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# Blowing Dust and Dust Storms: One of Arizona's Most Underrated Weather Hazards

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# Introduction

Blowing dust and dust storms have existed in Arizona for centuries. The dry climate, natural desert surface and abundance of arid soils provide the foundation for wind-blown dust. Blowing dust creates many impacts on society. These impacts include negative health effects, such as valley fever, increased particulate matter levels leading to poor air quality, and the highly publicized automobile accidents which have led to many fatalities. Based on statistics from 1955 through 2013, blowing dust is ranked as the 3rd deadliest weather phenomenon in Arizona after flooding and extreme heat and cold. This significance is shown in Figure 1 which is an update of the original work by Shoemaker and Davis (2008). The impacts from dust are not only a function of the number of dust events, but also the rapid population growth and the increased traffic volume on the state's major highways over the last few decades.

There are two types of blowing dust phenomena that are common across Arizona. The first is the more well-known haboob first defined by Sutton (1925). A haboob is a wall of dust that extends several hundred meters to up to a couple thousand meters into the atmosphere. In the United States, the word haboob was first used by Idso et al. (1972) in a paper entitled "An American Haboob." Since the early 2000's the usage of the word haboob has become more common with increased usage by meteorologists, media and the public. Haboobs move forward with the gust front of thunderstorms and are typically seen across the central and western deserts of the state during the summertime monsoon season. The second type of blowing dust is much more localized and occurs when large scale weather systems produce gusty winds, mainly in the fall, winter and spring with dust becoming airborne by more single point sources such as degraded desert, abandoned farmland and dirt roads.

This paper will look at the assessment of blowing dust and dust storms across the state as well as the station climatology of summer dust storms in Phoenix, Arizona. The paper will also discuss the impacts, detection, modeling and methods of warning the public of blowing dust and dust storms and conclude with a case study of the 5 July 2011 haboob.

# Part I: Assessment of Blowing Dust and Dust Storms in Arizona

## I. Overview

### A. Arizona Climate Regions

Arizona is one of the most diverse states in terms of climate in the United States with elevations ranging from near sea level to over 3,600 meters (Sellers and Hill, 1974). This wide range in elevation is the main driving force for the stunning diversity of weather and climate across the state. For this reason, six different climate regions developed by Sellers and Hill (1974) are used to better understand the spatial, seasonal, and diurnal distributions of blowing dust and dust storms in Arizona. Figure 2 shows a map of the six climate regions which include the Northwest, Northeast, Plateau, Central, Southwest and Southeast.

The Northwest region covers the western sections of the Grand Canyon and the Colorado River valley in the northwest corner of the state. The Northeast extends from the Four Corners region to the Little Colorado River valley and encompasses most of the Navajo Nation. The Northeast is a part of a larger region called the Colorado Plateau which extends into southeast Utah, southwest Colorado and northwest New Mexico. The Plateau climate region extends from the Kaibab Plateau and Grand Canyon southeast along the Mogollon Rim to the White Mountains of east-central Arizona. The Central covers the southern portion of the Mogollon Rim and the Verde River valley. The lower deserts of the state from the Colorado River around Yuma to Phoenix make up the Southwest climate region. The higher deserts elevations from Tucson to the International border and the New Mexico state line is referred to as the Southeast.

## B. Role of Weather Patterns

These six climate regions are influenced differently by weather systems and exhibit two distinct periods of precipitation in the winter and summer. Brazel and Nickling (1986) looked at dust storm events from 1965 to 1980 and identified four types of weather patterns generating these dust storms. The first type is classified as frontal, both pre-frontal and post-frontal. This type occurs mainly in the late fall, winter, and spring as Pacific storms pass through the desert southwest. The second type is generated by thunderstorms which occur more frequently during the summer months and peak in late July and early August. The third type is very rare and is associated with tropical disturbances in mainly September into early October. Lastly, the fourth type is related to cut-off low pressure systems that usually occur during May through June and from September to November.

## C. Roles of Land use and Vegetation

While the climate and weather patterns play an important part, the roles of land use and vegetation across Arizona have a very direct impact on the amount of windblown dust available for transport. The vast majority of Arizona is considered arid with desert type soils across much of the lower elevations in the state and these are the areas most susceptible to dust. Marcus (1976) found that much of the surface sediment in these locations is silt or a silt/clay aggregation. The higher mountains of Arizona are an exception to the arid climate due to more forest cover or grasslands at slightly lower elevations. Hyers and Marcus (1981) found that there are three types of major land use classes that characterize the deserts of Central Arizona. The first is natural desert, which is land that was never plowed or irrigated, but which may have been grazed. The second is land that is irrigated and seeded for at least part of the year and the third is abandoned farmland. Given the development and population increase in the last 30 years there is likely more urban/commercial land use at this time as well.

The type of land use most prone to eolian transport processes is abandoned farmland (Hyers and Marcus, 1981). This is exacerbated by further disturbance of the land such as All-Terrain Vehicles (ATVs) or animals. There are numerous reasons why farmland has a history of being abandoned in Arizona which include a decline in the water table, subsidence of groundwater, highway construction and more recently water rights issues. One factor that reduces the amount of windblown dust is increased vegetative cover, which is more likely in irrigated locations or during increasing rainfall. Growing season also relates to land use across the state. The growing season in Arizona is dependent on elevation with some of the lowest deserts near Yuma with year-round growing seasons. For more upland deserts including Phoenix and Tucson, the growing season ranges from about March through November. As farmers clear their land for the next crop, tilling is common. This tilling process creates a period where the land is more susceptible to blowing dust as the soils have been disturbed, thus resulting in lower wind thresholds for airborne dust before a new surface crust reforms.

### D. Role of Thunderstorms

Thunderstorms are responsible for a large number of dust storm events across Arizona, especially in the central deserts of the state. The thunderstorm season, which is controlled mainly by the North American Monsoon, accounts for most of the thunderstorm activity and as much as 50 to 70 percent of the region’s annual rainfall (Adams and Comrie, 1997). The onset of the North American Monsoon marks the start of the summer thunderstorm season which brings flash floods, dust storms, high winds, hail, and occasionally weak tornadoes to the state.

Although the large-scale flow pattern and influx of moisture associated with the North American Monsoon plays a major role, the spatial distribution of daily thunderstorms is strongly controlled by the location of mountains and higher terrain features. The higher terrain of the state (White Mountains in east-central, Mogollon Rim in central, Kaibab Plateau in north-central, and sky islands in southeast) provide a focusing mechanism for thunderstorm initiation due to surface convergence and lift due to increased direct solar insolation. The downdraft outflow from these thunderstorms travels downslope into the adjacent valleys, colliding with other outflow or forced upslope along the next mountain range, triggering additional thunderstorms. The merging of the individual thunderstorm outflows can produce the haboob type dust storms as the organized outflow travels into the lower deserts of central and western Arizona. These rain and evaporation cooled outflows are characterized by a cold pool of air at the surface which travels the path of least resistance down the slopes of the river basins and valleys as a density current.  These convective cold pools can take on the appearance of a solid wall of dust that span several kilometers in horizontal extent and vertically up to several thousand meters above the ground. On occasion, density currents associated with strong surface cold fronts can take on the appearance of solid walls of dust. That said, the term “haboob” is typically reserved for dust storms generated by thunderstorm outflow.

## II. Methodology

### A. Data

The data used in this paper is compiled from several sources with the attempt to capture the distribution of blowing dust and dust storms across Arizona. The two main sources come from the Arizona Department of Transportation (ADOT) which is merged with the second database created and used by Shoemaker and Davis (2008). This merging of the data sets results in a longer historical record from 1955 to 2011. The ADOT data is from 2000 to 2011 and also contained in the National

Highway Traffic Safety Administration's (NHTSA) Fatality Analysis Reporting System (FARS). This data is used mainly as a proxy for observed blowing dust on Arizona roadways since the type of weather conditions are reported with every traffic incident. The injuries and fatalities in this data may or may not be directly related to the reported blowing dust at the time of the incident. Thus, the total number of events in the ADOT data will be somewhat inflated compared to the other sources used by Shoemaker and Davis.

A previous study by Nickling and Brazel (1984) used station weather observations from only four locations in Arizona (Phoenix, Yuma, Winslow, and Tucson) from 1965 to 1980 to describe the spatial and temporal distributions of blowing dust in the state. The compilation of information from several sources in this paper is believed to provide a more detailed understanding of the distribution and significance of blowing dust and dust storms in Arizona. The data analysis is done using Quantum GIS (QGIS) which is an open-source desktop Geographical Information System (GIS) software application. The software is used to plot the dataset and carryout the spatial analysis for the six climate divisions and major highway corridors in Arizona.

# III. Results

## A. Statewide

The distribution of blowing dust and dust storms across Arizona shows a bias to population centers and along roadways as illustrated in Figure 3. The largest cluster is from Tucson to Phoenix followed by Yuma, Flagstaff, Winslow, and Willcox. This type of bias is common in most studies of severe and hazardous weather, especially in the National Centers for Environmental Information (NCEI) *Storm Data*. The nature of the data sources also results in reports along the roads and Interstates.

The total number of events from 1955 to 2011 is 1,521 of which 157 fatalities and 1,324 injuries are recorded. The seasonal distribution shows a peak in April and in July (Figure 4), with a peak between 5 PM and 6 PM MST (Figure 5). The peak in March is associated with the increased frequency of Pacific storm systems passing through the region. The July peak is related to the summer thunderstorms with the diurnal peak closely linked to the timing of thunderstorms across the state.

Several deadly traffic accidents have occurred in Arizona's history as the result of reduced visibilities in blowing dust. Most of the casualties occur on state highways when motorists encounter these low visibilities. The blinding dust can cause the lead vehicle to either stop suddenly or pull off to the side of the road with other vehicles following resulting in a chain reaction. The top five most significant dust storm events in Arizona's history in terms of the total casualties and number of vehicles involved are ranked as follows:

- 28 June 1970 – 12 fatalities after several vehicles collided on Interstate 10 near Casa Grande.
- 9 April 1995 – 10 fatalities and 20 injured on Interstate 10 near Bowie after 4 different accidents, totaling 24 vehicles.
- 12 July 1964 – 8 fatalities and 25 injured after 9 cars, 3 trailer rigs, and 1 pickup were involved in a chain reaction collision on Interstate 10 near Red Rock.

- 12 May 1971 – 7 fatalities and 25 injured after several vehicles collided on Interstate 10 near Casa Grande.
- 3 March 1989 – 2 fatalities and 43 injured after a bus, 12 trailer rigs and 24 cars were involved in a chain reaction accident on Interstate 10 near Bowie.

## B. Northwest

Most of the reports in the Northwest region are clustered around Bullhead City, Lake Havasu City, and Kingman. A total of 66 events from 1996 to 2011 suggest that most of the events in the Northwest climate region come from the ADOT information and not the other sources. A total of 11 fatalities and 45 injuries are recorded with each month of the year experiencing similar frequencies of blowing dust (Figure 6). The time of day shows a distinct increase around 6 PM MST (Figure 7).

The Northwest is affected by the frontal, pre-frontal and post-frontal, and the deep low pressure systems that sometimes become cut-off from the main flow and can linger over the desert southwest for several days. The influence of more localized summer thunderstorms appears to be less of a factor in this part of Arizona.

## C. Northeast

The Northeast climate region experiences blowing dust and dust storms during mainly the months of March through June as Pacific low pressure systems pass through the region. Figure 8 shows the monthly distribution of events which peak during the spring months. The total number of events is 134 with a total of 24 fatalities and 108 injuries from 1994 to 2011. The time of day varies a bit but tends to peak in the early afternoon and again in the early evening around 6 PM MST (Figure 9).

The arid to semi-arid soils in this region are very prone to blowing dust or sand. Figure 10 shows the northeast - southwest orientation of sand dunes caused by the predominant southwest wind direction. This region is part of the Colorado Plateau which is the largest area of sand dunes in the United States as shown in Figure 11 (Muhs and Been, 2013). One of these blowing dust events is captured by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite on April 16, 2013 (Figure 12). The image clearly shows the merging of separate dust and sand plumes across northeast Arizona spreading into southeast Utah and southwest Colorado.

## D. Plateau and Central

The Plateau and Central climate regions experience the least amount of events with a combined total of 128 occurrences, 50 injuries and 5 fatalities. The monthly distributions are similar with the frequencies peaking during the winter months (Figures 13 and 14). Winter storms that bring gusty winds and snow to the Plateau appear to be the main driving factor in causing localized blowing dust in the area. The time of day varies across the climate regions with events peaking around noon MST in the Plateau and late afternoon and early evening in the Central (Figures 15 and 16).

### E. Southeast

The Southeast region experiences a peak in April when the southern portion of spring low pressure systems pass through the area (Figure 17). The second most deaths reported in one event occurred on April 9 in this climate region which has a total 213 injuries and 27 fatalities. A secondary peak is observed in July during the North American Monsoon season when strong thunderstorm winds pick up dust. However, the classic haboob type dust storm is not frequently observed in this climate region of the state. The time of occurrences increases around 2 PM MST to roughly 6 PM MST as shown in Figure 18.

### F. Southwest

The Southwest region is known for the spectacular haboobs, and deadly traffic accidents on Interstates 8 and 10 which in recent years are caused mainly by localized blowing dust. The region by far has the most documented events in Arizona with a total of 1022 occurrences, 908 injuries, and 90 fatalities. The monthly distribution shows a peak in April and a more pronounced increase in the month of July (Figure 19). Events tend to occur more frequently in the afternoon and evening hours, peaking around 5 PM MST (Figure 20).

## IV. Summary

Arizona's diverse climate and landscape create an ideal environment for the wind driven transport of dust and sand in the state. Blowing dust caused by organized thunderstorm outflow make up a large percentage of the dust storms, especially in the central and western deserts of Arizona. Statewide, the monthly distribution shows a peak in the spring and again during the summer. The months of March through May account for 31 percent of the total events, with 34 percent for the months of June through August. Most of the events occur during the afternoon and early evening hours with 36 percent happening from 4 PM to 6 PM MST. The Southwest climate region accounts for 67 percent of the total reports followed by the Southeast at 11 percent and the Northeast region at 8 percent.

# Part II: Summer Dust Storms in Phoenix, Arizona

## I. Overview

The most common dust storm generation type in the deserts of Arizona is the thunderstorm. The mechanism for generating these dust storms is the organized outflow from individual downdrafts of decaying thunderstorms or precipitating clouds. The rain and evaporation cooled outflow is characterized by a cold pool of air at the surface which travels the path of least resistance down the slopes of river basins and valleys as a density current. These dust storms take on the appearance of a solid wall of dust and span up to 160 km horizontally and 2.4 km vertically (Idso et al. 1972). This type of dust storm is referred to as “An American haboob” after the name given to the severe dust storms that wreak havoc in Sudan (Sutton, 1931 and Farquharson, 1937). The name comes from the Arabic word “habb”, meaning “wind” as defined by American Meteorological Society (2016). On occasion, density currents associated with synoptic scale cold fronts can take on the appearance of solid walls of dust. However, the name haboob is usually reserved for dust storms generated by thunderstorm outflow.

This part of the paper is an extension of the work done by Ingram (1972) on summer dust storms from 1952 to 1971 in Phoenix, Arizona. The station climatology of dust storms for Sky Harbor International Airport is updated to include the years from 1948 to 2015. In addition to the station climatology, five distinct synoptic scale patterns associated with summer dust storms are identified using a subset of the total events.

# II. Background

## A. Summer Thunderstorm Season

Arizona is considered to be on the northern fringes of a region (western Mexico, New Mexico, and Arizona) that is subject annually to an influx of moisture in association with the North American Monsoon. This influx in moisture is brought on by the seasonal northward shift in the mean circulation associated with the subtropical high pressure ridge. For Arizona, the seasonal shift in the mid-tropospheric winds from the prevailing westerly direction to a more easterly and southeasterly direction establishes itself by late June and fluctuates through at least the middle of September. The onset of the Monsoon marks the start of the summer thunderstorms which bring flash floods, dust storms, high winds, hail, and occasionally weak tornadoes to the state.

The source regions of moisture across the southwestern United States have been investigated and debated for several decades by researchers and operational forecasters (Brenner, 1974; Hales, 1972; Carleton, 1986; Adams and Comrie, 1997). For Arizona, there exist two main moisture sources during the summer: (1) the Gulf of California, and (2) the Gulf of Mexico. In general, southerly low-level winds import moisture from the Gulf of California which mixes with higher level moisture that is transported from the Gulf of Mexico. In addition to the horizontal advection of moisture, the vertical transport of moisture due to convection plays a critical role in sustaining moisture levels during the summer.
The North American Monsoon accounts for as much as one-half of the regions annual precipitation. The relative location of the northward migrating subtropical high pressure ridge during the summer months directly impacts the rainfall patterns across Arizona. Several studies have shown that a northward displacement of the mean subtropical ridge coincides with a wetter season across the region (Carleton et al., 1990; Adams and Comrie, 1997; Comrie and Glenn, 1998). In contrast, the farther south the ridge axis is displaced the drier the season tends to be across the southwestern United States.

Since Arizona is on the northern edge of this seasonal pattern shift, variability during the summer occurs with *bursts* and *breaks* in the moisture advection. Several studies have investigated the upper-air patterns associated with these *bursts* and *breaks* in terms of precipitation patterns and thunderstorm activity. Watson et al (1994) used lightning data to identify periods of increased and decreased thunderstorm activity to examine synoptic scale patterns associated with each regime. Carleton (1986) used regional satellite climatology to subjectively identify significant increases and decreases in cloudiness for classifying surface and upper-air patterns associated with the *bursts* and *breaks* in Arizona precipitation.

In addition to classifying large scale patterns associated with *bursts* and *breaks* on a regional scale, other studies focus specifically on the central deserts of Arizona. Maddox et al (1995) identified three synoptic scale patterns associated with severe thunderstorms in the central deserts. Wallace (1997) looked at days in Phoenix with the average dew point temperature of 55 degrees Fahrenheit or greater for subdividing storm days based on the mean 700 to 400 hPa level wind direction. Overall, these pattern classification studies point to the importance of the flow regime in moisture advection as well as the development and propagation of precipitation systems.

### B. Role of Regional Geography and Movement of Thunderstorm Outflow

In addition to the role of the large-scale flow pattern, the location of mountains and higher terrain in the state play a significant part in the initial development of daily thunderstorms. The spatial distribution of thunderstorms is illustrated by the lightning flash density in Figure 21.

Thunderstorms typically develop in the mountains of southeast and east-central Arizona as well as in the plateau regions and higher terrain of the Mogollon Rim. The rain and evaporation cooled outflow air from thunderstorms travel down the slopes of the mountains into the nearby valleys, triggering new thunderstorms in the valley or in the adjacent mountain range. Eventually, these individual thunderstorm outflows merge and collectively form what is characterized as a cold pool of air at the surface. This cold pool of air behaves as a density current that travels down the slopes of valleys and river basins following the path of least resistance. Phoenix lies in a natural confluence region of major rivers and tributaries in which cold pools approaching from several directions collide and merge over the greater Phoenix metropolitan area. These colliding cold pools can trigger additional thunderstorms along with the merged cold pool traveling west and southwest toward Yuma and the Colorado River. Under the right conditions, the cold pools can pick up massive amounts of dust and sand in the form of a haboob. Figure 22 shows a conceptual diagram of cold pool formation and movement in Arizona.

## III. Methodology

### A. Station Data

For the years from 1948 to 2015 during the months of June through September, hourly surface observations at Sky Harbor International Airport (KPHX) in Phoenix, Arizona are used to identify the dust storm events. The surface observations are obtained from the NCEI and compiled from *local records* at the National Weather Service (NWS) office in Phoenix. The following criteria must be met to be considered a dust storm event: (1) a visibility reduced to one-half of a mile or less with blowing dust reported, and (2) a directional shift in the wind and/or an increase in speed accompanying or following the reduction in visibility by blowing dust. These criteria are taken from the original study conducted by Ingram (1972).

The Sky Harbor International Airport is located in the east-central portion of the greater Phoenix metropolitan area just to the southeast of downtown. Since PHX is centrally located with respect to the metropolitan area, dust storms identify in this study are assumed to be of major areal importance. Such an assumption does not rule out the possibility that dust storms of similar magnitudes do not impact other portions of the area without detection at PHX. Furthermore, this assumption does not account for dust sources near the airport contributing to the reduction in visibility. In general, it is believed that most of the dust storms meeting the criteria used in this study are representative of the haboob type storms.

### B. Synoptic Scale Pattern Classification

For an initial look at the synoptic scale patterns associated with dust storm events, atmospheric soundings from 1964 to 1994 are used to construct upper-air charts at 850, 700, 500, and 250 hPA levels. A total of 72 cases are used to subjectively classify patterns with a focus on conditions at the 1200 UTC 500 hPA level leading up to the dust storm event. The subjective method used to identify the synoptic scale patterns is similar to that used for classifying the McCollum severe thunderstorm types described by Maddox et al. (1995). This type of subjective classification is chosen over statistical methods for the purpose of using the three McCollum severe thunderstorm types as a model for the dust storm patterns. In addition, the McCollum severe thunderstorm types serve as a good reference point since other weather hazards such flash flooding, tornadoes, and severe thunderstorms occur on dust storm days.

From the initial 72 cases, four similar recurring patterns based on the general location of ridge and trough positions relative to Arizona are identified. Three of the four 500 hPA level patterns fit the McCollum severe thunderstorm types. The fourth pattern identified is somewhat anomalous compared to the average 500 hPa level flow during the summer rainy season. Although this fourth pattern is not documented as a McCollum severe thunderstorm type, it shows up frequently especially during the summer months of 1993.  It should be noted, though, that the McCollum types were derived from events in the months of July and August thereby avoiding the transitory periods of June and September. This might explain some of the reason why the fourth pattern is not captured as a McCollum severe thunderstorm type.

To further refine and quantify the frequency of the initial patterns, a total of 167 cases from 1948 to 2009 are investigated. Upper-air charts for the 500 hPa level obtained from the NCEP/NCAR reanalysis dataset at the Climatic Diagnostic Center (CDC**)** are used. From this expanded dataset, five distinct patterns are classified. The fifth pattern is a subset of one of the initial four patterns identified in the 72 cases. This fifth pattern occurs quite frequently during the summer, and is commonly recognized by forecasters to be associated with active thunderstorm days in Arizona. Eight of the cases could not be classified.

## IV. Results

### A. Decadal Trends

For a period from 1948 to 2015, Phoenix has averaged 2.8 or approximately 3 dust storms per year during the months of June through September (Figure 25). In contrast, over the last 30 years this figure has decreased to an average of 1.6 or almost 2 dust storms per year during the summer months. Some of this decline in dust storm frequency can be attributed to the rapid population growth of Phoenix and the subsequent expansion of the urban area (Figure 23). This urban growth would tend to reduce the number of dust storms meeting the criteria by removing or altering the dust source areas. Figures 3 and 4 also illustrate the decline in dust storm frequency and the increase in population growth of Phoenix by decade, respectively.

In March 1994 the NWS commissioned the Automated Surface Observing System (ASOS) as the official weather observations for PHX. The ASOS is located approximately one mile from the previous manual observation site. This relocation could have reduced the influence of local dust sources; thus, explaining some of the observed decline in dust storm frequency in recent years. In addition to the physical site change, the method of taking visibility observations changed from using the human eye to an automated sensor. This change in the way visibility distances are measured may also contribute to the observed decline in dust storms at PHX since 1994.

Taking the station data for PHX at face value suggests that the haboob type dust storms are vanishing in the central deserts of Arizona. However, this decline in dust storm frequency is misleading. Massive dust storms continue to impact the region with several deadly and costly ones occurring near Phoenix in recent years. In fact, the summer of 2011 saw a significant increase in haboobs with subjectively one of the most ominous one in decades occurring on 5 July 2011. It should also be noted that there was a widespread hard freeze across the deserts of Arizona in early February 2011 with temperatures as low as -7°C in Pinal County that might have contributed to the killing of natural vegetation and thus may have enhanced dust storms in subsequent years. Figure 24 also shows this increase in dust storm frequency after 2010 in Maricopa County. Thus, the decrease in frequency is likely the result of the PHX site becoming less representative of the greater metropolitan area. This is especially the case for capturing the haboobs in the station data based on the visibility criteria used in this study. The dust storms that appear in the PHX station data during the past 10 to 20 years are likely the result of more intense thunderstorm outflows. These stronger winds have the potential to uptake and transport larger quantities of dust and sand which can penetrate the interior portions of the city.

## B. Annual Variability

The observed frequency in dust storms at PHX can vary dramatically from year-to-year. Figure 25 illustrates the annual variability in dust storm frequency from 1948 to 2015. Brazel and Nickling (1986) suggest that the annual variability in dust storm frequency is strongly affected by antecedent conditions such as soil moisture, vegetation cover, and soil crusting. In general, increased precipitation directly influences the amount of vegetation cover and the formation of soil crusting. These conditions tend to reduce the potential of dust events or at least increase the wind speed threshold necessary for uplift dust and sand.

In addition to these weather related antecedent conditions, human factors such as agriculture and spurts in construction associated with the Phoenix urban sprawl can also help explain some of the annual variability in dust storm frequency. In the 1960’s and early 1970's construction of new highways led to the purchase of farmland and disruptions in irrigation (Brazel and Nickling, 1986). This construction resulted in the abandonment of cropland which eventually disturbed vegetation patterns along and near the interstates.

## C. Frequency by Month and Time of Day

The dust storm frequency of occurrence peaks in late July and early August (Figure 26). This peak in dust storm frequency coincides with the summer peak in rainfall at PHX. The average daytime arrival of dust storms at PHX is around 6:30 pm LST. Figure 27 shows the distribution of arrival times at PHX. The arrival time can vary depending on the direction from which the thunderstorm outflow travels. In general, dust storms arriving from the east through southeast hit PHX between 5 and 9 pm LST, while the ones approaching from the north and northeast arrive between 3 and 7 pm LST. The closer proximity of the higher terrain to PHX accounts for the earlier arrival time of dust storms from the north and northeast by about 2 hours. In some cases, the outflow from north of Phoenix is delayed and results in outflows from the southeast and north colliding right over the metropolitan area. These colliding outflow boundaries typically generate intense thunderstorms with damaging microburst winds. One such case is 14 July 2002 when a haboob approaching Phoenix from the southeast collided with outflow from the north producing a severe thunderstorm with damaging microburst winds of near 100 mph at the Sky Harbor International Airport.

## D. Frequency by Wind Direction

Approximately 68 percent of the dust storms approach Phoenix from the east to south with the dominant direction being from the southeast (Figure 28). The average wind direction associated with all of the dust storms is from the southeast (121 degrees). Outflow originating from thunderstorm complexes over the mountains straddling the Cochise and Pima county lines southeast of Phoenix account for most of the southeast approach storms. The cold pool travels down the Santa Cruz river valley toward Phoenix, following the path of least resistance. A small percentage of these southeast approach dust storms originate from organized thunderstorms stretching across northern Sonora Mexico and Santa Cruz county of Arizona. Ingram (1972) refers to these storms as Sonoran-type squall lines which pass through Tucson and somewhat intensify as they travel down the Santa Cruz river valley toward Phoenix. A general rule-of-thumb is that it takes these dust storms about 3 1/2 hours to reach Phoenix after the outflow moves through the Tucson International Airport.

About 25 percent of the dust storms approach PHX from the north-northeast. These storms are typically generated by less organized thunderstorm cells that develop in the higher terrain north through northeast of the city. Because of the shorter distance from the thunderstorm source area, the outflow is usually not very well organized by the time it passes through Phoenix. In many cases, the outflow does not become full-fledged until it travels to the west and south of Phoenix merging with other cold pools traveling northwest toward the metropolitan area. This merging results in an organized outflow that advances west and southwest reaching the Colorado River in western Arizona late in the evening.

The remaining 6 percent of the dust storms approach PHX from the southwest-northwest. These storms are typically associated with thunderstorms that develop during the transition months of June and September. During these months, low pressure troughs move through the region and encounter enough moisture and instability for thunderstorm development. The stronger vertical wind shear in this type of environment results in longer lived thunderstorms embedded in the mean westerly steering flow. These longer lived thunderstorms generate outflow that can travel upslope and up-valley in most west approaching dust storms.

### E. Frequency by Wind Speed and Visibility

Wind shear along the leading edge of dust storms can be a hazard to general aviation and airport ground operations. Fortunately, only 6 percent of the maximum wind speeds associated with dust storms exceeds 57 mph. The average maximum wind speed of all the dust storms is 43 mph. About 40 percent of the maximum wind speeds are between 36 and 46 mph with 28 percent between 47 to 57 mph. The remaining 26 percent of the maximum wind speeds are less than 36 mph. Figure 29 shows the distribution in wind speed by categories.

The reduction in visibility is the most hazardous attribute of dust storms. Too often motorists are caught off guard due to the rapid reduction in visibility by a consuming dust storm. Major multi-vehicle accidents occur each summer on Arizona’s interstates due to dust storms.  For Sky Harbor International Airport, over 60 percent of the dust storms have visibilities of 1/4 of a mile or less. The remaining 40 percent have visibilities of 1/2 of a mile or less but greater than1/4 of a mile.

## V. Synoptic Scale Patterns

### A. Pattern I (A and B)

Dust storm pattern I is similar to the McCollum severe thunderstorm type I pattern which is characterized by a broad high pressure ridge over the central and southern United States at the 500 hPa level. The pattern also is characterized by a secondary circulation with the high cell centered over the Four Corners region. Because of this secondary feature, the type I pattern has been divided into two subset patterns based on the amplitude of the area of high pressure centered over the Four Corners.

Pattern I A resembles the mean July and August 500 hPa heights, with a deep easterly flow established over Texas, New Mexico, and eastern Arizona as shown in Figure 30. Pattern I B resembles the more classical pattern that weather forecasters refer to as the “Four Corners high” and is typically associated with outbreaks of severe weather across Arizona during the monsoon season. This pattern I B usually has a well-established and more amplified high cell over the Four Corners.

Both patterns occur frequently during the monsoon season, but pattern I B is slightly more frequent based on the cases in this study. Pattern I A occurs about 22 percent of the time with pattern I B having a 27 percent frequency. The overall distribution of the direction in which the dust storms approach from are quite similar with the most frequent approach being from the southeast. The average arrival times from the southeast are 7:27 PM MST and 7:54 PM MST for patterns I A and I B respectively. Figure 30 shows the flow patterns and frequencies of the approach directions along with the average arrival times at PHX.

## B. Pattern II

Dust storm pattern II resembles the McCollum severe thunderstorm type II. In this pattern, the high migrates northwest becoming centered over the Great Basin region of southwest Utah and southern Nevada. An unusually deep trough of low pressure extends over the eastern one-third of the United States. At the surface, a cold front occasionally pushes south through the Plains and west toward the Arizona and New Mexico state lines. This pattern is less common than patterns I A and I B, and occurs most frequently during late July and early August.

Figure 31 shows the typical flow pattern and areas in which the cold pools form. The most frequent direction is from the southeast (37 percent) with an average arrival time of 8:24 PM MST. In contrast, dust storms approaching from the north and northeast arrive on average roughly 2 to 3 hours earlier than from the southeast. Storms approaching from the east arrive about 2 hours later than the southeast.

## C. Pattern III

Dust storm pattern III is the least common type and is quite different than the other summer patterns. It is characterized by a broad ridge of high pressure extending over the southern United States, much farther south than average, with usually two separate high pressure centers. One circulation is centered over southern California and northern Baja and the other one over the southeast United States. This pattern is also well known for low pressure disturbances becoming more or less trapped between the two circulation centers in the vicinity of the desert southwest.

This pattern is also unique in that the most frequent (35 percent) approach is from the north with the average arrival time of 5:01 PM MST. This arrival time is about 2 to 3 hours earlier than the most common approach direction for the other patterns. The earlier arrival time from the north is mainly due to the closer proximity of the mountains and Mogollon Rim to the city of Phoenix. Figure 32 shows the pattern and associated average arrival times.

## D. Pattern IV

Dust storm pattern IV is considered a transitional type of pattern as it occurs typically during the months of June and September. However, it is not limited to these months as this pattern can evolve during the peak of the North American Monsoon. Figure 33 shows the general pattern that features a trough of low pressure along the West Coast and a ridge of high pressure centered over the southern Plains. Another low pressure trough axis usually extends along the East Coast.

This pattern occurs more frequently than dust storm patterns II and III with the most common approaches from the south and southeast. Average arrival times from these directions are around 6:30 to 7:00 PM MST.

## VI. Summary

Thunderstorms during the summer months are the most common dust storm generation type for the deserts of Arizona. At Sky Harbor International Airport in Phoenix, Arizona, dust storms in the form of haboobs impact the airport 2 to 3 times per year with widely varying frequencies from year-to-year. About 68 percent of these haboob type dust storms approach the airport and city from the southeast with the average arrival time of all storms being 6:30 PM MST. Forty-five percent of the dust storms are followed by observed rainfall at the airport within one hour of the arrival time.

The dust storms peak during late July and early August in association with the peak in rainfall patterns during the North American Monsoon. Five distinct large-scale mid-tropospheric flow patterns are associated with most dust storm days. The most frequent pattern is referred to as the Four Corners high. This type of pattern accounts for nearly 50 percent of the dust storm events in this study. Although the station data shows a decreasing trend in the frequencies of dust storms during the past 6 decades, an upswing in activity since 2011 clearly suggests that haboobs will continue to impact the deserts of Arizona. The impacts of blowing dust and dust storms will be explored in the next section of this paper.

# Part III: Impacts of Blowing Dust and Dust Storms in Arizona

## I. Overview

Part III of this paper take a look at the impacts of blowing dust and dust storms across Arizona. Further research still needs to be done in terms of understanding and quantifying the impacts of these events. That said, much of Part III comes from an interdisciplinary literature review which looks at the aspects of health, air quality, traffic accidents, climate change, and economic impacts.

## II. Impacts

### A. Health

Blowing dust has a major effect on public health in Arizona due to Valley Fever, also known as Coccidioidomycosis or cocci. Valley Fever is a fungal disease caused by inhalation of soil dwelling fungi, *Coccidioides immitis* or *Coccidioides posadasii*. (Brown et al., 2013) These are very similar with *Coccidioides posadasii*. found across a broad area of the deserts of the Southwestern United States and Northern Mexico including Arizona. Meanwhile, *Coccidioides immitis* is found in Central and Southern California such as the San Joaquin Valley, where it is most endemic (Fisher et al, 2002). The fungus is able to spread as spores which become wind borne due to disturbance of the dust from wind, farming, construction, off road vehicles, etc. Human infection starts in the lungs due to inhalation of these spores. Within Arizona, Valley Fever is most common across the highly populated deserts of Arizona including Phoenix and Tucson.

The effects of valley fever among individuals vary widely, with about 60% of infected persons asymptomatic. Thus, some of the population in an endemic area may have had Valley Fever and not even know it. Most of the remainder of the population experiences more severe effects including pulmonary infections. Otherwise, about 1% see the most severe effects due to disseminated disease to other parts of the body and can in a worst case scenario lead to death (Kolivras et al, 2001). People working outside with greater dust exposure such as agricultural or constructions workers have increased vulnerability.

*Coccidioides posadasii* are commonly found in warm to hot desert regions of the Southwestern United States, Northern Mexico and portions of Central and South America that receive few harsh freezes and contain sandy, alkaline soils (Laniado, 2007). Since the fungus in the first or mycelial phase requires moisture in the soil to grow (Tamerius, 2011), it is usually seen in greatest abundance after wetter periods. However, a dry period is needed before the spores mature into Arthroconidia where they reproduce and become resistant to desiccation. The spores become inhaled in this Arthroconidia phase.

Precipitation in the cool (winter) season has been found to result in increased fungal growth in the soil (Hugenholtz, 1957), with greater precipitation amounts related to increased incidence of Valley Fever in Arizona the following summer and fall. (Comrie, 2005) The highest prevalence of Valley Fever exposure occurs during June through July and from October through November. The June through July period corresponds to the tail end of the dry period before monsoonal precipitation moves in. Meanwhile, the October through November time period represents the arid dry season in the fall before winter rainfall moves in. Corresponding PM10 data also indicates an increase in PM10 levels during the same periods, which fits the common hypothesis of increased dust exposure resulting in increased Valley Fever cases. Comrie found that precipitation during the hottest and driest part of the year (April through June) as opposed to other wetter seasons is most favorable for *Coccidioides* growth in the environment. These fungal spores may accumulate in the soil for several years, thus the lags for precipitation and antecedent lags for dispersion can occur for well more than one season or year.

Within Arizona, there has been a marked increase in the annual number of Valley Fever cases over the past 20 years or so with a significant spike from 2009 to 2012, before lowering closer to pre 2009 values in 2013 and 2014. The changes in 2009 which resulted in increased cases and again in 2013 with reduced cases were largely attributed to changes in laboratory reporting practices. (Valley Fever 2014 Annual Report) Overall incident rates in Arizona have risen from 7 cases per 100,000 persons in 1990 to about 250 cases per 100,000 persons in 2011, with declines to 89 and 84 cases per 100,000 persons in 2013 and 2014 respectively. There are numerous reasons for these overall increases and they range from changes in reporting practices to improved awareness of the disease, an increase in the greater than 60 year old population most at risk of symptomatic effects and finally climate changes over time (Ampel, 2010).

## B. Air Quality

With Arizona being primarily desert, windblown dust causes an abundance of air quality issues. Air Quality is measured by Particulate Matter (PM) which is a complex mixture of small particles and liquid droplets found in the air. Particulate Matter is often directly emitted from sources such as unpaved roads, construction sites, fires etc. and is found in the air through dust, smog, soot, smoke and ash. Particulates are measured by their particle size in micrometers (µm). Most dust particles are 10 µm or less and are quantified as PM10 and are small enough that they can pass through the throat and nose and enter the lungs with potential serious health effects. The smallest particulates are considered fine particles of 2.5 micrometers or less in diameter (PM2.5) and have the greatest health risks to humans. PM2.5 aerosols are usually from combustion activities such as motor vehicles and power plants. (EPA, 2013)

The Environmental Protection Agency (EPA) is required by law as part of the Clean Air Act to set national air quality standards for particulate matter that is considered harmful to public health and the environment. Through air quality sensors placed around the state it is determined what locations meet the standards set forth by the EPA. These air quality standards are based on PM10 or PM2.5 concentrations by averaging measuring both annually and on a 24 hour basis. For PM10, averaged 24 hour values greater than 150 $\mu g/m^3$ may not be exceeded more than once per year over three years. For PM2.5, the annual standard is exceeded whenever the annual mean, averaged over 3 years exceed 15 $\mu g/m^3$. 24 hour standards for PM2.5 are exceeded when the 3 year average of the annual 98th percentile of values is greater than 35 $\mu g/ m^3$. Locations that do not meet the criteria are considered a “nonattainment area” and the state and local governments are then responsible to develop a state implementation plan and submit it to the EPA within 3 years.

The latest EPA data for Arizona indicates that portions of Maricopa County are considered “serious” classification for Nonattainment in PM10 with portions of Yuma, Pinal, Pima, Gila, Santa Cruz and Cochise counties under the “moderate” classification for PM10 nonattainment. The areas that are nonattainment for PM2.5 are much more localized in Western Pinal County and in the Nogales area. A few of the control measures that have historically been put in place include road stabilization plans, increased permits for earth moving to mitigate emissions, increased fines for open burning, additional paving of dirt roads. For days that have high winds, control measures have more limited effects as strong winds may overwhelm the measures developed. (ADEQ, 2009) An exceedance of criteria will not count as a violation if it is classified an exceptional event and the EPA concurs. This has occurred with significant haboob events where the 24 hour exceedance standards were met or exceeded.

## C. Traffic Accidents and Transportation System

Blowing dust over the past few years has had increased exposure as a significant weather event due to the news coverage of multi vehicle fatal accidents, especially along Interstate 10 between Tucson and Phoenix. Shoemaker (2008) determined that blowing dust is the third ranked weather event in Arizona for deaths and injuries from 1955-2004, behind extreme heat/cold and flooding with the latest data indicating about 157 fatalities statewide since 1955.

Anytime there is significant blowing dust along major roadways which cause serious or fatal accidents, this leads to road closures of major interstate highways. Given the rural nature of Arizona, this leads to very long detours and very long backups of traffic as the interstate will be closed for hours as accidents which are chain reaction or multi vehicle are investigated. Meanwhile, during the monsoon when haboobs move northward into the Phoenix metropolitan area, mainly from the south and east, this results in reduced visibility and increased delays at Phoenix Sky Harbor International airport until conditions improve.

Arizona Department of Transportation (ADOT) accident data was analyzed from 2000-2011 and found that 1,446 accidents statewide were flagged as having dust/sand as a weather factor identified. Of those, 29 incidents had 1 or more fatalities, 520 incidents had 1 or more injuries with no fatalities and there were 897 incidents with no injuries or fatalities. A review of the monthly breakdown (Figure 4) shows that dust incidents occur year round but there are two peak months of incidents, April and July. This makes meteorological sense as April is the peak of the large scale synoptic gradient wind events. Most of the non-summer dust incidents on the interstates are very localized and emanate from point sources which produce plumes or channels of dust that move downwind onto the Interstate with drivers abruptly traveling into areas with little to no visibility. A large number of monsoonal thunderstorms occur in July, which is still early in the season when the lower atmosphere is drier and more conducive to downbursts producing strong wind and large scale blowing dust events or haboobs as the ground conditions are still dry.

Geographic analysis of the data (Figure 3) shows that dust related accidents occur statewide with a concentration on Interstate highways, especially those with greatest traffic density. Two major corridors of Interstate 10 account for 42 percent of the total fatalities in Arizona. The deadliest corridor of Interstate 10 stretches from Phoenix southeast to Red Rock and is historically known for being a dust prone area due to land use, especially in Pinal County (Marcus, 1976). From 1955 to 2011 a total of 176 events have resulted in 260 injuries and 45 fatalities. The most fatalities from a dust storm caused vehicle accident in Arizona's history occurred along Interstate 10 near Casa Grande killing 12 people on 28 June 1970. Figure 34 shows an increase in frequency of events in this corridor during the months of April and May followed by another period from July through October. Accidents seem to increase around noon, and again in the afternoon from 3 pm to 6 pm MST (Figure 35).

The next blowing dust prone section of Interstate 10 extends from near Benson east to the Arizona and New Mexico state boundary. This corridor of Interstate 10 experiences considerably fewer events of only 29 which account for 117 injuries and 21 fatalities. Arizona's second most deadly event occurred along this stretch of the Interstate on 9 April 1995 near the town of Bowie and resulted in 10 fatalities and 24 injuries. Abandoned cropland and the Willcox Playa are the main dust sources for this section of Interstate 10.

## D. Climate Change

The impact of Arizona dust events on climate change and conversely the impacts of climate change on Arizona dust is largely unknown at this time, though there has been some research showing anecdotal links. Dust has increased across the Western United States over the past 100 to 200 years due to human activities as land use has changed with increased livestock grazing which peaked in the mid-20th century. (Neff, 2008)

Painter et al. (2007) researched the effect of blowing dust from lower elevations on mountain snowpack in the San Juan Mountains of Colorado. With increased dust deposition, there was greater radiative forcing with snow cover duration decreasing about 18 to 35 days. Painter et al. (2010) also found that this same process results in an earlier spring runoff season with increased evapotranspiration reducing runoff by about 5 percent annually.

Miller and Tegen (1997) researched the impacts of desert dust storms and the link to climate concentrating on the deserts near the Arabian Sea. It was found that dust aerosols have the same effect as clouds, reducing net radiation to the surface. However, absorption of sunlight by dust particles results in heating of the cloud itself. The net result was found to be slight cooling under the dust cloud on the order of about 1°C.

### E. Economic

There is a wide breadth of economic impact that occurs with dust events in the state of Arizona. Unfortunately, there have been no local studies to quantify the impact. The obvious economic impact from blowing dust events are from the shutdown of certain infrastructure such as Interstate 10 for many hours following serious accidents. This results in a delay in the transport of goods and services. In a large scale haboob event, the Phoenix Sky Harbor airport for example does incur delays due to reduced visibilities but these impacts may easily be dwarfed by the large impacts of the thunderstorms that often shortly follow the dust. There would potentially be economic agricultural impacts from blowing dust but information on this is limited.

The closest information found to quantify economic impacts from dust is from an economic study that looked at a major event that impacted Sydney Australia in September 2009. Sydney is not known to often get blowing dust transported from the interior of Australia. This single event resulted in about Australian $425 million in economic losses (Tozer, 2012) with the majority of losses on households due to cleaning and other costs.  It is likely that after a major haboob event in a high population center such as Phoenix, that cleanup from residual dust would be a significant cost to the economy. However, it can be argued that certain businesses stand to gain positive economic impact such as car washes, pool cleaning, street sweepers etc.

## III. Summary

Blowing dust and dust storms have far reaching impacts both short and long term. A full understanding of these impacts will be necessary to be able to effectively mitigate and cope with these hazardous weather events. In the next section, technology and methods used to detect blowing dust and dust storms will be discussed. More importantly the current ways of warning the public of these dangerous events will be described.

# Part IV: Dust Storm Detection and Warnings in Arizona

## I. Detection

### A. Low Cost Air Quality Sensors

Low-cost technologies are now available to easily prototype sensor systems. These methods are being used in a prototype project to deploy dust sensors across vulnerable areas. By keeping the costs very low (~$100 each), the National Weather Service (NWS) can plan for many more installations which means higher density and thus a greater chance to provide early detection of developing dust storms. Each sensor measures the dust particulate level (PM10) at 30 second intervals. Regular data observations are sent to a central server. In addition, if any one sensor detects a significant and sudden increase in dust levels it can immediately send an alert out to a mailing list of responders.

To date nine sensors have been installed in the field and more are being deployed in the coming days. The concept has caught the attention of agencies including the Arizona Department of Transportation which has proposed a dense network of over 100 of these sensors based on the NWS prototype project. The hope is that this system will provide early detection of dust storms in order to give heads up notification to responders and transportation officials as well as to the NWS for use in evaluating the need for Dust Storm Warnings.

### B. Weather Spotters

NWS offices across Arizona and the U.S. as a whole are heavily reliant upon trained spotters to provide critical weather information as it is happening. Given that the spotter network is a human based network, there is a strong correlation in the number of spotters to population centers across the state. However, with targeted recruitment efforts there has been success bringing in many spotters from more rural locations.

Each spring, potential spotters are recruited to attend training sessions spread throughout the region before the upcoming monsoon season. These training sessions are designed to train new spotters (and provides refreshers for veteran spotters) on the background meteorological information and subsequent criteria that is important for the NWS to know about. Thus, when the spotter sees different severe weather phenomena they can correctly identify it and report it to the local NWS office. This is crucial information as it provides an observational based “ground truth” from a trained spotter the NWS gives more credibility towards.

When a spotter observes reduced visibility due to blowing dust, they will report the estimated visibility and location of the dust to the NWS office. This is critical information, especially away from urbanized areas where less observational systems are in place. It is important to note that while the meteorologist might be able to determine there is likely dust based on radar, especially in locations that are closer to the radar, there is no concrete way for a meteorologist to determine the resulting visibility from the dust. This is what makes spotters so crucial in the detection process for dust and the warning process as well with the critical visibility information.

## C. Automated Surface Observing System (ASOS)

The automated surface observing system (ASOS) and automated weather observing system (AWOS) is another key link in identifying surface dust and visibility. ASOS and AWOS stations are located at all of the major airports across Arizona and many of the smaller/minor ones as well. The advantage of the ASOS stations is they report hourly 24 hours a day with data in 1 minute and 5 minute increments available. This automated system is a key to dust observations, and when combined with spotters is very useful to give the forecaster or warning meteorologist critical visibility information.

## D. Doppler Weather Radar

The primary real time tool that meteorologists use to determine the presence of dust storms is Doppler radar imagery. Doppler radar is primarily useful for the stronger convectively driven larger scale dust storm events that are prevalent in the summer months. The smaller scale events are usually too small in scale and low to the ground to be depicted by radar.

In the last few years, Doppler radar has been aided by the introduction of dual polarization (Dual-Pol) radar technology. Dual-Pol radars send both horizontal and vertical pulses, which provide a two dimensional picture of the returns. This enables the meteorologist to have more specific information on the targets or hydrometeors that are detected by the radar. Before the advent of Dual-Pol there were only reflectivity and velocity data to view. These newer Dual-Pol datasets are very helpful and have been key to determine outflow boundaries from thunderstorms and their strength, thus providing important information on the location of possible dust.

With the Phoenix (KIWA) radar and Yuma (KYUX) radars located in the lower elevations, the lower scans of these radars have always been useful. The Tucson (KEMX) radar is located at about 1,500 meters MSL or about 750 meters above the Tucson valley so the lowest radar scans do not quite capture the low levels in the Tucson metro as well.

A major dust storm (haboob) event occurred in the Phoenix metropolitan area on 5 July 2011 (Figure 36). Fortunately, the KIWA radar already had the Dual-Pol technology installed and gave us our first indications of how to detect dust storms using the new technology. The base reflectively seen in Figure 37 from 5 July 2011 shows two outflow boundaries, the southernmost boundary south of Phoenix near the San Tan Valley and the northern boundary near Peoria. The southern boundary moving towards the north was the significant haboob as it developed across the deserts south of Phoenix. Figure 38 shows radial velocity at the same time. Note that inbound velocities to the radar were approximately 40-45 kts which is easily enough to pick up loose dust from desert soils, especially given the extended dry period the area had been in prior to this event.

The Dual-Pol products from 5 July 2011 were quite interesting in what they revealed. One of the Dual-Pol products is called Correlation Coefficient (CC), which measures the uniformity of the targets. CC values visually range from 0 to 1, where 0 represents no uniformity and 1 is perfect uniformity. Figure 39 shows the CC values from this event. Note the CC values are near one in the locations with strong reflectivity returns in Figure 37 but along and just south of the boundary near the San Tan Valley the CC values average about 0.5 showing there is considerably less uniformity. This gives us a strong indication that the area in question along and just south of the outflow is not hydrometeors. Another product called the Hydrometeor Classification (HC) algorithm takes all the Dual-Pol data to provide a best guess. In this case, as seen in Figure 40, the area in question was deemed biological. Note that there is no way for the HC to classify dust.

Another event that produced a significant haboob in the Phoenix area was on 27 August 2013. Given the usefulness of the Dual-Pol CC data and to confirm the trends we saw in the 5 July 2011 event, there are similar trends in the data for August 26, 2013. Figure 41 shows CC data indicating values of about 0.5 near and just behind the outflow boundary which produced the haboob. The higher CC values near 1.0 are indicative of hydrometeors.

A key finding from analyzing Dual-Pol data from these two events is the similarity of winds in excess of 25 knots, especially given non-uniform CC values and antecedent dry conditions which are a forecaster rule of thumb to use in dust events.

## E. Satellite

The main satellite methodology historically used to depict blowing dust is the 11-12 μm brightness temperature difference product. This product was routinely available in near real time as part of the GOES 11 and GOES 12 imagers but the newer GOES satellites that are currently operational such as GOES 15 do not have the 12 μm channel as they have been replaced by the 13.3 μm channel.

At the time of this writing, there are 12 μm channels on polar orbiting satellites via the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the polar-orbiting NASA Terra and Aqua satellites and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP). The main disadvantage with the polar orbiting satellites is that they only pass a twice per day so the likelihood of capturing a dust event in progress is much reduced.

The MODIS true color images that are available in higher resolutions are also able to depict larger scale areas of blowing dust although only available during the daytime (Figure 42). Meanwhile, the IR brightness temperature difference product is useful for determining areas of blowing dust day or night, although still restricted by the number of passes on the polar orbiting satellite (Figure 43). VIIRS imagery captured a blowing dust event on a smaller scale on 29 October 2013 as it just happened to be doing a pass while the event was ongoing. Figure 44 shows the streaks from small scale point sources from this event in Pinal County.

The satellite product timeliness situation is expected to improve in the future as the Advanced Baseline Imager (ABI) sensor will be a part of the GOES-R satellite products. This will enable the viewing of products along the lines of the brightness temperature difference but in much more frequent time increments, up to every 5 minutes or even less and with spatial resolutions of 0.5 to 2 km..

### F. Traffic Cameras and Web Cams

ADOT has widespread cameras along the major limited access highways in both the Phoenix and Tucson metropolitan areas. These cameras are useful for dust detection as it lets meteorologists see the location of dust in real time. However, with these cameras in the population centers there are usually many reports of dust from other sources. For more rural locations where dust is a problem there are more limited traffic and web cams. ADOT has weather stations with webcams in rural locations along the interstates as part of the Road Weather Information System (RWIS) that are mostly clustered in northern Arizona, particularly along Interstate 40 with just a couple of sites in eastern Cochise County along Interstate 10.

## II. Warning the Public

### A. Dust Storm Warning and Wireless Emergency Alerts

The public is alerted to significant blowing dust hazards by the NWS using Dust Storm Warnings and Blowing Dust Advisories. Dust storm Warning criteria is met when visibilities are one quarter of a mile or lower. Blowing Dust Advisory criteria occurs when the visibility is greater than one quarter of a mile but less than or equal to one mile.

When the local NWS office issues a dust storm warning it has widespread dissemination through traditional methods such as existing NWS platforms and the media through the Emergency Broadcast System. In 2012, Wireless Emergency Alerts (WEA) started which is a program through the Federal Emergency Management Agency (FEMA) in which critical messages from the government are sent to cell phone users instantly. When the NWS issues Dust Storm Warnings, these are automatically sent via WEA to cell phone users in the warned areas most directly at risk from dust storms.

There are a couple of minor drawbacks to WEA transmission of Dust Storm Warnings. Due to internal technological issues, the NWS issues “zone based” Dust Storm Warnings and not “polygon” warnings which are used for flash flooding and Severe Thunderstorm Warnings. Zone based means they are for pre-defined areas that take up a large portion of a given county. The main disadvantage of the zone based Dust Storm Warnings are that the WEA alerts will in some cases alert people that might be up to 100 km away from the actual dust impacts. Phone users do have the ability to turn WEA alerts off and if they feel they are getting too many of them, the users are more likely to turn it off which could hamper the ability to get critical weather information at a later time.

### B. ADOT Message Signs

ADOT has variable message boards across the highway system in Arizona. Through a close working relationship with the NWS, ADOT monitors the NWS forecasts and will flash messages to drivers across the state indicating that there are high winds and blowing dust is possible. This is another effective way to communicate to drivers that blowing dust is a hazard. Given that many of the drivers on the Interstates in Arizona are from out of state, it is important to have such messages on the highways to provide notice of possible dust.

### C. Social Media

Social Media, especially Twitter, has proven to be a very valuable asset for both obtaining information about dust storms and disseminating critical safety information. The NWS embraced Social Media starting in 2011 with Facebook and 2012 with Twitter as each weather forecast office nationwide established a presence on these sites.

The NWS Tucson staff initially found out about numerous dust events which had fatal accidents on Interstate 10 through Twitter from 2012 through 2015. Information via Twitter would often come from ADOT which has a big presence on the network or through other media partners. Facebook hasn’t proven to be as useful given that it is not built as much for real time breaking events and information. A very useful aspect of social media is the two way interaction that takes place.

Once Dust Storm Warnings are issued from the NWS, it has become a best practice to disseminate the information out via Twitter and Facebook for even greater exposure.

Additionally, starting in 2014 the NWS offices in Tucson and Phoenix have been proactive in issuing Blowing Dust Advisories with up to 12 hours of lead time before a monsoon convective event with high confidence of a potential haboob. Social media has been instrumental in helping get the message out to the public.

## III. Safety and Education

### A. Pull Aside Stay Alive

In 2011, the NWS developed a slogan for motorists to keep in mind regarding dust safety while driving titled Pull Aside Stay Alive. ADOT then collaborated with the NWS on a major public safety campaign built around Pull Aside Stay Alive which included videos, public safety announcements, a website and a unique campaign called the haboob haiku where the public would submit haikus about dust storms and safety. This haboob haiku was extraordinarily successful and received widespread local media interest and even national and global media interest.

### B. Annual Workshops

Starting in 2012, the NWS offices in Phoenix and Tucson partnered with ADOT to host what has become an annual multi agency and multidisciplinary workshop to bring together those who have an interest in the dust problem across Arizona. The last workshop held in 2016 had over 70 attendees from over 2 dozen different agencies.

The goal of these workshops is multifaceted. Most notably, it is an extraordinary opportunity to bring folks with many different backgrounds that have an interest in solving the blowing dust problem together. The workshops have proven to be useful in establishing short and long term mutual goals for Education, Detection and Prediction and Mitigation of dust. The results of these workshops are seen in long term collaboration and mutually beneficial projects.

## IV. Summary

NWS offices use a wide array of sources from remote sensing including radar and satellite to ground truth observations including weather spotters, law enforcement, media and the public to help detect the presence of dust. Using these tools together gives the NWS a fairly representative picture of the significance of the dust event. On the warning side, technology has evolved considerably over the last decade to allow for wider dissemination of life saving dust storm warning information through systems such as Wireless Emergency Alerts. In addition, strategic partnerships with agencies such as ADOT have been enhanced with dealing with the dust issue, leading to statewide public safety campaigns including “Pull Aside Stay Alive.”

# Part V: Prediction and Evaluation: A Case Study of the 5 July 2011 Haboob

## I. Overview

Dust aerosols generated by dust storms in Arizona have a strong local to regional level impact (Idso et al., 1972; Raman et al., 2014; Vukovic et al., 2014; Sorooshian et al., 2011) and significantly affect public health (Sprigg et al., 2014), transportation, air quality and atmospheric chemistry, precipitation cycle, and the economy. In particular, recent reports on dust emissions in the western US have alluded to the increase in frequency or magnitude of these extreme events in the recent decade (e.g., Brahney et al., 2013; Seager et al., 2007), and the impact of local dust on aerosol abundance in Arizona, especially during the North American Monsoon (e.g., Raman et al., 2016; Lopez et al., 2015). These dust storms are massive, local and have strong implications for air quality and public health.

As discussed previously, haboobs are generated by thunderstorms and the resulting downbursts in southern Arizona which cause massive societal impacts in Phoenix and neighboring regions. The downbursts generate regions of decreased surface temperature (‘cold pools’) near Tucson which then propagate towards Phoenix. As they propagate, they lift dust from the hot, dry, barren lands across the Interstate 10 corridor. In terms of air quality, the blowing dust typically lasts for 3-6 hours and emits more than 100 µg $m^{-3}$ of particulate concentrations in the atmosphere (Raman et al., 2014). Previous studies have investigated the spatial and temporal variability of haboobs from ground observations, meteorological charts, satellite, and models (e.g., Chen and Fryrear, 2002; Nickling et al., 1984; Brazel et al., 1986; Raman and Arellano, 2013; Raman et al., 2014; Huang et al., 2015). We provide detailed review of observational analyses of haboobs in parts I-IV of this report. In this section, we focus on the modeling of haboobs in Arizona.

Although haboobs attracted a lot of modeling attempts in the Middle East and Africa (Knippertz et al., 2007; Miller et al., 2008), limited studies have focused on modeling of Arizona haboobs due to the challenging nature of dust sources, and complex topography of this region. For example, Suck et al., 1978 used numerical simulations of particulate matter to investigate dust transport from fall and winter dust storms in Maricopa County. This study concluded that most of the dust sources in this region are local fugitive sources, and modeling of dust storms in Maricopa county require detailed description of sources (e.g., size distribution of aerosols, land cover characteristics, surface roughness) and parameterizations of sinks (e.g., dry deposition).

During the last decade, a dozen numerical models have been developed for global dust modeling and transport. Vukovic et al., 2014 used regional coupled atmospheric-dust model NMME-DREAM to simulate the 5 July 2011 haboob that hit Phoenix. This study used a mask combining NASA land cover products and MODIS NDVI to identify dust sources. The model simulations captured the spatial pattern of the dust but underestimated the $PM_{10}$ concentrations over Phoenix. Their results highlighted that simulations of such high intensity dust storms in Arizona require high resolution simulations with precise descriptions of dust source pathways. Raman and Arellano, 2013 used a regional coupled community model to better understand the key meteorological features and air quality processes of the 5 July 2011 haboob. The authors used Weather Research and Forecasting (WRF) model coupled with chemistry to simulate the cold pools and aerosol abundance over Phoenix during and after the haboob. The results suggested that the dust lingered over Phoenix almost until the next morning and the haboob was a result of three major dust walls in Southern Arizona. The case study, described in the following sections, illustrate the key results from this study.

Recently, Huang et al., 2015, used a combination of multiple satellite and ground observations to create decadal dust records in Arizona. This study identified Sonora and Chihuahua as major dust sources for dust events in Phoenix. They also used NAQFC 12km CMAQ model to simulate a case study of a haboob in Arizona. Their results suggest that dust records are anti-correlated with surface indicators such as NDVI, PDSI, and soil moisture. The study emphasized the importance of incorporating additional satellite data products on aerosol and surface characteristics to improve predictions of haboobs.

## A. Activities at UofA

The department of hydrology and atmospheric sciences provides operational forecasting for significant weather conditions during the monsoon season (http://www.atmo.arizona.edu/?id=wrf&section=weather). As a part of this operational forecasting, model simulations based on the Weather Research and Forecasting model (WRF), provide forecasts of potential meteorological conditions that can result in haboobs (Mike Leuthold, personal communication). However, these simulations only suggest potential meteorological indicators of haboobs and do not explicitly provide forecasts of dust abundance in the atmosphere.

Previously, dust research at UofA utilized Dust regional atmospheric model (DREAM, Nickovic et al., 2001) to model dust emission, transport and deposition for public health related applications (Yin et al.,2005; www.atmo.arizona.edu/research/dust/PHAiRS_Initial_Benchmark.pdf). DREAM is based on the Eta modelling system and the Eta/NCEP regional atmospheric model. However, DREAM lacked the high operational mesoscale resolution dust forecast capability which is important for capturing haboobs. Previous studies on dust modeling using DREAM found that the dust concentrations were underestimated by DREAM (e.g., Vukovic et al., 2014). Possible factors for the discrepancies listed by these studies include: 1) lack of knowledge about size distribution of dust during dust storms, 2) obsolete land use and need for finer resolution erodibility datasets. Recently, Raman and Arellano, 2013 demonstrated dust modeling studies using a full coupled high resolution online weather chemistry model. Present research using an online coupled chemistry shows promising results to be transitioned into a quasi-operational high resolution dust forecasting system. The current framework is only a preliminary attempt to include dust forecasts for haboobs. Future work will incorporate satellite observations of surface and aerosol properties and include ensemble simulations in WRF-Chem.

## II. Dust storm modeling framework: Current Status

The important components of this framework are:

**1. WRF-Chem**

- High resolution simulation of meteorological indicators such as cold pools.
- Inclusion of dust forecasts and coupling between meteorology and chemistry.
- Understand dust source regions, dust transport from haboobs, and lifetime of dust from haboobs. Although these efforts require comprehensive evaluation with observations, preliminary results using a WRF-Chem case study indicate the model can capture the spatial and temporal variability of aerosol loading from haboob.

**2. Radar reflectivity and hydrometeor classification data from KEMX and KIWA radars.**

- Help detect the dust pathways from cold pool movements based on radar reflectivities and hydrometeor classification products
- Compare model simulations of cold pools against radar images.

**3. IMPROVE, EPA-AQS particulate matter and dust speciation concentrations.**

- Ground air quality monitoring networks such as EPA-AQS and IMPROVE (Interagency Monitoring of Protected Environments) provide hourly and daily particulate matter concentrations respectively.
- Identify stations with peak concentrations during the haboob.
- Identify dust pathways based on concentration gradients during the haboob.

**4. Satellite based aerosol abundance (e.g., MODIS aerosol optical depth, CALIPSO vertical feature mask).**

- Explore horizontal and vertical distribution of aerosol loading in the atmosphere after the haboobs. Most of the polar orbiting satellites have overpass times in the morning/afternoon. So, they can be useful only for assessing the dust loading on day after the event and not

during the haboob event since most of the dust events during the monsoon, occur in the evening.
- Assess model performance of aerosol abundance using multi satellite aerosol retrievals.

## III. Model Description

This study employs WRF-Chem v3.4.1 (Grell et al., 2005; Fast et al., 2006), a chemistry version of the Weather Research and Forecasting model (Skamarock et al., 2008) to investigate the meteorology and dust transport from the 5 July 2011 haboob in Arizona. WRF-Chem is a fully coupled meteorology-chemistry community regional model used to simulate the concentrations of trace gases and aerosols simultaneously with the meteorology (e.g., Zhang et al., 2010; Barnard et al., 2010). Unlike other air quality models, the transport of the chemical species in WRF-Chem is driven by online meteorology (where the chemistry is completed embedded in the model). The model also accounts for the feedback between meteorology and chemistry.

The WRF-Chem model configuration covers the highly complex topographical landmass over the southwestern US encompassing the arid deserts of Arizona, California, New Mexico, and Utah. Due to the complex nature of the terrain and the downbursts that occur during the monsoon period, we need high resolution convection resolving models to simulate haboobs. In order to do this, this setup includes 2 domains, one at 5.4 km and another at 1.8 km horizontal resolution defined on the lambert-conformal projection. The larger (smaller) domain has 300 (397) grid points in the east-west direction and 420 (406) grid points in the north-south direction. The vertical grid is composed of 38 levels from the surface to 50 hPa. The static geographic fields such as land cover, albedo, terrain height etc. are interpolated by the WRF preprocessing system (WPS) from 30 second United States Geographical Survey data. This set up is similar to the WRF configuration already in use at UofA, Department of Hydrology and Atmospheric Sciences, for convective scale forecasting of thunderstorms during the summer.

The initial and boundary conditions for the meteorology are taken from National Center for Environmental Predictions (NCEP) Final Analysis Fields (FNL) at 1 degree horizontal resolution at every 6 hours (Kalnay et al., 1996). The cloud microphysics is represented by Thompson scheme for ice, snow, rain, and graupel processes particularly suitable for high-resolution simulations in WRF. The radiative transfer processes in longwave and shortwave are represented by Rapid Radiative Transfer Model for GCMs (RRTMG) radiative transfer scheme. We use NOAH land surface model to represent surface physics. The boundary layer parameterization is represented by Mellor-Yamada-Janjic (MYJ) turbulent kinetic energy scheme.

We use the chemistry package MOZCART for representing the chemical processes. This option uses gas phase chemistry mechanisms from Model for Ozone and Related tracers (MOZART-4) and aerosol mechanisms from Georgia Tech / Goddard Global ozone Chemistry Aerosol Radiation and Transport Model (GOCART) (Chin et al., 2002). GOCART dust scheme in WRF-Chem provides size resolved dust aerosol concentrations with effective radii at 0.5, 1.4, 2.4, 4.5, and 8 µm respectively. The model also allows for feedback between aerosols and radiation. The initial and boundary conditions for chemistry are based on 6h outputs from offline global chemical transport model MOZART-4 (Model for Ozone And Related chemical Tracers, version 4) (Pfister et al., 2011; Emmons et al., 2010). We use US National Emission Inventory (NEI-05) hourly anthropogenic emissions at 4km resolution for point and area sources (http://www3.epa.gov/ttnchie1/net/2005inventory.html). The anthropogenic emissions have diurnal variation. However, they do not include seasonal variation. Biomass burning emissions are provided to WRF-Chem via Fire Inventory from NCAR (FINN v1 Wiedinmyer et al., 2011). Biogenic emissions of isoprene, monoterpene, and other volatile organic compounds are calculated online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN**)** (Guenther et al., 2006).

## A. Dust in WRF-CHEM

Dust parameterization uses GOCART-AFWA scheme (Jones and Creighton , 2011) that calculates the dust flux using the following equation :

$$F_p = \{ CSs_p u_{10m}^2 (u_{10m} - u_{*t})\ if\ \ u_{10m} > \ \ u_{*t}\ otherwise\ \ 0 \} \qquad (1)$$

Where F is the vertical dust emission flux for the particle size bin ‘p’ (Kg $m^{-2}$ $s^{-1}$), ‘C’ is the tunable erodibility constant which can be tuned for different regions in the world. Ginoux et al., 2001 defined C as equal to 1 µg $m^{-5}$ $s^{2}$ for the global dust distribution simulations using GOCART. Here, we use C = 10. Previous studies have reported that increasing the default value of C can increase dust concentrations (e.g., Kumar et al., 2012). These studies also explored tuning C based on aerosol optical depth and angstrom exponent observations. ‘S’ is the source function for dust that represents the erodibility of the region based on the vegetation fraction. All vegetated lands are assumed to have zero erodibility. In other words, ‘S’ is the probability of sediments settling at a particular grid cell, calculated based on the elevation in the neighboring grid cells in a $10^o \times 10^o$ bounding box. In general, this assumes, lake beds, depressions, playas are potential dust sources. The changes in erodibility with respect to vegetation are not considered. $'s_p'$ represents the fraction of soil composition in each grid cell. GOCART assumes each erodible grid cell has 50% sand, 25% silt, and 25% clay soil. $U_{10m}$ is the 10m wind speed in the model, and $u_{*t}$ is the threshold friction wind velocity below which dust emission cannot occur. $u_{*t}$ is a function of soil moisture and land cover characteristics. C, $u_{*t}, and\ s_p$are some of the tunable quantities in the model. The continuity equation for dust concentrations includes dust source transport by horizontal and vertical advection, turbulent diffusion, dry, and wet deposition.

The model was run from 04 July 12Z, 2011 until 08 July 00Z, 2011 over the two domains. The model requires high resolution convective scale simulations. However, we do not need long periods of runs for haboobs since they are rapid and spontaneous. WRF-Chem outputs were simulated every hour. We discuss below the general meteorology and dust emission observed in the model, and the evaluation of these features.

# IV. Results and Discussion

## A. Cold pool formation

The haboob that occurred in Phoenix on 5 July 2011 was associated with severe downbursts from thunderstorms that produced strong surface wind speeds. Massive dust emission from this haboob was linked to the extreme antecedent winter conditions that destroyed most of the vegetation the preceding winter and spring, thus, favoring dust emissions during the summer. The synoptic meteorological conditions during the haboob are described in other sections of this report and also in

Raman et al., 2014. In this section, we focus on the mesoscale features of the haboob and dust source transport during and after the haboob.

Haboobs in Arizona usually occur as two to three massive walls of dust merging across Interstate 10. These dust walls are created by strong near surface winds that pick up dust as they move across the south central (e.g., Casa Grande) and south western Arizona regions (e.g., Yuma). Figure 45 shows the predominant dust source regions in Arizona. They extend to more than 160 km horizontally and 2.4 km vertically with maximum wind speeds of 22-26 m $s^{-1}$ (Idso et al., 1972). The mesoscale feature of a haboob is also characterized by strong directional vertical wind shear and moderately moist conditions in the lower levels of the atmosphere.

Figure 46 shows the radar reflectivities from KIWA Phoenix radar on 5 July 2011. These images show the origin and evolution of the storm as it crosses Interstate 10 on 5 July 2011. We use these radar images along to qualitatively examine the propagation of cold pool from WRF-Chem. Fig. 47 (left panels) show the radar reflectivities from the outflow boundaries at 0.50 tilt for 0154Z, 0213Z and 0250Z on 6 July. The storm outflows are seen as bow echo patterns with weak radar reflectivities representing the cold air reaching the surface. Here, we find three major outflow boundaries from the northwest (NW), southeast (SE) and southwest (SW) of Phoenix during this period.

Model simulations indicate that the cold pools started developing in the early evening around 23Z**,** local time and the major downburst and merging of cold pools occurred around 03Z, showing some similarity to the radar observations over this region. We show in Figure 47, 10m temperature and 10m total wind vectors from WRF-Chem to analyze the cold pool development. Although WRF-Chem outputs are available only at hourly resolution, the comparison against the pattern of cold pool development from radar images show that WRF-Chem reproduces the spatial pattern and direction of propagation of cold pools near Tucson, Interstate 10, and Phoenix. We see that the downbursts start occurring near Tucson from 23Z. At 01Z, they become more active and the cold pools or regions of reduced surface temperatures start appearing around Tucson and they propagate towards Phoenix (They appear as patterns that swipe things off the surface along Interstate 10). The downburst causes diverging surface wind patterns and both the model and radar observations indicate north westward transport of the haboob from south central AZ. This is similar to the direction of propagation mentioned in previous studies for American haboobs (e.g., Idso et al., 1972). The locations of Phoenix (north), and Tucson (south) are indicated by black circles in Figure 47. The bow echo patterns appear at 03Z when the dust walls merge to cause the massive haboob in Phoenix. The role of bow echo pattern in redistributing the transport of dust across Interstate 10 is consistent in radar and WRF-Chem simulations.

## B. Storm propagation

The storms originated during the late afternoon hours near Vail, Benson, and Tucson. This can be seen in Figure 48 (A) where radar reflectivities from KEMX show storm initiation near Benson at 2256Z (3:56 pm local time). These storms moved northwest with peak Doppler mean velocities of 29 m $s\_^{1}$. At 2314Z, they formed a continuous forward propagating system that organized into squall lines with high reflectivities (Figure 48B). Several downdrafts and outflow boundaries resulted within 20 min, as the storms dissipated. These outflow boundaries started moving northwards from Benson at a speed of 4-9 m $s^{-1}$ towards Phoenix, which is at a lower elevation compared to the surrounding areas. As the outflow boundaries from primary storms moved towards Phoenix, they accelerated several storms along their tracks. This resulted in outflows that were observed from KIWA Dual-Pol radar southeast of Phoenix during the period 5 July 2300Z to 6 July 0300Z (Raman et al., 2014).

## C. Air quality during the haboob

Aerosol Optical depth (AOD) represents the attenuation of solar radiation by particles in the atmosphere. AOD at 600nm was simulated by WRF-Chem. Figure 49 in combination with Figure 47 reveal that the cold pools pushed dust across Phoenix. AOD maps in figure 49 indicate higher aerosol abundance west of Phoenix after 02Z. Significantly higher AOD values extend over southwestern and southeastern Arizona, showing similarity to the patterns in hydrometeor classification shown in Figure 45. Figure 49D shows the emergence of two dust walls, one from the southwest and another from the southeast. The dust plumes appear to merge across Interstate 10.

Figure 50 shows $PM_{10}$ concentrations from WRF-Chem at 03Z, and the comparison with EPA-AQS ground air quality monitoring stations in Phoenix (denoted by circles). The observed peak time in $PM_{10}$ matches with the simulated peak time from WRF-Chem. The model also captures the spatial homogeneity between the stations near Phoenix. The similar patterns of $PM_{10}$ concentrations observed (circles in Figure 50, Figure 51 A, B,C) and simulated (Figure 50) indicate that dust was being transported through these regions rather than being entrained from within these regions. This can also be witnessed in Figure 51 where the temporal evolution of $PM_{10}$ shows peaks at all three stations at about 8pm. The peak magnitude of PM10 reaches more than 1900µg $m^{-3}$ in Esterbrooks Blvd near Phoenix. These magnitudes of PM10 concentrations were underestimated by the model by a factor of 10. This bias in $PM_{10}$ concentrations in the model can be related to the underestimation of dust emission over source regions such as over Casa Grande and regions near Yuma (see Figure 44 for dust source regions), use of static landuse in the simulations, and bias in soil moisture. Evaluation of dust plumes was challenging because of the limited ground and satellite observations that were available during the event. Since, the polar orbiting satellites have overpass times in the afternoon/morning, these satellites were not able to capture the actual event, as it happened. Most of the ground monitoring stations for air quality did not have data during this period. Figure 52 shows vertical cross section of PM10 across Phoenix. Although the PM10 concentrations are not as high compared to observations in WRF-Chem (in terms of actual magnitude), the model captures the spatial pattern of horizontal and vertical distribution of dust from the haboob.

A vertical cross section of $PM_{10}$ perpendicular to the cold pool propagation is shown in Figure 52 This shows that the dust plume from the haboob was advected to greater 3km along the leading edge of the storm. Despite the strong vertical mixing during this time, PM10 concentrations decrease significantly with altitude due to the gravitational settling of particles. The peak dust concentrations are seen close to 1km. Since Phoenix is a valley, the particulates have a circling pattern and take a longer time to be completely removed from the region. The dust concentrations lingered around Phoenix on the next day.

## D. Air quality after the haboob

AOD retrievals from Moderate Resolution Imaging Spectroradiometer (MODIS) at 550nm (Remer et al., 2005; Levy et al., 2010) were compared with model simulations of AOD on 6 July 2011 (overpass at ~10:30am), to comprehend the transport of dust after the haboob event. Figure 53 shows comparison of MODIS AOD to WRF-Chem AOD on 6 July 2011. The AOD values radially decrease away from Phoenix both in the model and MODIS AOD retrievals.

The dust plume was also captured by CALIOP instrument (Cloud Aerosol Lidar with Orthogonal Polarization) onboard CALIPSO (Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite during the overpass on 6 July at 2000Z, approximately 350 km northwest of Phoenix at an altitude of 2 km above ground and extending up to 4 km. This dust plume is shown in Fig. 54 based on the VFM product from CALIOP **(**see Vaughan et al., 2004 for details on VFM product). The location of the aerosol layer (35.7$^o$N, 113.5$^o$W), which is noted in Fig. 54 as a light green-filled square, is in good agreement with the areas observed to have relatively high AODs (in comparison with MODIS AOD in Fig. 53) on 6 July. For our case, the aerosol feature classified as polluted dust can be argued to be the dust plume from the haboob based on our previous discussion on the speed of advance of the haboob and consistency with other datasets. Although the peak dust concentrations lasted only for an hour in Phoenix, the average speed of advance of haboobs mobilized the dust towards the northwest boundaries of Arizona in less than a day. The apparent transport of dust to the northwest is also supported by the 24-hr HYSPLIT isentropic forward trajectories (Stein et al., 2015; Draxler and Hess, 1998) shown in Fig. 54. The ensemble trajectories were initiated from an altitude of 2 km (Idso et al.,1972) on 6 July 0300Z at USEPA/ AQS Esterbrooks (PHX) station where the peak concentration was observed. Although not shown here, we note that the altitudes of the end points from HYSPLIT ensemble forward trajectories comprise the lower to upper end of the plume altitude inferred from CALIOP. There were no surface PM measurements available in this area to verify the vertical extent of the plume (see Raman et al., 2014 for details).

MODIS AOD from 8 July 2011 overpass (Fig. 55) shows that aerosol abundance has decreased around Phoenix. However, WRF-Chem still shows increased aerosol abundance near Phoenix. It is not sure if the aerosol abundance near Phoenix on 8 July is from the same haboob or from successive dust storms that happened in this region.

# V. Current limitations and suggestions

Simulation of dust events are better for synoptic level dust storms compared to intense local haboobs like those in Arizona. Robust testing and evaluation of high resolution simulations of dust storms from coupled regional models like WRF-Chem are necessary because they are highly local, rapid, and are driven by complex meteorological processes. The current limitations in haboob modeling in Arizona and the potential suggestions for improvements are listed below.

## A. Lack of high resolution dust sources

Erodible dust sources depend on the vegetation fraction and land cover characteristics such as soil moisture, surface roughness, and topography. Most of the model inputs on land surface characteristics are static and therefore do not provide enough information on the temporal variability of erodible dust source regions. Further, they are designed for coarser resolution dust sources unlike those in Arizona that are highly localized. Incorporation of satellite based daily or seasonally erodibility for dust emission can improve definition of these dust sources. For example, Ginoux et al., 2010 identified dust sources based on MODIS deep blue aerosol optical depth retrievals and land use data at 0.1 degree resolution. They also classified dust based on natural and anthropogenic sources. Incorporation of such satellite based datasets to derive surface erodibility can improve dust emission in the models.

### B. Lack of air quality measurements near potential dust sources in Arizona

For example, Raman et al, 2014 and Tong et al., 2012 have noted that the current air quality measurements lack monitoring stations near some of the important dust sources in Arizona such as near Yuma. South western Arizona is a potential dust source for haboobs. Improving air quality monitoring in these locations can improve assessment of air quality during the haboobs and also help evaluate particulate matter concentrations in the model.

### C. Overpass times of polar orbiting satellites do not match with the timings of the haboob

Most of the dust storms occur during the evening in summer. The convection starts building during the afternoon and massive walls of dust propagate towards Phoenix around 17:00 local time to 21:00 local time. On the other hand, polar orbiting satellites such as MODIS have overpass times close to morning (~10:30 local) or afternoon (13:30 local). So, most of them do not capture the haboob. Future geostationary monitoring systems like the NOAA Geostationary Operational Environmental Satellite (GOES-R, http://www.goes-r.gov), NASA Geostationary Coastal and Air Pollution Events (GEOCAPE, http://geo-cape.larc.nasa.gov) missions that are aimed to monitor and capture AQ events at high temporal resolution can provide better monitoring of haboobs.

We also emphasize the need to integrate multiple satellite observations and model to better capture these events (e.g., Huang et al., 2015). As shown, improving dust prediction not only requires assimilating multiple data sources in atmospheric dust models but also capturing the key meteorological features of the storm. Therefore, assimilating satellite retrievals and/or ground measurements of particulate matter alone may not significantly enhance the accuracy of predicting haboobs. Accurate understanding and precise definition of dust sources and sinks, and the meteorological drivers are key to improve prediction of haboobs in Arizona.

## Part VI: Summary

Blowing dust is a significant underrated meteorological hazard in Arizona with impacts across many disciplines and sectors of the economy including transportation, public health, and air quality. As technology has improved over the past few decades, considerable progress has been made in detection and warning systems along with the modeling and prediction of large scale blowing dust events. We also have a much greater understanding of the most significant trouble spots, particularly along Interstate 10 between Tucson and Phoenix. However, with many blowing dust events on a localized basis, efforts will need to continue to better mitigate small scale blowing dust threats.

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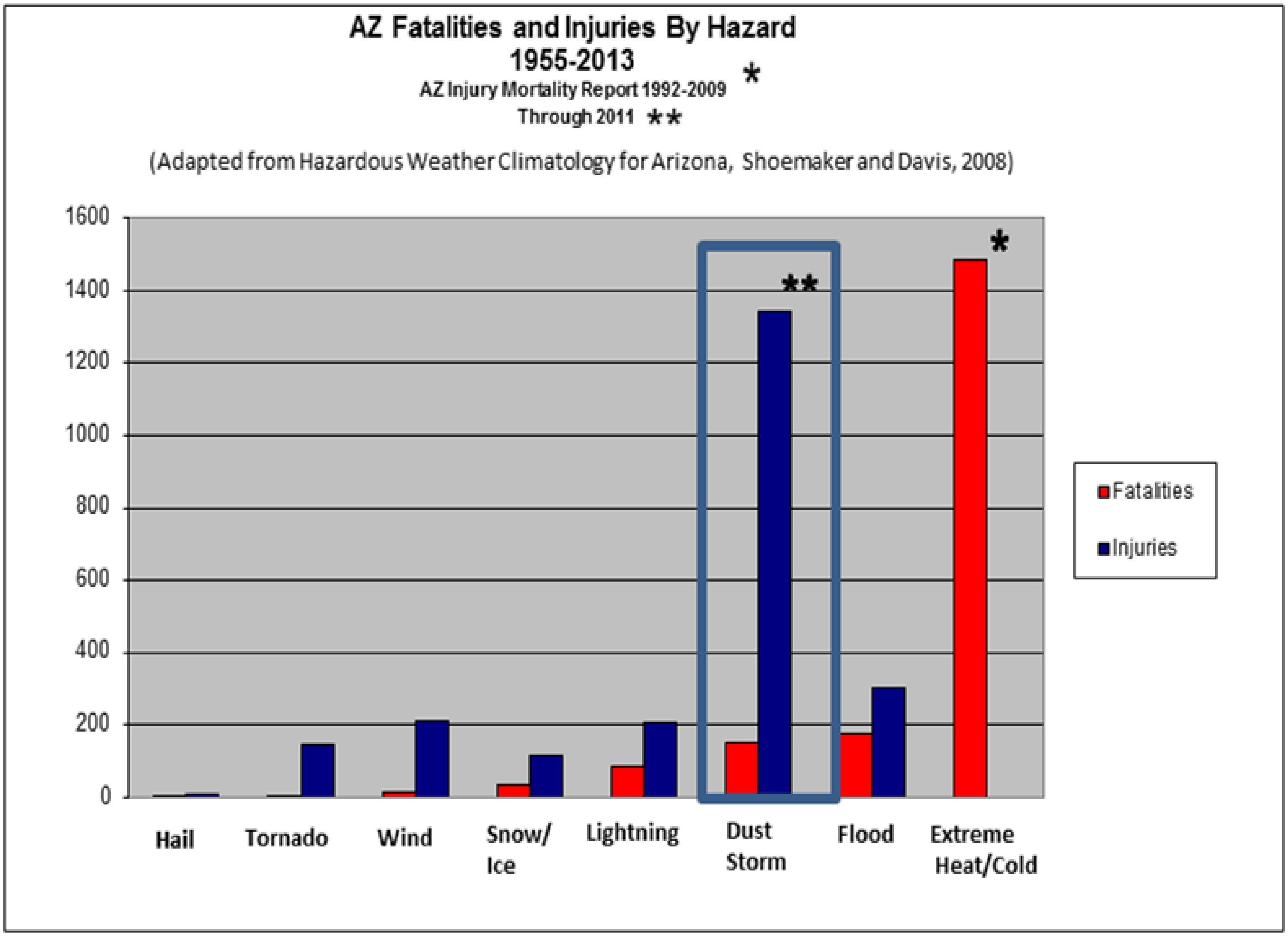


Figure 1. Injuries and fatalities in Arizona sub-divided by weather hazard from 1955 to 2013.

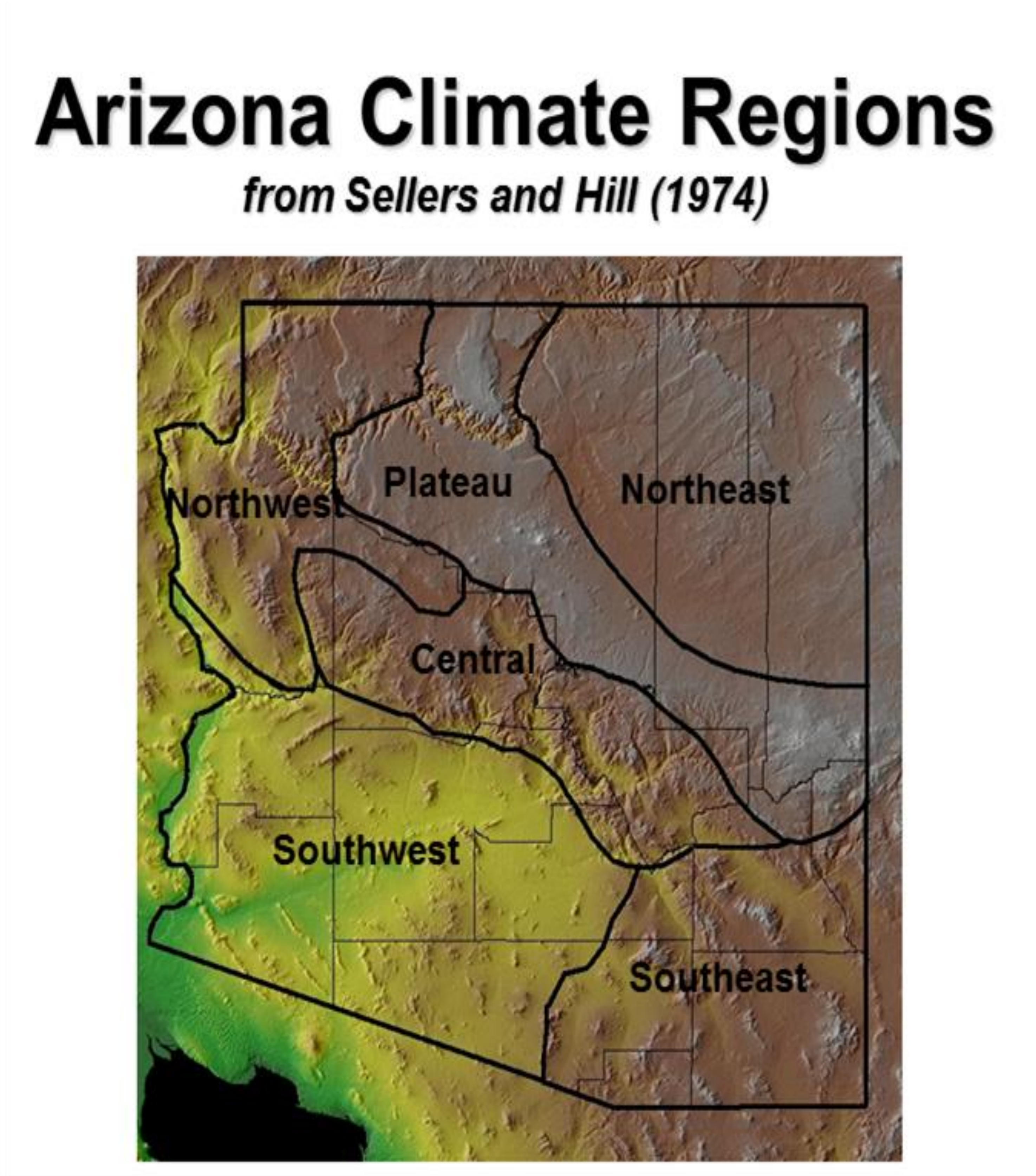


Figure 2. Arizona climate regions used in this study as defined by Sellers and Hill (1974).

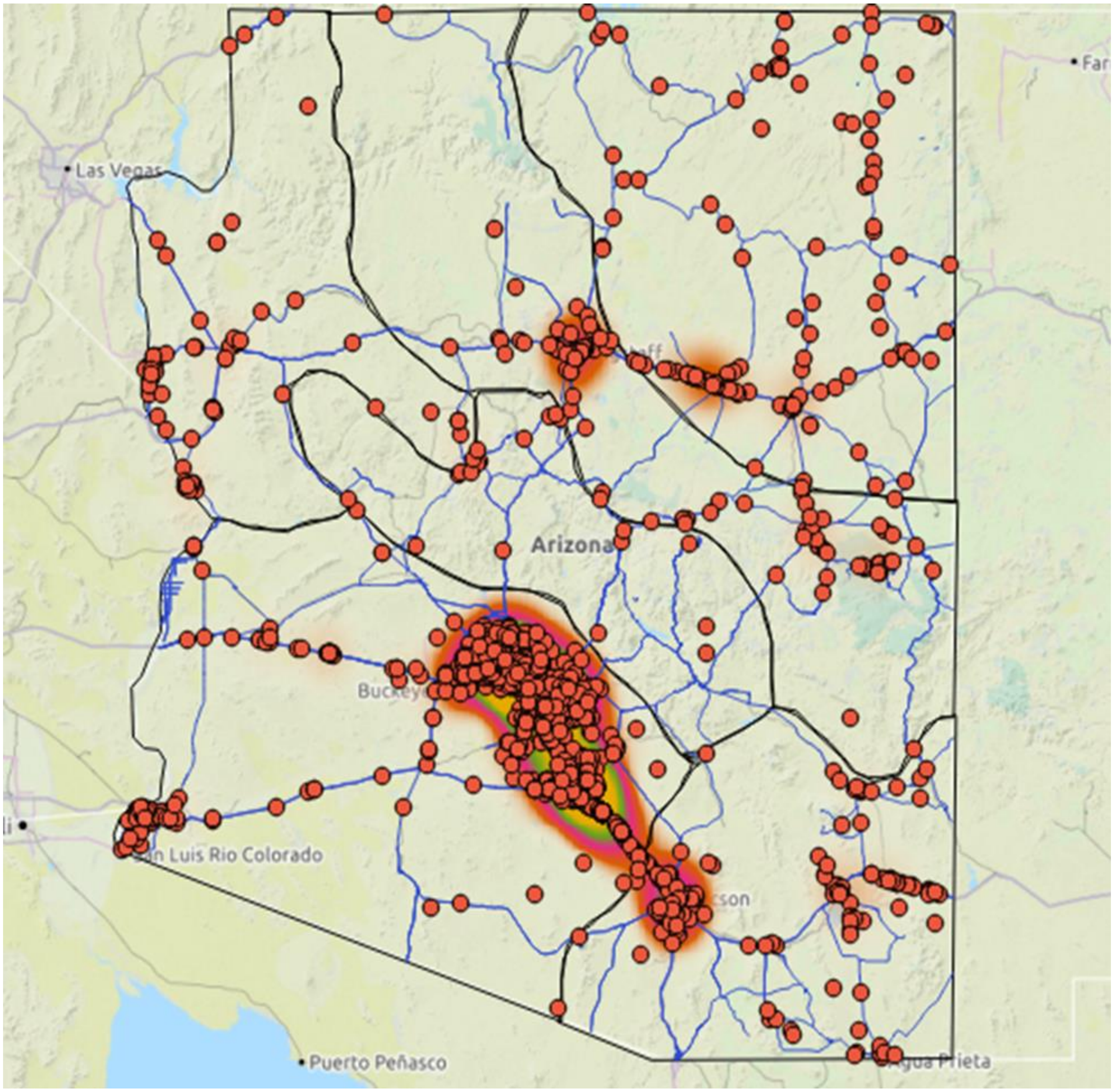


Figure 3. Heat map showing the concentration of reported events from 1955 to 2011.

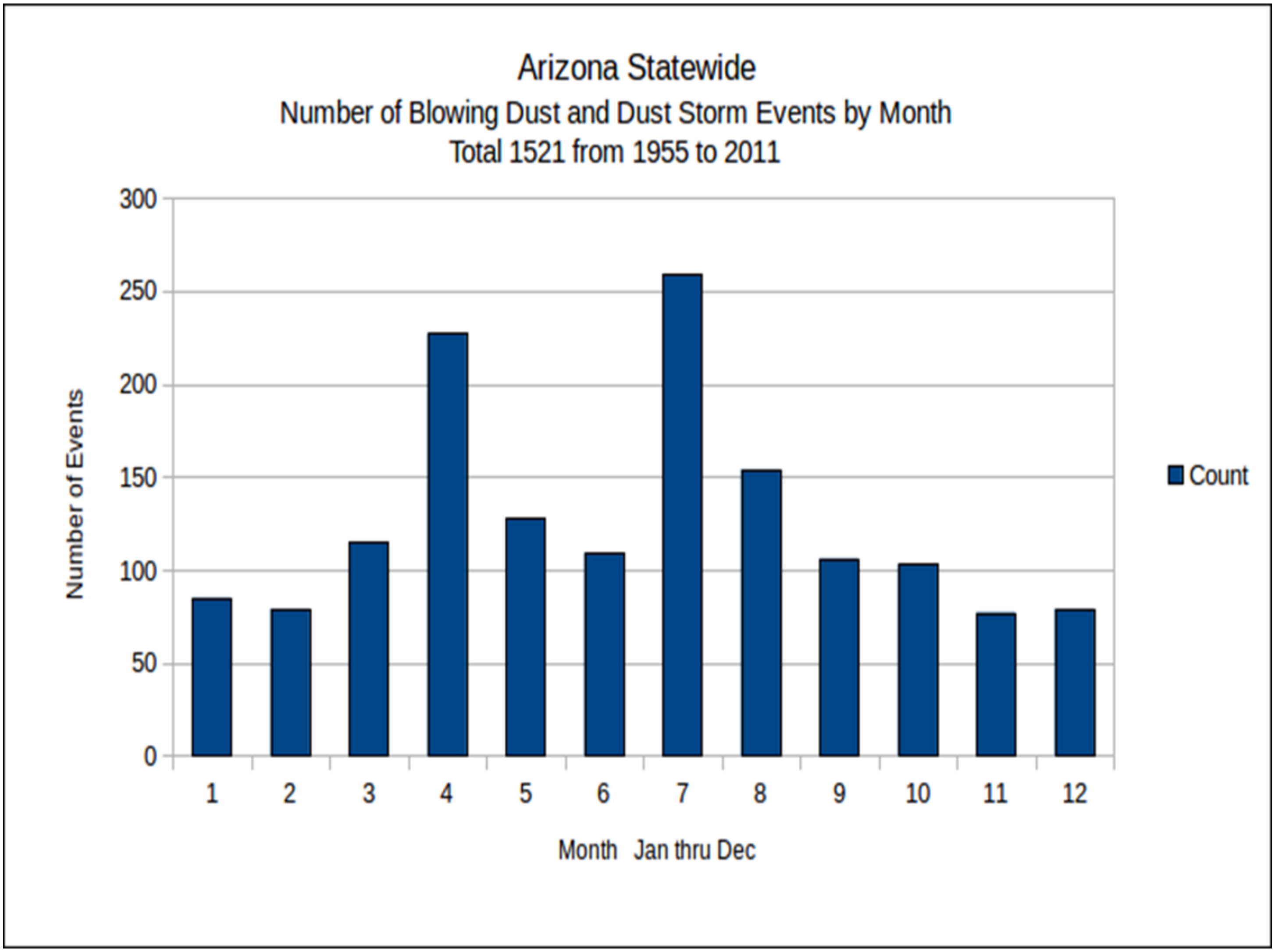


Figure 4. Statewide frequency by month from 1955 to 2011.

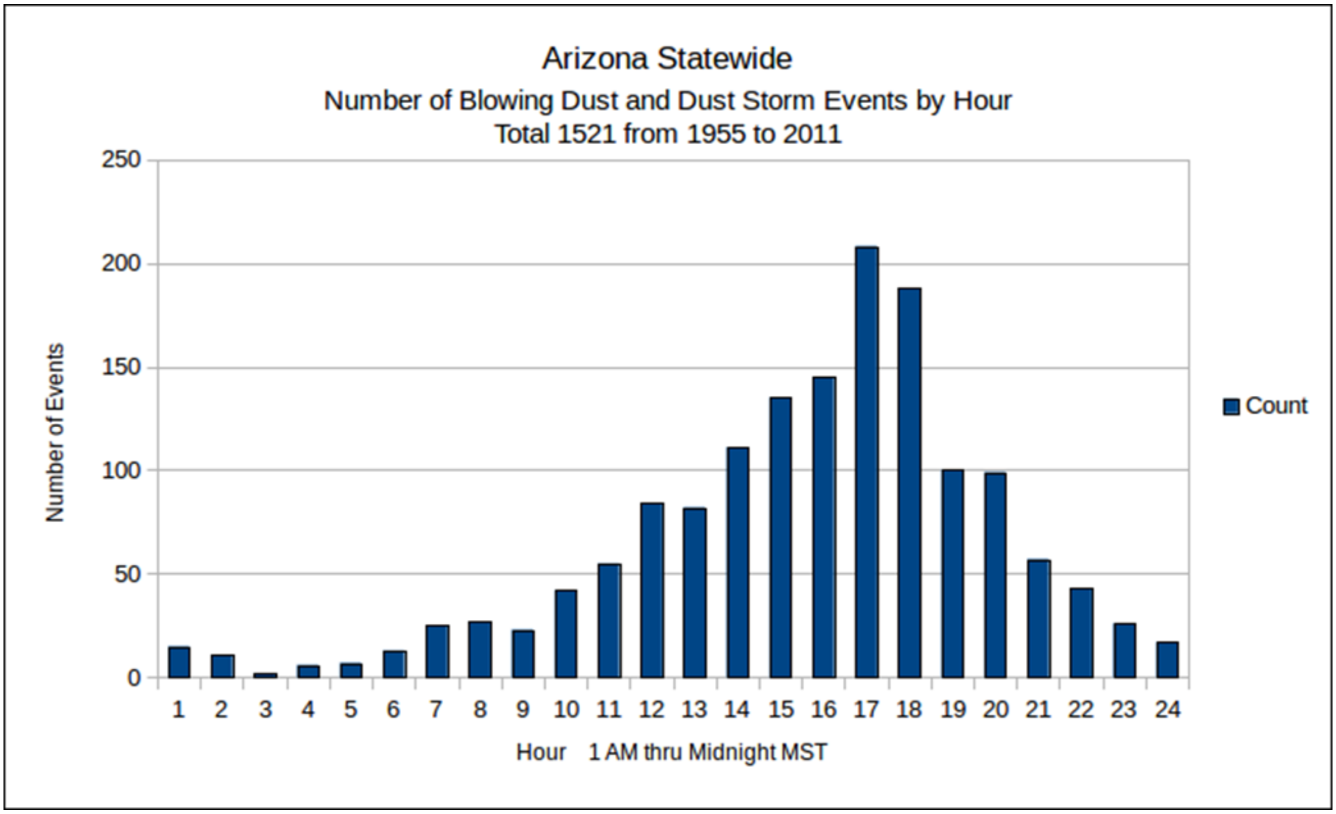


Figure 5. Statewide frequency by hour (MST) from 1955 to 2011.

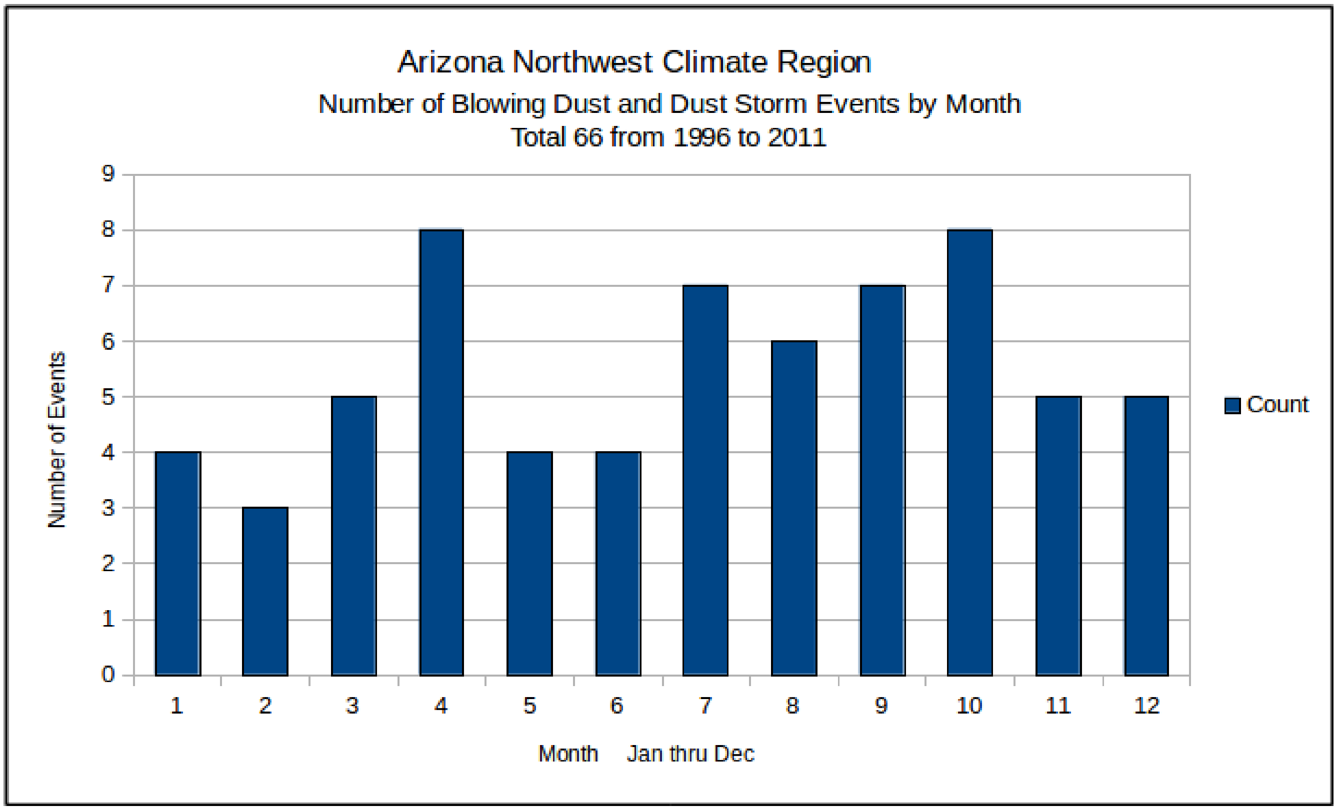


Figure 6. Northwest climate region frequency by month from 1996 to 2011.

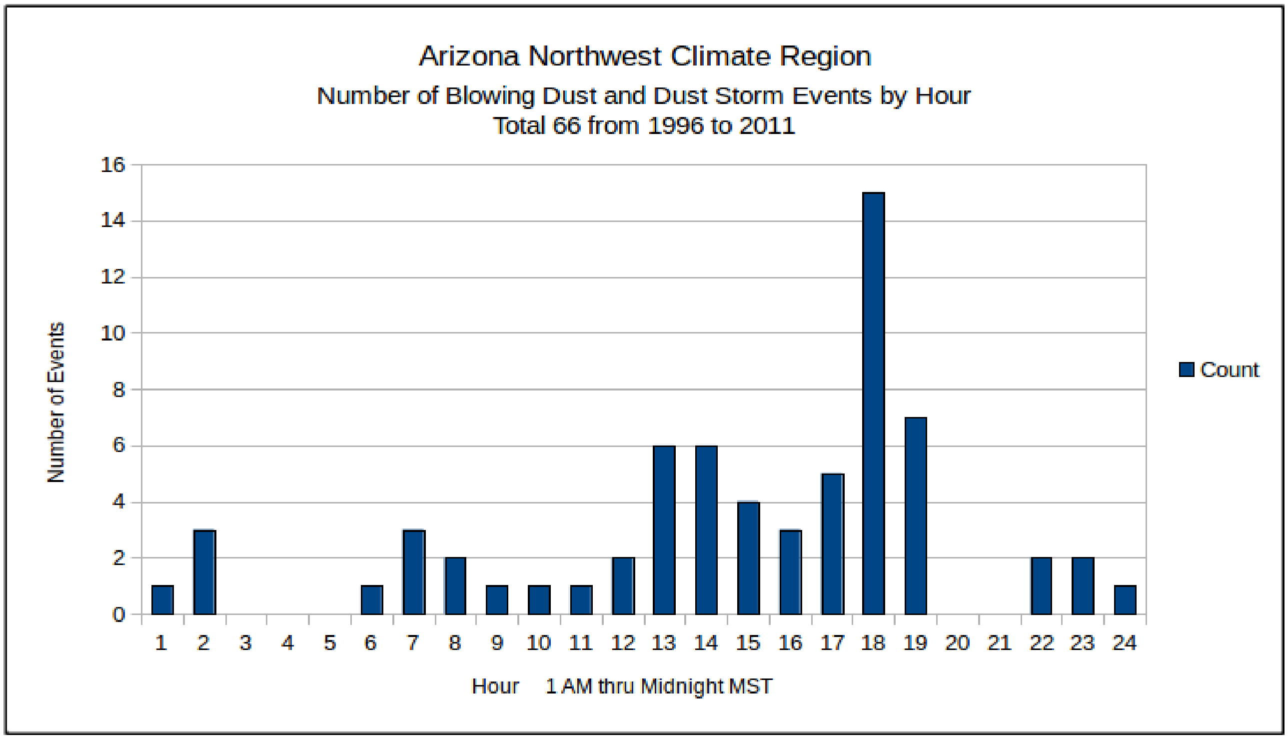


Figure 7. Northwest climate region frequency by hour from 1996 to 2011.

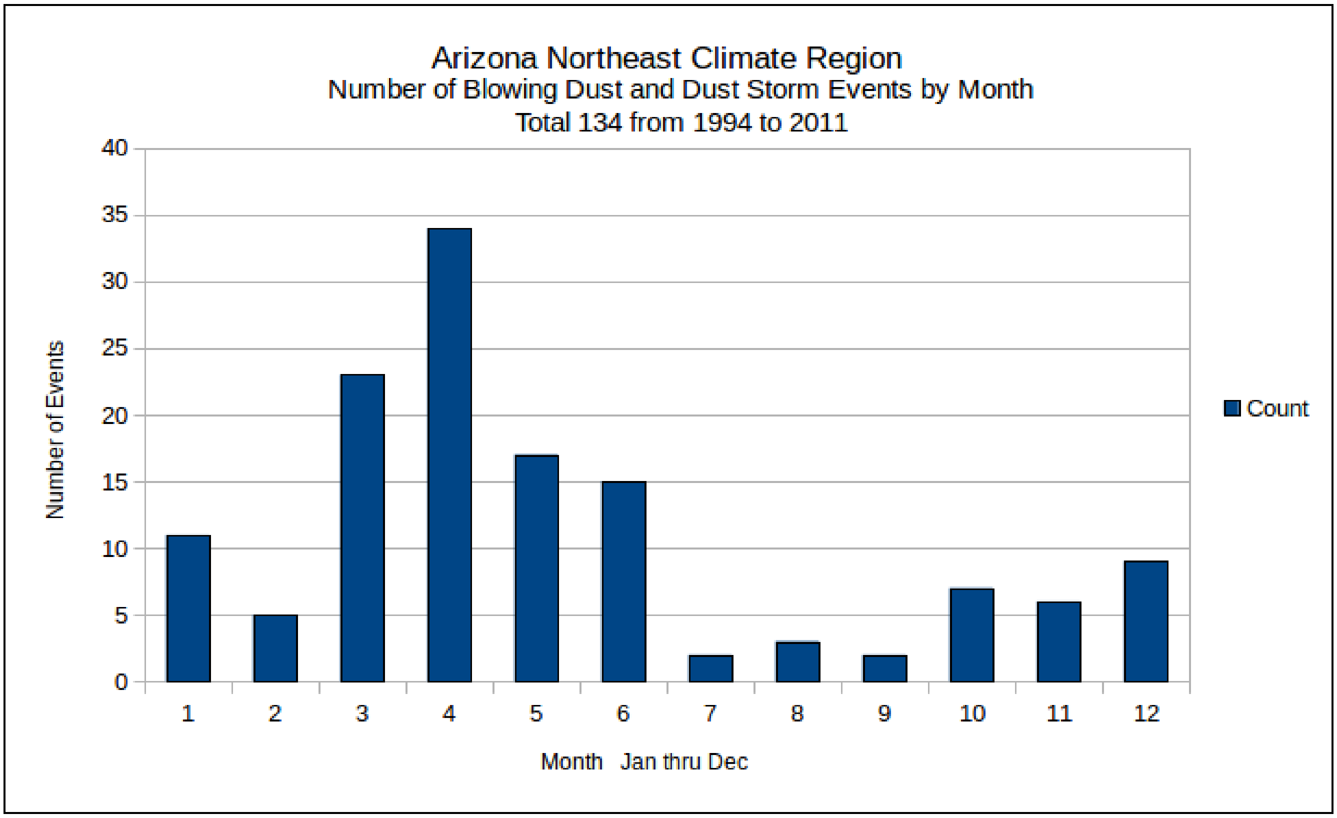


Figure 8. Northeast climate region frequency by month from 1994 to 2011.

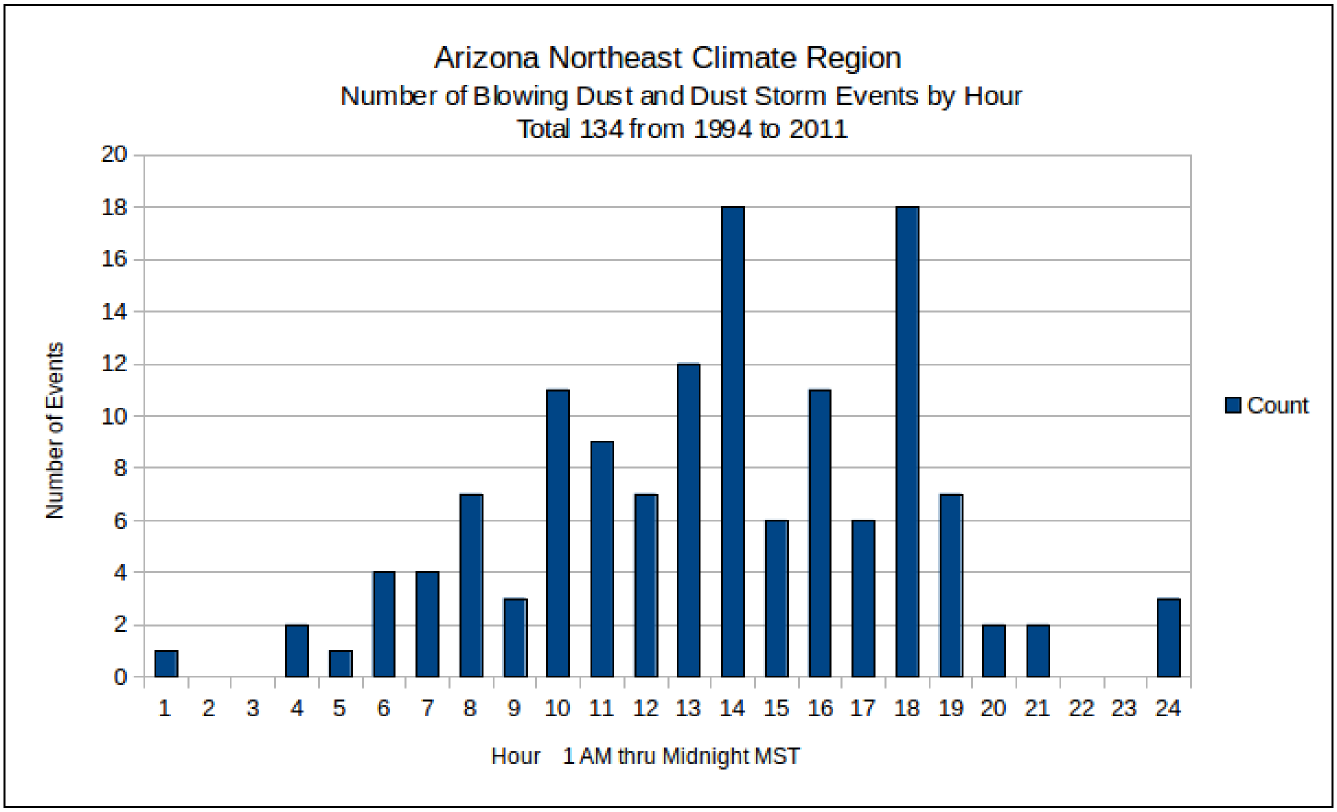


Figure 9. Northeast climate region frequency by hour (MST) from 1994 to 2011.

Figure 10. Image showing the eolian (wind-blown) sheets of sand in the Northeast climate region. Image courtesy of Google.

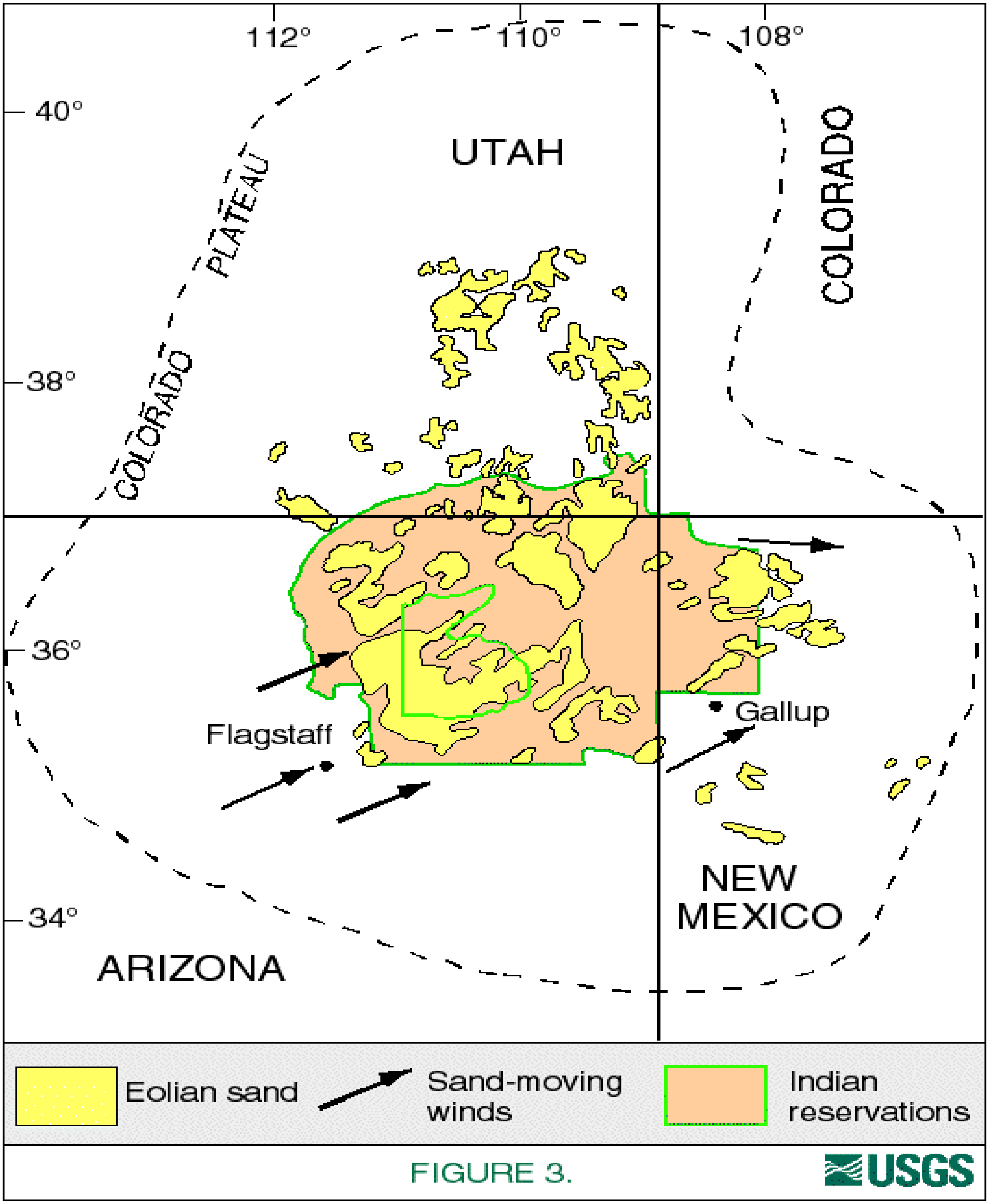


Figure 11. Location of sand dunes across the Colorado Plateau (United States Geological Survey).

http://geochange.er.usgs.gov/sw/impacts/geology/sand/

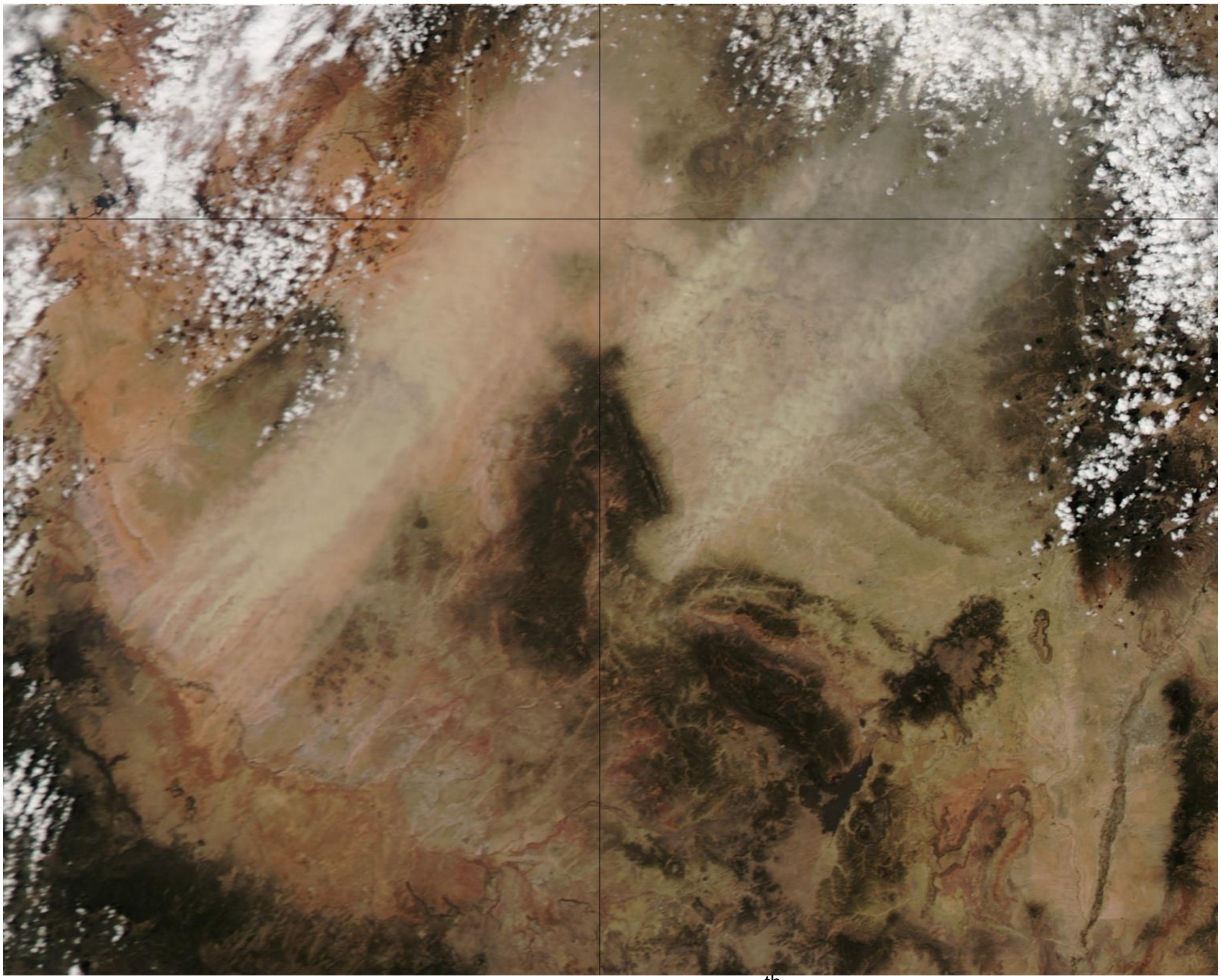


Figure 12. NASA's Aqua MODIS satellite imagery on April 16th, 2013 showing large plumes of dust blowing from northeast Arizona and northwest New Mexico (NASA MODIS image of the day).

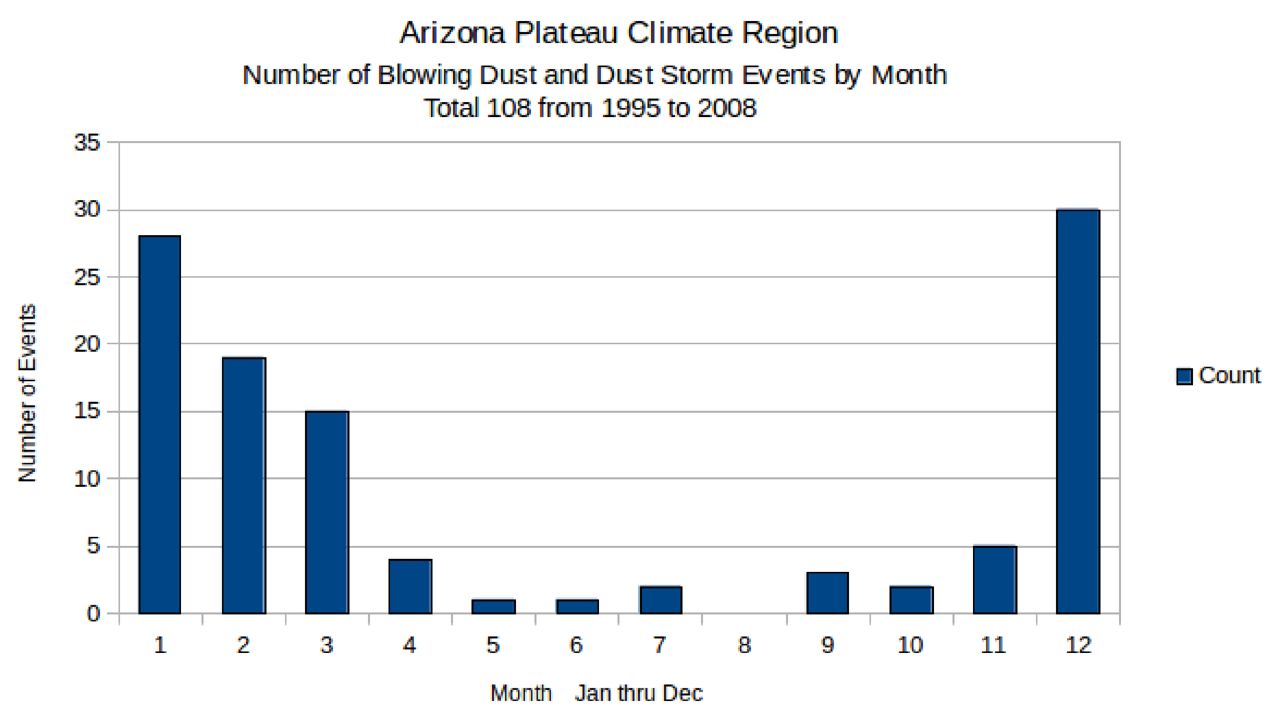


Figure 13. Plateau climate region frequency by month from 1995 to 2008.

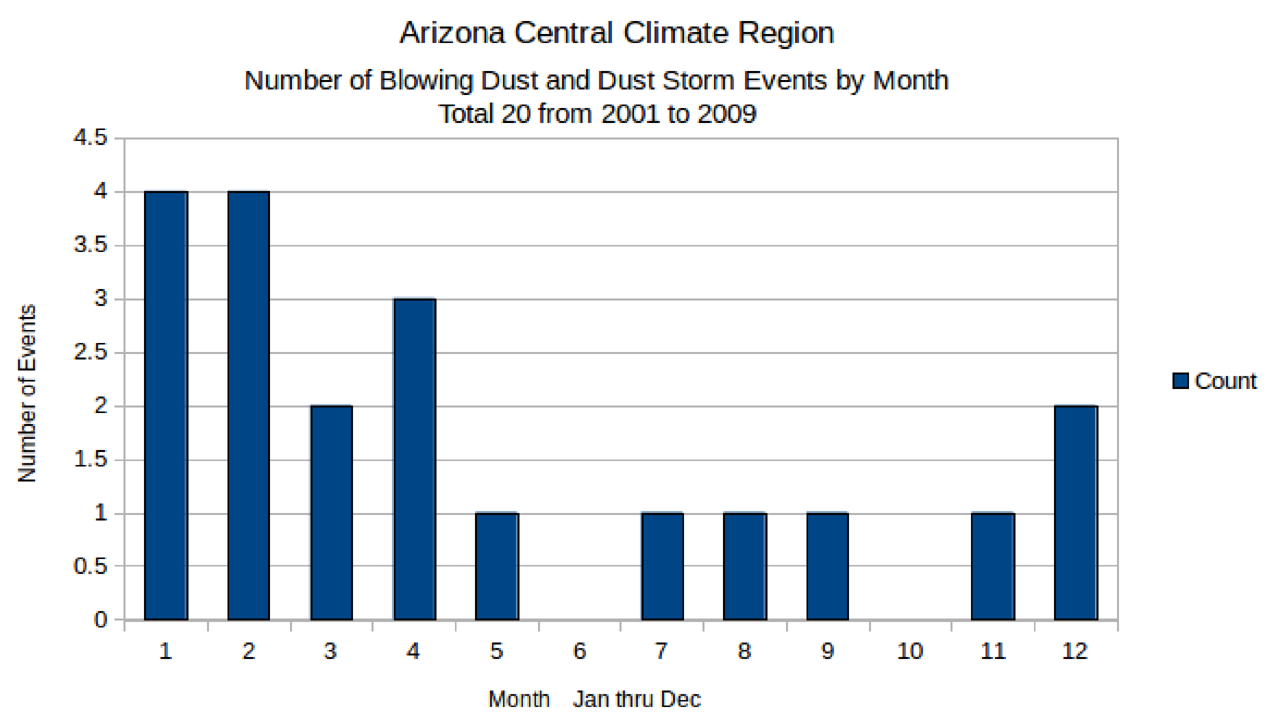


Figure 14. Central climate region frequency by month from 2001 to 2009.

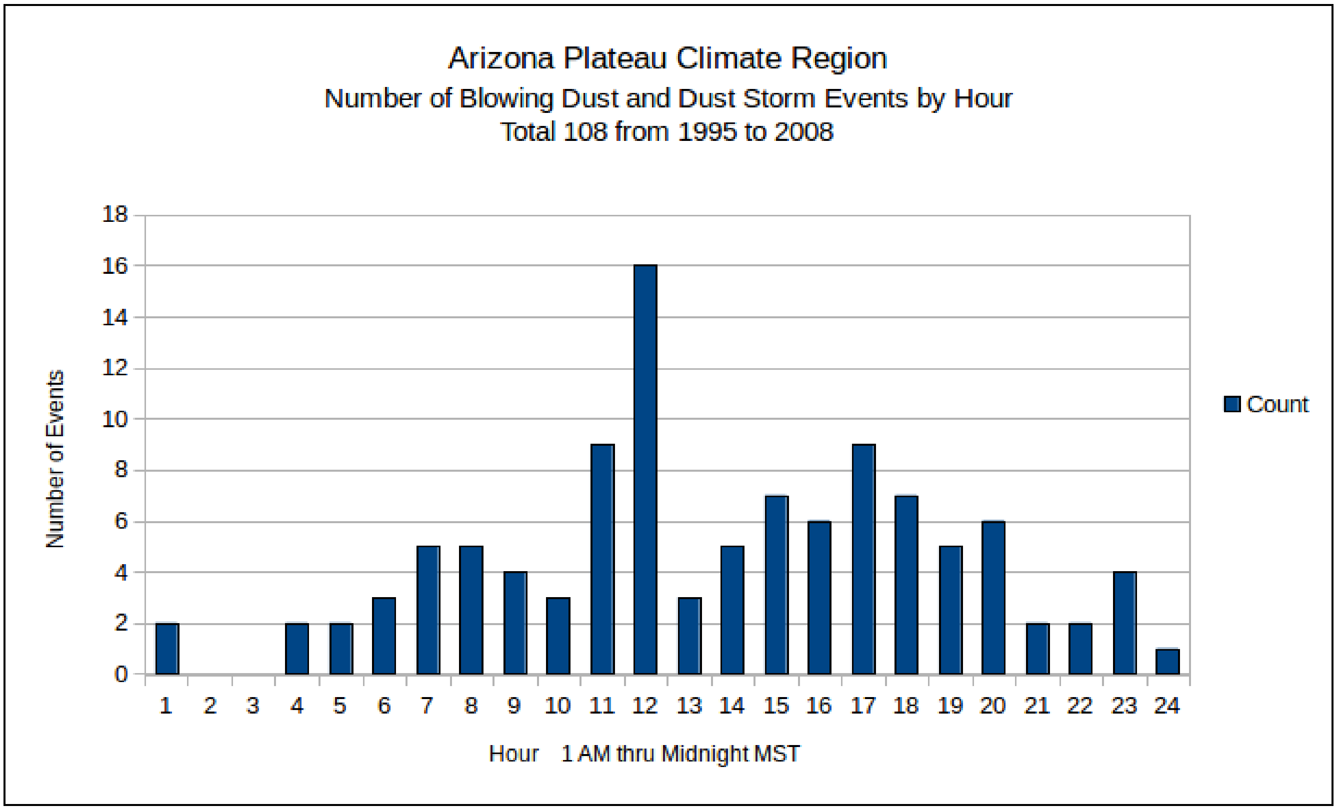


Figure 15. Plateau climate region frequency by hour (MST) from 1995 to 2008.

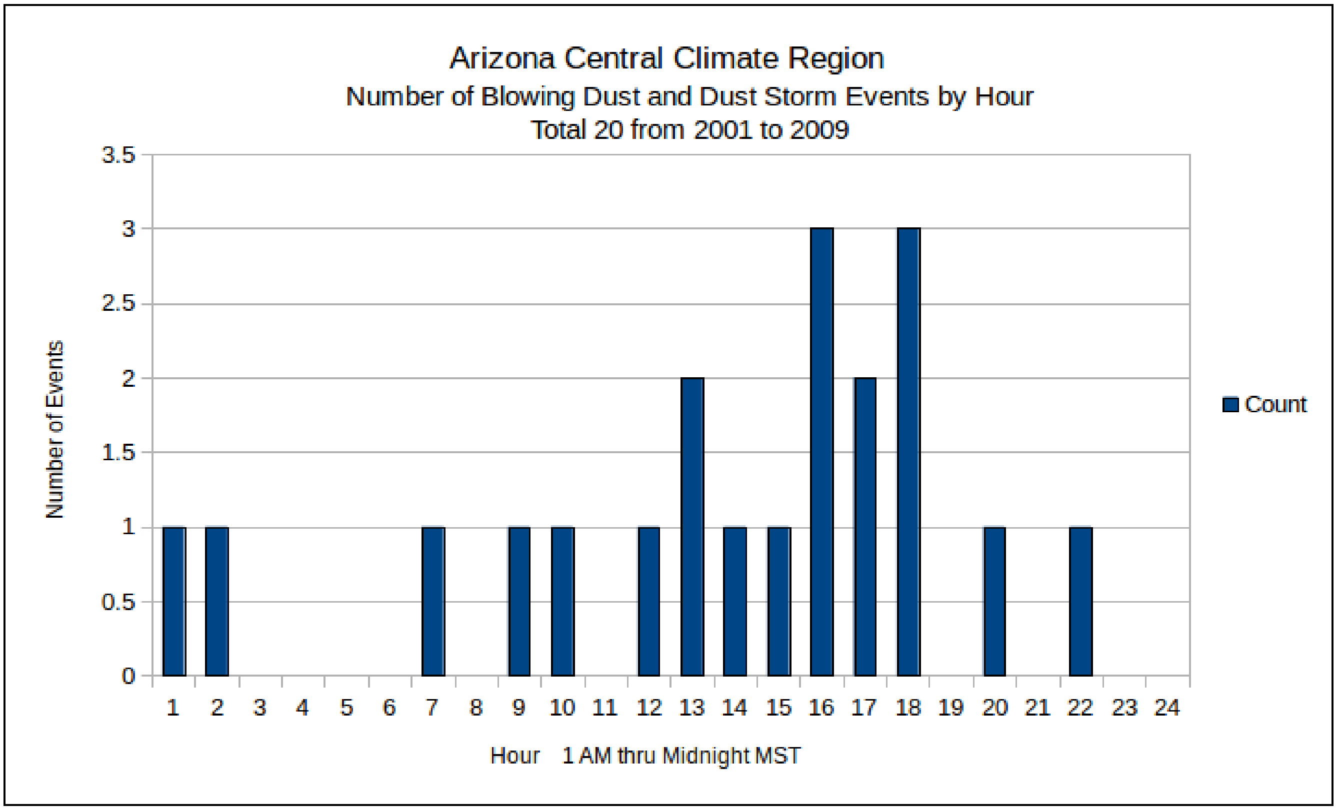


Figure 16. Central climate region frequency by hour (MST) from 2001 to 2009.

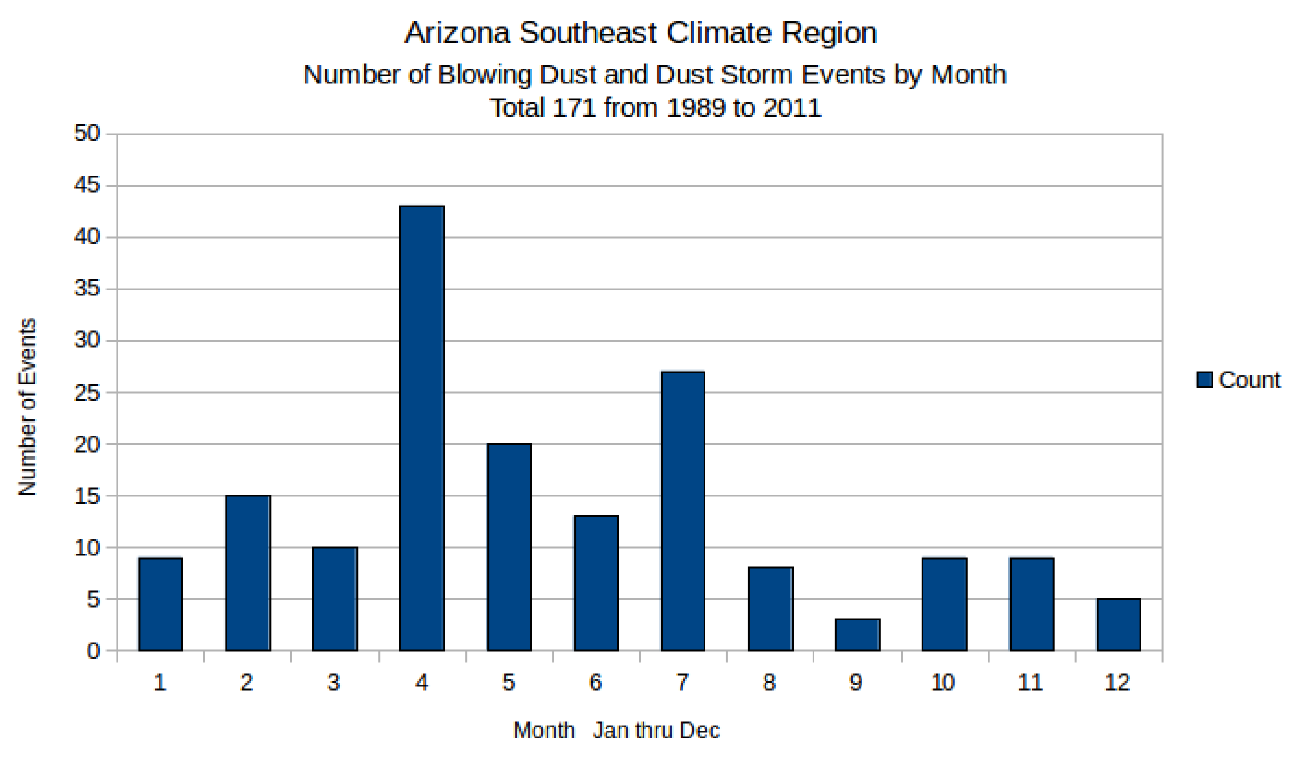


Figure 17. Southeast climate region frequency by month from 1989 to 2011.

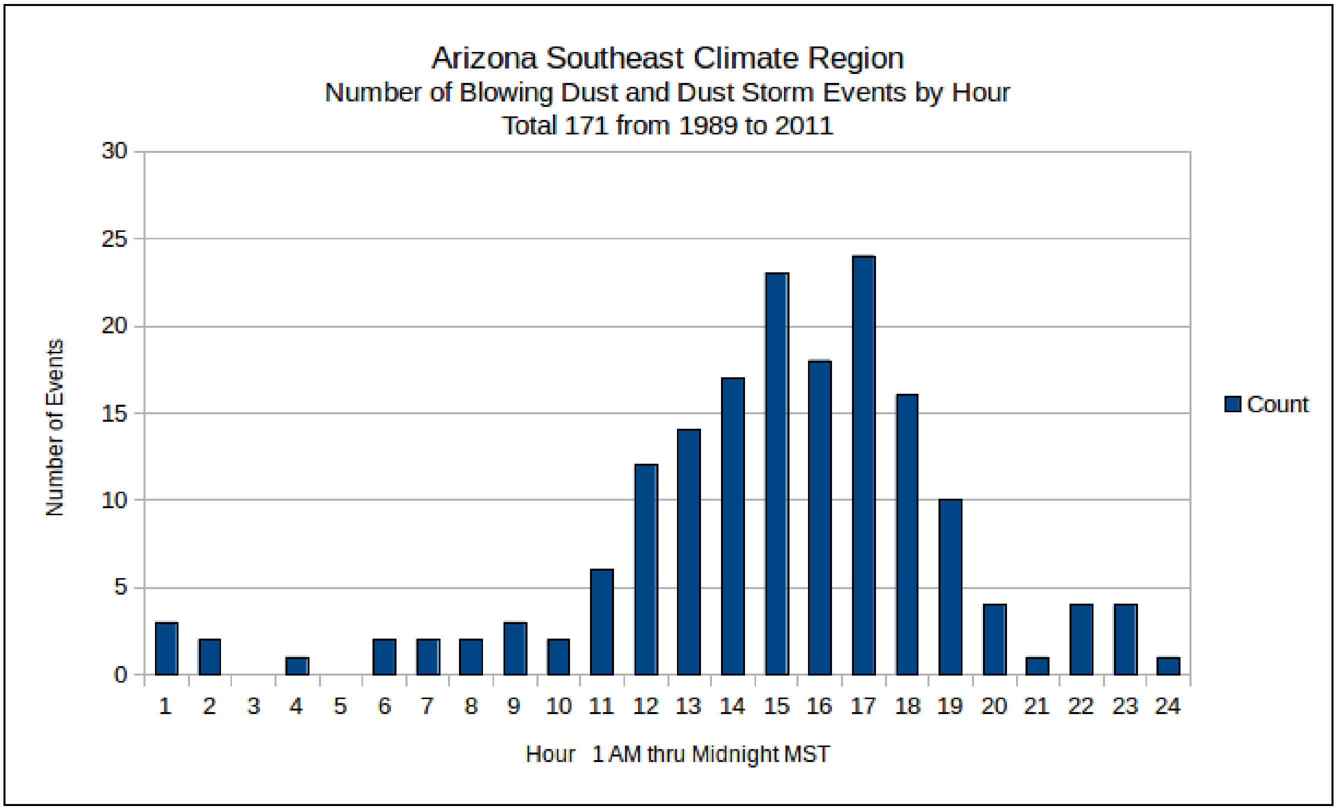


Figure 18. Southeast climate region frequency by hour (MST) from 1989 to 2011.

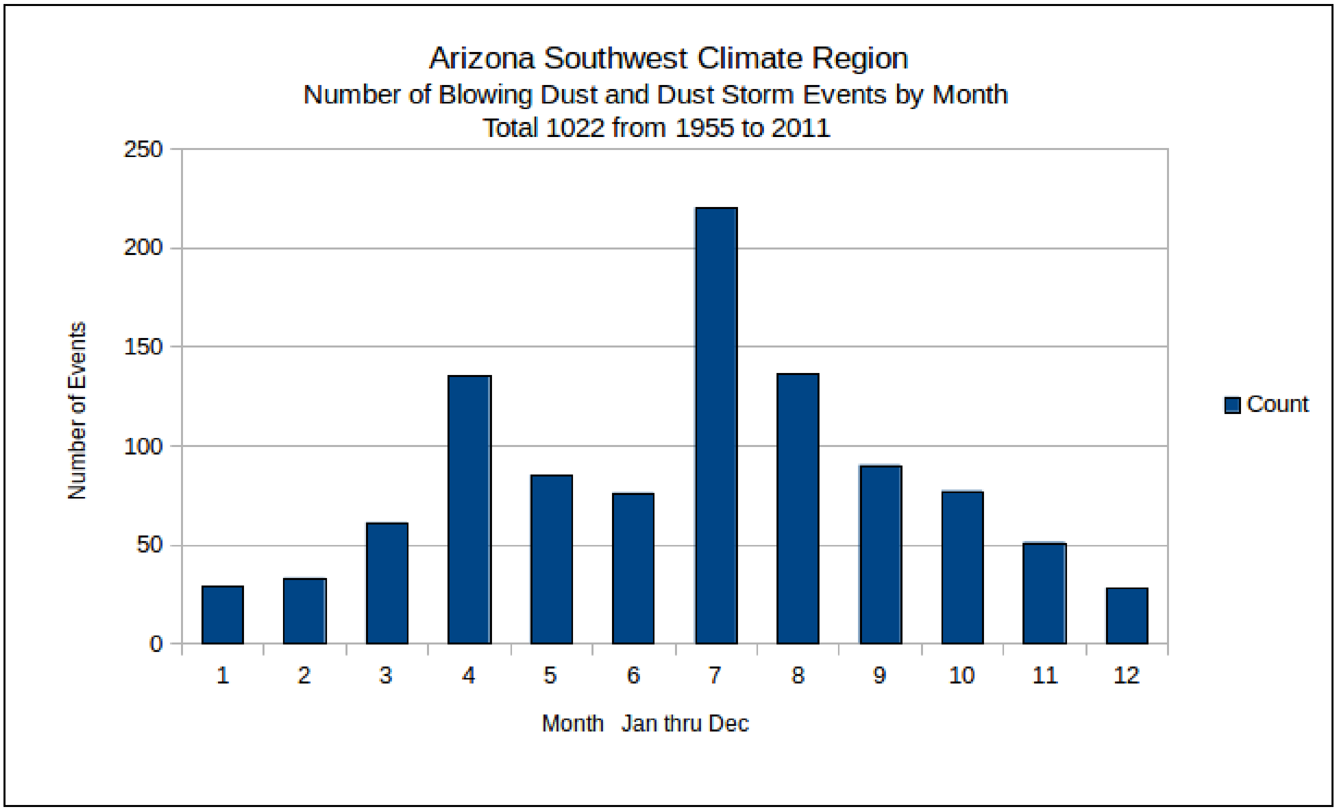


Figure 19. Southwest climate region frequency by month from 1955 to 2011

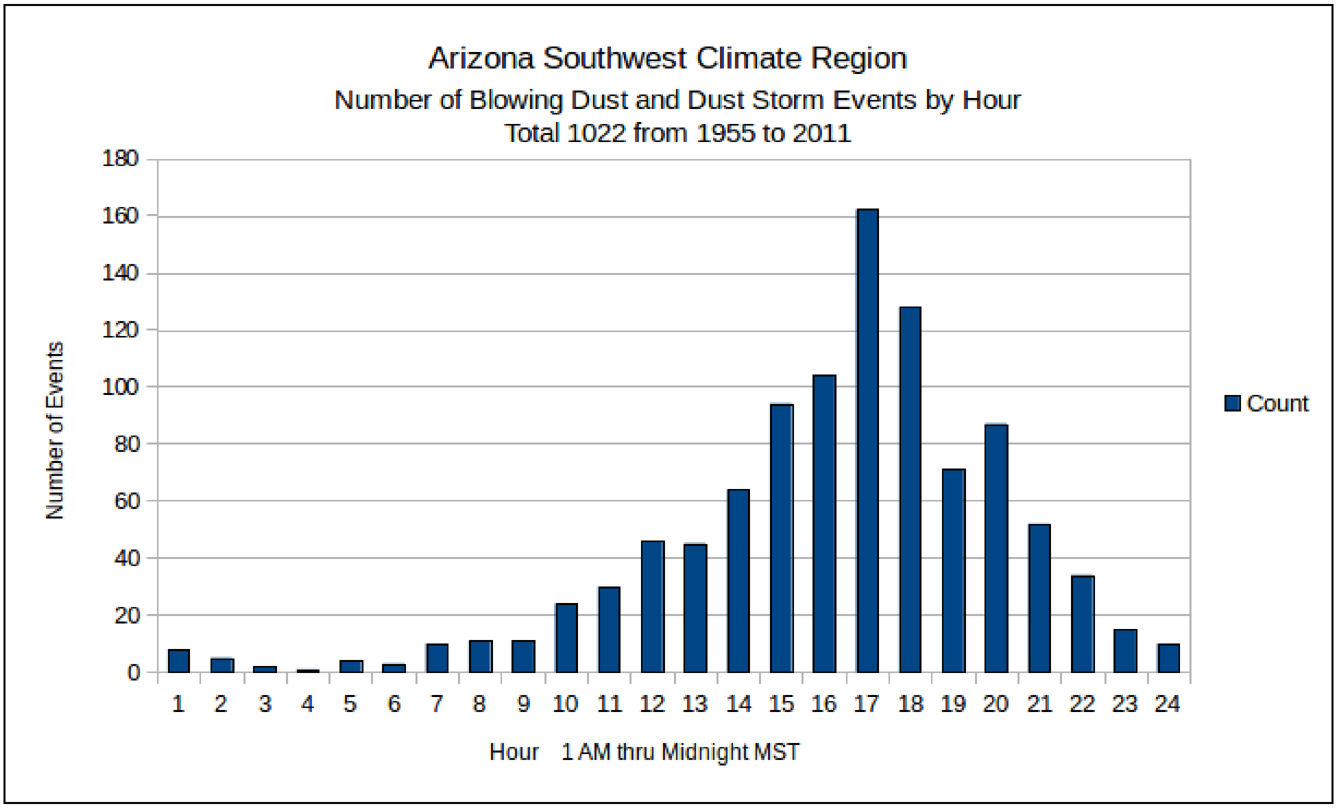


Figure 20. Southwest climate region frequency by hour (MST) from 1955 to 2011.

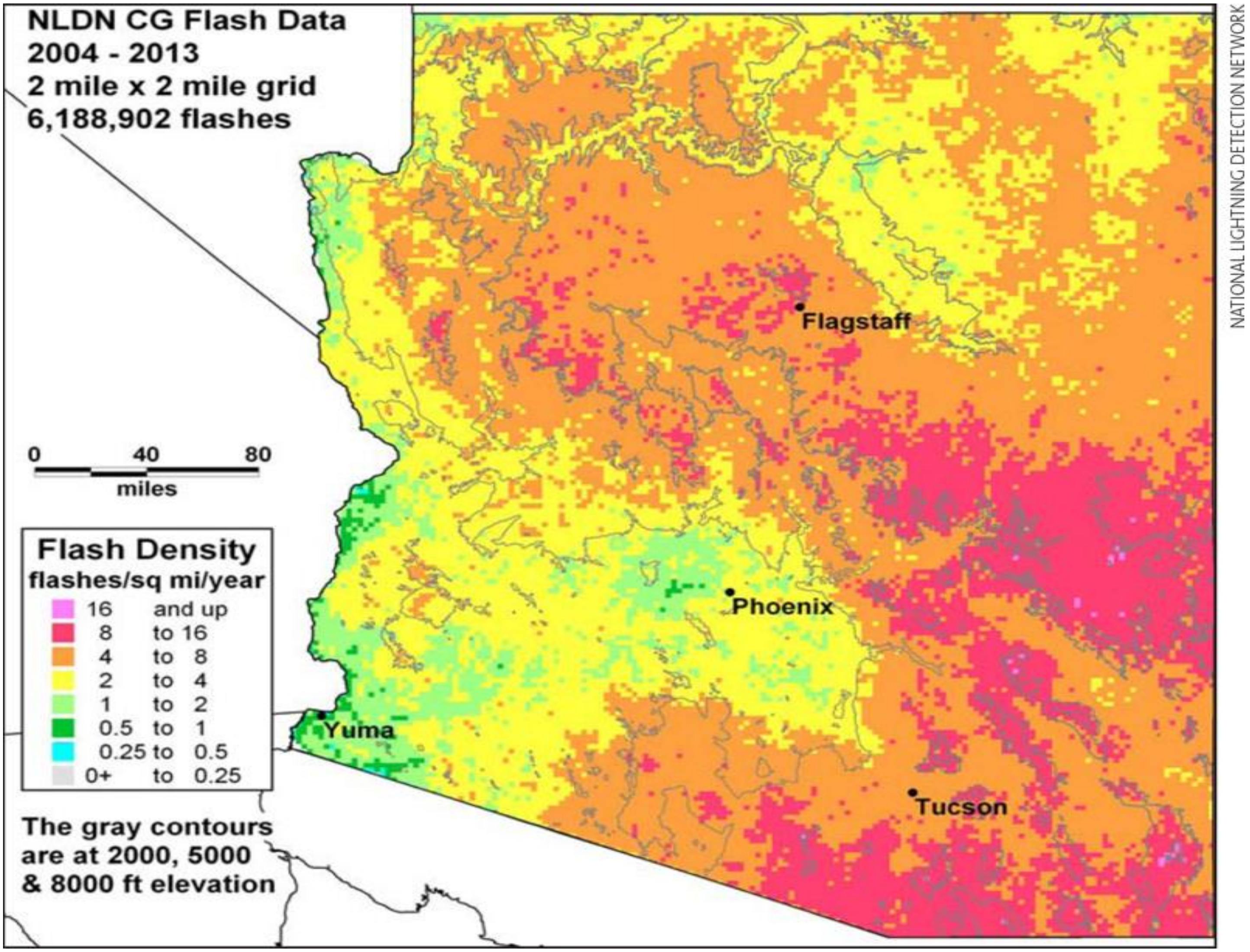


Figure 21. Cloud-to-ground flash density over Arizona 2004 through 2013 from Vaisala's National Lightning Detection Network (Holle et al 2015, Weatherwise Magazine).

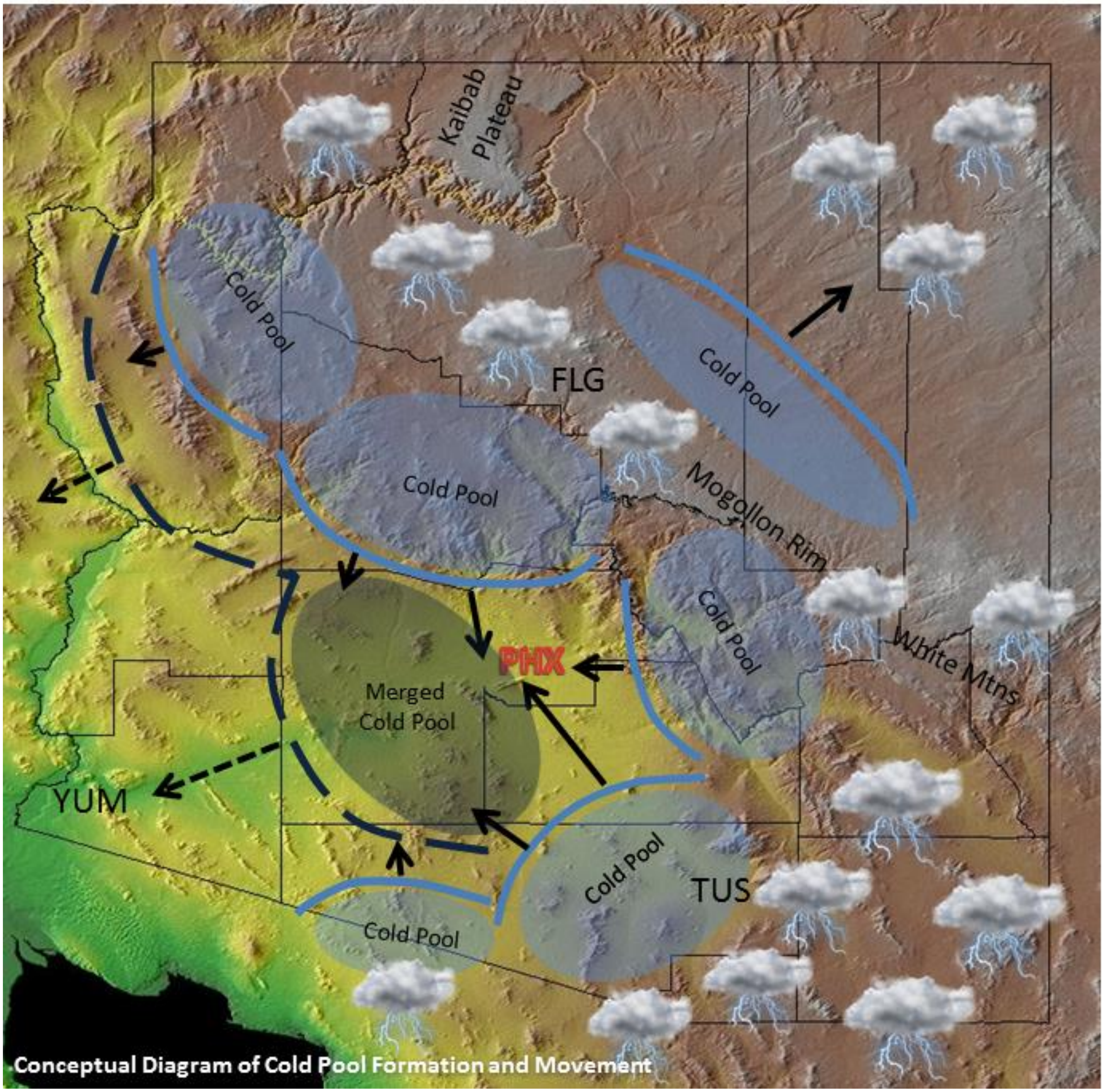


Figure 22. Conceptual Diagram of Cold Pool Formation and Movement.

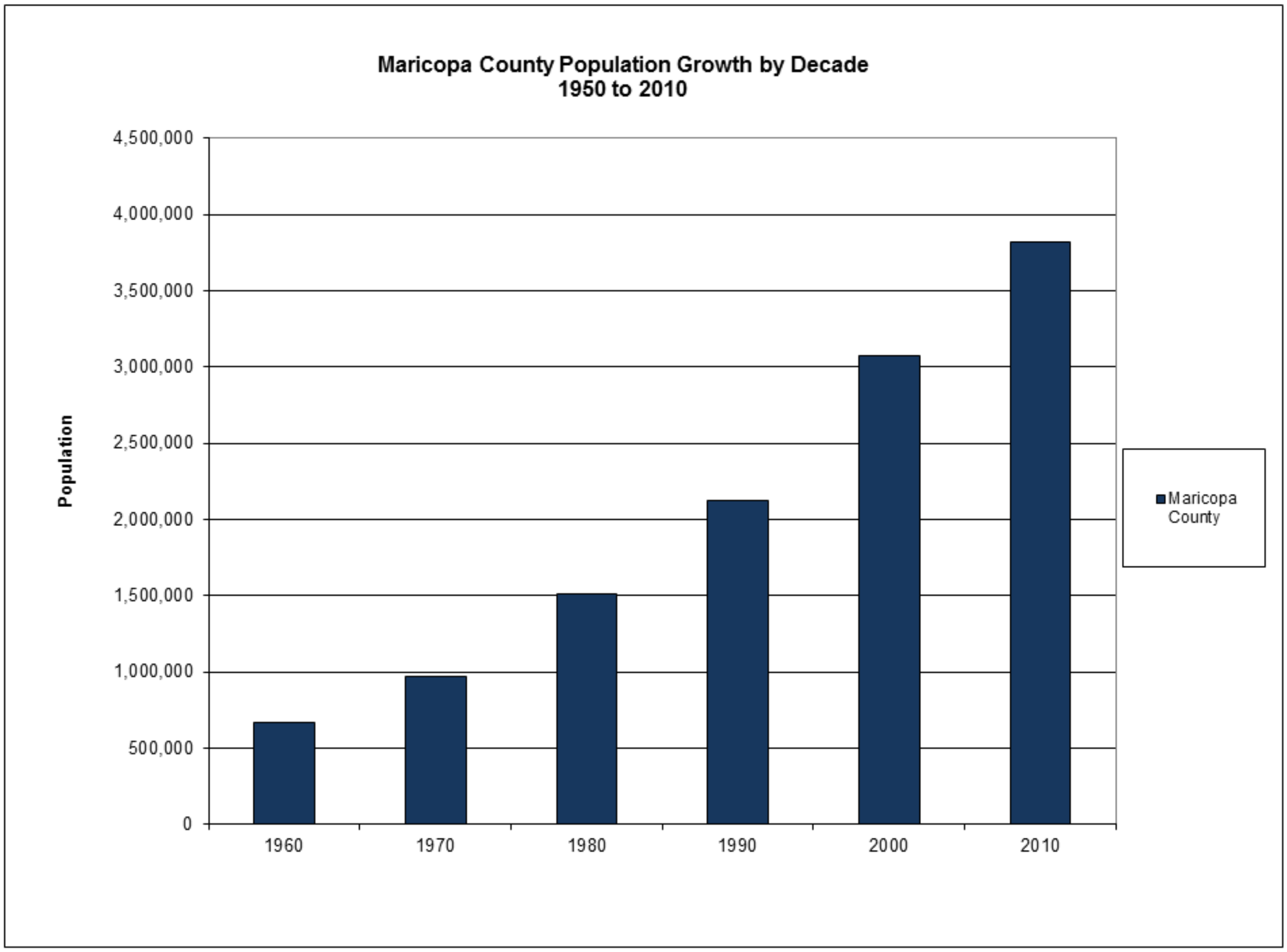


Figure 23. Population by Decade in Maricopa County, Arizona.

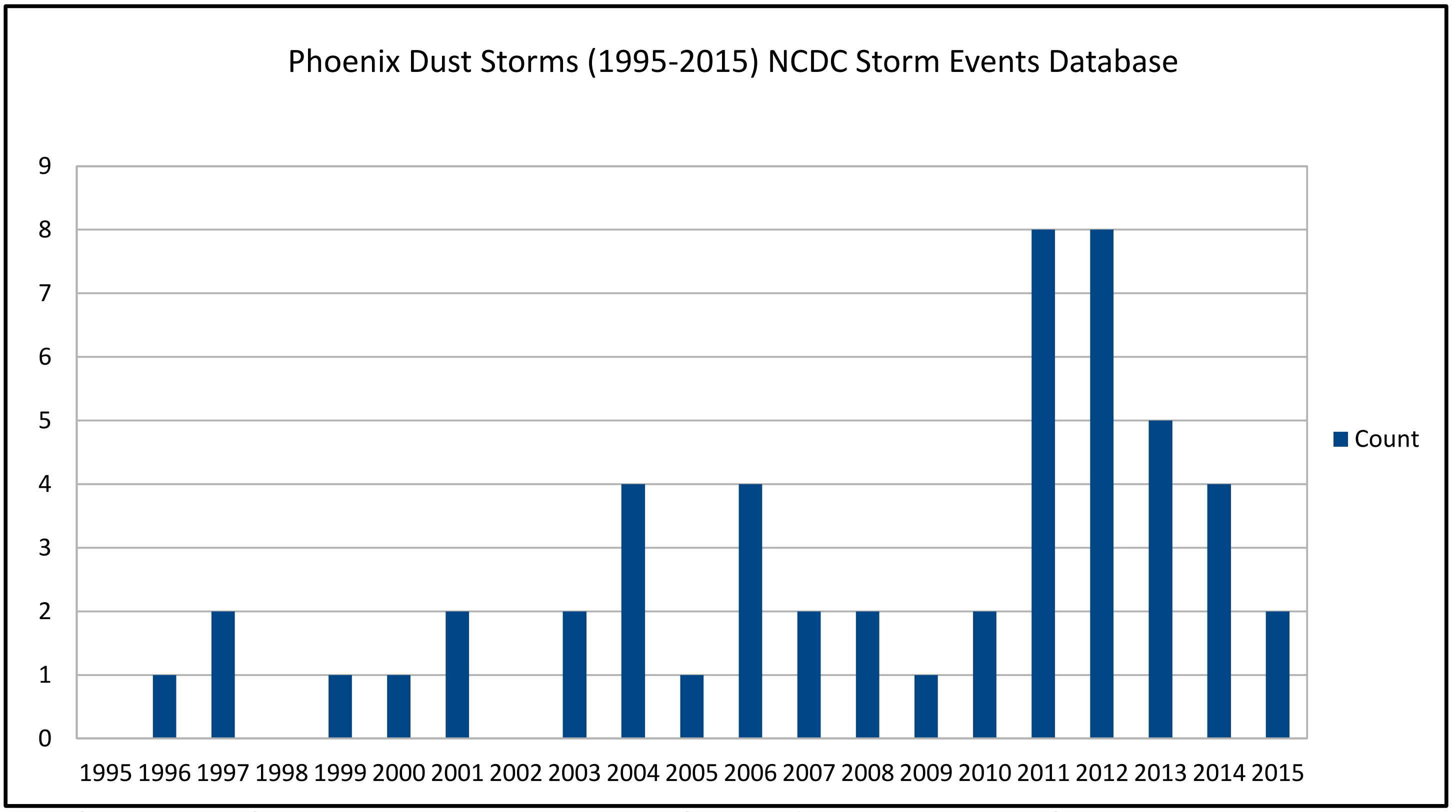


Figure 24. Maricopa County Dust Storm Events by Year from 1995 to 2015. (NCDC Storm Events Database).

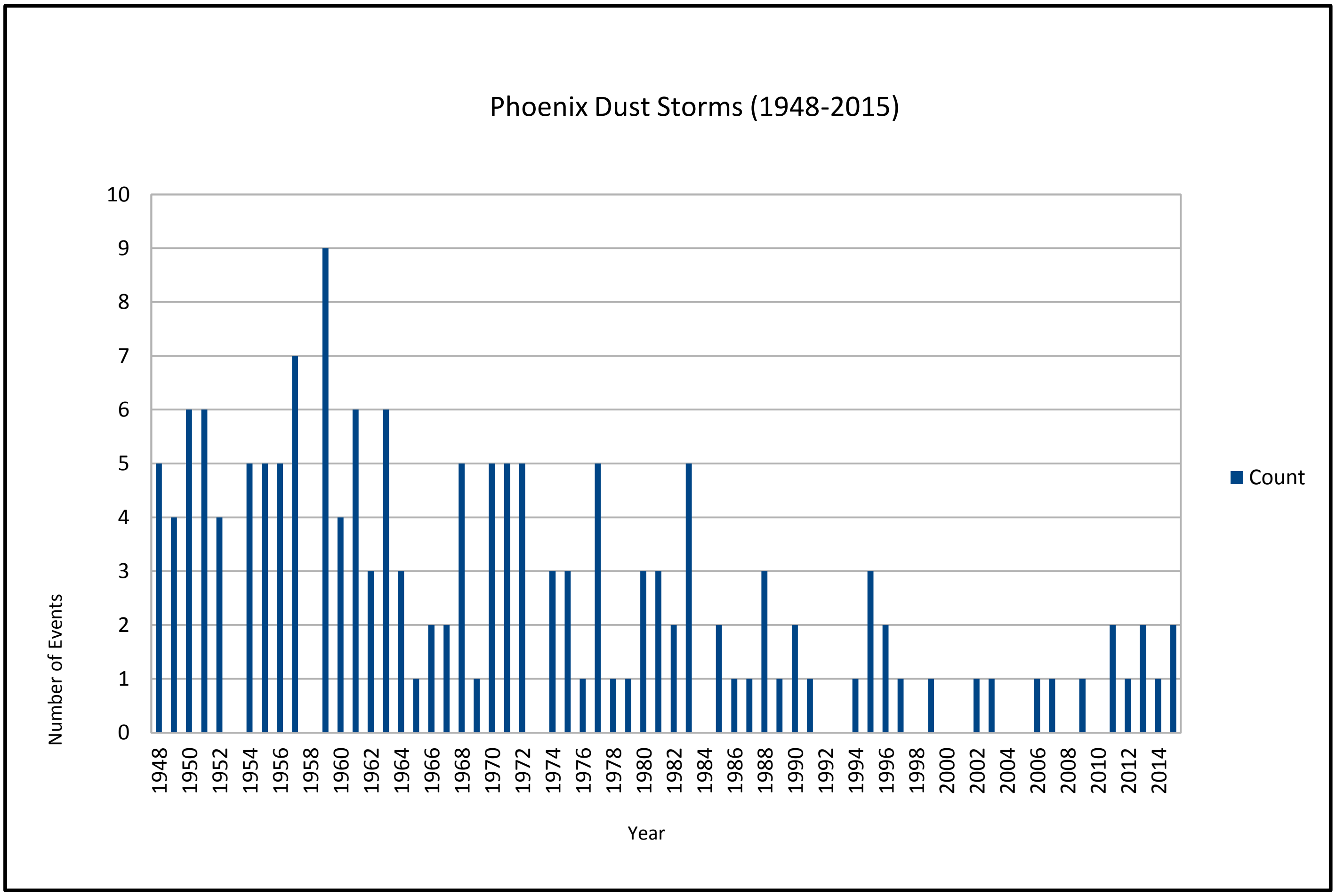


Figure 25. Number of Summer Dust Storms by Year in Phoenix, Arizona from 1948 to 2015.

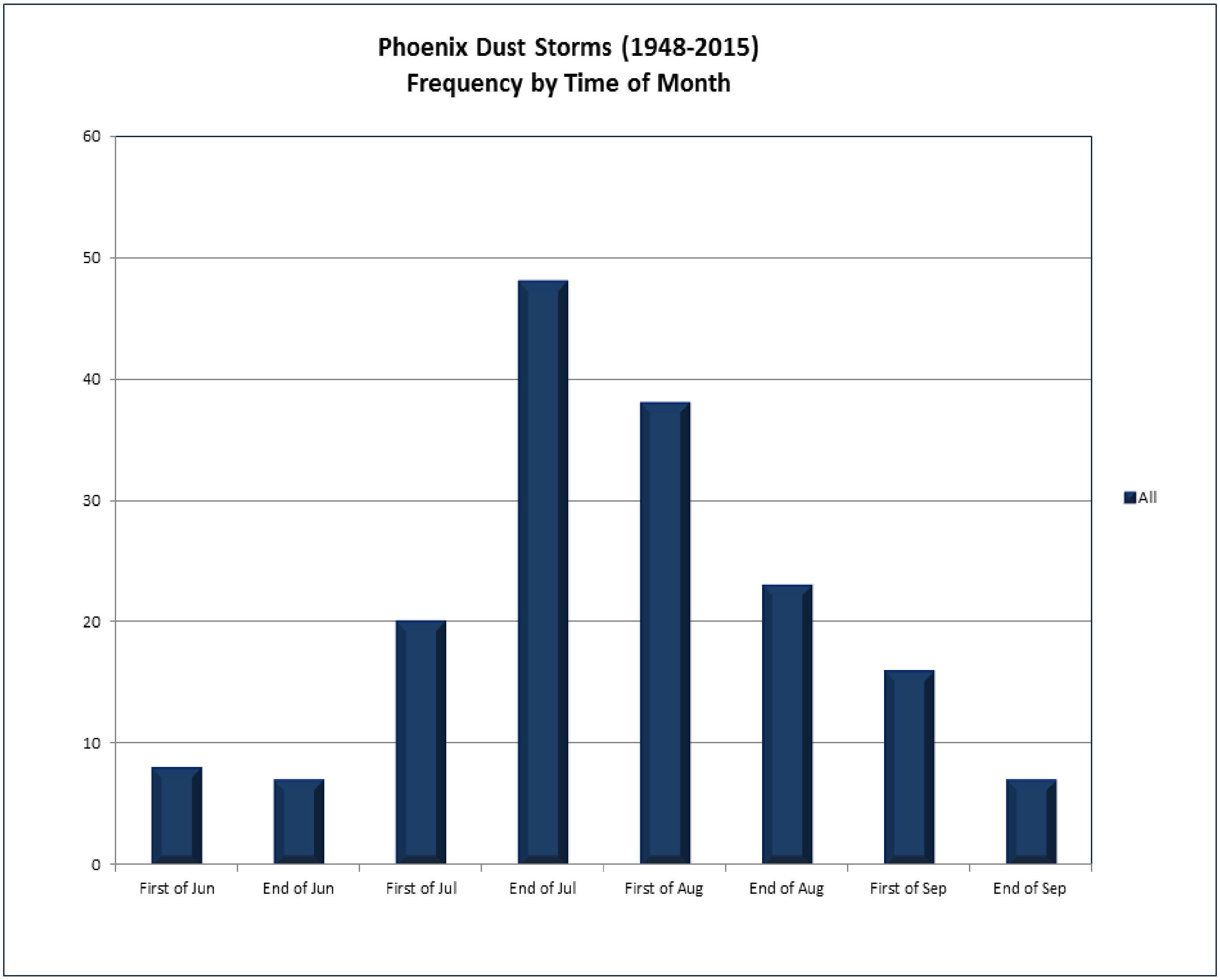


Figure 26. Number of Dust Storms by Time of Month in Phoenix, Arizona.

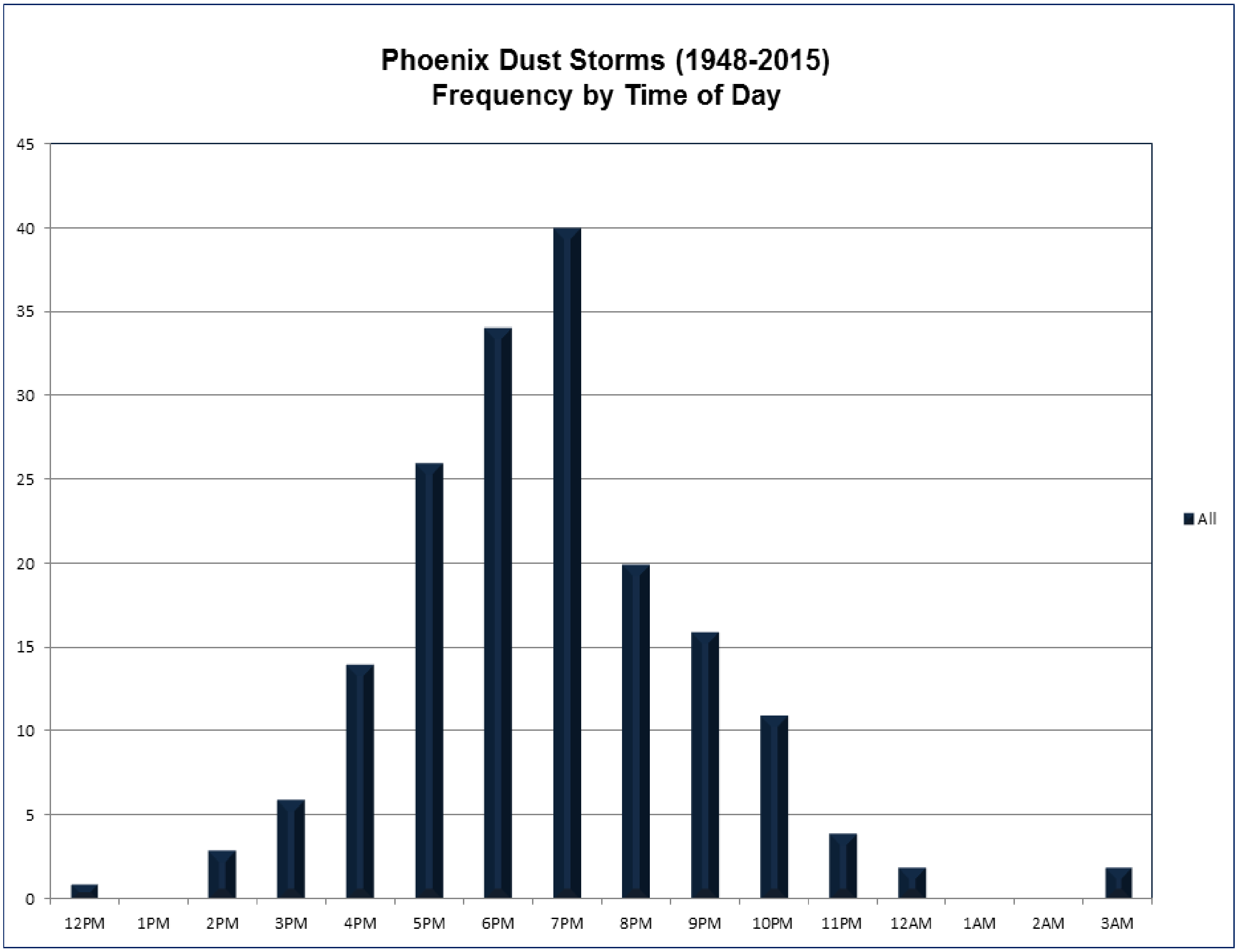


Figure 27. Number of Dust Storms by Time of Day in Phoenix, Arizona.

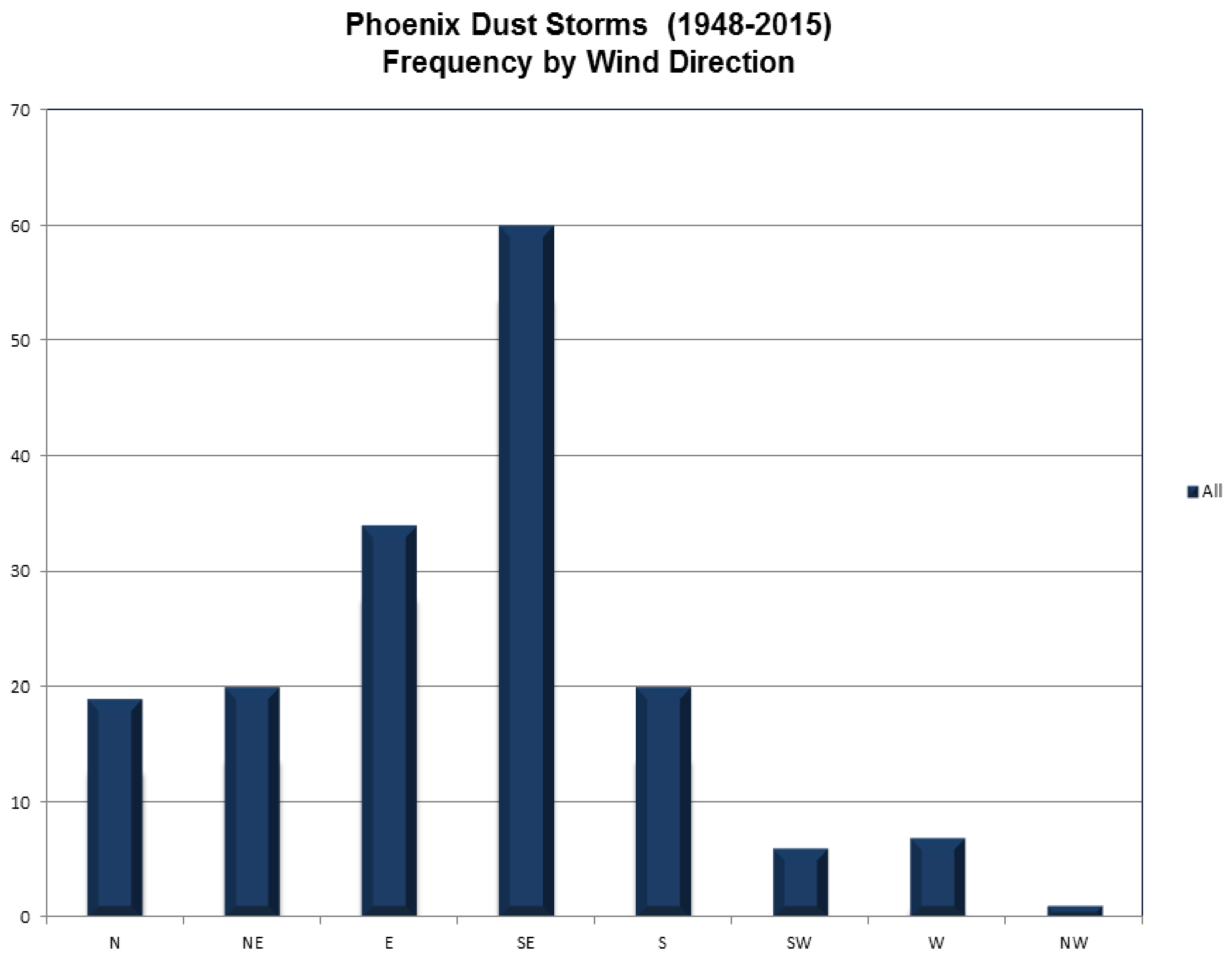


Figure 28. Number of Dust Storms by Wind Direction in Phoenix, Arizona.

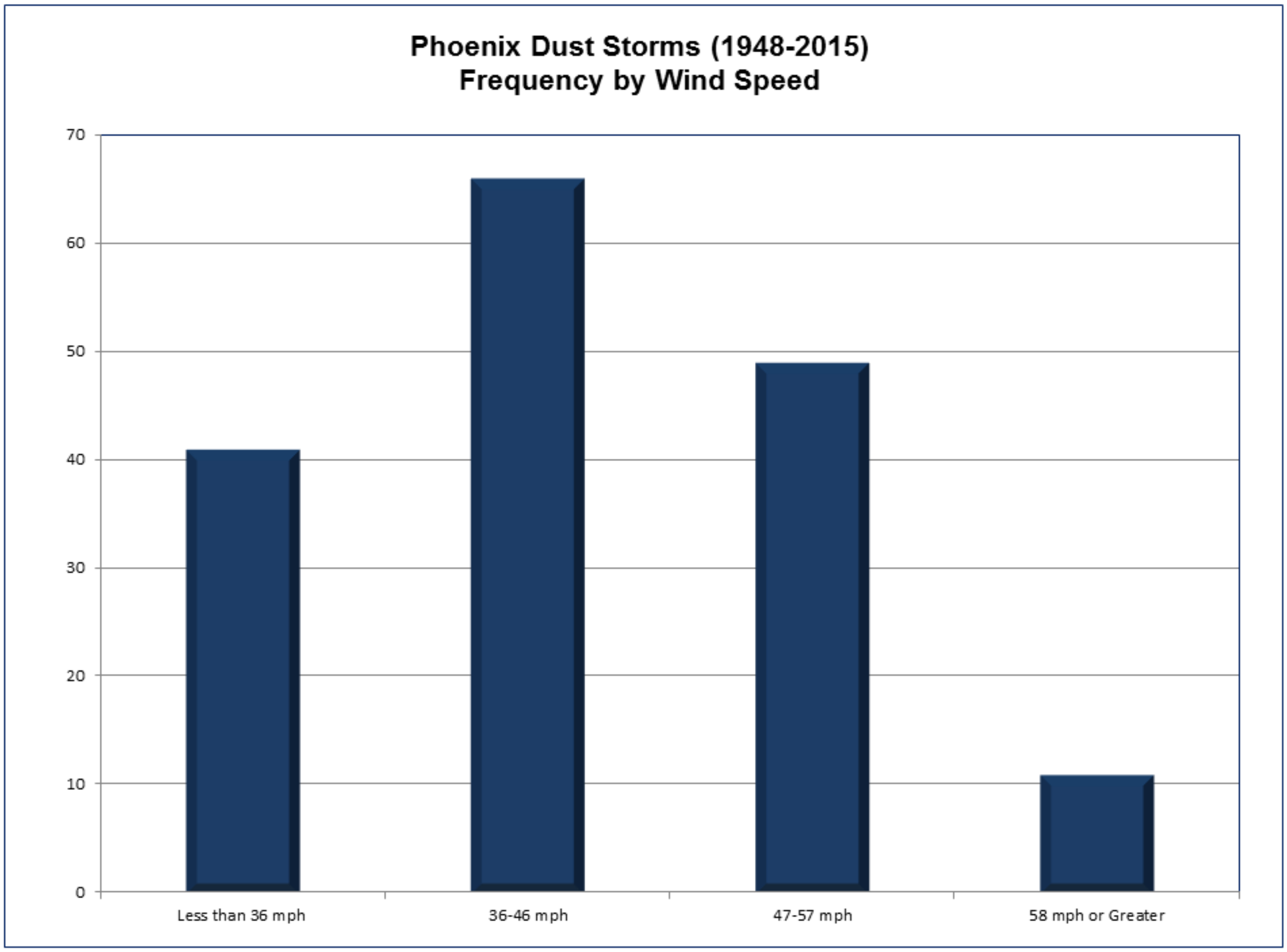
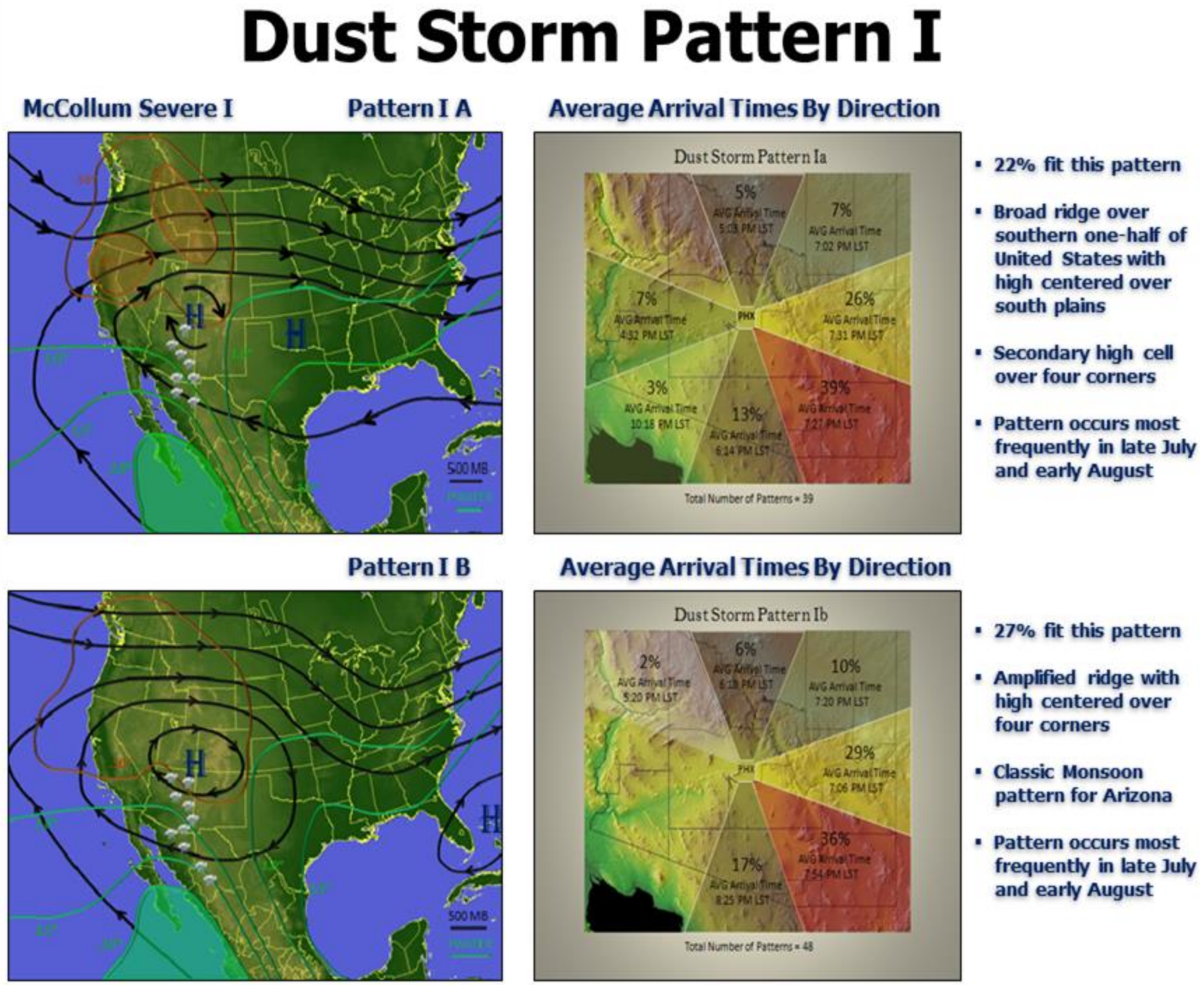


Figure 29. Number of Dust Storms by Wind Speed in Phoenix, Arizona.



# Dust Storm Pattern I

**McCollum Severe I**

**Pattern I A**

**Average Arrival Times By Direction**

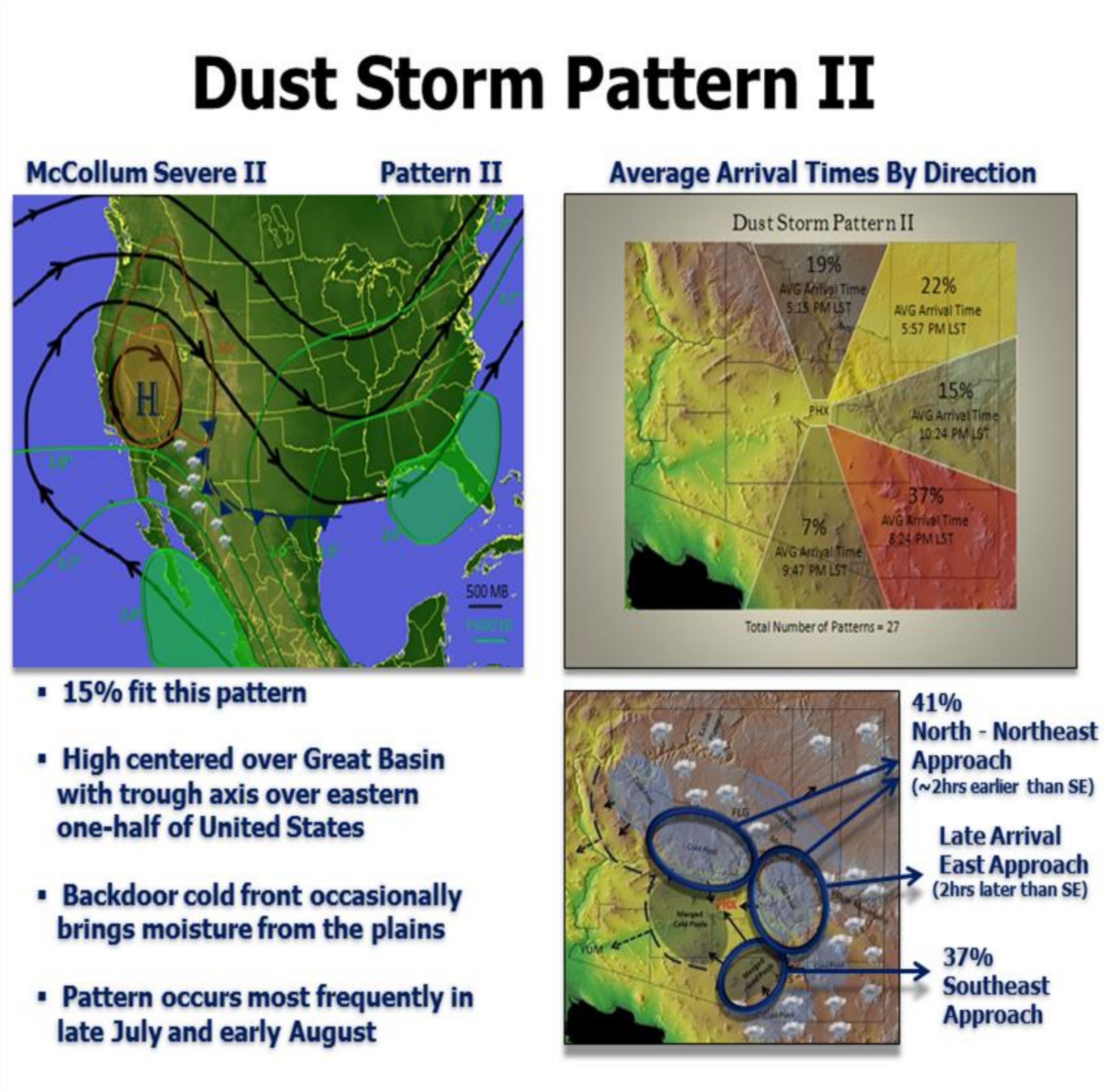
- 22% fit this pattern
- Broad ridge over southern one-half of United States with high centered over south plains
- Secondary high cell over four corners
- Pattern occurs most frequently in late July and early August

**Pattern I B**

**Average Arrival Times By Direction**

- 27% fit this pattern
- Amplified ridge with high centered over four corners
- Classic Monsoon pattern for Arizona
- Pattern occurs most frequently in late July and early August

Figure 30. Dust Storm Patterns I A and I B.



# Dust Storm Pattern II

**McCollum Severe II** **Pattern II**

- **15% fit this pattern**
- **High centered over Great Basin with trough axis over eastern one-half of United States**
- **Backdoor cold front occasionally brings moisture from the plains**
- **Pattern occurs most frequently in late July and early August**

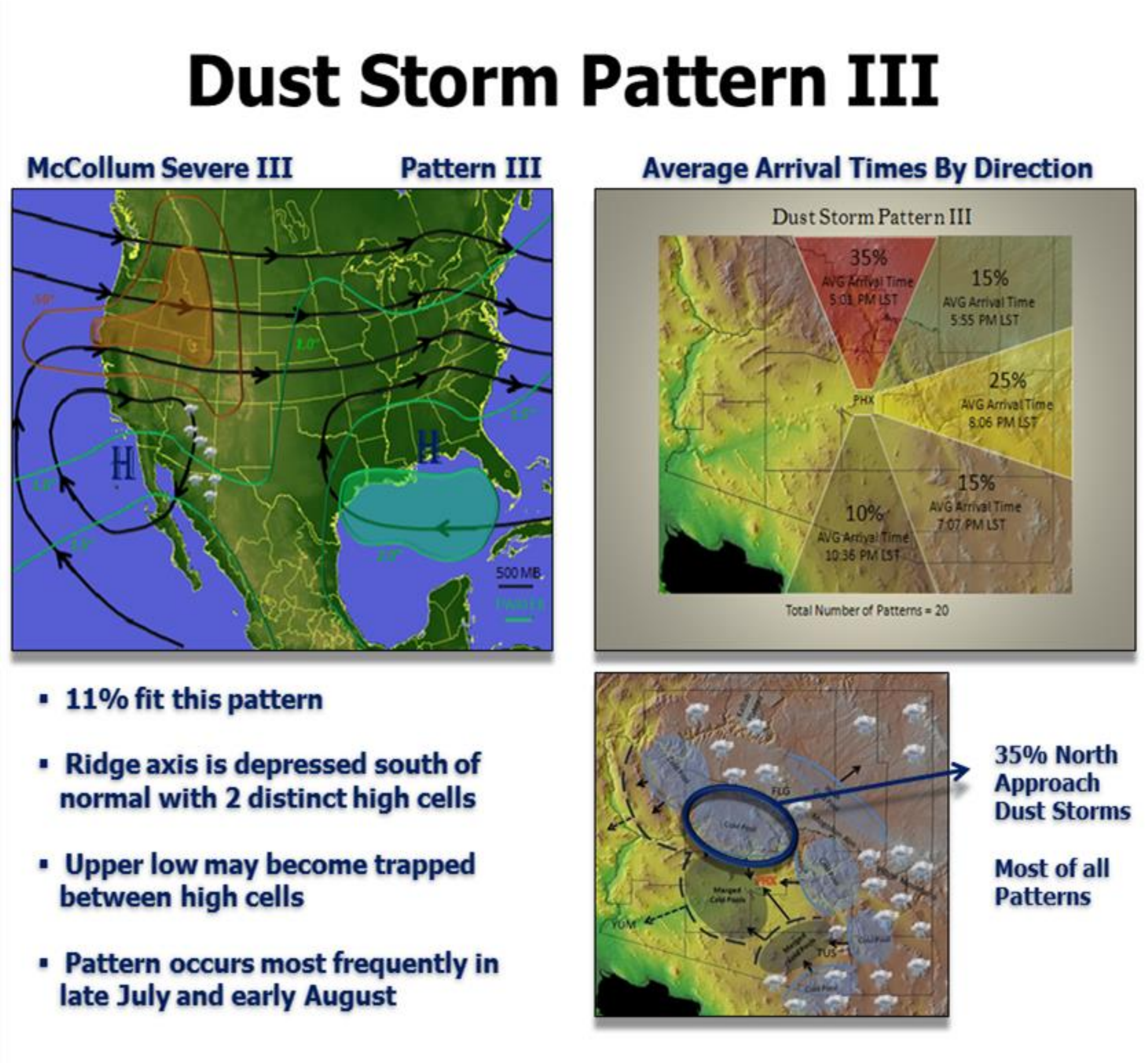
**Average Arrival Times By Direction**

**41%**
**North - Northeast Approach**
**(~2hrs earlier than SE)**

**Late Arrival East Approach**
**(2hrs later than SE)**

**37%**
**Southeast Approach**

Figure 31. Dust Storm Pattern II.



# Dust Storm Pattern III

**McCollum Severe III** **Pattern III**

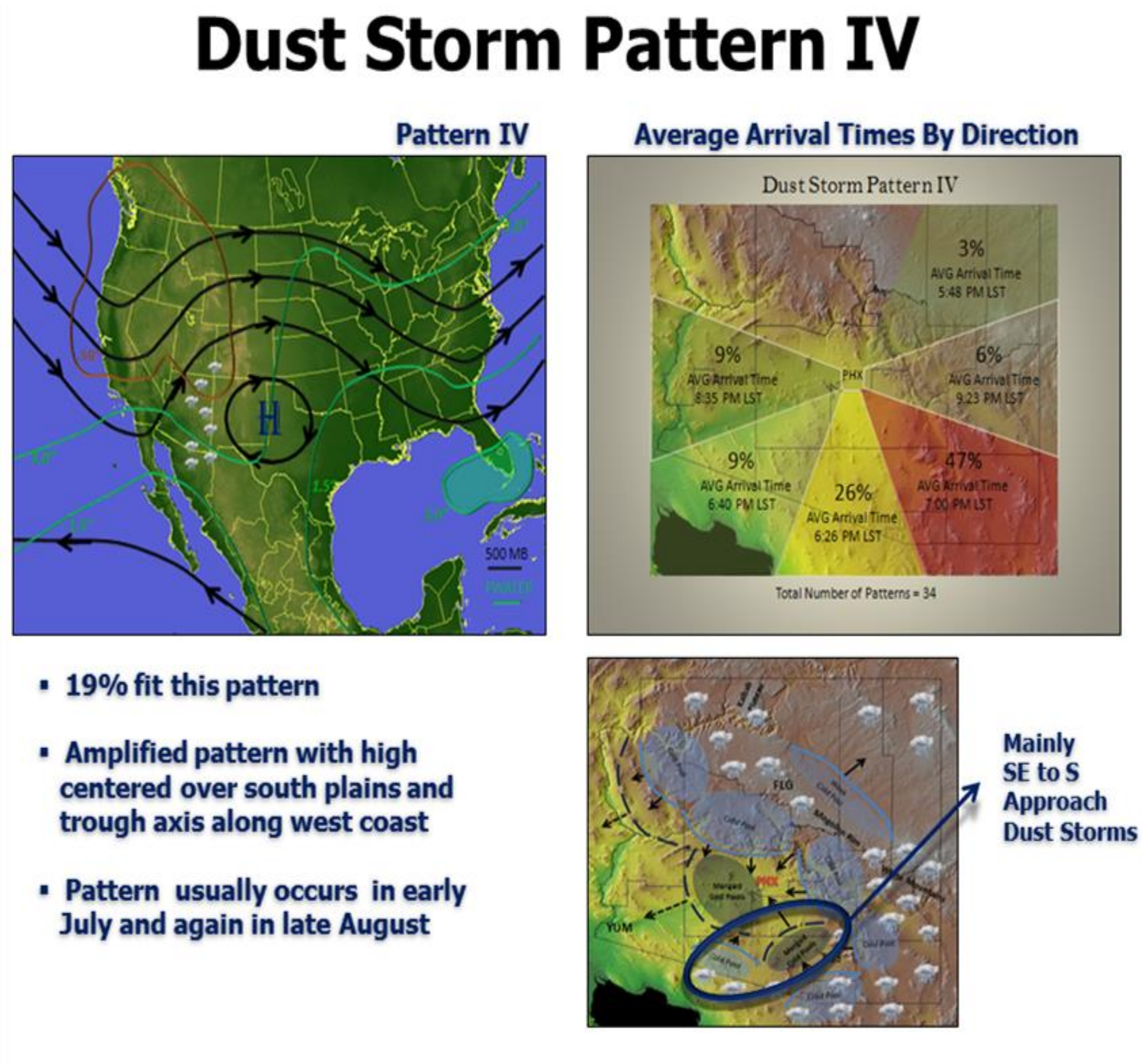
**Average Arrival Times By Direction**

- **11% fit this pattern**
- **Ridge axis is depressed south of normal with 2 distinct high cells**
- **Upper low may become trapped between high cells**
- **Pattern occurs most frequently in late July and early August**

**35% North Approach Dust Storms**

**Most of all Patterns**

Figure 32. Dust Storm Pattern III.



# Dust Storm Pattern IV

**Pattern IV**

**Average Arrival Times By Direction**

Dust Storm Pattern IV

Total Number of Patterns = 34

- 19% fit this pattern
- Amplified pattern with high centered over south plains and trough axis along west coast
- Pattern usually occurs in early July and again in late August

Mainly SE to S Approach Dust Storms

Figure 33. Dust Storm Pattern IV.

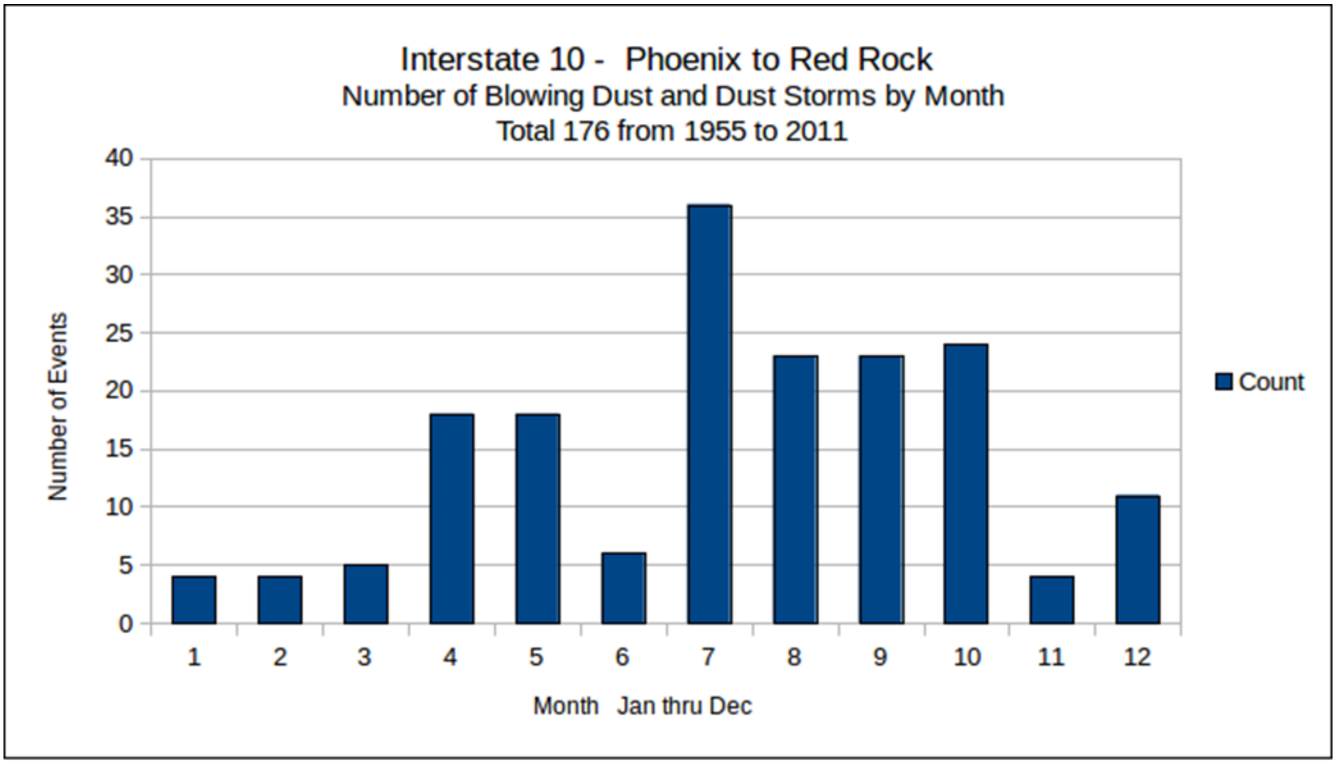


Figure 34. Interstate 10 from Phoenix to Red Rock frequency by month from 1955 to 2011.

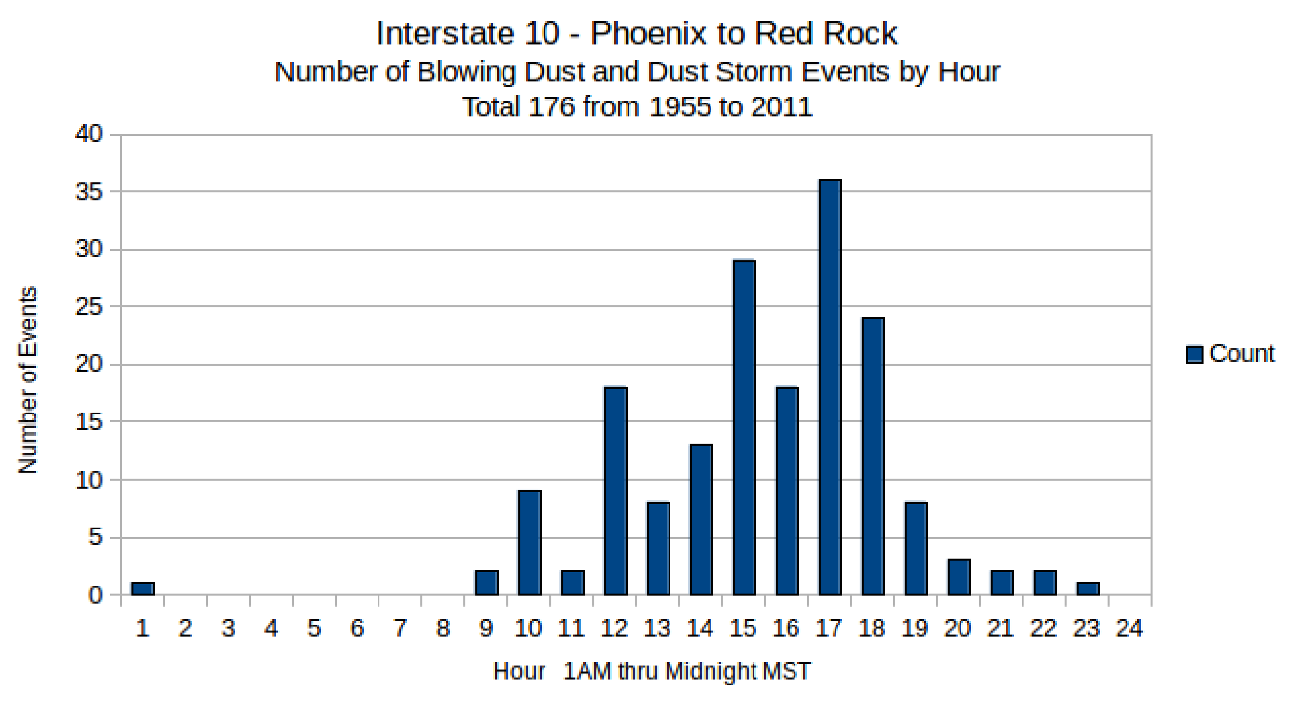


Figure 35. Interstate 10 from Phoenix to Red Rock frequency by hour (MST) from 1955 to 2011.

Figure 36: Picture from the Phoenix NWS office as the July 5, 2011 haboob approached.

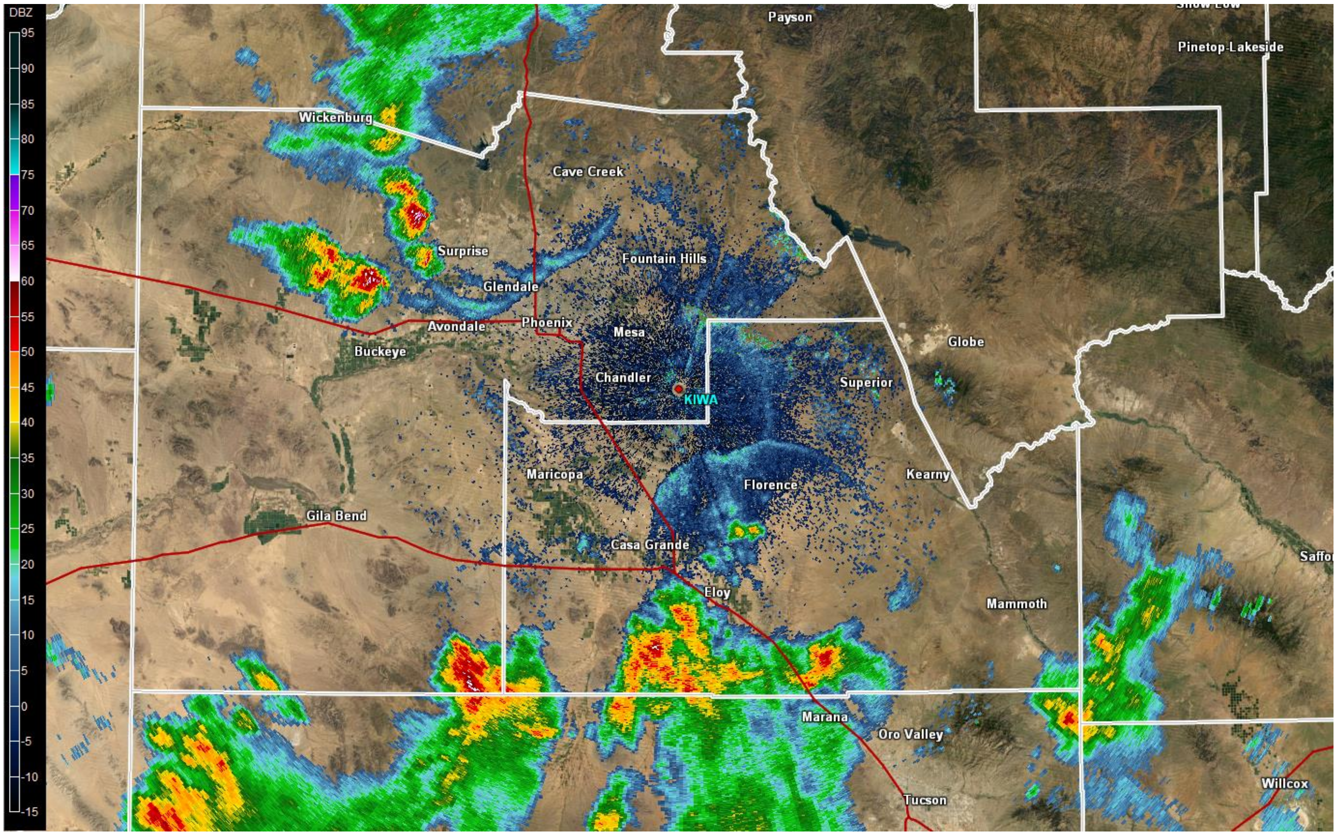


Figure 37: KIWA 0.9 degree base reflectivity valid 01:54Z July 6, 2011.

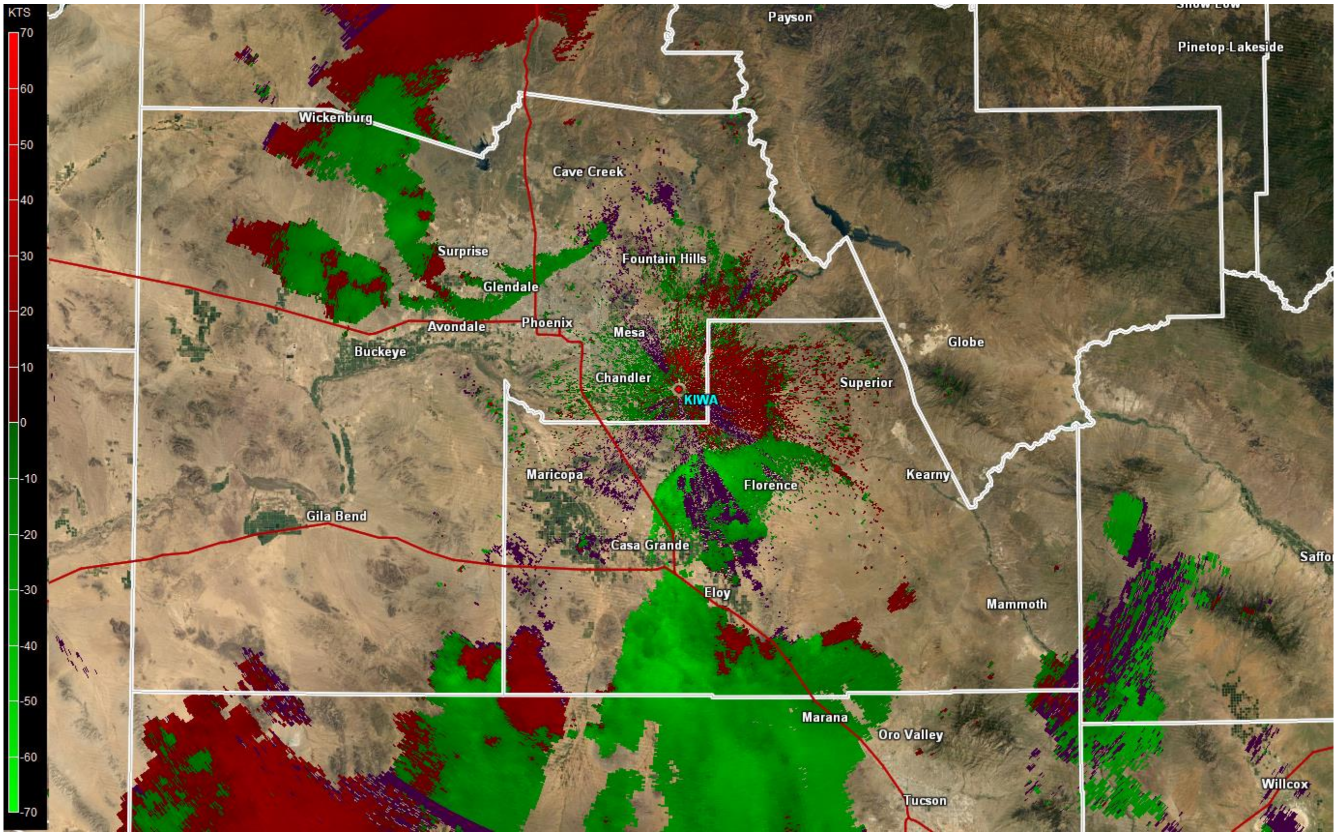


Figure 38: KIWA 0.9 degree radial velocity valid at 01:54Z on July 6, 2011.

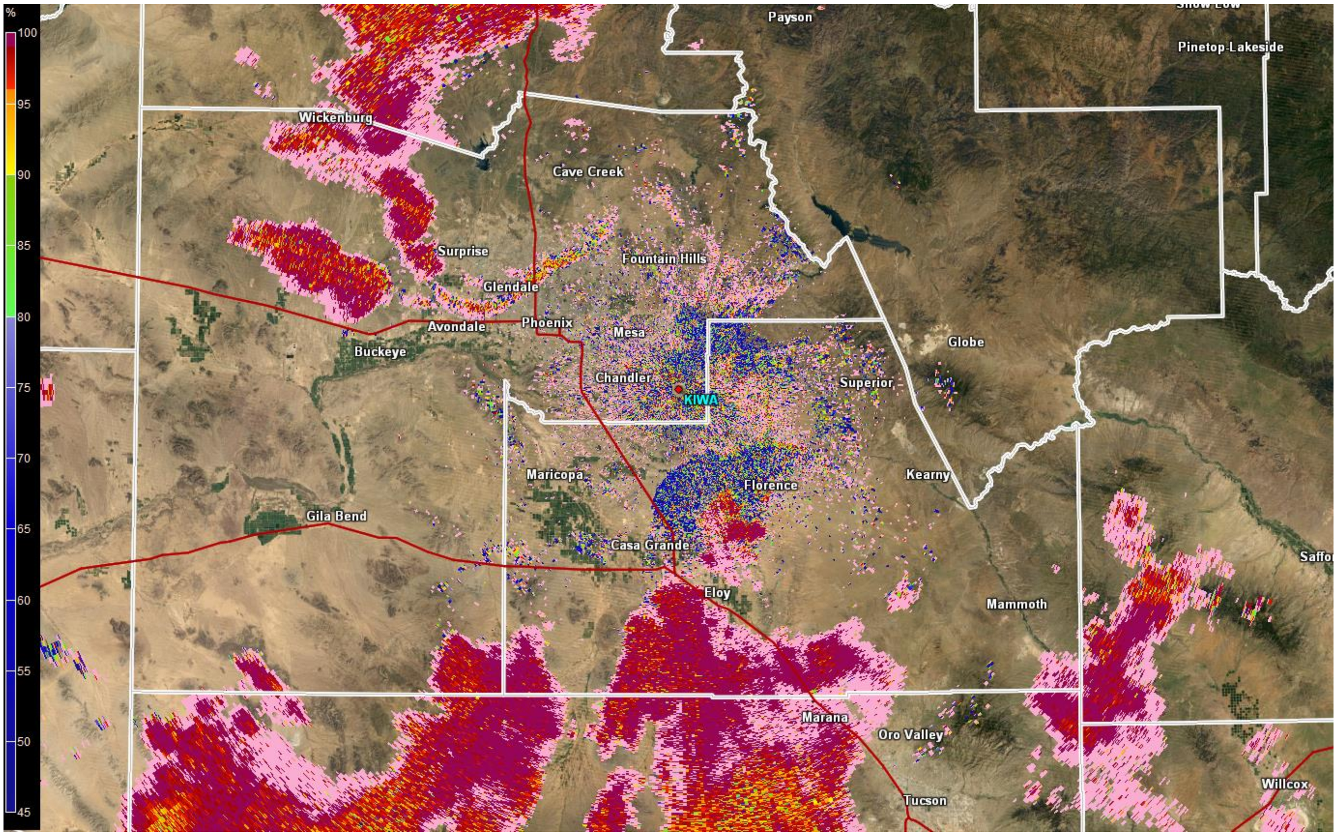


Figure 39: KIWA 0.9 degree Correlation Coefficient valid at 01:54Z on July 6, 2011.

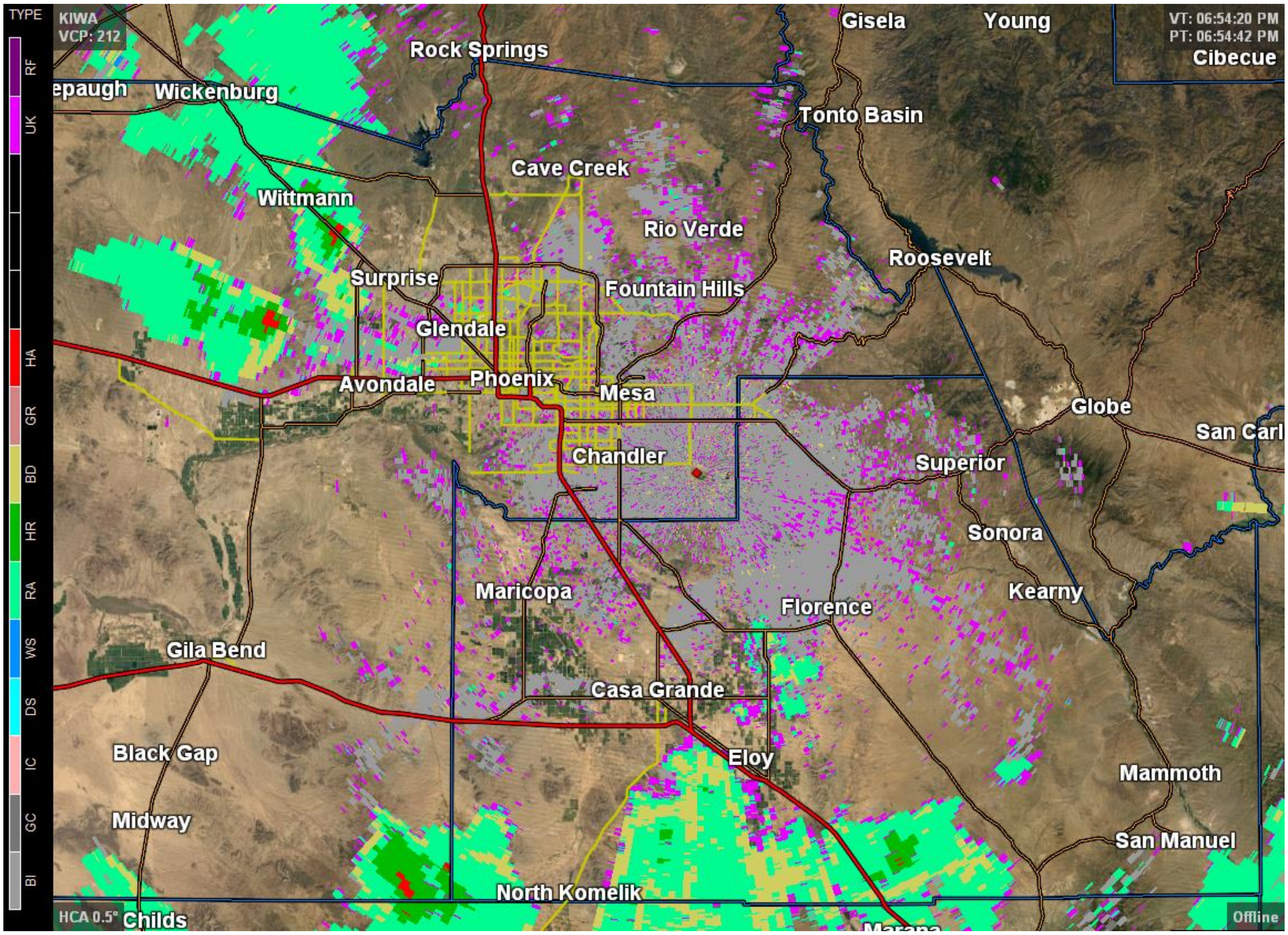


Figure 40: KIWA 0.9 degree Hydrometeor Classification valid at 01:54Z July 6, 2011.

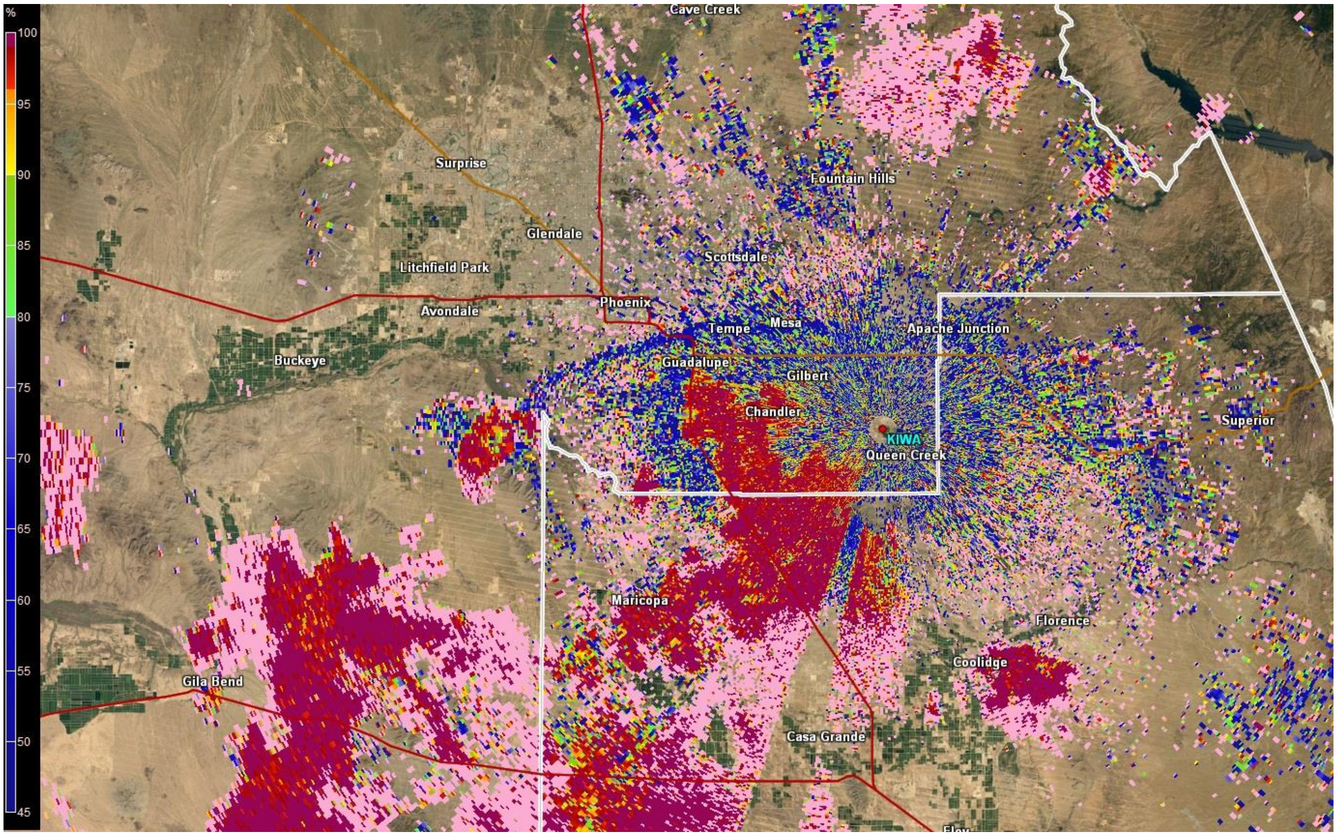


Figure 41: KIWA radar from 01:27Z on August 27, 2013.

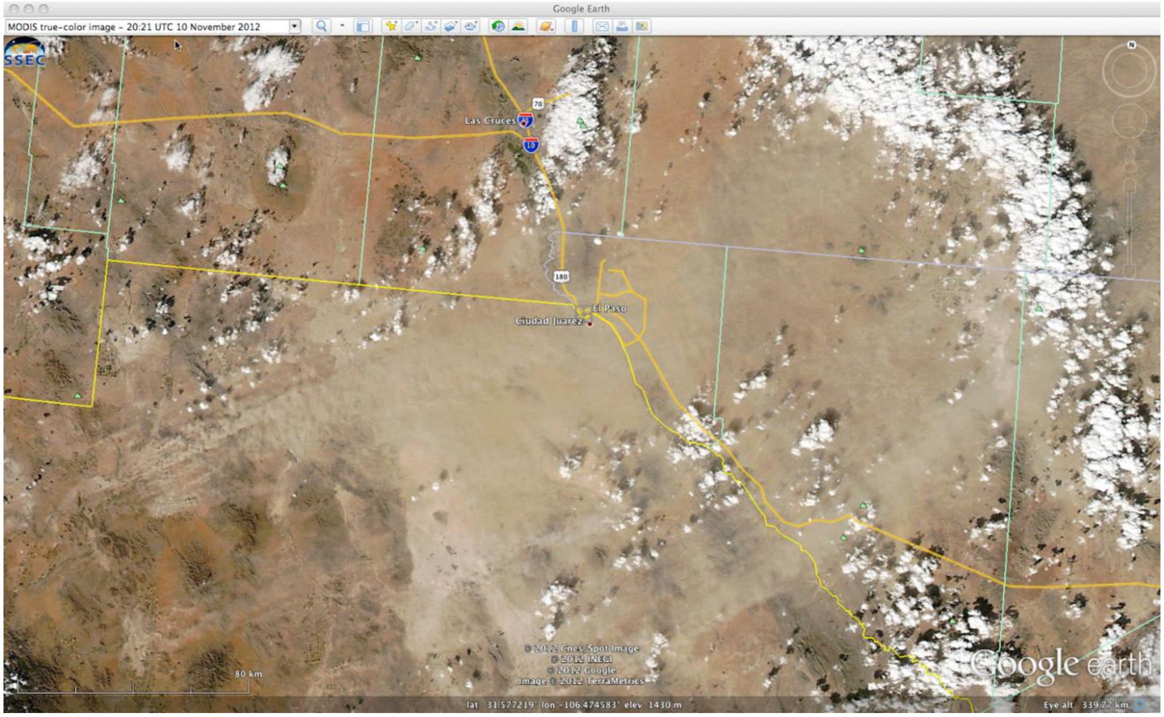


Figure 42: MODIS true color imagery of blowing dust across northeast Mexico into West Texas and Southern New Mexico. Image courtesy of CIMMS satellite blog.

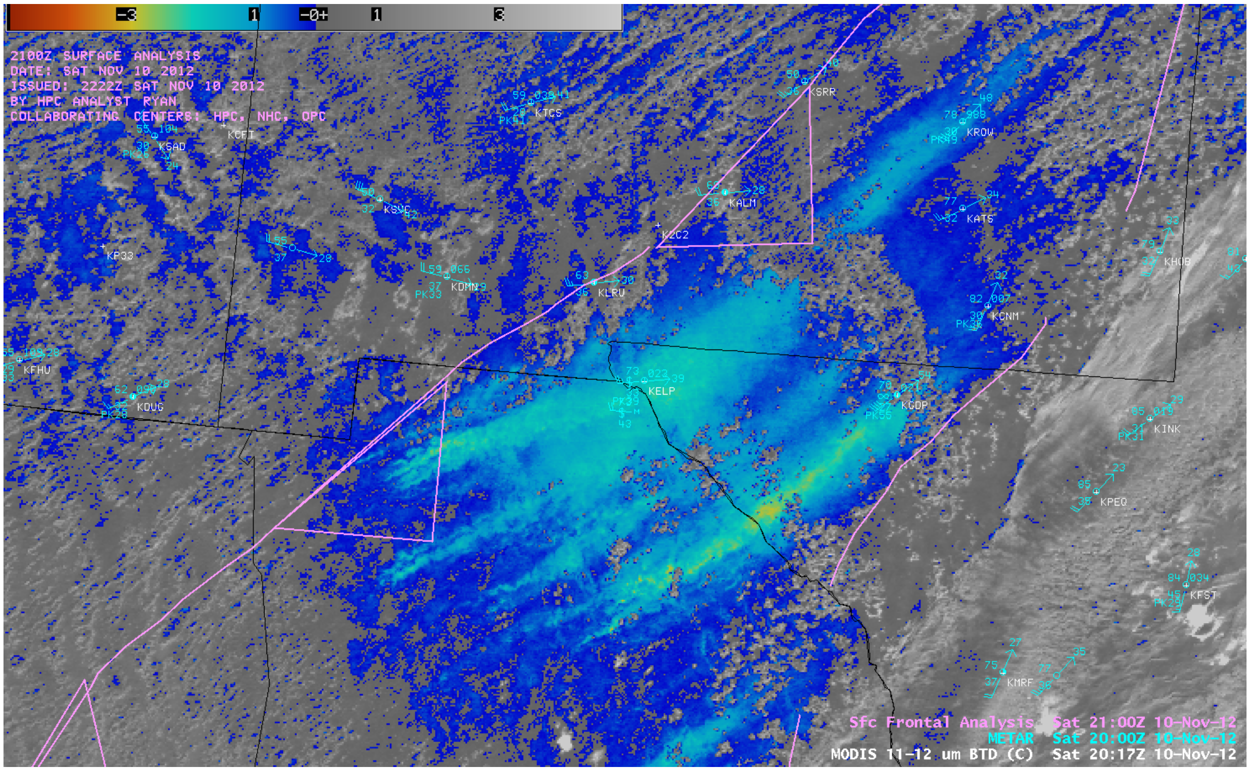


Figure 43: MODIS 11-12 μm IR brightness temperature difference with surface observations and front analysis. Image courtesy of CIMMS satellite blog.

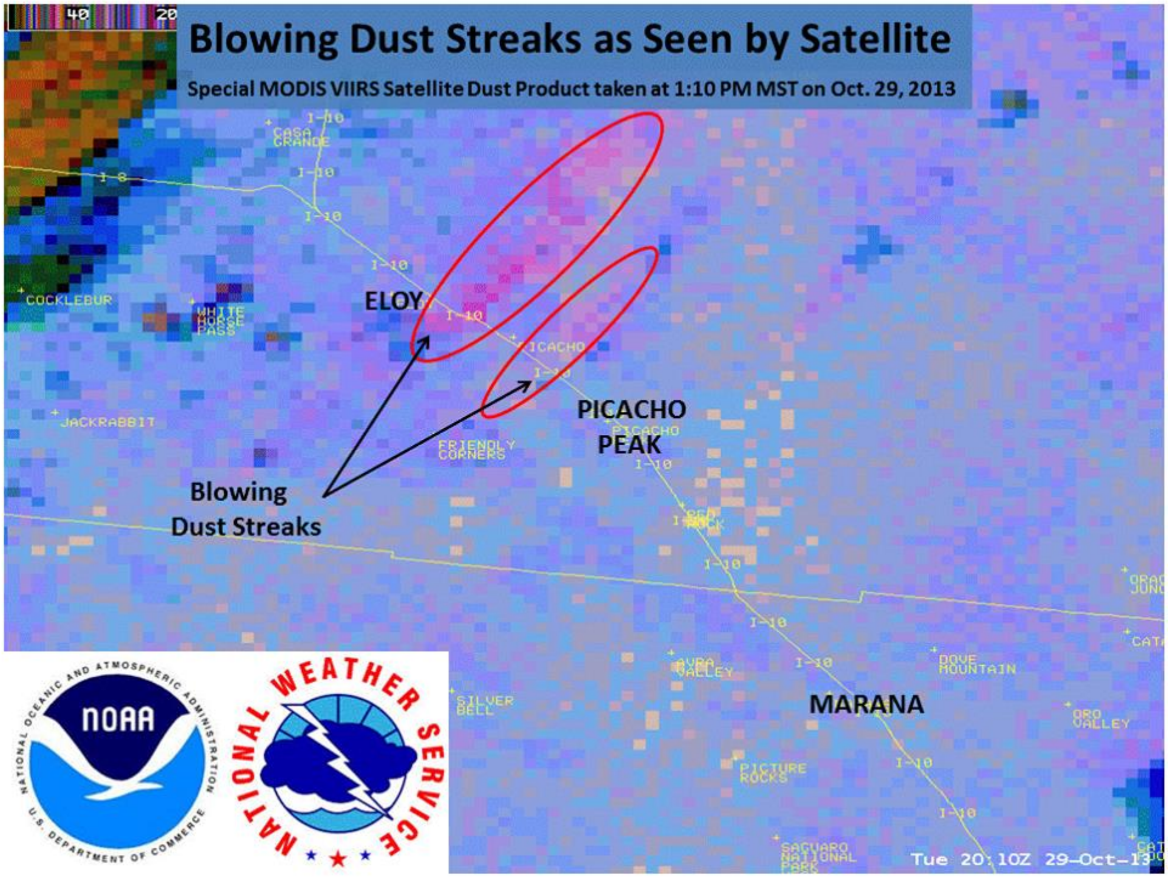


Figure 44: VIIRS dust product showing blowing dust streaks. Image courtesy of CIMMS satellite blog.

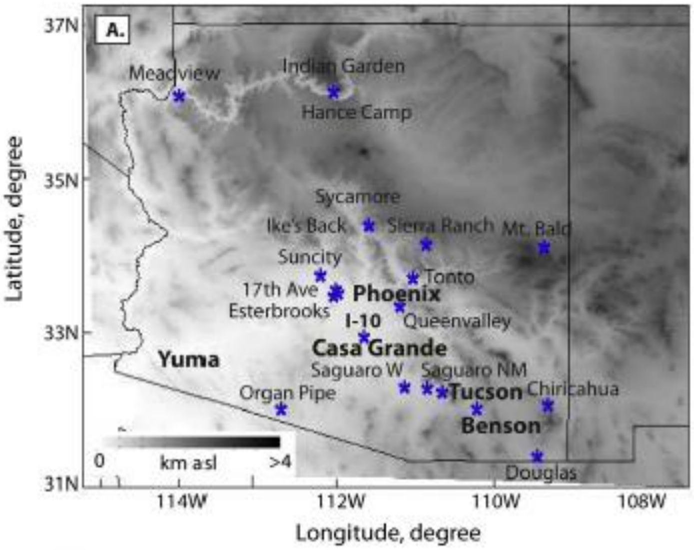


Figure 45: USGS topographic map showing predominant dust source regions and key air quality monitoring stations in Arizona that were identified to have data during the haboob (Raman et al., 2014). The prime dust source regions identified based on the path of cold pool propagation and land use are shown in bold.

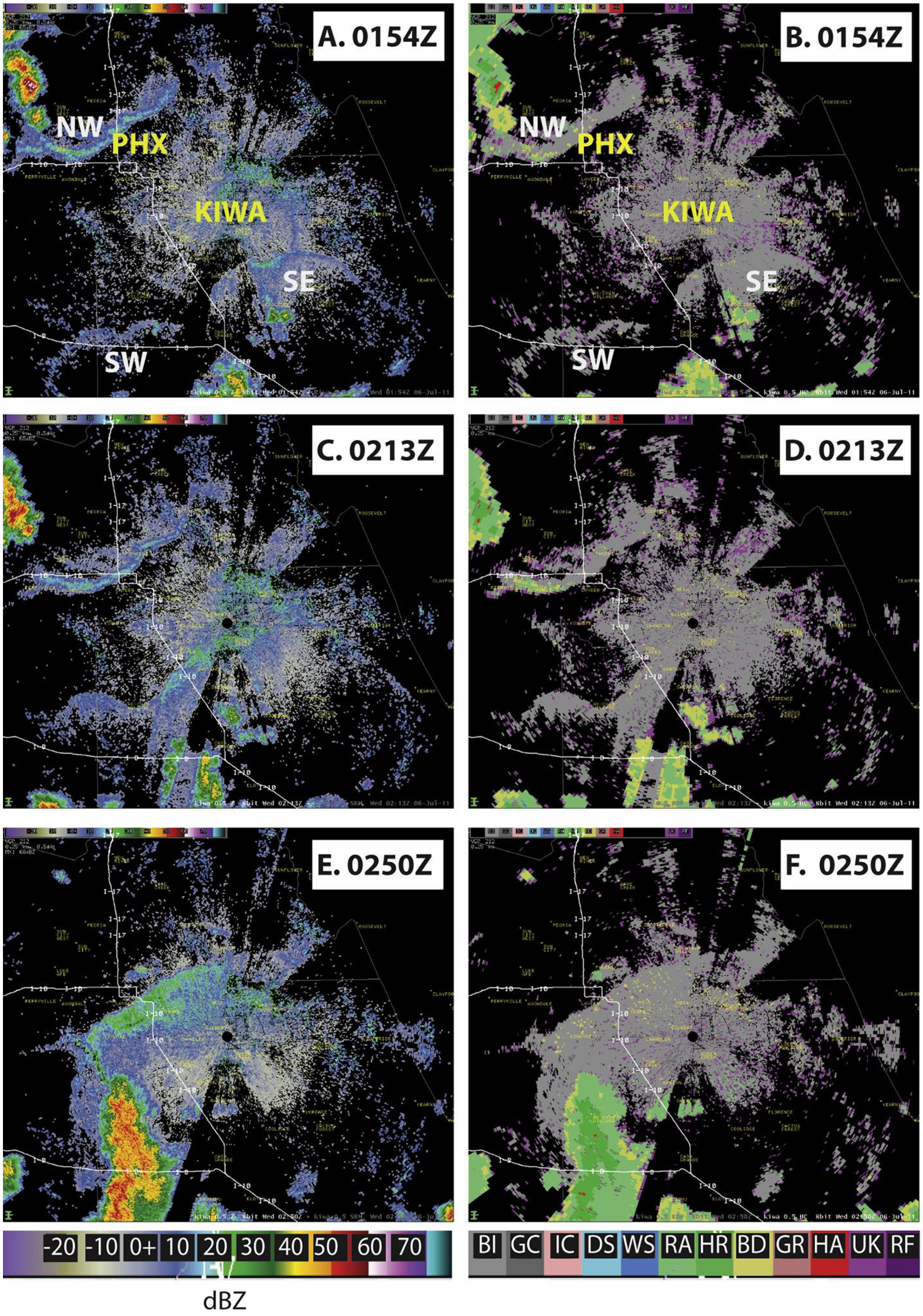


Figure 46 : Radar reflectivities (left) and hydrometeor classification (right) images form KEMX radar.

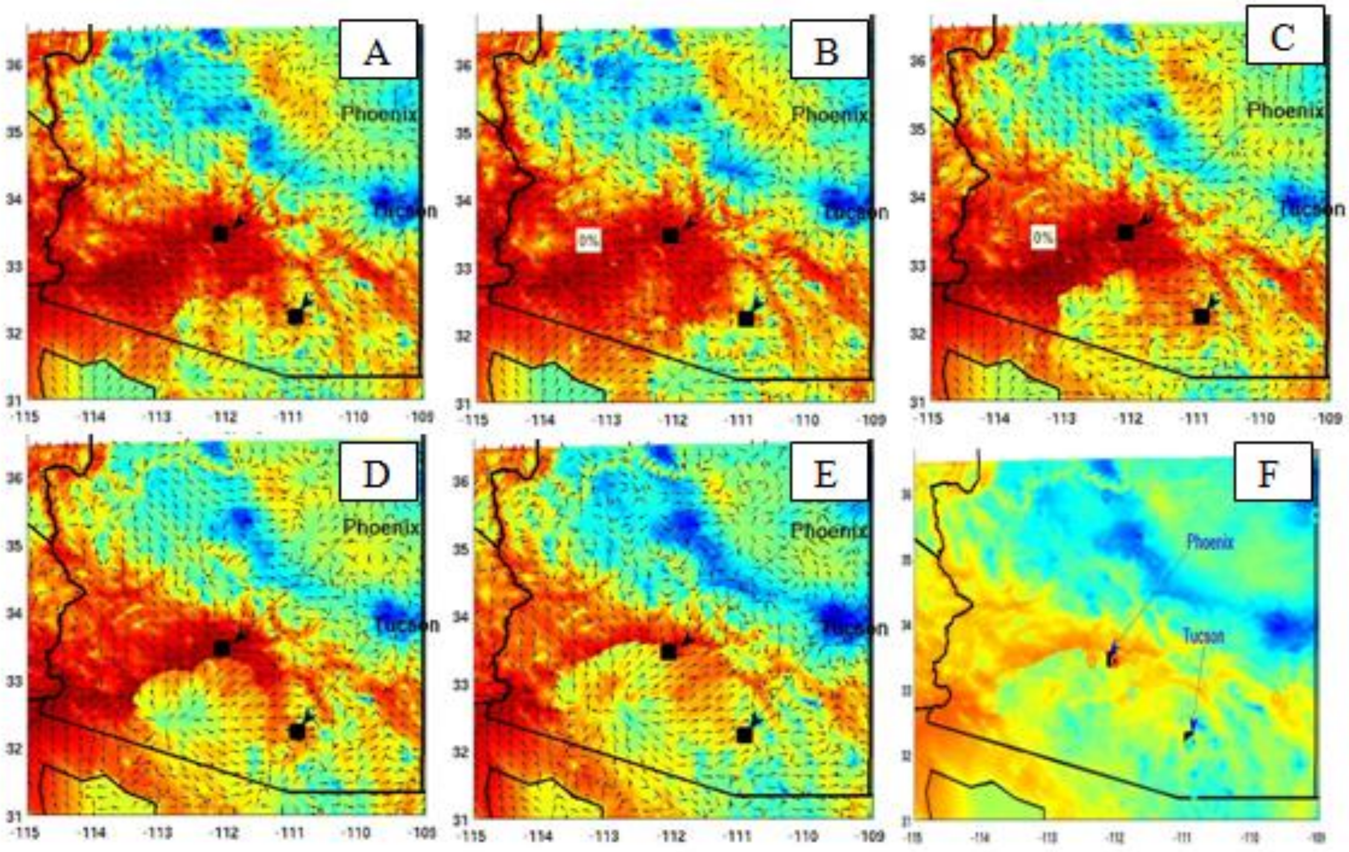


Figure 47: Maps showing cold pool propagation in WRF-Chem. The panels show hourly outputs of 2m temperature and 10m wind vectors. A) 4pm, B)5 pm, C) 6pm, D) 7pm, E) 8pm, F) 9pm

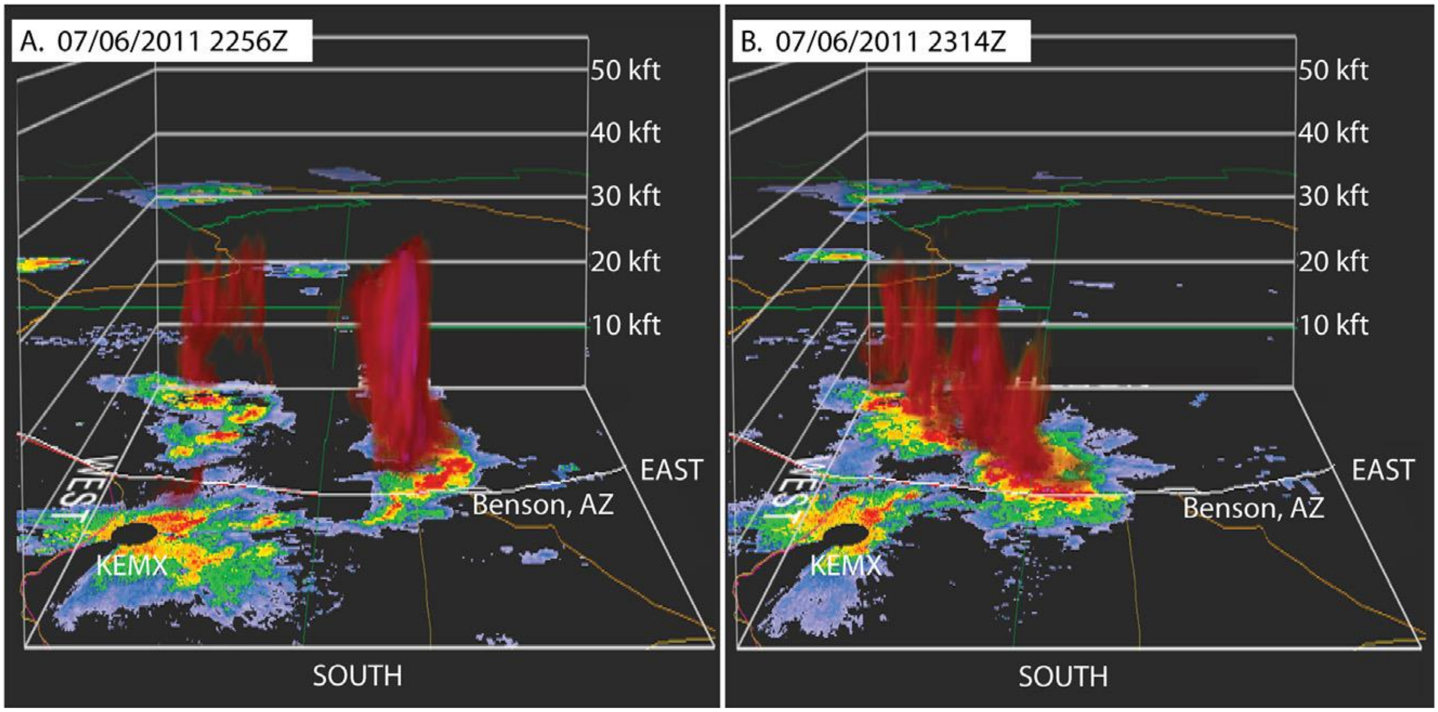


Figure 48 : Vertical profiles of radar reflectivities from KEMX radar at 2256Z and 2314Z on 5 July 2011 (Raman et al., 2014).

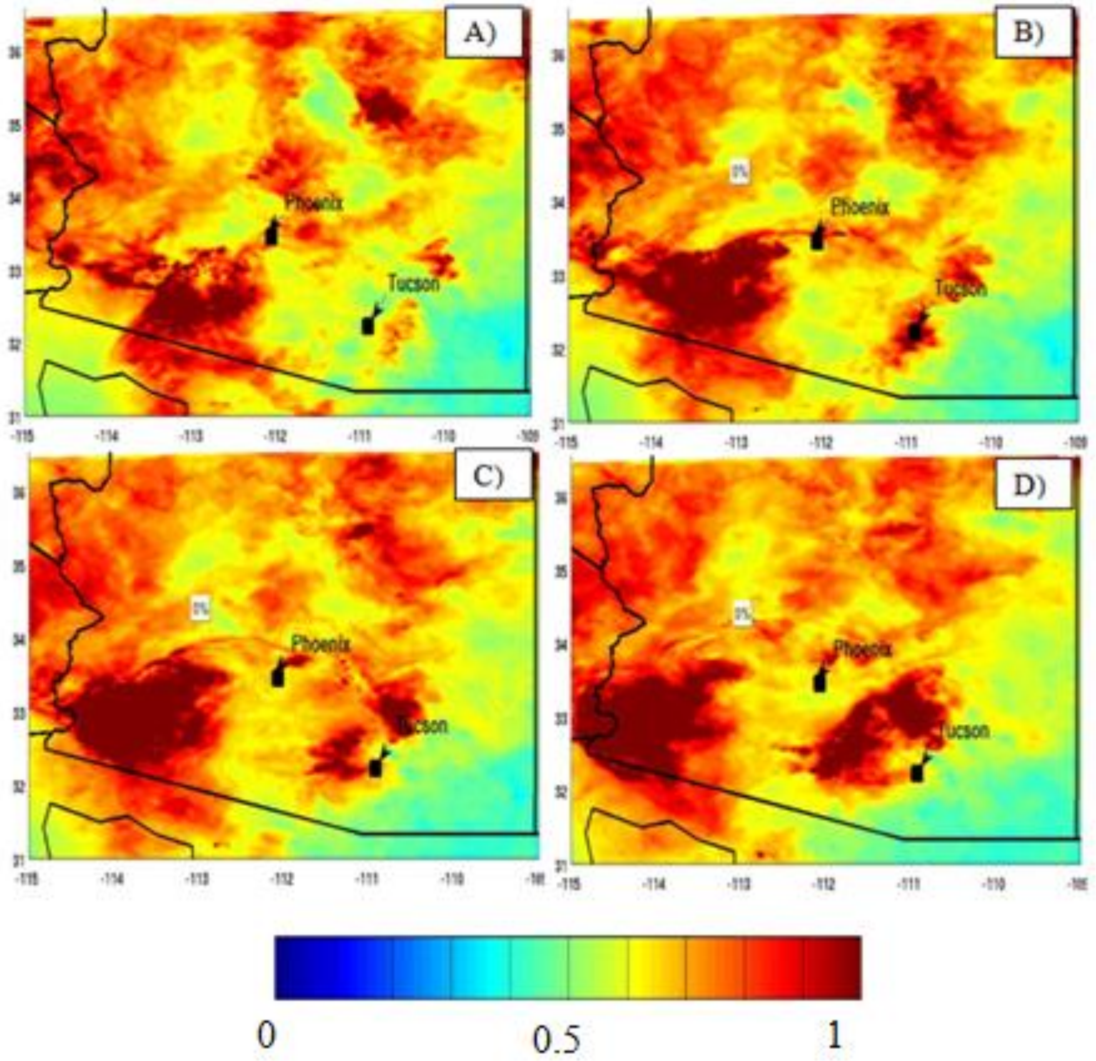


Figure 49 : Simulated Aerosol Optical Depth (AOD) from WRF-Chem. Panels A) 00Z, B) 01Z, C) 02Z, D) 03Z.

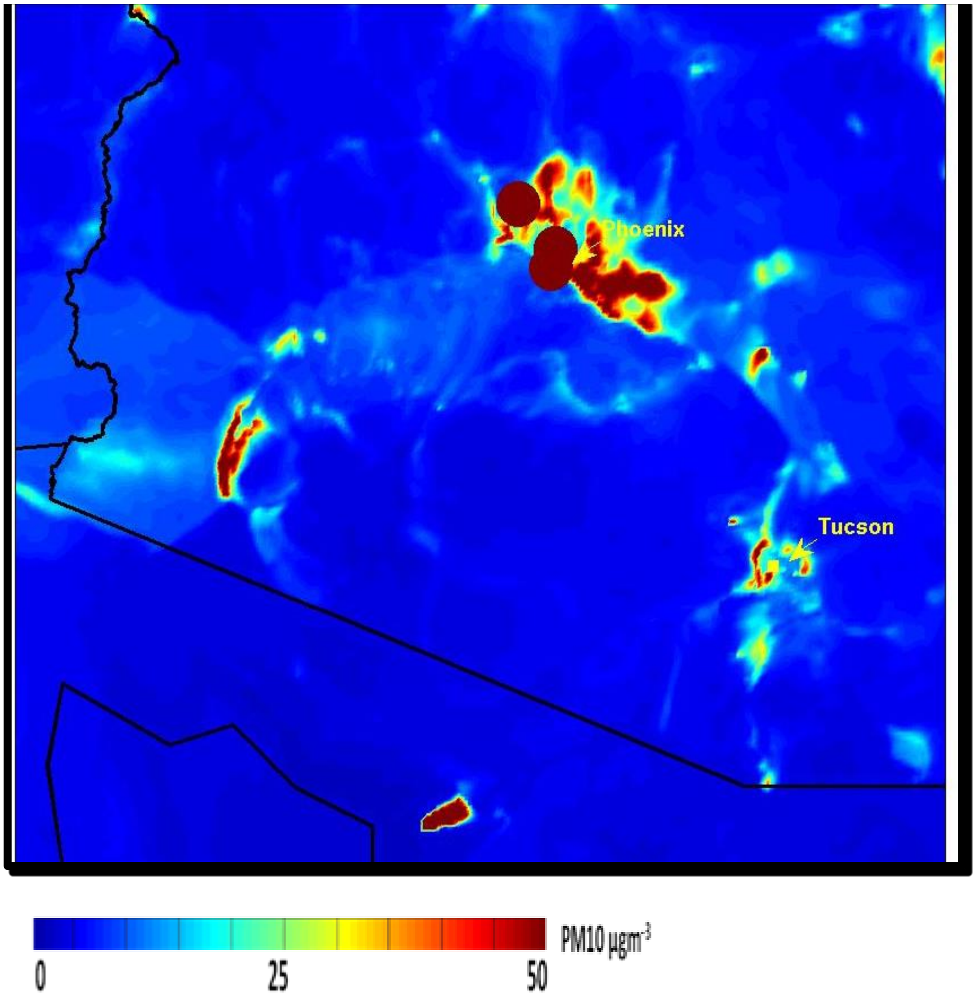


Figure 50: WRF-Chem $PM_{10}$ concentrations at 8 pm. The red circles over Phoenix represent observations from EPA-AQS monitoring stations near Phoenix.

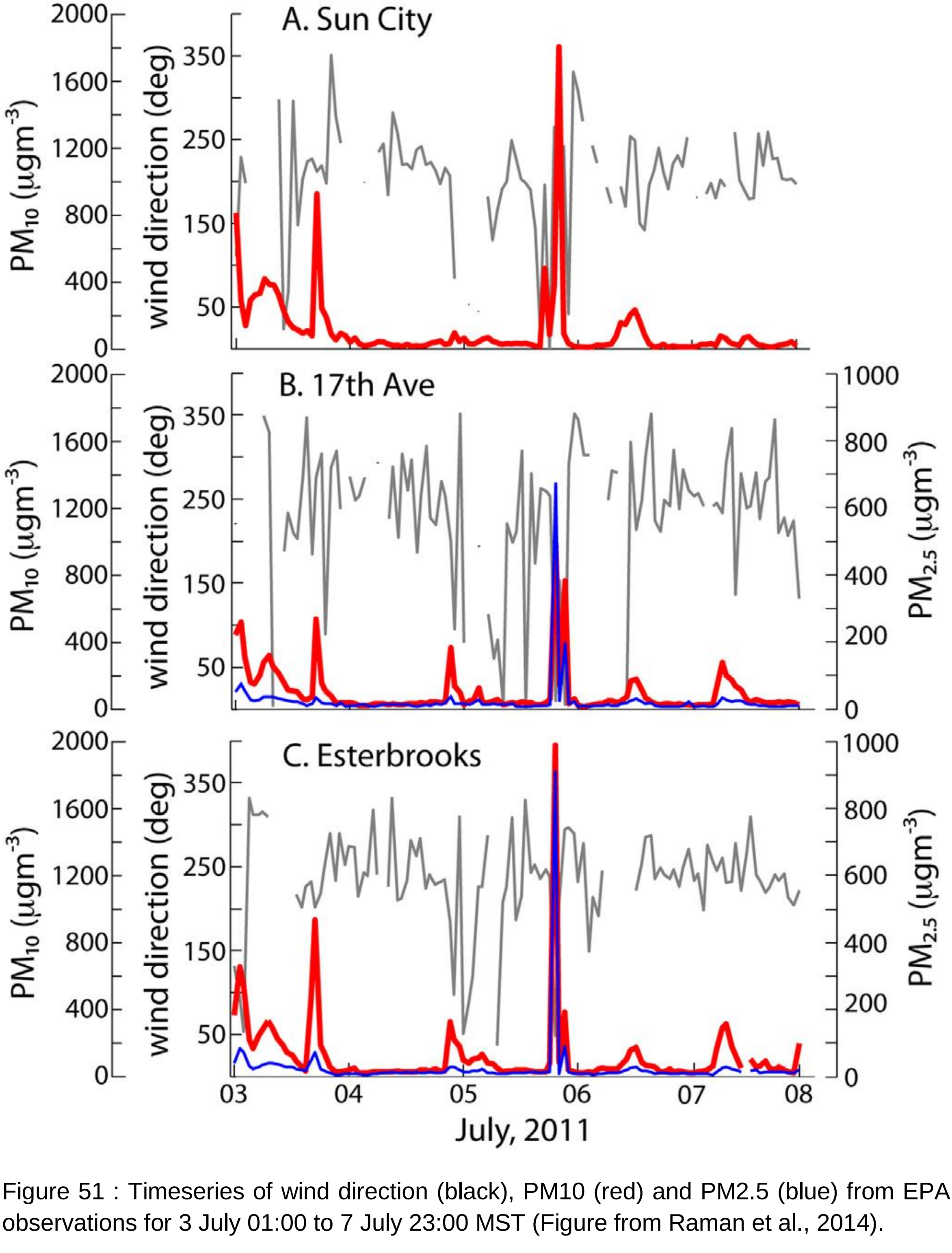


Figure 51 : Timeseries of wind direction (black), PM10 (red) and PM2.5 (blue) from EPA-AQS hourly observations for 3 July 01:00 to 7 July 23:00 MST (Figure from Raman et al., 2014).

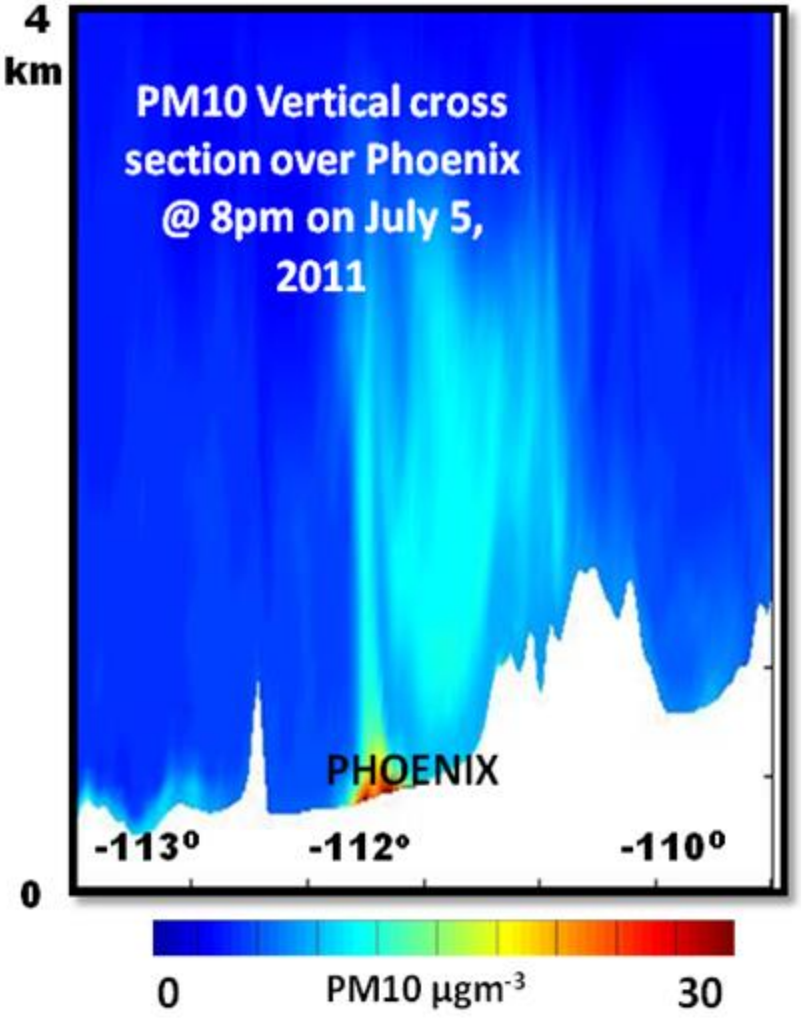


Figure 52 : Vertical cross section of dust concentrations near Phoenix from WRF-Chem at 8pm on 5 July, 2011.

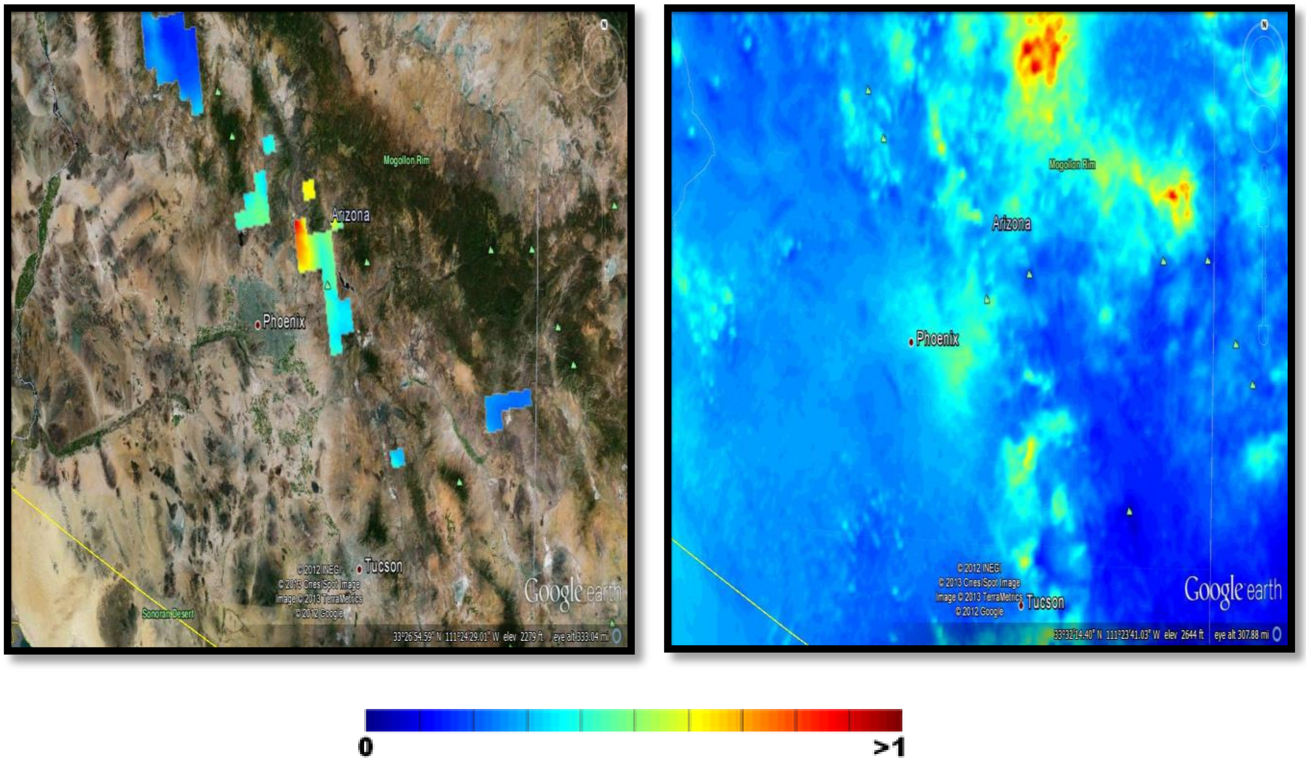


Figure 53: Aerosol Optical depth from Aqua MODIS (left) at ~1:30 pm and WRF-Chem (right) on 6 July 2011.

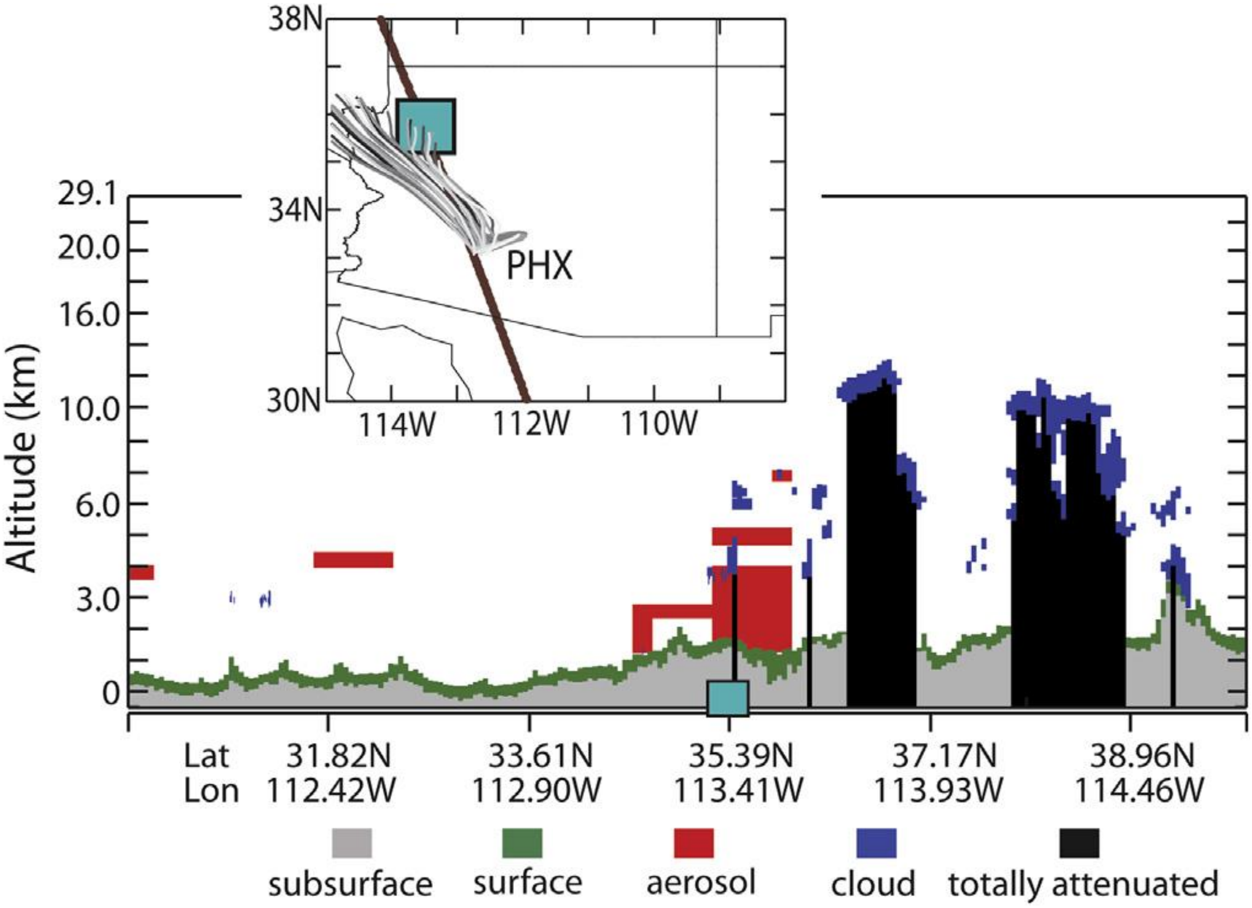


Figure 54. Vertical Feature Mask (VFM) derived from 6 July 2011 CALIOP measurements along the state of Arizona. (Inset) CALIPSO overpass superimposed with HYSPLIT forward trajectories initiated over PHX coordinates (33.4°N, 112.2°W, 2 km agl at 6 July 2011 0300Z).

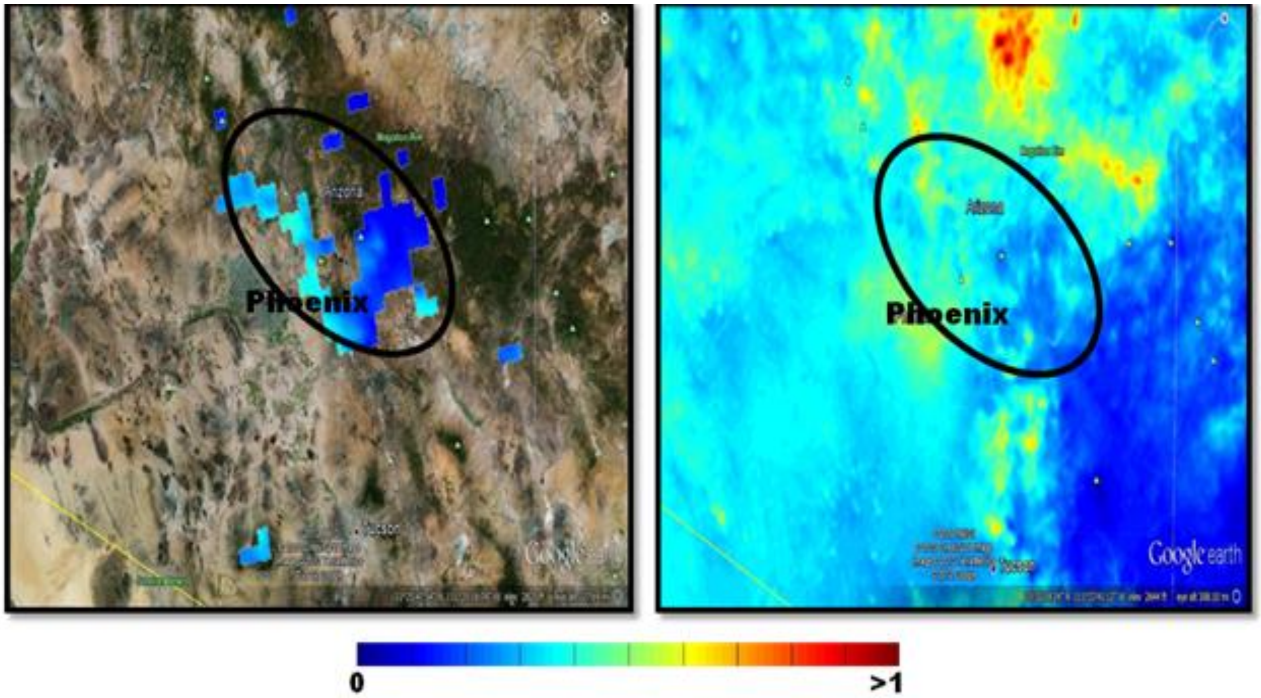


Figure 55: Aerosol Optical depth from MODIS (left) and WRF-Chem (right) on 8 July 2011, ~10:30am (MODIS), and 11:00am (WRF-Chem) respectively.