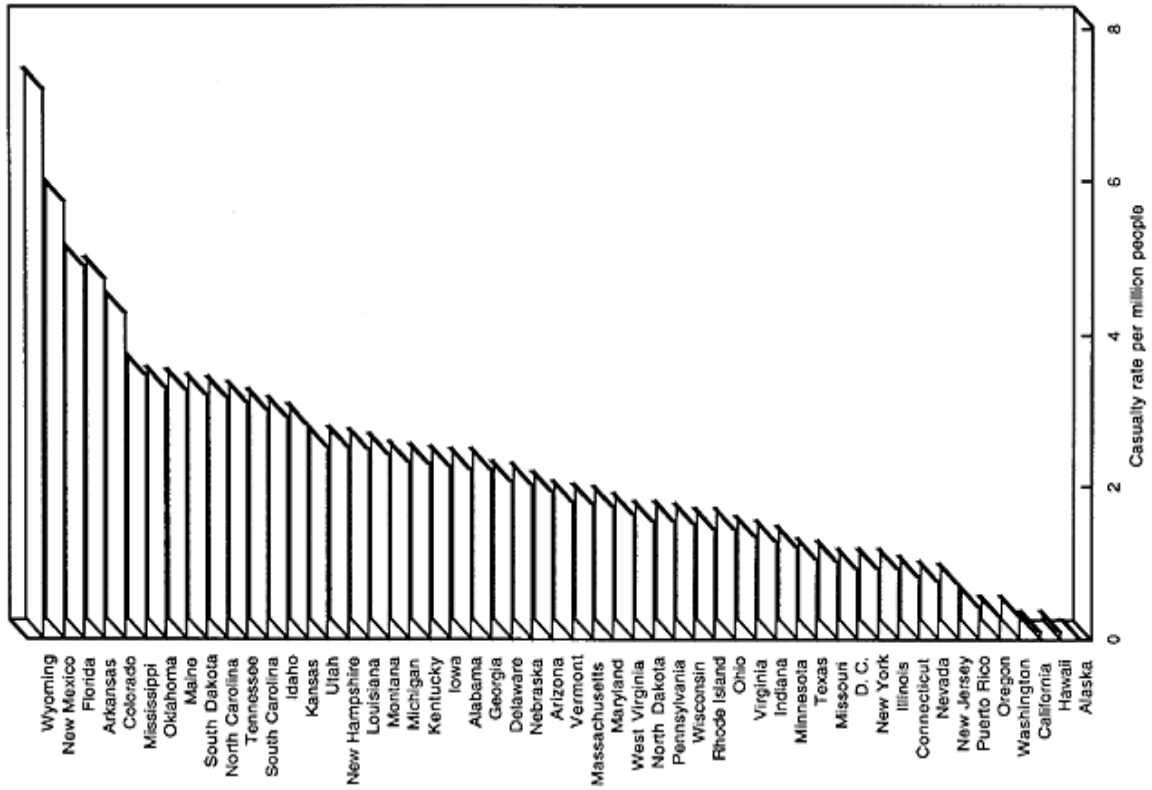


Figure 29. Rate of lightning casualties (deaths and injuries combined) per population ordered by state from 1959 to 1994 (Curran, et. al, 2000)

State	Fatality Rate Per Million People from 1997 to 2006	Rank of Fatality Rate Per Million	State	Fatality Rate Per Million People from 1997 to 2006	Rank of Fatality Rate Per Million
Wyoming	1.21	1	Virginia	0.13	26
Colorado	0.70	2	Missouri	0.13	27
Montana	0.55	3	Texas	0.12	28
Utah	0.49	4	Ohio	0.11	29
Florida	0.44	5	Maryland	0.11	30
Arkansas	0.41	6	West Virginia	0.11	31
South Dakota	0.40	7	New Jersey	0.11	32
Mississippi	0.39	8	Iowa	0.10	33
Alabama	0.36	9	Michigan	0.10	34
Louisiana	0.36	10	Indiana	0.10	35
Vermont	0.33	11	Pennsylvania	0.10	36
South Carolina	0.32	12	Illinois	0.09	37
Rhode Island	0.29	13	Puerto Rico	0.08	38
Georgia	0.26	14	Kansas	0.07	39
North Carolina	0.24	15	Connecticut	0.06	40
Nebraska	0.23	16	Nevada	0.05	41
Oklahoma	0.23	17	Minnesota	0.04	42
Tennessee	0.21	18	New York	0.04	43
Arizona	0.18	19	Massachusetts	0.03	44
Kentucky	0.17	20	Oregon	0.03	45
New Mexico	0.16	21	California	0.02	46
Maine	0.16	22	Alaska	0	47
North Dakota	0.16	23	Delaware	0	48
Idaho	0.15	24	D.C.	0	49
Wisconsin	0.15	25	Hawaii	0	50
			New Hampshire	0	51
			Washington	0	52

Figure 30. Rate of lightning fatalities per population ordered by state from 1997 to 2006. Data and image provided courtesy of Vaisala NLDN (Vaisala Inc.)

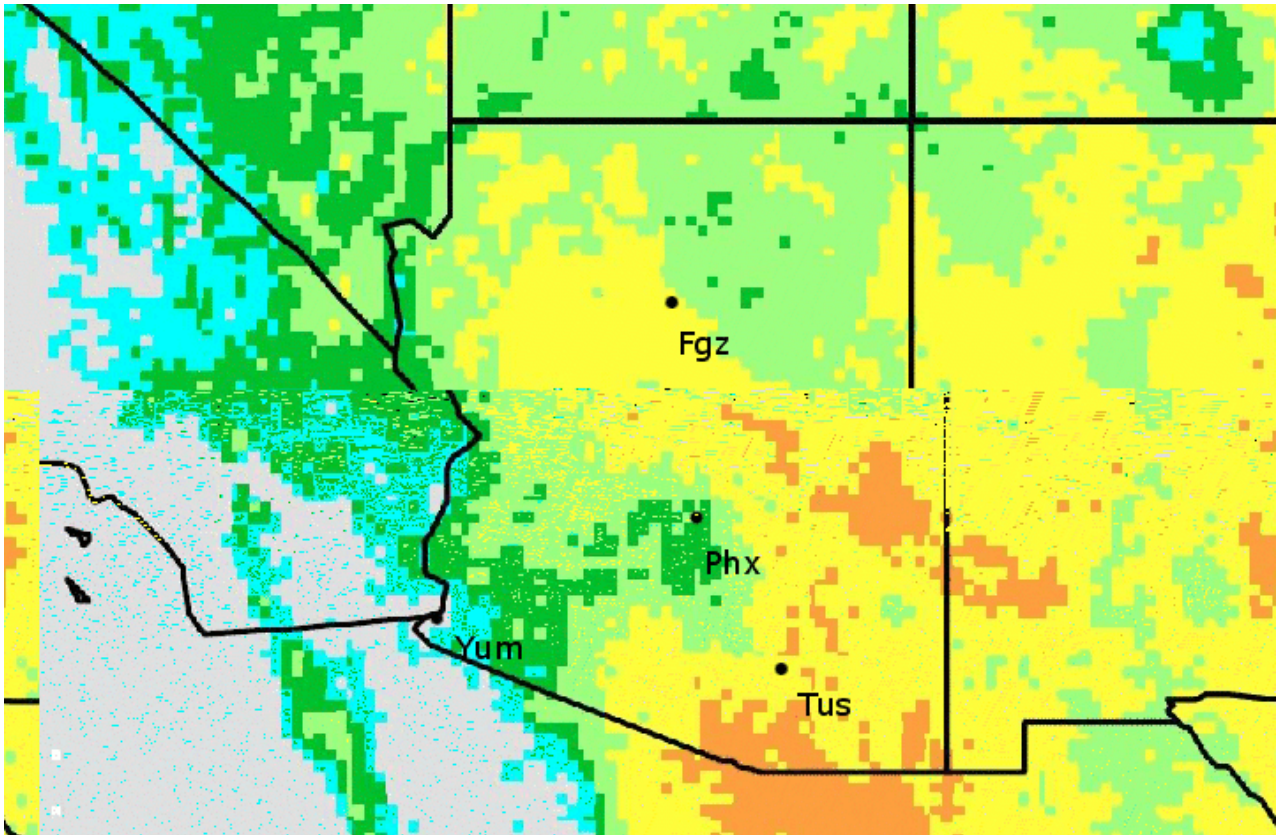


Figure 31. A close up of the ten year flash density for Arizona from 1996-2005 (Vaisala Inc.)

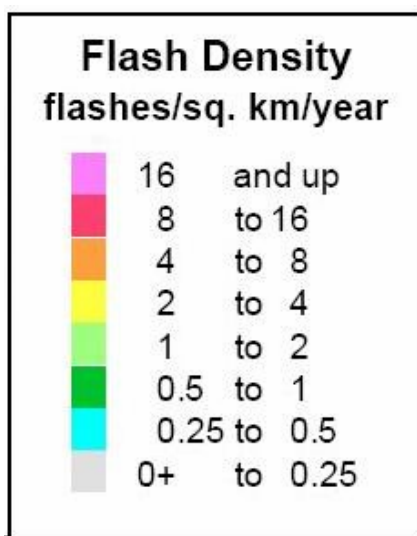


Figure 32. Flash density key (Vaisala Inc.)

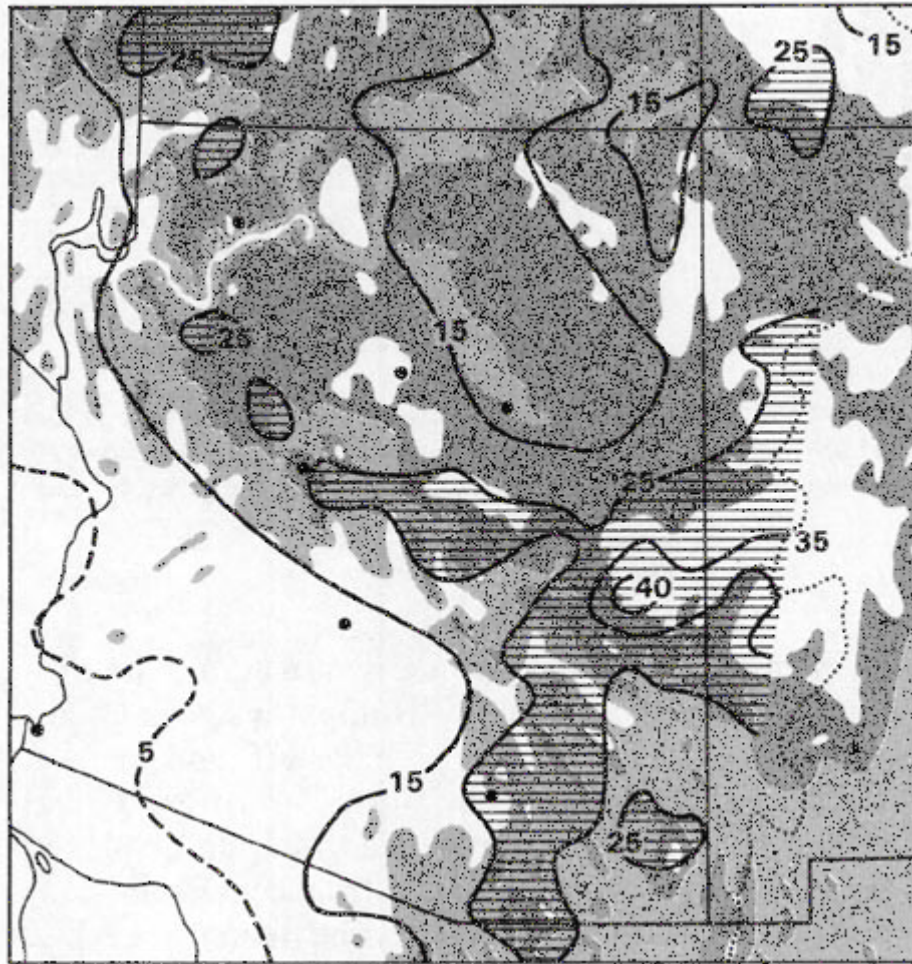


Figure 33. Flash densities (flashes per 100 km² per monsoon season) for 20 km x 20 km boxes during all hours for 1985-1990 (Watson, et. al 1993).

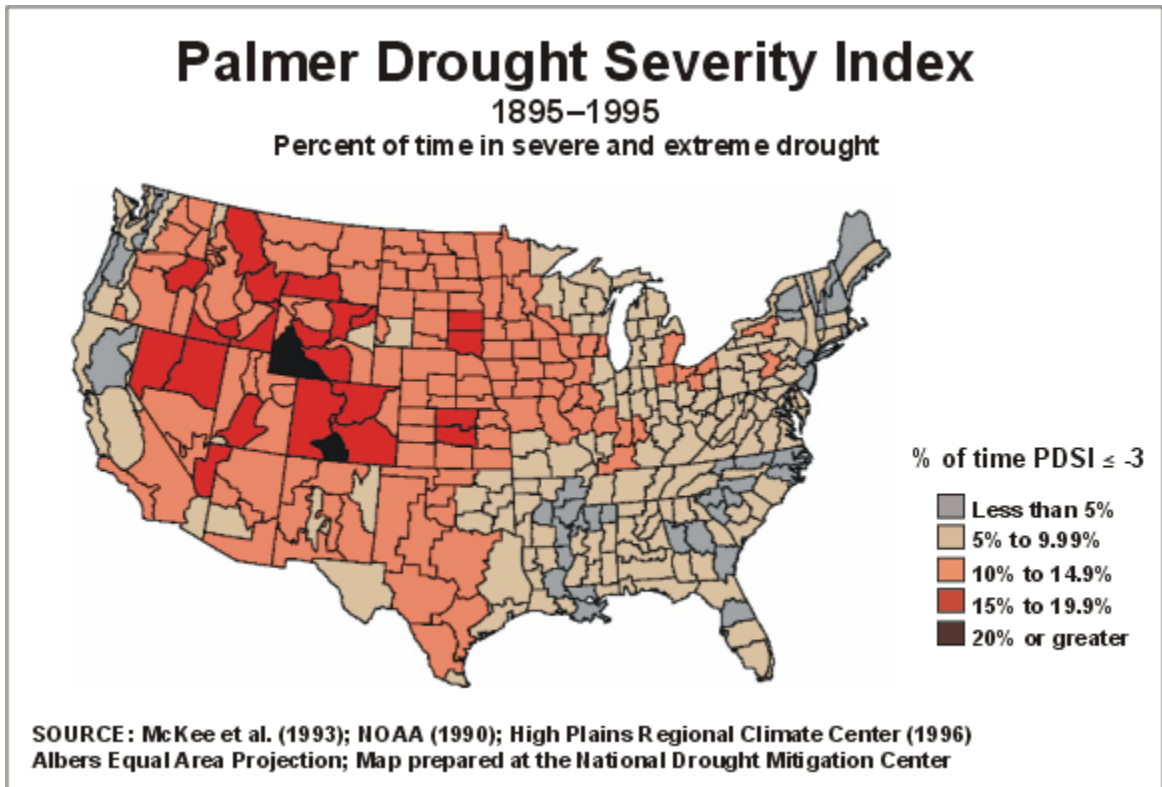
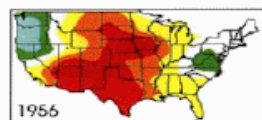
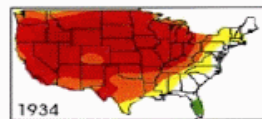


Figure 34. National Palmer Drought Severity Index (1895-1995)
(National Drought Mitigation Center)

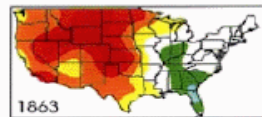
DROUGHT EXTENT and LENGTH



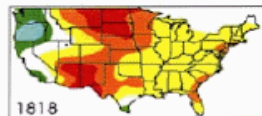
1950s
5 years



1930s
8 years



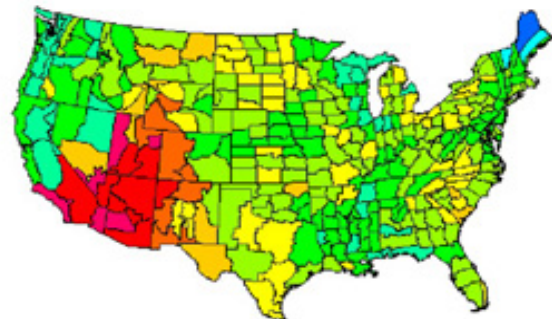
1860s
7 years



1810s
6 years

DRY ■ ■ ■ ■ ■ ■ WET
Drought Index

Composite Palmer Drought Severity Index
1950 - 1995



≤ -4 ≤ -3 ≤ -2 ≤ -1 ≤ 0 ≤ 1 ≤ 2 ≤ 3 ≤ 4 > 4

Figure 35. Drought Extent, Length and Composite Palmer Drought Severity Indexes for Arizona (1950-1995) (Climate Prediction Center)

Areal Extent of Droughts

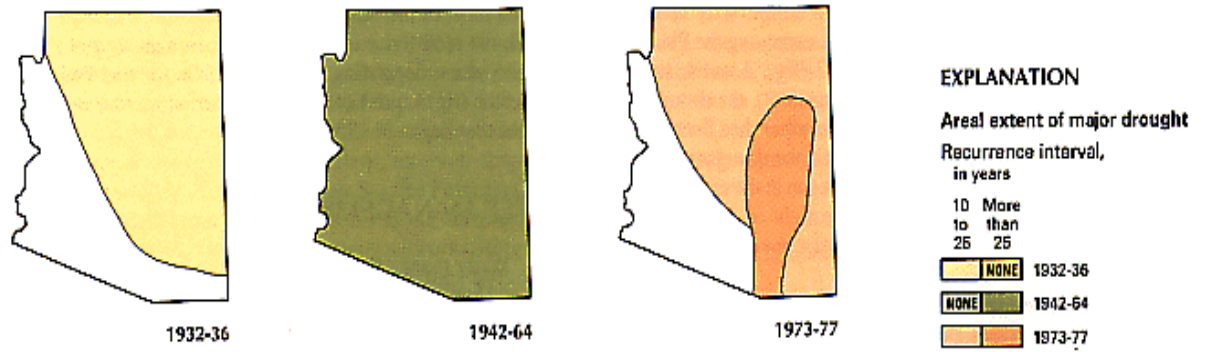


Figure 36. Areal extent of some historical droughts in Arizona (Paulson, et al.)

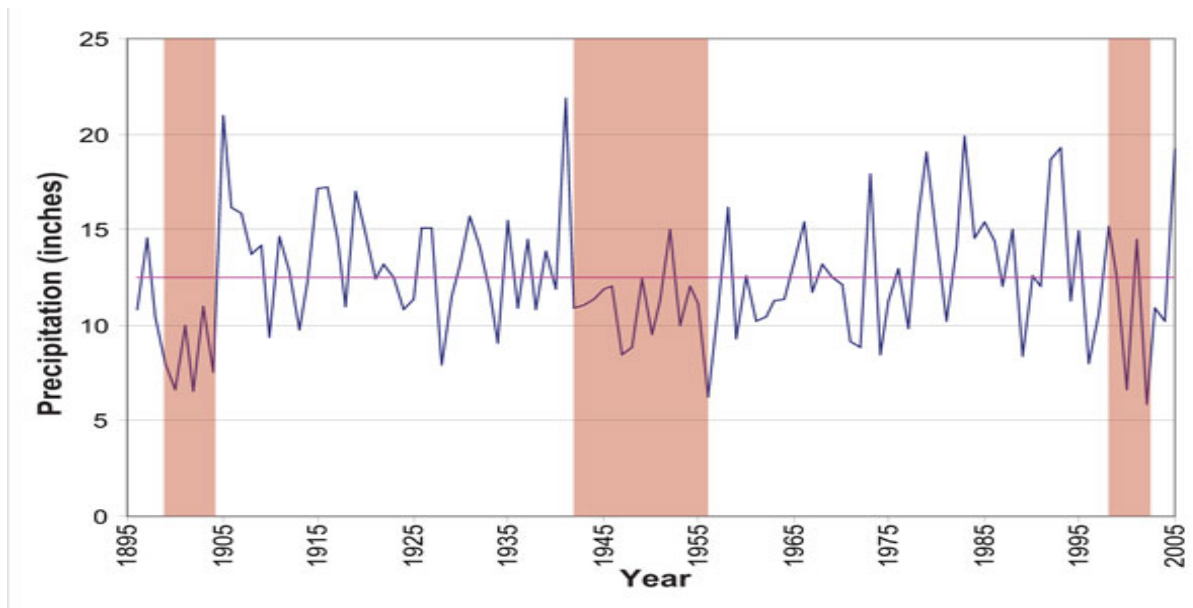
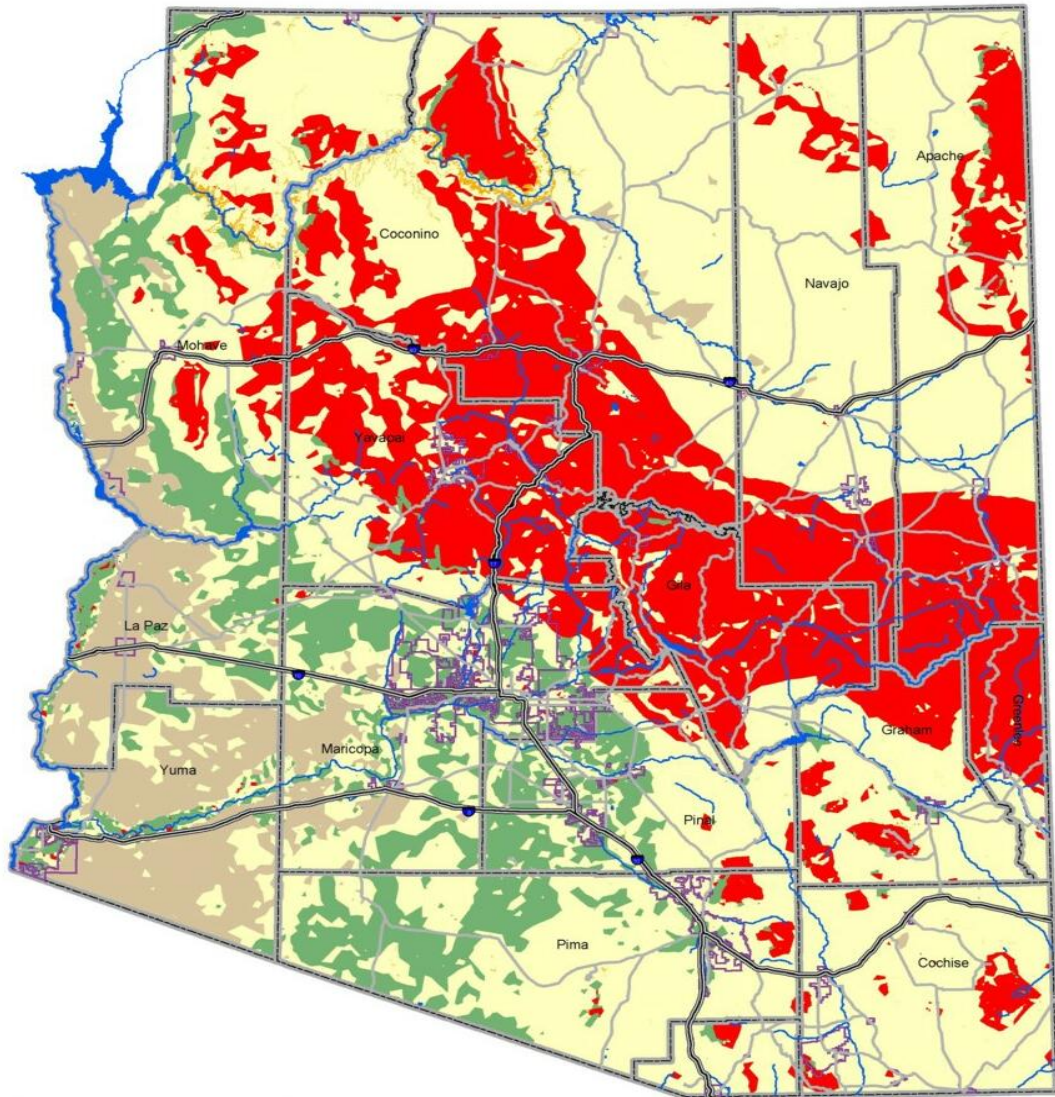


Figure 37. Arizona statewide water year precipitation, 1896-2005 (CLIMAS). Red highlights time periods of low precipitation.



Wildfire Hazard Severity

- Extreme
- High
- Medium
- Water (not included)
- Agriculture (not included)
- Barren (not included)

Note: Based on Urban-Wildland Fire Interface Code, IFCI 2000.

Figure 38. Wildfire Hazard Areas Map (Arizona State Land Department: Forestry Division)

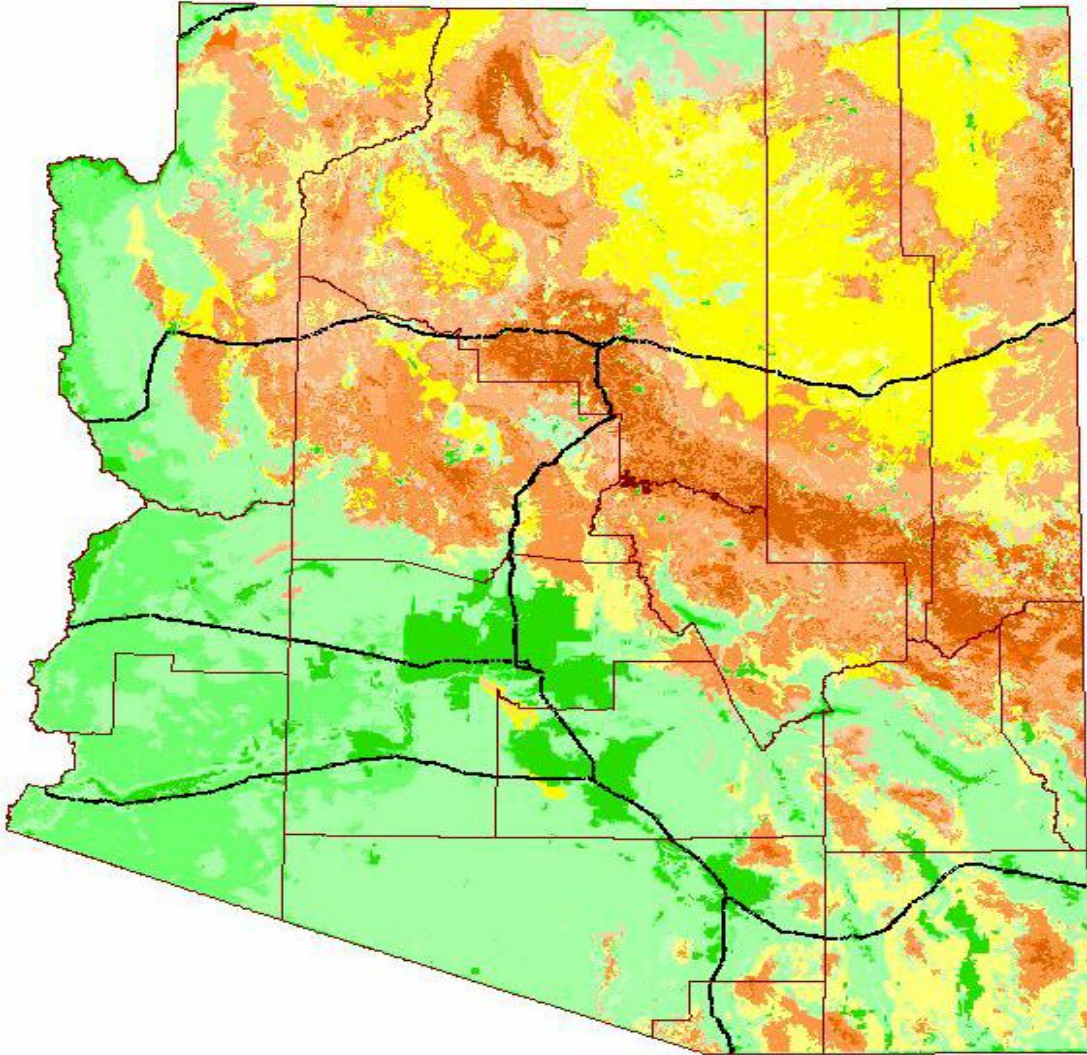


Figure 39. Fire Hazard is based upon factors such as fuel types and condition, natural fire regimes, and topography and the influence of structures.
 (Arizona State Land Department: Forestry Division)



Figure 40. Fire hazard key (Arizona State Land Department: Forestry Division)

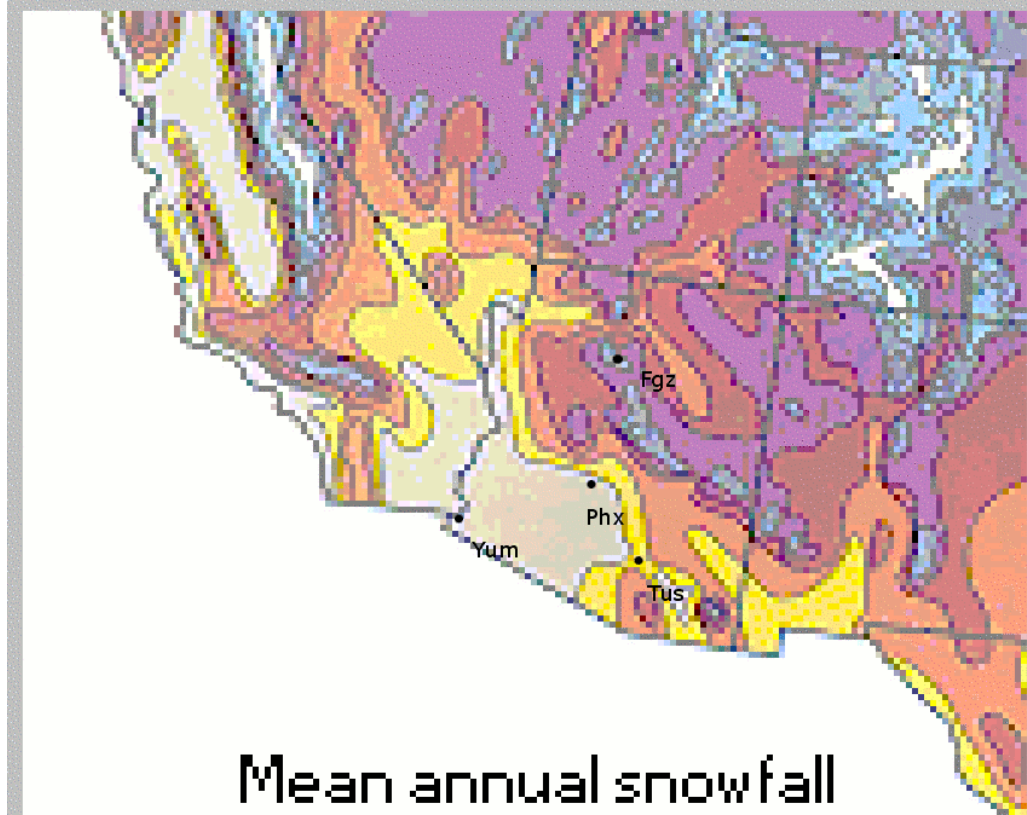


Figure 41. Mean annual snowfall for Arizona for the period 1961-1990
(Colorado Climate Center)

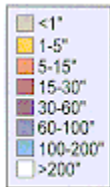


Figure 42. Key for mean annual snowfall for Arizona for the period 1961-1990
(Colorado Climate Center)

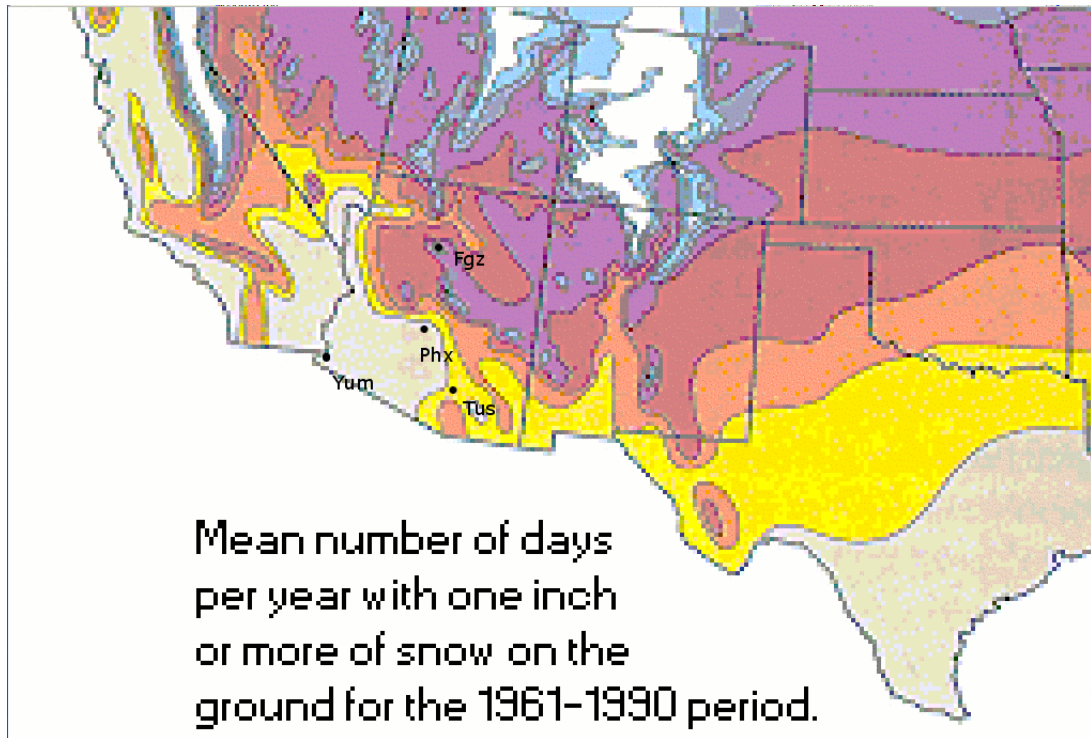


Figure 43. Mean annual snowfall days for Arizona for the period 1961-1990 (Colorado Climate Center)

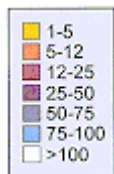


Figure 44. Key for mean annual snowfall days for Arizona for the period 1961-1990 (Colorado Climate Center)

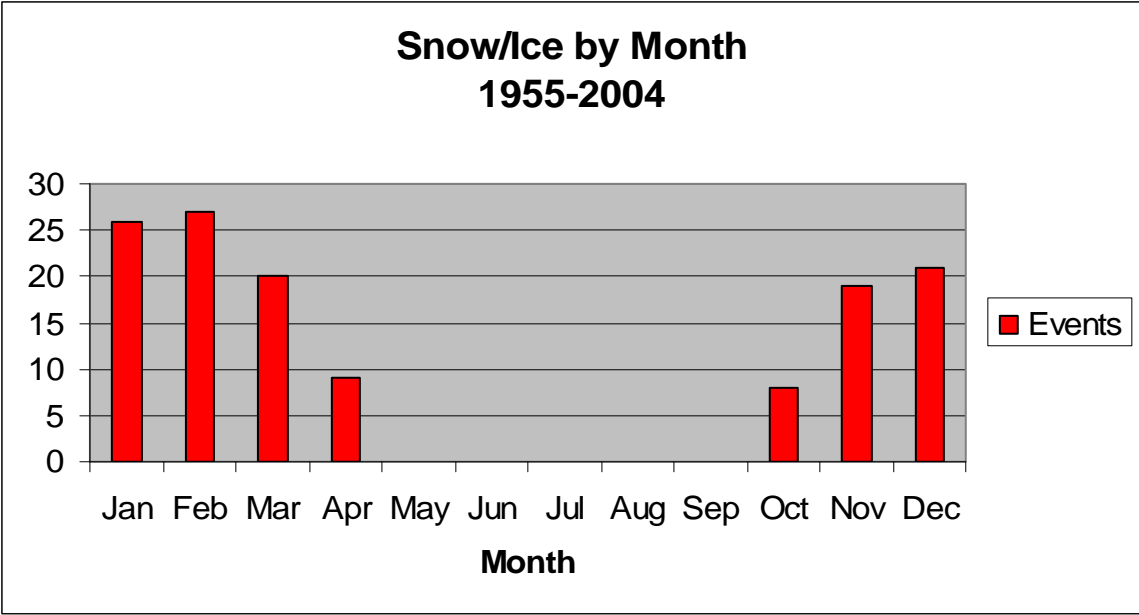


Figure 45. Snow and Ice by month from 1955 to 2004

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