Cracking the AQ Code

ADEQ Arizona Department of Environmental Quality

Air Quality Forecast Team

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Arizona Tornadoes

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October 6, 2010, is a day that every Arizonan should know. For those that don't believe tornadoes occur in Arizona, this day shouts out loud and clear that tornadoes indeed happen in the Grand Canyon State. On this day, Arizona experienced its largest, single-day tornado outbreak in its recorded history. When all was said and done, eight tornadoes were officially recorded in northern Arizona. This day further proved that, tornadoes are not only possible here in Arizona, but, they can even be dangerous to both life and property. In this edition of Cracking the AQ Code, we'll take a look at Arizona's unique tornado history and statistics, uncover tornado formation, examine the two types of tornadoes in Arizona, and as always, bring it back home to air quality.

Figure 1. An EF0 tornado in Illinois.

Source: NOAA National Weather Service (link to photo)

About "Cracking the AQ Code"

In an effort to further ADEQ's mission of protecting and enhancing the public health and environment, the Forecast Team has decided to produce periodic, in-depth articles about various topics related to weather and air quality.

Our hope is that these articles provide you with a better understanding of Arizona's air quality and environment. Together we can strive for a healthier future.

We hope you find them useful!

Upcoming Topics…

- Prescribed Burns
- $PM_{2.5}$ Around the World

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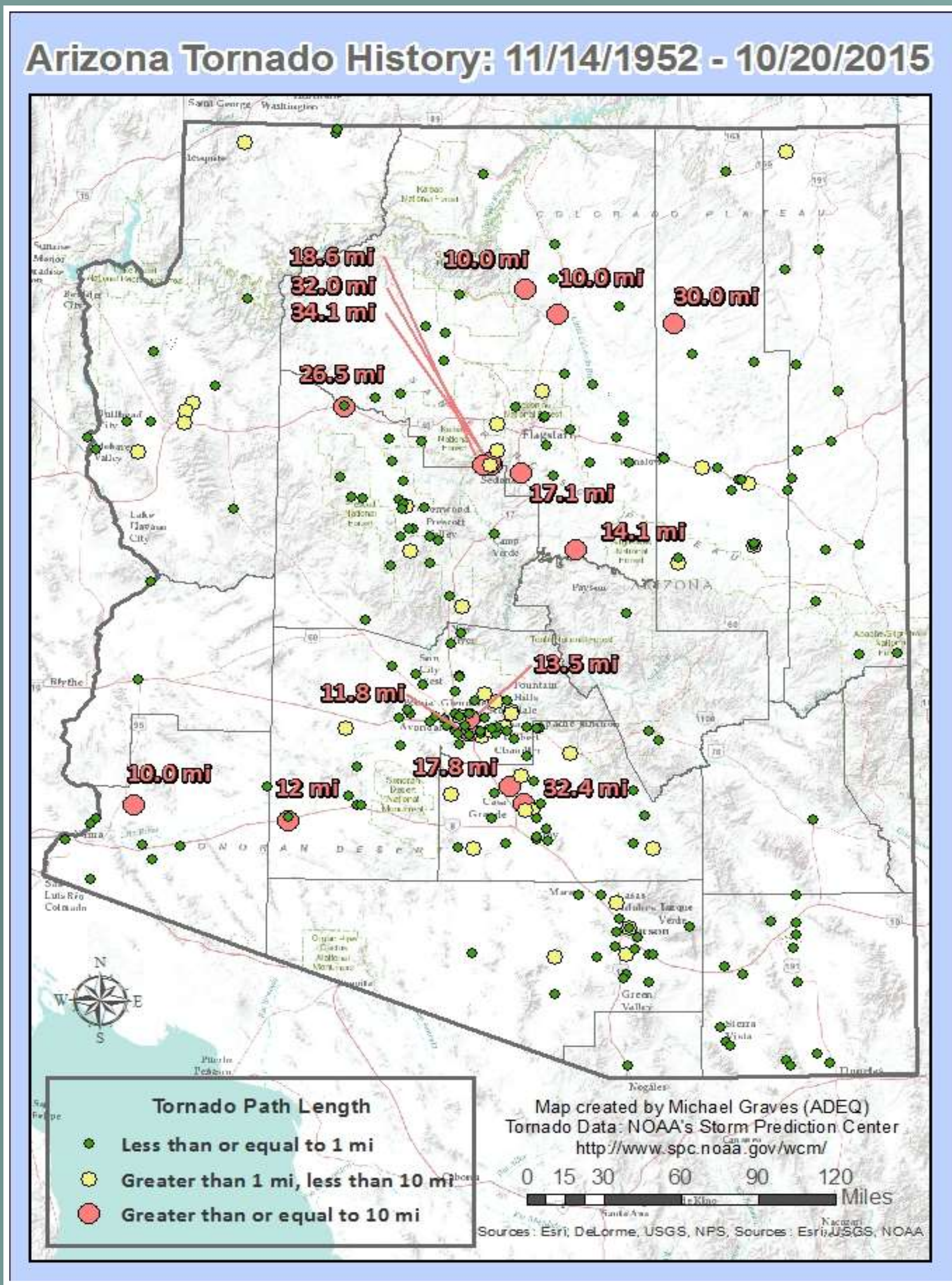
A Historical Perspective

According to the severe weather database maintained by the Storm Prediction Center in Norman, OK, there have been 242 tornadoes officially observed in Arizona since November 1952. That comes out to be an average of almost four tornadoes per year. However, it is very likely that there have been more tornadoes in Arizona since 1952. Because Arizona is a sparsely populated state, tornadoes can potentially go unnoticed by the human eye. This potential would have been even greater in the mid-20th century when Arizona's population was less than half of what it is now. Also, the nation's [weather radar]() network did not have Doppler technology until the 1990s, which is known to greatly improve severe weather detection. Regardless of how many tornadoes have actually occurred, tornadoes certainly have had a presence here in Arizona.

Figure 2: A map of Arizona showing the touchdown locations for all 242 officially observed tornadoes since November 1952. Each point represents a tornado. Tornadoes are classified by their path length: small green points represent tornados with path lengths less than or equal to 1 mile; yellow, medium-sized points represent tornadoes with path lengths between a mile and 10 miles; large red points represent tornadoes with path lengths 10 miles or greater. Tornadoes 10 miles or greater also have their path length labeled in red.

Source: Tornado data: NOAA Storm Prediction Center; map made in ArcGIS with ESRI basemap



Take a look at Figure 2, which shows a map of the touchdown locations for all 242 officially observed tornadoes in Arizona. Each tornado is classified by its path length. The five southern-most tornadoes in Coconino County that had tracks greater than 10 miles long (red points) all happened on October 6, 2010. At first glance, one can see that tornadoes are possible all around the state. In fact, every county has had at least one recorded tornado. Secondly, it is interesting how recorded tornadoes seem to cluster around the urban areas of Phoenix, Casa Grande, Tucson, and perhaps Prescott, too. This is a reflection of the tornado detection issue discussed above, that tornadoes will be documented where there are people or radars to see them.

Tornado Frequency

Now, if we take all of Arizona's 242 officially observed tornadoes and count the number of times a tornado has occurred during each month of the year, we obtain the histogram in Figure 3. The main takeaway from this graph is that tornadoes are more common from July to October. During the summer months, it is the monsoon pattern that primarily drives the thunderstorms that sometimes produce tornadoes. As we then transition into the fall months, the jet stream begins to shift southward from Canada and the increased frequency in low pressure systems from the Pacific becomes the primary driver of thunderstorms and thus, tornadoes in Arizona. Low pressure systems also play a large role in the spring months and the smaller peak in tornado frequency during May. Overall, Arizona has seen tornadoes in every month of the year. Just remember, statistically, Arizona averages about four tornadoes per year. Thus, tornadoes still remain rather uncommon for the state. Figure 4 puts this into perspective as we see Arizona's tornado tracks compared to the rest of the U.S.

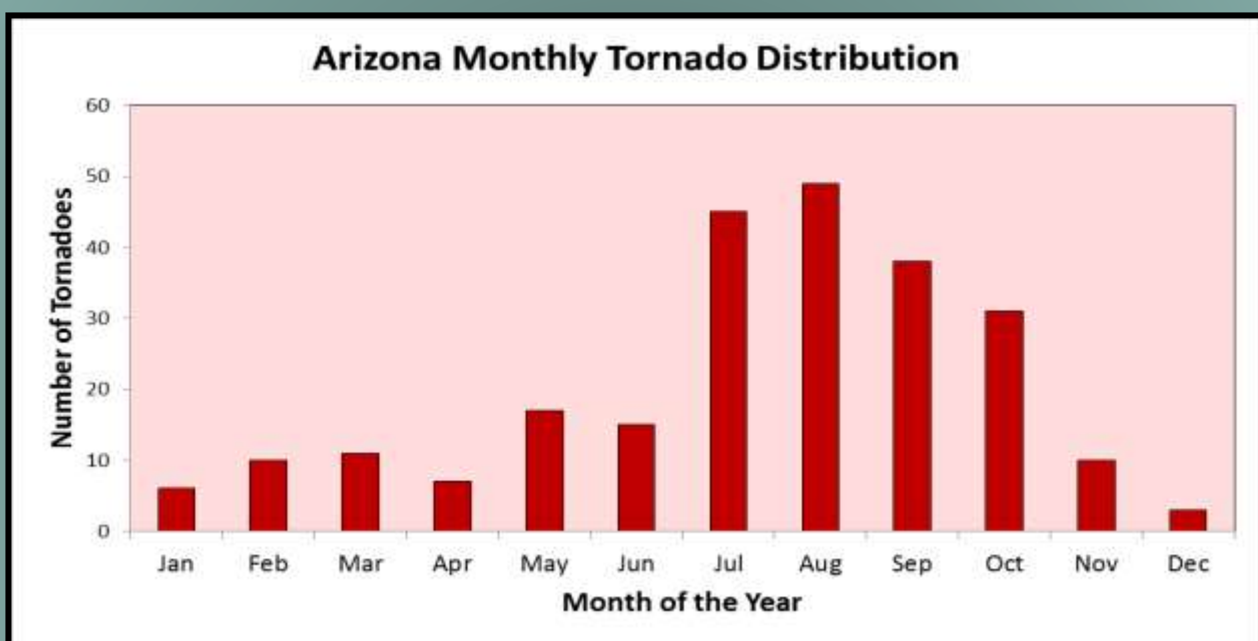


Figure 3: A histogram showing the number of observed tornadoes for each month of the year, based on the official, observed record (242 total tornadoes from 1952-2015) from the Storm Prediction Center.

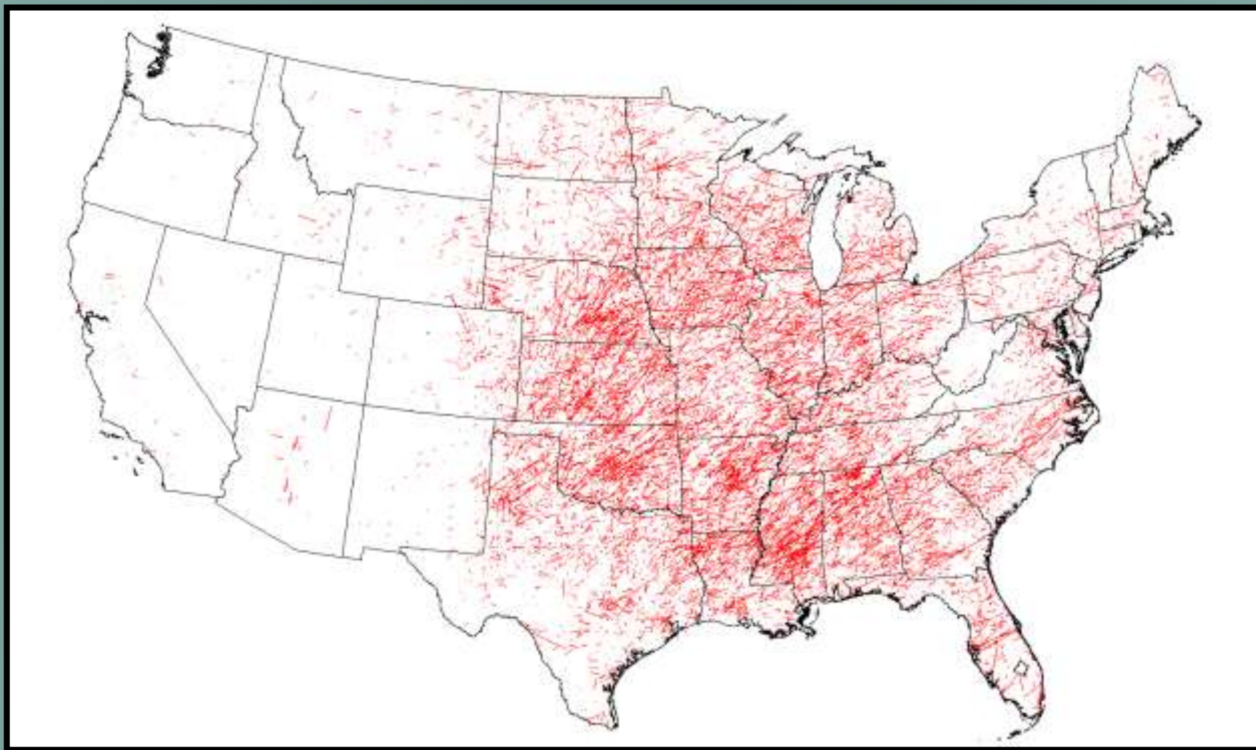


Figure 4: A map of all tornado tracks for 1950-2015 in the United States.

Source: NOAA Storm Prediction Center (link here)

October Madness!

Did you know that Arizona has a top rank on at least one list related to U.S. tornadoes? When it comes to the month of October and comparing U.S. counties, Coconino County is tied for first with two other counties (Harris County, Texas and Acadia County, Louisiana) for the greatest number of tornado touchdowns (13) in the nation. This is shown in Figure 5. As you can see, Coconino County really sticks out. The tornado outbreak on October 6, 2010, greatly contributed to this statistic. Also, notice how other counties in Arizona have decent tornado density values for the month of October.

Arizona Tornado Characteristics

When you hear the word "tornado", what kind of tornado do you imagine first? Is it a scrawny, rope-like vortex thinly stretching down from the sky to the ground? Or is it a more ominous and large one capable of leaving great devastation in its wake? Most likely, your mind goes to an image closer to the latter. Arizona, though it hasn't seen extraordinary tornadoes like those we quickly imagine and that occasionally form in the Great Plains and Southeast states, does have its share of a few "strong" tornadoes. To get a better grasp of Arizona's tornadoes, let's explore some of their characteristics. We'll begin with tornado intensity.

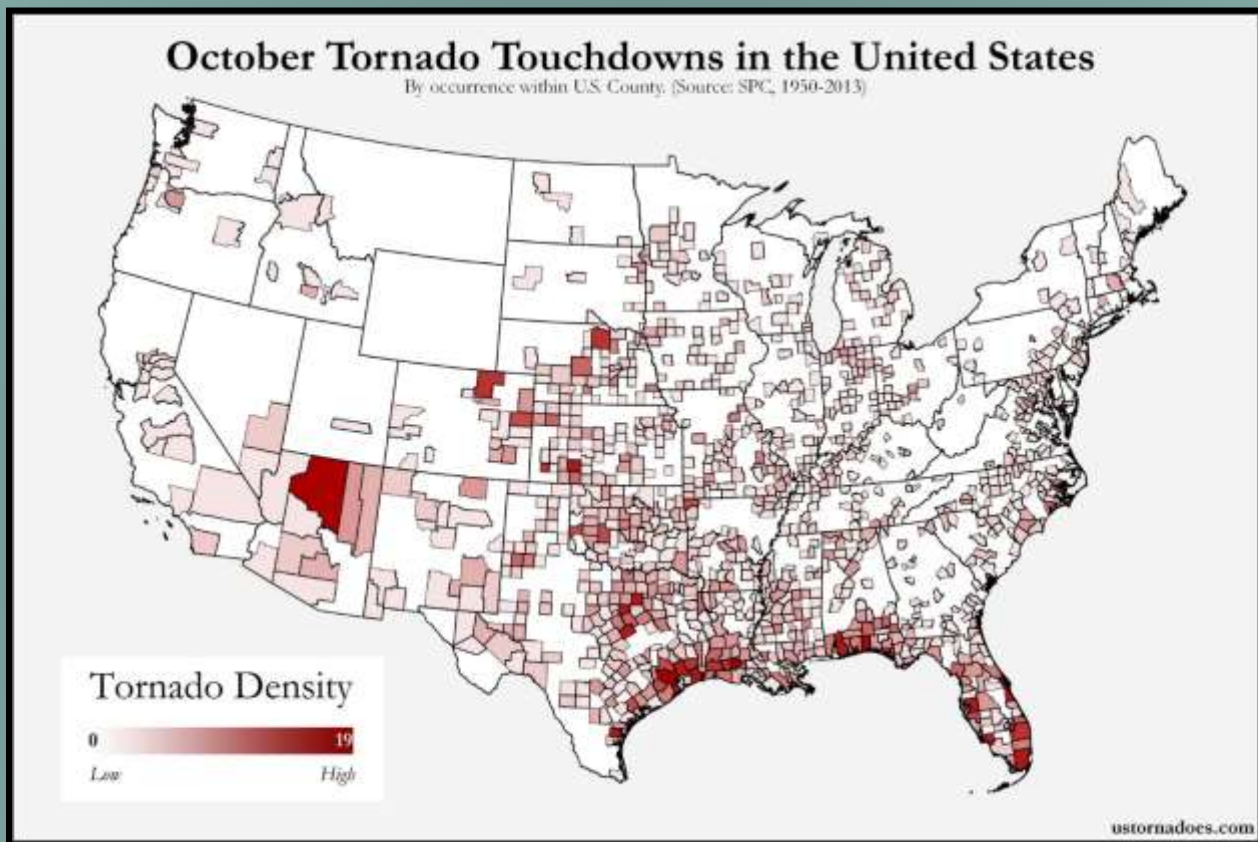


Figure 5. A map showing the tornado density (number of tornadoes) for various counties around the United States for the month of October. The map includes tornado data from 1950-2013.

Source: Ian Livingston, usatornadoes.com

Tornado Intensity

Tornado intensity is currently measured by the "Enhanced Fujita Scale" (EF Scale), which succeeded the "Fujita Scale" in February 2007 (see Table 1). This scale ultimately estimates the wind speed of a tornado based on the damage it leaves behind. Because surveys of damage have to be conducted to determine a tornado's rating, tornadoes are not officially rated until after the storm. From November 1952 to December 2015, Arizona has had 19 "strong" tornadoes. That comes out to around 8% of Arizona's tornadoes. Three of those tornadoes were classified as EF3/F3. The other 223 officially observed tornadoes were rated "weak" (92%). No "violent" tornadoes have been observed in Arizona in recorded history (see Figure 6, left graph).

For perspective, let's consider a state well-known for its tornadoes: Oklahoma. Out of Oklahoma's officially observed 3,560 tornadoes for the same time period, 2,673 (75%) tornadoes were rated "weak", 830 (23%) were rated "strong", and 57 (2%) were rated "violent". Compared to Oklahoma, Arizona clearly does not see as many tornadoes, but it also has a much smaller percentage of tornadoes rated "strong" (see Figure 6, right graph).

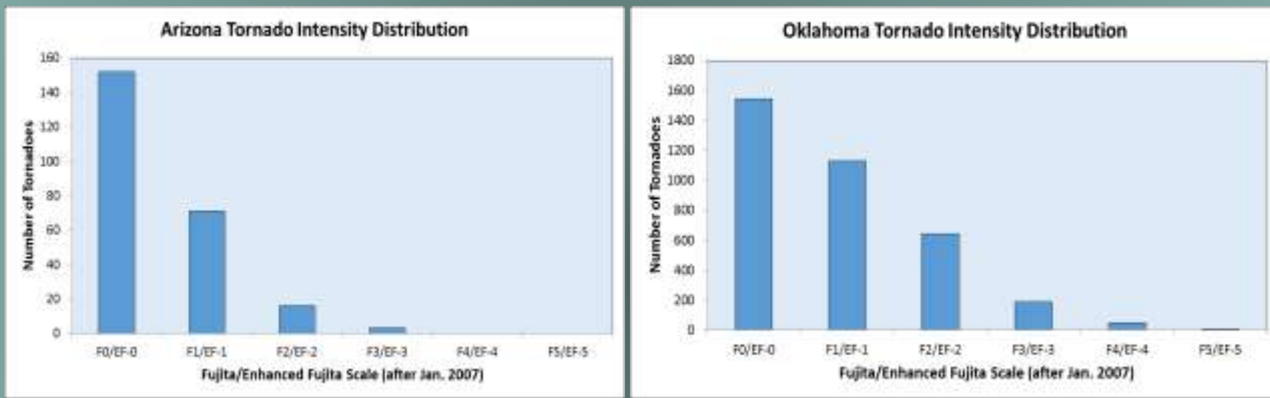


Figure 6. A comparison of the intensity of tornadoes between Arizona (left) and Oklahoma (right) for the time period of November 1952 to October 2015. Each vertical bar represents the total count of tornadoes that fall into a particular intensity category. Notice the large difference in the values along the vertical axes between each graph.

Path Length

Another important characteristic of tornadoes to consider is their path length. In general, Arizona tornadoes have short path lengths. In other words, they typically do not travel for very long on the ground. The majority of the time, tornadoes in Arizona have traveled no more than a mile along the ground. From there, only a handful have reached two to three miles. Tornadoes with longer path lengths are much more uncommon (see Figure 7, left graph). The longest recorded path length is 34.1 miles, which occurred on October 6, 2010. In contrast, tornadoes in the Great Plains have the potential for much longer path lengths. Oklahoma saw 24 tornadoes with path lengths greater than 50 miles between November 1952 and October 2015. In fact, three of those tornadoes traveled more than 100 miles on the ground (see Figure 7, right graph).

Table 1. The Enhanced Fujita Scale (EF Scale) and Fujita Scale. The EF Scale is the current, official method used to rate the strength of tornados and is a revision of the previous Fujita Scale. After 33 years of use, the Fujita Scale ultimately proved to be insufficient in its wind speed estimations and needed improvement. In February 2007, the National Weather Service replaced the Fujita Scale with the EF Scale. The EF scale, unlike its predecessor, takes into account the quality of how buildings are constructed and provides a better match between damage and wind speeds.

Enhanced Fujita Scale			Fujita Scale			
Scale	Wind Speed	Damage	Scale	Wind Speed	Damage	
EF0	65-85 mph	Light	F0	< 73 mph	Light	Weak
EF1	86-110 mph	Moderate	F1	73-112 mph	Moderate	
EF2	111-135 mph	Considerable	F2	113-157 mph	Considerable	Strong
EF3	136-165 mph	Severe	F3	158-206 mph	Severe	
EF4	166-200 mph	Devastating	F4	207-260 mph	Devastating	Violent
EF5	>200 mph	Incredible	F5	261-318 mph	Incredible	

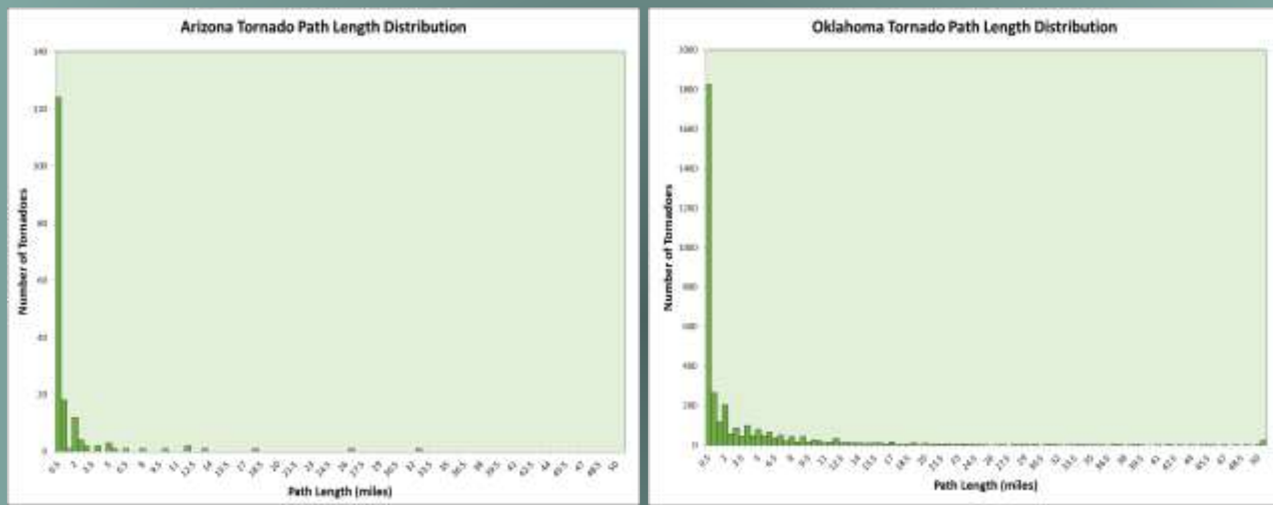


Figure 7. A comparison of the path lengths of tornadoes between Arizona (left) and Oklahoma (right) for the time period of November 1952 to October 2015. Notice the large difference in the values along the vertical axes between each graph. Each vertical bar represents the total count of tornadoes that fall into a particular range of path lengths. The right-most bar on Oklahoma's graph represents the 24 tornadoes with path lengths greater than 50 miles.

Path Width

Another characteristic we can look at to learn more about tornadoes is their path width. In a general sense, one would expect stronger tornados to exhibit wider paths. For example, four tornadoes on October 6, 2010, were rated as "strong" and had path widths greater than 1000 ft. The tornado with the widest path ever recorded in Arizona (July 22, 1984) had a width of 4,500 ft. (1 mile is 5,280 ft.) and was rated an F2. However, this is not always reality. Ninety-six tornadoes had a recorded path width of 30 ft., which was the most common path width. Seventy-one of those tornadoes were rated EF0/F0; twenty-one were rated F1; two were rated F2; and two were rated F3. Figure 8 shows the relationship between tornado intensity and path width for both Arizona and Oklahoma. In Oklahoma, there is a noticeable increase in path width from EF0/F0 to EF3/F3. However, there is not a clear relationship in Arizona. Once again, Oklahoma is on an entirely different plane than Arizona regarding tornadoes: Arizona's tornadoes just don't achieve the substantial path widths that can be found in in the Great Plains.

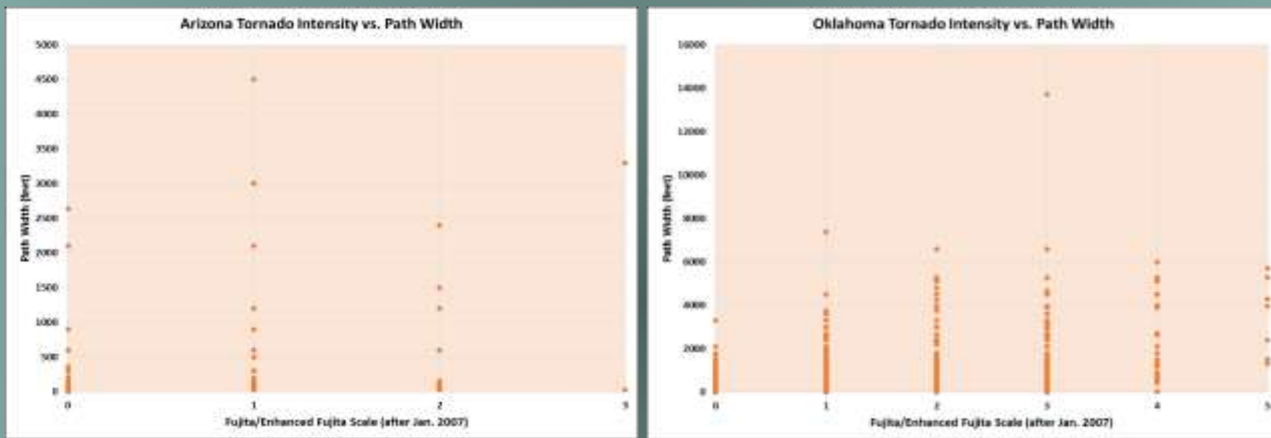


Figure 8. A comparison of the relationship between tornado intensity and path width between Arizona (left) and Oklahoma (right) for the same time period of November 1952 to October 2015. Notice the large difference in the values along the vertical axes between each graph. On the right graph, the lone dot near the top represents Oklahoma's and in fact, the U.S.'s, widest tornado in recorded history. It was rated an EF3 and reached nearly 14,000 ft. wide (2.6 miles). That was the El Reno, Oklahoma tornado on May 31, 2013.

Tornado Formation

Now that we have an understanding of the nature of tornadoes in Arizona, we are ready to learn why they are the way they are. If you read our issue about the genesis of thunderstorms, then you saw that there are three main ingredients for thunderstorms: instability, moisture, and a source of lift. One more ingredient is needed for severe thunderstorms and tornadoes. This ingredient is what meteorologists call, "wind shear". Simply, wind shear is the change in wind speed and/or direction with height in the atmosphere. Where the wind shear originates ultimately determines the type of tornado that forms.

Supercell Tornadoes

The most common and typically most dangerous tornadoes originate from "supercell" thunderstorms. What distinguishes supercell thunderstorms from ordinary thunderstorms is that they have a rotating updraft. How does a thunderstorm's updraft begin rotating? One idea is illustrated below in Figure 9. In the left image, winds several thousand feet above the ground are stronger and moving in a different direction than winds near the surface (direction denoted by the red arrows). This regional, environmental wind shear leads to a circulation along a horizontal axis (green spiral lines). If a thunderstorm develops in this environment, this circulation is then "tilted" into the vertical by the storm's updraft (blue arrow, middle image). Eventually, the updraft begins to rotate (right image).

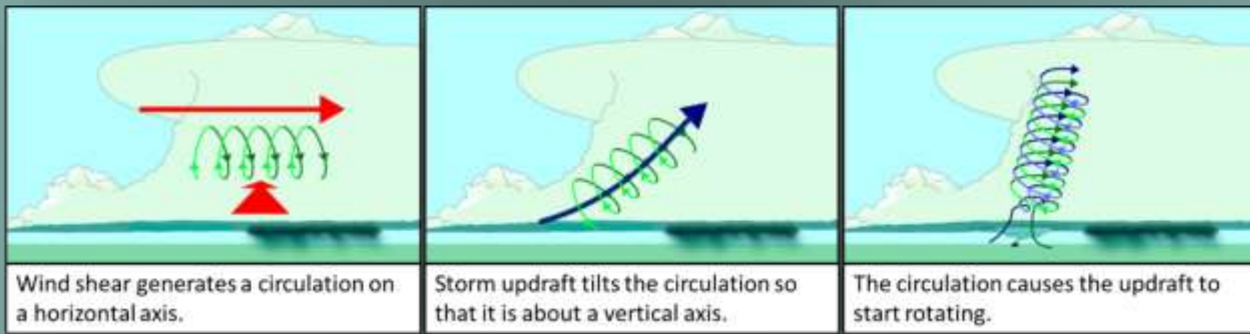


Figure 9. The development of a rotating updraft within a supercell thunderstorm.

Source: Vanessa Ezekowitz, CC BY-SA 3.0, [link to left image](#) [link to middle image](#) [link to right image](#)

When a storm's updraft obtains rotation, the system itself often takes on a very visually stunning form called a "mesocyclone" (an example is shown in Figure 10). Mesocyclones are a characteristic of supercell thunderstorms. The rotation of the system is very apparent in the clouds in Figure 9. From here, a tornado…may form. In fact, most supercells do not produce tornadoes. It is still not fully understood why some supercells produce a tornado and others do not. It is theorized that a downdraft of air on the back side of a supercell thunderstorm called the "rear-flank downdraft" (RFD) plays an important role by bringing the twisting motion of air in the updraft near to the ground (Figure 11). Additionally, air flowing from the RFD into the updraft will accelerate as it enters the updraft and thus, "stretch". This stretching action narrows the flow and increases the rotation rate of the twisting motion (think of an ice skater pulling in her arms to spin faster). If the pressure within this twisting motion gets low enough, air will condense and a funnel cloud will become visible. The funnel cloud becomes a tornado only if it reaches the ground. [Click here](#) for an animated video on supercell tornado formation and the role of the RFD.

Figure 10. A classic example of a fully developed mesocyclone in Woodward, Oklahoma. The rotation of the supercell's updraft is evident in the striations in the clouds. Supercell thunderstorms won't likely be this defined in Arizona.

Source: Lane Pearman, flickr, [link to photo](#), license: [CC BY 2.0](#)

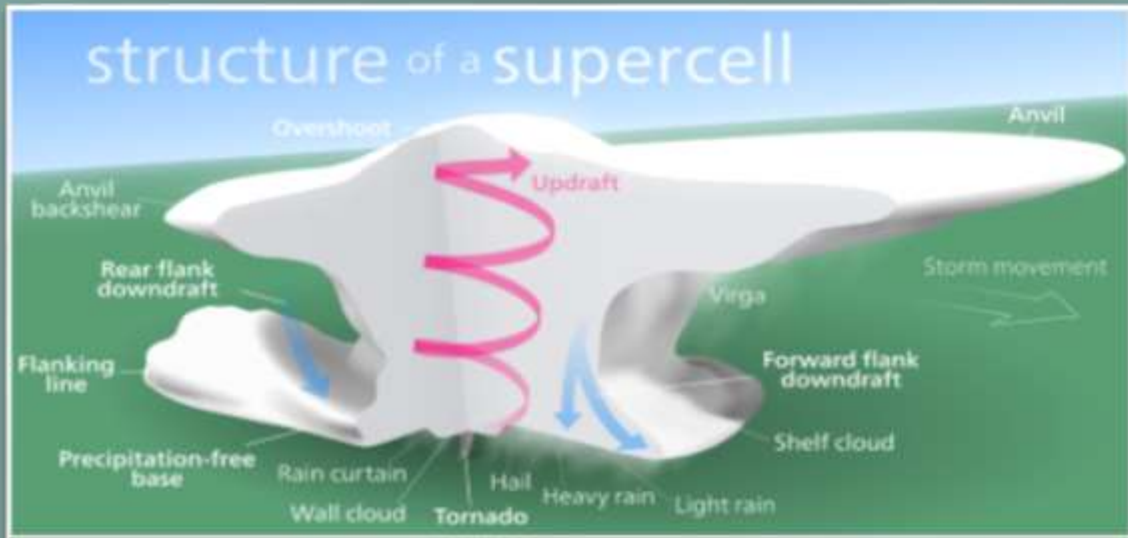


Figure 11. A diagram of the structure of a supercell thunderstorm. Notice the location of the rotating updraft, the rear-flank downdraft (RFD), and the tornado. This diagram helps to illustrate the RFD, as it might not be readily visualized well. The precipitation-free base underneath the RFD is a result of the RFD bringing down cooler and drier air. It is believed that the RFD plays a key role in the formation of supercell tornadoes.

Source: Wikipedia user, Kelvinsong, CC BY-SA 3.0

Non-Supercell Tornadoes

Tornadoes can also form apart from supercell thunderstorms. Instead of originating from a rotating storm, non-supercell tornadoes develop from the ground up. Wind shear for non-supercell tornadoes arises when surface winds converge across boundaries such as fronts, sea breezes or storm outflows. Such wind shear near the ground results in local areas of rotating air near the ground. If a thunderstorm moves overhead, its updraft may pull the surface rotation upwards and form a rotating column of air. This class of tornadoes includes whirls such as landspouts (see Figure 12) and waterspouts.

Figure 12. A landspout that formed in the afternoon near Safford, AZ on July 31, 2015. This tornado was confirmed as an EF0 tornado by the National Weather Service.

Source: KPHO/KTVK News

Tornadoes in Arizona

Now that we have explored the two types of tornadoes, which type do we typically see here in Arizona? Let's consider supercell tornadoes first. During an active monsoon pattern, a ridge of high pressure is usually spread out across the Southwest (left map, Figure 13). Ridges of high pressure are usually associated with weak winds near the ground and weak winds higher up in the atmosphere (which is why thunderstorms generally move slowly in the summer). As a result, there is not a big change between the winds near the ground and winds higher up in the atmosphere, which means weak wind shear. Since supercell thunderstorms require strong wind shear, the monsoon is not favorable for supercell tornado formation.

As previously mentioned in the Tornado Frequency section, the seasons of spring and fall are associated with an increase in low pressure troughs impacting Arizona. These systems, as opposed to ridges, are associated with stronger, upper-level winds. This opens the door for stronger wind shear. On the right map in Figure 13, a low pressure trough is situated directly over Arizona. On this particular day in October 2005, three tornados were observed in northern Arizona, two of them with path lengths of ten miles or longer. Individual storms on this day were fast-moving due to the strong, upper-level winds. Tornadic storms were of the supercell type (originating from the cloud). A case of a springtime, supercell tornado is shown in Figure 14. Overall, low pressure troughs introducing stronger winds into the upper-levels of the atmosphere are necessary for supercell tornadoes to form in Arizona.

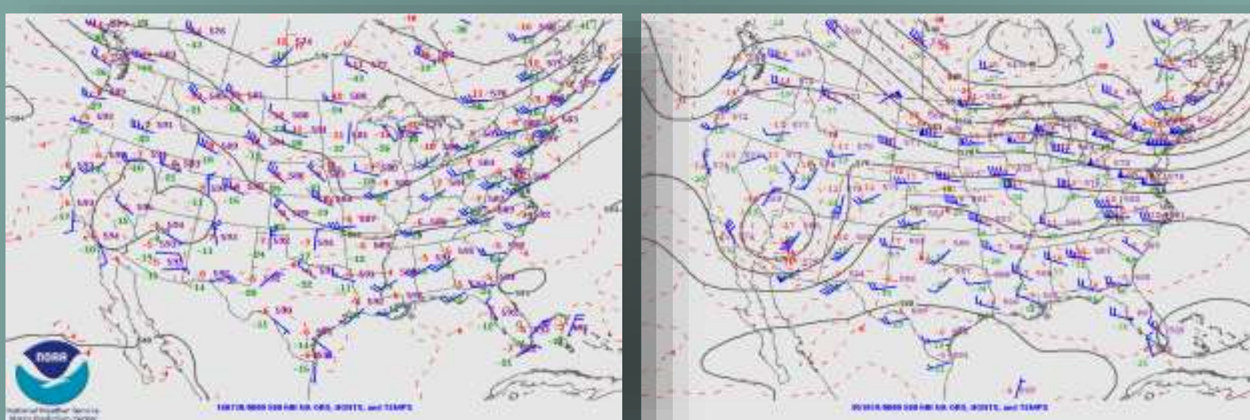


Figure 13. Left map: Map of the upper-level wind flow pattern over the U.S. on July 29, 2016. A large, monsoonal high pressure ridge is situated over the Southwest. Blue barbs represent wind speed and direction. Upper level winds over Phoenix are about ten mph and out of the east. Right map: Same as the left map, but on October 18, 2005. A low pressure trough is positioned directly over Arizona. Upper-level winds over northern Arizona are approximately 50 mph and out of the south.

Source: NOAA

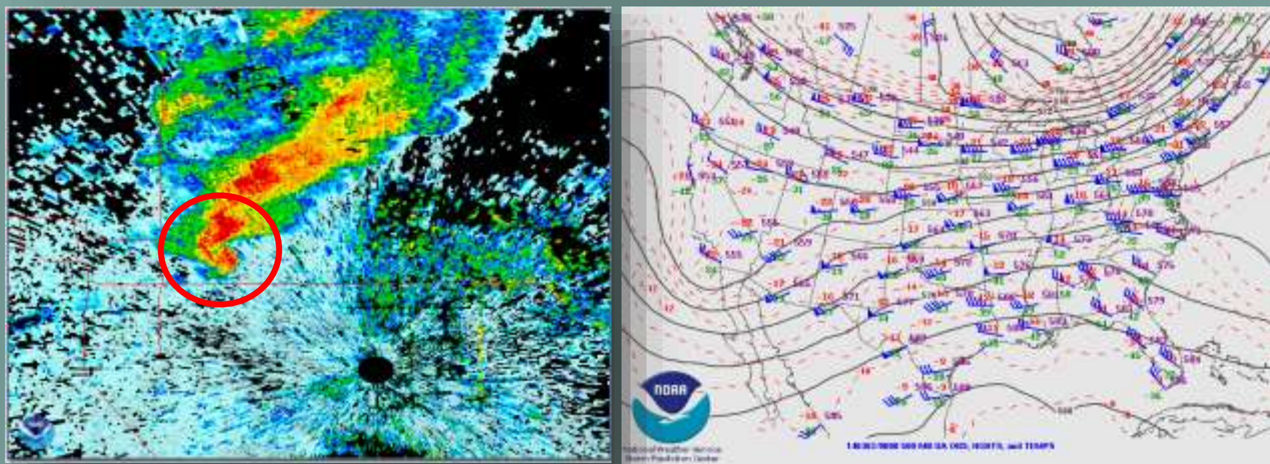


Figure 14. Left: A radar image at 12:50 PM on March 1, 2014, showing a supercell thunderstorm exhibiting a "hook echo" signature (inside red circle), which is indicative of the presence of a mesocyclone. This storm soon produced a weak tornado that resulted in damage in Mesa. This tornado was rated as an EF0. Right: Map of the upper-level wind flow pattern over the U.S. on March 1, 2014, showing the low pressure trough that provided strong winds and thus, wind shear for rotating storms and a tornado in the Valley.

Source: NOAA

Considering the relatively infrequent nature of atmospheric waves impacting Arizona throughout the year, it is likely that non-supercell tornadoes are the most common tornado type. For one, when looking at Arizona's tornado record, most tornadoes are small, relatively weak, and have short lifespans. Referring back to Figure 3, July and August are the months with the greatest number of observed tornadoes. Since supercell thunderstorms are rare in the summer, these tornadoes were probably of the non-supercell type.

The October 6, 2010 Tornado Outbreak

Between the 4th and 5th of October 2010, a large, upper-level low pressure system quickly developed and intensified over California, resulting in a strong, southerly flow over Arizona. The combination of moisture, instability, and lifting dynamics associated with the atmospheric wave resulted in thunderstorms over southern Arizona. Overnight and into the morning, these storms made their way into northern Arizona. Once the wind shear began increasing due to a small disturbance in the upper-level flow, the storms were able to develop rotation and become tornadic. Since the larger system was moving slowly, multiple tornadic storms were able to form over the same area. When all was said and done, eight tornadoes were officially recorded, four being rated as EF2 tornadoes and one being rated as an EF3 tornado. One tornado even derailed a train (Figure 15). If you are interested in learning more, the National Weather Service office in Flagstaff compiled an informative meteorological and damage summary of this event (click here).

Figure 15. The tornado with the second longest path length in Arizona's tornado record (32.02 miles) derailed a train in the Bellemont, AZ area. 28 rail cars were damaged. It was rated an EF2 tornado.

Source: CNN

Tornadoes and Air Quality

Regardless of what type of tornado forms, tornadoes are, in essence, small. In fact, in comparison to their parent or inducing thunderstorms, tornadoes are very small and extremely local. So, an individual tornado's impact on the overall air quality of an area would be miniscule. And this is not taking into account the typical, brief lifespan of tornados in Arizona. In the grand scheme of things, it's not the potential for a tornado that we would consider when forecasting for air quality, but the thunderstorm as a whole or the overall weather system.

If a tornado does have an effect on air quality, it would be pretty much limited to the tornado's exact location and path. More or less, it would have a similar effect as a dust devil, just stirring up dust and debris. The larger and stronger the tornado, the greater the stirring of dust and debris. Also, as a tornado digs into the ground along its path, it can strip the land of vegetation, increasing bare ground and thus, the potential for local dust in the future. Figure 16 shows the fresh paths created by two tornadoes near Bellemont, AZ during the October 6, 2010, outbreak event. Notice how vegetation has been uprooted from within each scar and thus, how more dirt is exposed to the air. Another potential ramification could be the creation of debris (i.e. broken tree limbs, uprooted vegetation, etc.) that must be eventually removed through methods such as prescribed burning. In this way, the tornado would have an indirect impact on air quality. One example of this includes a prescribed burn project appropriately named, "Tornado Piles", that resulted from the 2010 Arizona tornado outbreak.

Figure 16. An aerial photo taken of two tornado scars near Bellemont, AZ. These tornadoes were two of a total of eight tornadoes that occurred on October 6, 2010.

Source: NOAA National Weather Service

As we have seen, tornadoes are in fact possible in Arizona. Arizona even experiences both types of tornadoes, supercell tornadoes and non-supercell tornadoes. That being said, tornadoes are still a rather rare weather phenomenon, and when they do occur, are usually rated lower on the EF Scale. Many likely go unseen as well, due to Arizona's overall sparse population. Regardless, it's good to be aware of the possibilities, especially during the fall season.

Severe Weather Watches and Warnings

- **Severe Thunderstorm Criteria:**
  - 1) Wind of 58 mph or higher AND/OR
  - 2) Hail 1" in diameter or larger
- **Severe Thunderstorm Watch:** Issued when severe thunderstorms are possible in and near the watch area. It does not mean that they will occur. It only means they are possible.
- **Severe Thunderstorm Warning:** Issued when severe thunderstorms are occurring or imminent in the warning area.
- **Tornado Watch:** Issued when severe thunderstorms and tornadoes are possible in and near the watch area. It does not mean that they will occur. It only means they are possible.
- **Tornado Warning:** Issued when a tornado is imminent. When a tornado warning is issued, seek safe shelter immediately.

Taken directly from the National Weather Service (click here)

Thanks for reading!

Sincerely,

The ADEQ Forecast Team
ForecastTeam@azdeq.gov

If you haven't already, click **HERE** to start receiving your Daily Air Quality Forecasts (Phoenix, Yuma, Nogales)

In case you missed the previous Issues…

June 2015: Tools of the Air Quality Forecasting Trade: Capturing Dust Storms on Doppler Radar
July 2015: Ozone: An Invisible Irritant
Sept 2015: North American Monsoon
Oct 2015: The Genesis of a Thunderstorm: An Arizona Perspective
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Feb 2016: All About Fog
April 2016: Jet Streams and Fronts
May 2016: Consequences of the New Ozone Standard Change
June 2016: Tools of the Air Quality Forecasting Trade Part 2: Predicting and Tracking Wildfire Smoke
August 2016: Dust in Arizona and Around the World
September 2016: Tropical Cyclones

Here's a look at what we'll be discussing in the near future…

- Prescribed Burns
-$PM_{2.5}$ in Arizona and Around the World

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