Cracking the AQ Code

ADEQ Arizona Department of Environmental Quality

Air Quality Forecast Team

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Tropical Cyclones

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Hurricanes, Typhoons and Cyclones

What is the difference between hurricanes, typhoons, and cyclones? If you guessed nothing, then you're absolutely right because all of these terms describe the same weather phenomenon. Depending on the "basin", an oceanic region where these storms occur, one of these terms might be familiar to you (Figure 1). For example, "hurricane" is used in regards to the Atlantic and Northeast Pacific basins. If you reside in eastern Asia near the Northwest Pacific basin, "typhoon" is the term of choice. Looking at the Southwest Indian and the North Indian basins, the term "cyclone" is more appropriate. While, off the coast of Australia, "tropical cyclone" is the popular choice.

Figure 1: A map of the different basins around the world with a typical path (indicated by the arrows) of tropical cyclones. The red line across the center of the image is the equator.

Source: NWS Corpus Cristi, TX

About "Cracking the AQ Code"

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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…

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

Despite all of these different names, in the end, they portray the same powerful weather system universally known as a tropical cyclone. Although they can form at any time of the year, each basin around the world typically has a “season” for these weather systems. In the Atlantic basin, the hurricane season runs from June 1st through November 30th, with most activity occurring from August to October (Figure 2). Typhoons and cyclones also have their own season, ranging from May to November in the Northeast Pacific and June to December in the Northwest Pacific.

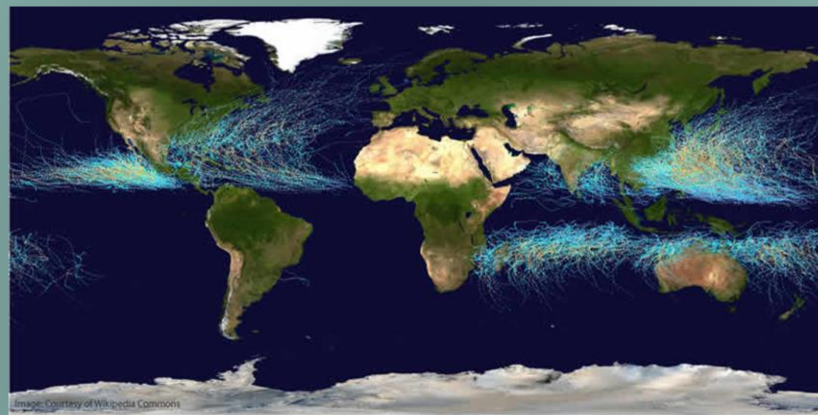


Figure 2: A map of the typical tracks of tropical cyclones around the world. Depending on the region, they can be referred to as hurricanes, typhoons, or cyclones.

Source: Wikipedia

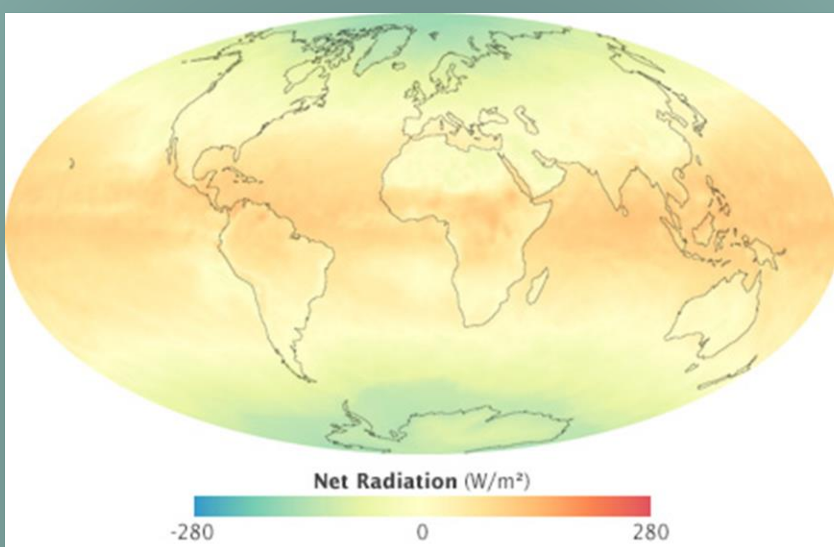


Figure 3: A map of the net radiation (energy) received from the sun at the tropics and the poles. The reds near the equator indicate a surplus of energy, while the greens at the north and south poles indicate a deficit of energy. Tropical systems will develop near the equator and attempt to transport this excess energy to the poles.

Source: NASA Earth Observatory

Tropical Cyclone Defined

Before we move forward, let’s first define what a tropical cyclone is. A tropical cyclone is a synoptic-scale (large, usually several hundred miles wide), organized weather system that develops over the warm ocean waters near the equator with deep convection and a defined circulation. Tropical cyclones undergo multiple stages/phases before reaching maturity. Once forged, they maintain and/or increase their strength by absorbing heat energy from the hot surface waters of oceans and releasing it into the atmosphere. Tropical cyclones are basically giant heat engines that use warm, moist air as fuel with one purpose: to transport heat. In general, the purpose of weather is to transport heat from one location to another. Since the tropics receive more energy from the sun than at the poles an energy imbalance occurs on the planet (Figure 3). Earth mitigates this imbalance through weather and ocean currents. Tropical cyclones are just one of the many types of weather phenomena that occur on the planet every year that carry out this purpose.

Genesis

These majestic beasts do not come to fruition overnight. Variables such as sea surface temperatures, wind shear, low-level moisture, and distance from the equator need to be ideal. Sea surface temperatures play a vital role because they provide the storm with warm, moist air as fuel. Ocean surface temperatures of at least 80°F (26.7 °C) over a depth of 150 feet (50 meters) are required for tropical cyclones. Warm ocean waters lead to increased evaporation, which results in more warm, moist air available for the tropical system to feed on. If ocean waters are cool, the storm will likely die because there isn't enough energy available to absorb. In addition, the tropical system also needs low wind shear (less than 23 mph) from the surface to the top of the troposphere (approx. 40,000 feet). Wind shear is the change in wind speed and/or direction with height. While a severe thunderstorm thrives in a high wind shear environment, a tropical cyclone needs an area with low wind shear to keep its structure intact. (Video: Wind shear effect on a hurricane) On top of that, plenty of low-level moisture is needed to keep the system going. Since moist air provides the storm with energy, a moist air mass from the surface to around 15,000 feet will favor continuous development of new thunderstorms, resulting in growth of the tropical system.

Often times, all of these variables will be present, favoring tropical cyclone formation. However, if the distance from the equator is not right, then it does not matter. Too close to the equator, the system cannot get enough spin from the Coriolis force. Too far away, and sea surface temperatures may not be ideal. Thus, a minimum distance of at least 300 miles (500 Kilometers) from the equator is needed for a tropical system to acquire spin. In the northern hemisphere, storms will rotate counterclockwise, while the opposite is true for the southern hemisphere. In order for a tropical cyclone to make its debut, it has to overcome many odds. Hence, it can be quite a thrill to witness a simple cluster of thunderstorms in the tropics morph into a raging disk of wind and rain.

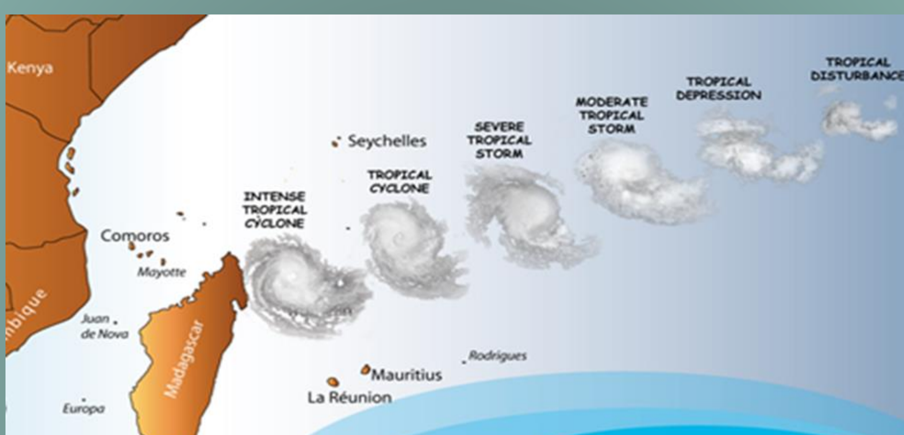


Figure 4: A diagram of a tropical cyclone formation in the southern Indian Ocean, east of southern Africa near Madagascar. The earlier stages of a tropical cyclone is unorganized. However, during the latter stages, the organization is much more defined. Since this tropical system is in the southern hemisphere, it will spin clockwise.

Source: Anne-Claire Fontan

They Grow Up so Fast...

Before a tropical cyclone can reach maturity, it begins as a low pressure disturbance near the equator. Over time, this area of low pressure leads to a cluster of unorganized thunderstorms, formally known as a tropical disturbance. When sustained wind speeds increase to above 23 mph (20 knots) and a surface pressure chart reveals at least one closed isobar (lines of constant pressure) at the center of the system, it's classified as a tropical depression. Around the center of a tropical depression, winds blow between 23 and 39 mph (20-34 knots) with a noticeable organized circulation. Furthermore, if the tropical system remains over warm ocean waters, surface pressure at the center will drop, forming additional thunderstorms. Meanwhile, the tropical depression shows more organization and becomes more circular in shape. Once sustained wind speeds within the storm increase between 40 mph and 74 mph, the tropical depression is upgraded to a tropical storm and assigned a name. The rotation of a tropical storm is much more recognizable than that of a tropical depression. Figure 4 is a snapshot of the different stages of a tropical system forming in the southern Indian Ocean east of Africa.

What Happens Now?

When a tropical storm tracks over warm ocean waters inside an environment with low wind shear, the surface pressure at the center of the circulation drops. As a result, the tropical storm strengthens and spins faster, resulting in increased rotational wind speeds. When these sustained speeds reach 74 mph (64 knots), the tropical storm is officially classified as a tropical cyclone and assigned a category (Video: Hurricane Joaquin in the Bahamas). Once again, depending the region, a tropical cyclone can be referred to as a hurricane, typhoon, or a cyclone. For storms in the Atlantic and Northeast Pacific basins, they're recognized as hurricanes.

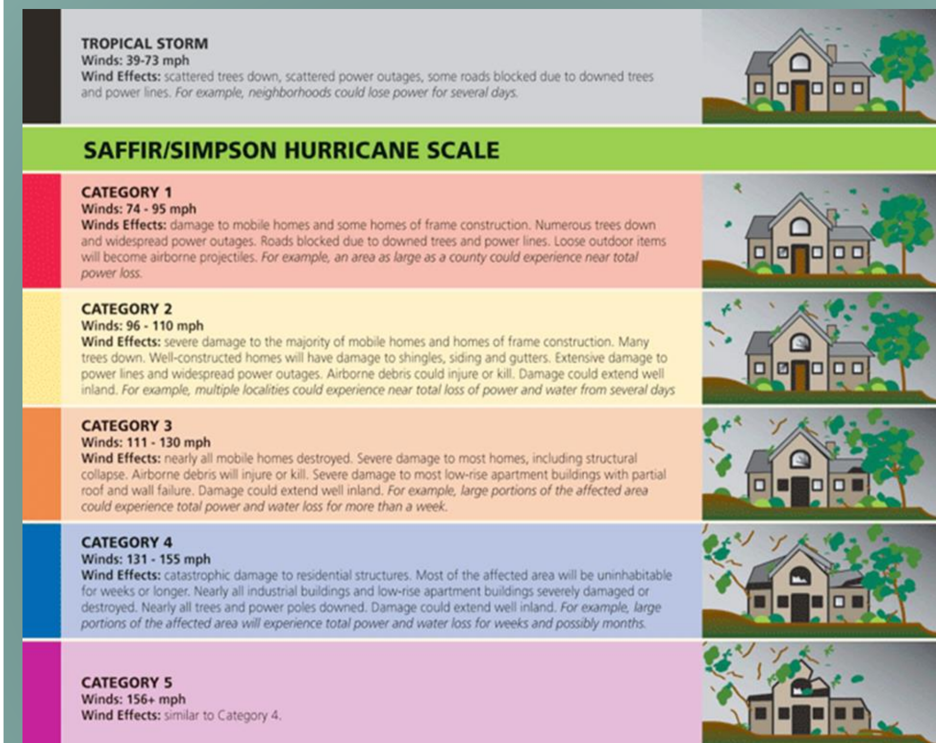


Figure 5: Saffir-Simpson Hurricane Scale. Hurricanes are assigned a category based on their sustained wind speeds.

Source: Coastal Breeze News

How Are They Classified?

A hurricane is a more intense version of a tropical storm. Based on the hurricane's sustained wind speeds, it can be classified into a category between 1 and 5 on the Saffir-Simpson scale (Figure 5). In the Atlantic and the East Pacific, the National Hurricane Center (NHC) takes the maximum 1-minute average sustained wind speeds to assign a category to a hurricane (Video: Two hurricanes in the eastern Pacific). Hurricanes reaching Category 3 or higher are considered "major hurricanes", due to their greater potential to cause significant loss of life and/or damage. Meanwhile, over in the Pacific, extreme versions of typhoons are identified as "super typhoons" (Video: Super Typhoon Haiyan). Even though a Category 1 hurricane is far weaker than a Category 5 hurricane on paper, it does not mean a Category 1 hurricane should be taken lightly or without caution. These are one of Earth's most powerful weather systems, capable of releasing extraordinary amounts of energy. Just to put it in perspective, on average, a tropical cyclone's winds alone have the potential to produce around half of the world's annual electrical generating capacity! But wait, there's more! A tropical cyclone also releases energy through the formation of clouds and rain, a process known as latent heat. On average, this comes out to around 200 times the total yearly electrical generating capacity of the world. That's a lot of power!

Breaking It All Apart

Although tropical cyclones come in many different categories and sizes, their structure is the same. (Figure 6). The three main features of a hurricane are the eye, eye wall, and rain bands. The **eye**, which is situated in the center, is a relatively calm, clear area usually 20-40 miles across with little to no rain. It has the lowest surface pressure value within the storm and can grow or shrink as the storm strengthens or weakens. Most people assume the eye to be the worst part of the storm, but that's not the case. Surrounded by a dense wall of thunderstorms, the **eye wall** contains the strongest winds and the heaviest rains, making it the most dangerous part of the storm. Located just past the eye wall are the **rain bands** that radiate outward and form the outer most fringes of the storm. They are characterized as long, arching bands of clouds and thunderstorms. Not all rain bands are the same length. Some tropical cyclones have bands that extend a few hundred miles, while others can have them stretch over 500 miles from the center.

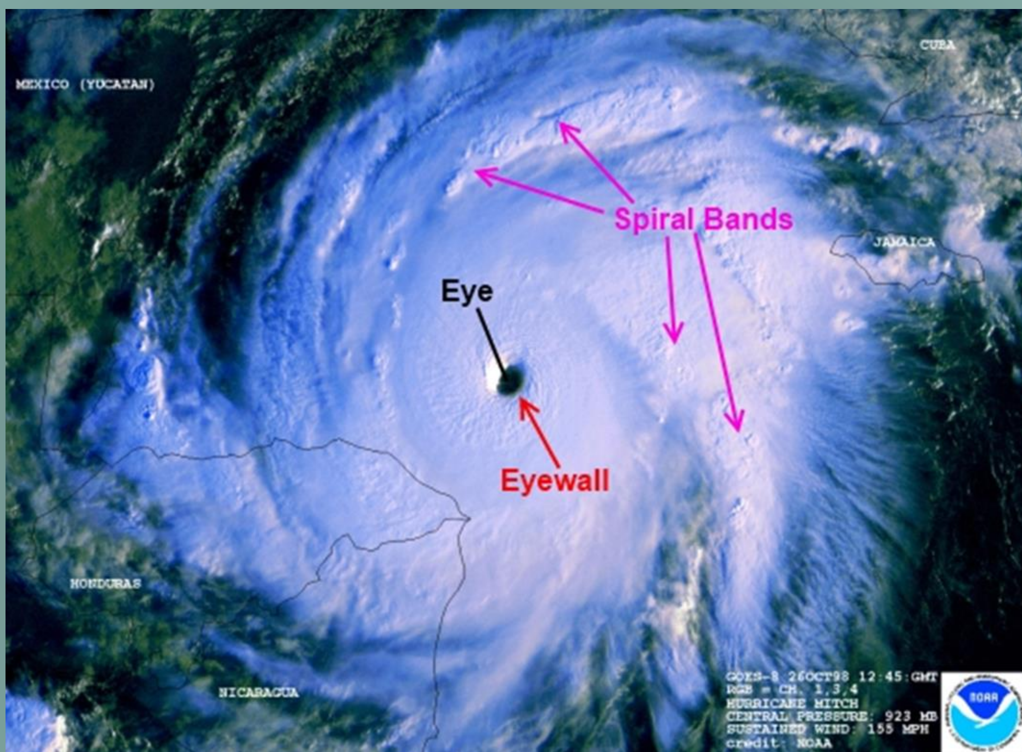
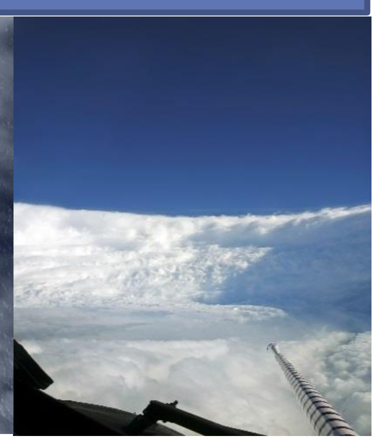


Figure 6: Hurricane Mitch (1998) captured on satellite by the National Oceanic Atmospheric Administration (NOAA) over the Atlantic Basin. This Category 5 monster of a storm reached max sustained wind speeds of 180 mph and caused around $6.2 billion in damages.

Source: NOAA

What's the best way to get information on Tropical cyclones? Fly directly into them, of course! That's exactly what Hurricane Hunters do. Learn more **HERE**



Who Names Them?

The naming convention for cyclones/hurricanes/typhoons is determined by the World Meteorological Organization. It was created to help in the quick identification of storms in warning messages since names are much easier to remember than numbers and technical terms. The names selected are those that are familiar to the people in each region and are not named after any particular person. Typhoons in the Northwest Pacific will have different types of names compared to hurricanes in the Atlantic (Figure 7). The names going down the list alphabetically each year will alternate between male and female. Each list for a basin is repeated every seven years and only edited if a name is to be retired. A name is retired if the storm becomes too deadly or costly that the future use of its name on a different storm would be inappropriate for reasons of insensitivity. For example, Katrina, associated with one of the costliest hurricanes to hit the United States in 2005, is officially retired and will never be used again.

Caribbean Sea, Gulf of Mexico and the North Atlantic Names

2016	2017	2018	2019	2020	2021
Alex	Arlene	Alberto	Andrea	Arthur	Ana
Bonnie	Bret	Beryl	Barry	Bertha	Bill
Colin	Cindy	Chris	Chantal	Cristobal	Claudette
Danielle	Don	Debby	Dorian	Dolly	Danny
Earl	Emily	Ernesto	Erin	Edouard	Erika
Fiona	Franklin	Florence	Fernand	Fay	Fred
Gaston	Gert	Gordon	Gabrielle	Gonzalo	Grace
Hermine	Harvey	Helene	Humberto	Hanna	Henri
Ian	Irma	Isaac	Imelda	Isaias	Ida
Julia	Jose	Joyce	Jerry	Josephine	Julian
Karl	Katia	Kirk	Karen	Kyle	Kate
Lisa	Lee	Leslie	Lorenzo	Laura	Larry
Matthew	Maria	Michael	Melissa	Marco	Mindy
Nicole	Nate	Nadine	Nestor	Nana	Nicholas
Otto	Ophelia	Oscar	Olga	Omar	Odette
Paula	Philippe	Patty	Pablo	Paulette	Peter
Richard	Rina	Rafael	Rebekah	Rene	Rose
Shary	Sean	Sara	Sebastien	Sally	Sam
Tobias	Tammy	Tony	Tanya	Teddy	Teresa
Virginie	Vince	Valerie	Van	Vicky	Victor
Walter	Whitney	William	Wendy	Wilfred	Wanda

The six lists are used in rotation. Thus, the 2016 list will be used again in 2022.

Figure 7: Future names for tropical storms in the Atlantic basin.

Source: World Meteorological Organization

Living on Borrowed Time

Although these behemoths may seem like an unstoppable force of nature, they're still vulnerable. For example, if the tropical system were to move over cooler waters (less than 80°F), then it would have less moist air to feed on and weaken over time. The storm can also tear apart should it traverse into a region with high wind shear. If dry air finds its way inside, the storm will choke and die. For tropical systems in the Atlantic, the Sahara Desert is a major culprit for this phenomena. Above the Sahara (5,000 – 20,000 ft.) is a layer of hot, dry air moving west towards the Atlantic Ocean, also known as the Saharan Air Layer (SAL). When a tropical system crosses paths with the SAL, it inevitably begins the end phase of its journey because dry air will suppress any new development of thunderstorms. Over the years, there have been countless tropical systems in the Atlantic that have suffered at the hands of the SAL and met with their ultimate fate.

While these factors can shorten the lifecycle of a tropical system, there is nothing more effective at tearing these violent storms apart than land. Once a tropical cyclone moves over land, its outcome is already determined. Remember, the primary source of power for these systems is moist air from the warm ocean waters. When this is cut off, the storm cannot properly feed itself and will starve to death. But, that's not to say they go down without a fight. During landfall, tropical cyclones certainly have an aptitude for displaying their raw power.

“Land Ho!”

Even though hurricanes have strong winds associated with them, they are generally slow moving structures. Depending on where they develop over the ocean, it can take several days or weeks before reaching land. It’s not really until they make landfall that we’re able to perceive their true destructive nature. Upon hitting the coastline, they can cause damage through wind, storm surge, flooding, and severe weather. Winds from a major hurricane can easily tear buildings apart and hurl around debris as lethal projectiles. Heavy rainfall near the eyewall and rain bands can lead to flash floods and landslides. Storm surges (Figure 8) can also be quite perilous considering that strong winds can act like a giant fan and produce colossal waves that can reach further inland, causing more flooding. Just to visualize, here is a video of Super Typhoon Haiyan obliterating a house in the Philippines. Flood damage should not be overlooked when it comes to these storms, because in just a few hours, tropical cyclones can easily drop several inches of rain over a large area. In addition to all the dangers mentioned above, tropical cyclones may also cause severe weather after landfall. Thunderstorms within the rain bands can produce tornadoes, leading to more destruction.

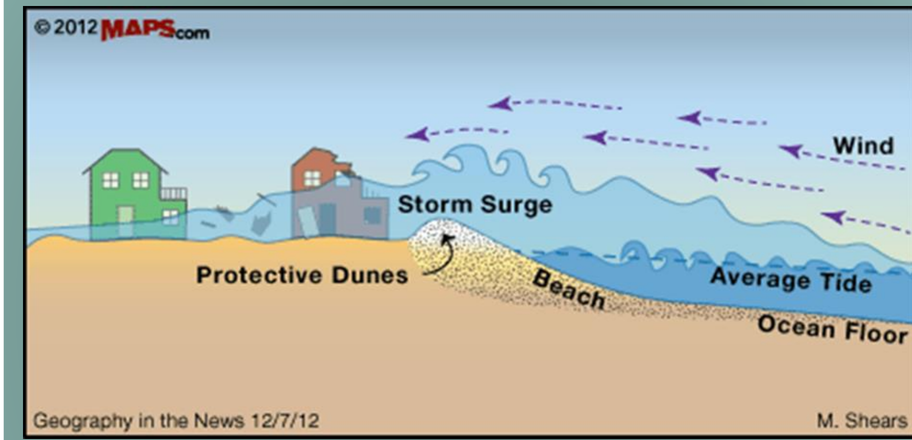


Figure 8: Storm surges are notorious for flooding. The height of the storm surge depends on the strength of the tropical cyclone and its winds. Faster winds will result in a more severe storm surge.

Source: National Geographic

Figure 9: Hurricane Katrina over the Gulf of Mexico before slamming into New Orleans. She reached Category 5 over the Gulf of Mexico and weakened to a Category 3 before landfall. (Video of Hurricane Katrina strengthening over Gulf of Mexico).

Source: NASA

In 2005, the United States saw one of its most active hurricane seasons on record, giving birth to major hurricanes including: Katrina, Rita, and Wilma, which caused extensive damage to the southern states. Even though Hurricane Katrina (Figure 9) was only a Category 3 storm when slamming into New Orleans, it produced heavy rains and strong winds that caused levees to fail and flooded the city (Figure 10). To this day, Hurricane Katrina remains the costliest hurricane to ever hit the United States with a price tag of almost two thousand lives and over $100 billion in damages.

Figure 10: The aftermath of Hurricane Katrina in New Orleans, LA.

Source: Kat Five

Rapid Intensification & El Niño

Like hurricanes in the Atlantic, hurricanes in the eastern Pacific can be just as strong, if not stronger. Last year, Hurricane Patricia (Figure 11) took home the title not only as the strongest hurricane on record in the Northeast Pacific basin, but as the most powerful hurricane on record in the Western Hemisphere. Patricia was one of the rarest types of hurricanes because she underwent rapid intensification. Rapid intensification is an increase in the maximum sustained winds of a tropical cyclone of at least 35 mph (30 knots) within a 24-hour period. Rapid intensification can be very scary because it indicates that the environmental conditions for the storm are ideal, namely very little wind shear, no dry air intrusion into the storm, and warm sea surface temperatures. On October 23, 2015, just off the coast of Mexico, Hurricane Patricia made history. Within 24-hours, she increased her sustained winds by 115 mph (100 knots), reaching a max of 200 mph with a central pressure value of 880 millibars. In comparison, Hurricane Katrina, the costliest storm in U.S. history, had a minimum central pressure of 902 millibars with peak sustained winds of 175 mph (Video: Hurricane Patricia in the East Pacific).

Figure 11: Patricia while she was just a tropical storm over the eastern Pacific Ocean, southwest of Mexico on October 21, 2015.

Source: NASA

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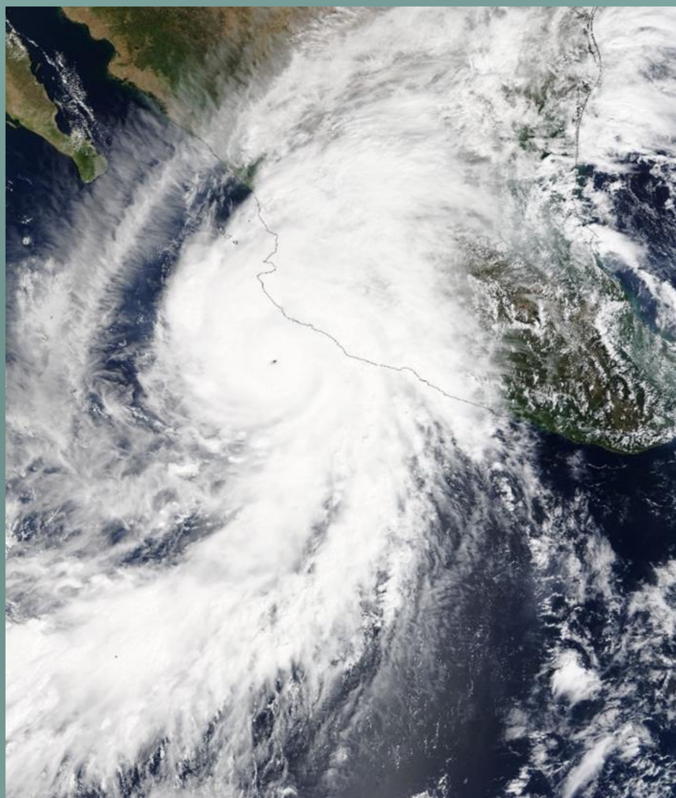

Figure 12: Hurricane Patricia after she rapidly intensified to a Category 5 hurricane in the Northeast Pacific basin on October 23, 2015.

Source: NASA's Terra Satellite

Why was Patricia so special? Well, on top of having the right conditions, 2015 was also a year of one of the strongest El Niño's on record, resulting in warmer than normal sea surface temperatures in the East Pacific. So, when Patricia tracked over the extra warm ocean waters, she had access to a tremendous amount of fuel (moist air) with nothing to stop her from raging (Figure 12). Fortunately, the increased awareness of the massive storm system, as well as, the scarce population near the area of landfall, Patricia did not result in any deaths after making landfall in western Mexico. It is typical during El Niño years for the Northeast Pacific basin to see higher than normal tropical cyclone activity because of the warmer than normal sea surface temperatures in the region.

Bring It Home

Now that you've gained some insight on the behavior of tropical cyclones, let's discuss how they can affect Arizona and the Desert Southwest. It's rare for a tropical cyclone to directly impact Arizona. But, it's not impossible. Every few years, a hurricane in the Northeast Pacific basin may venture up north towards Baja California. A fully mature hurricane impacting Arizona is unlikely, but the moisture accompanying it, can be more than enough to create some active weather in the Southwest.

On their journey towards the Baja, hurricanes are met with a lot of obstacles. When they reach the coast of Baja, they inevitably weaken due to the cooler sea surface temperatures (Figure 13) and rough terrain. Approaching Arizona, a well-developed hurricane roaring in the eastern Pacific usually becomes no more than just a tropical depression. But, even at this stage, the tropical system can still pack enough moisture for heavy rain and widespread flooding. In September of 2014, Hurricane Norbert managed to push against the odds and plowed its way into Arizona. Although just a fraction of its former self when reaching Arizona, Norbert was an energetic Category 3 hurricane in

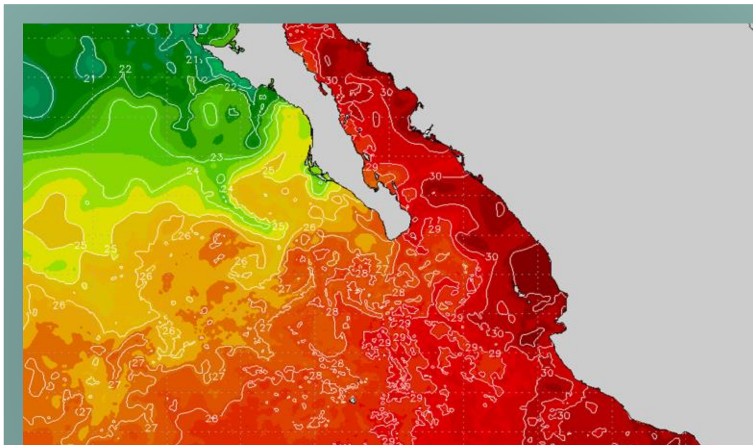

Figure 13: Sea surface temperatures near Baja California. Cooler waters (green) just west of Baja California prevent any tropical systems from developing in this region. Even though ocean waters east of Baja California are warm (red), the terrain in this region is an obstacle these storms can't overcome.

Source: Surfline

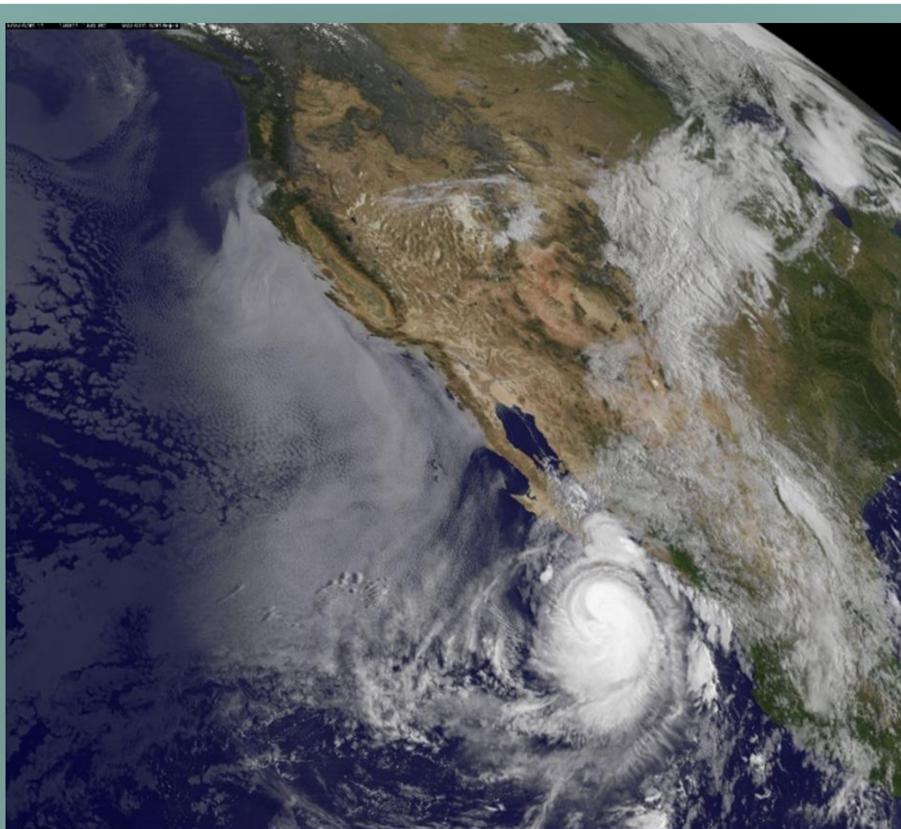

Figure 14: Hurricane Norbert in the Eastern Pacific just south of Baja near Cabo, Mexico. As the storm tracked northward, it deteriorated due to topography and cooler waters of the Pacific.

Source: NOAA

the eastern Pacific with winds around 125 mph that caused irreparable damage in Cabo, Mexico (Figure 14). After tracking over cooler waters just west of Baja California, Norbert was downgraded to a tropical storm on September 7, 2014. Through further deterioration, the system lost its deep organized convection and stood as just remnants of a tropical system. Atmospheric flow guided this leftover moisture towards Arizona, dumping rain along the way in Yuma, Tucson, and much of southern Arizona.

On the morning of September 8, 2014, remnants of Norbert finally reached the Phoenix Metro area and caused severe flooding after dropping over six inches of rain in West Chandler in just seven hours. Just a few miles west, Phoenix Sky Harbor recorded 3.30 inches of rain, breaking a 75-year old daily rainfall record. To put it into perspective, the average annual precipitation for Phoenix is around seven inches.

Figure 15: Cars flooded due to heavy rainfall from Norbert during the morning of September 8, 2014.

Source: AZ Central

Norbert wreaked havoc on the transportation system in Phoenix that morning. State Route 51, Interstate 10 & 17, and U.S. Route 60 were flooded in many areas and became completely inaccessible to morning commuters. (Figure 15). Governor Jan Brewer declared a state of emergency for Maricopa and La Paz counties due to the severe flooding. Despite Norbert being a fraction of its former self, it still managed to become a major problem for the public in Arizona. With that in mind, just imagine what kind of damage this storm would have caused if it struck Arizona during its full strength.

Air Quality

Tropical systems moving through Arizona can lead to great air quality. Just like weather, air quality is always changing. The ADEQ Forecast Team is constantly watching the weather and informing the public of air quality behavior through Air Quality Forecasts. During the passage of a tropical system, air quality will be excellent across the board. Particulates become heavily suppressed under rainfall and ground-level ozone production shuts down due to the cloud cover. However, before and/or after, the state of air quality can change for the worse. A couple of days before Norbert made its debut in Phoenix, moisture ahead of the system resulted in strong convective activity in southern and central Arizona. Outflows produced from these storms led to heavy dust activity, causing elevated PM_{10} levels in central Pinal and southern Maricopa Counties (Figure 16). Once the system moved through, soils became more stable from the rain and PM_{10} returned to normal levels.

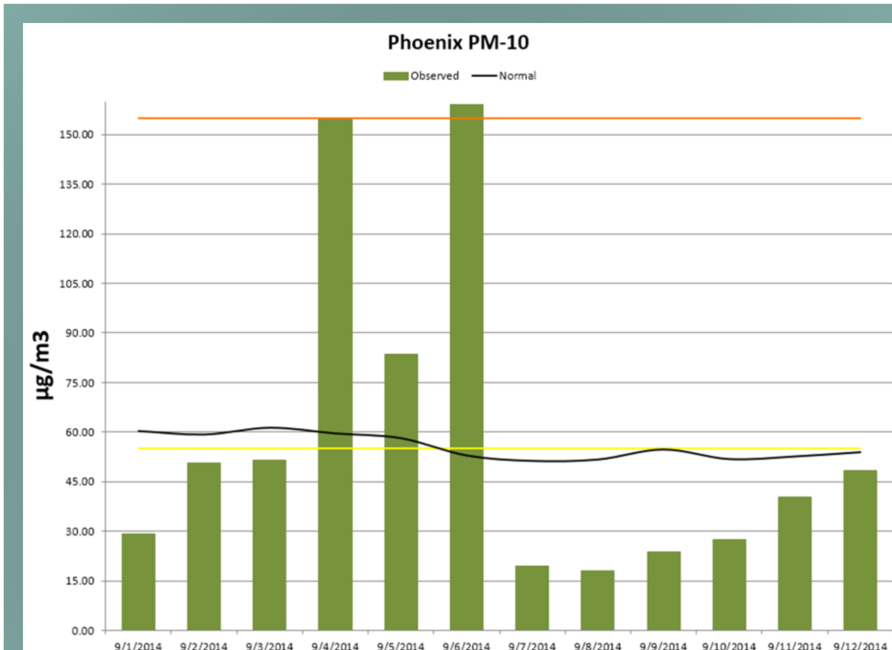

Figure 16: Observed PM_{10} concentrations across the Phoenix. The arrival of Norbert is visible from the sharp decline in PM_{10} levels.

Source: ADEQ

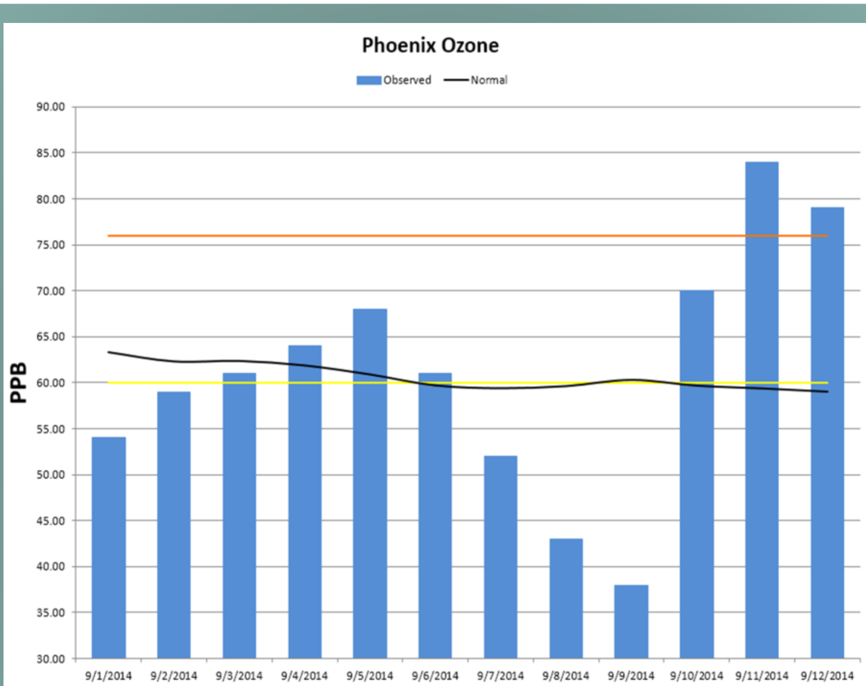

Figure 17: The sharp decline around 9/7/14 is due to the increasing cloud cover from Norbert. After Norbert's exit, sunny skies and elevated ozone levels returned to the Valley.

Source: ADEQ

Ozone also fluctuates under the influence of a tropical system (Figure 17). Through chemical reactions between Nitrogen Oxides (NO_x), Volatile Organic Compounds (VOCs) and sunlight, ozone can accumulate near the surface. In the presence of cloudy skies, this chemical process is hindered, reducing ground-level ozone formation. Furthermore, rain and wind from thunderstorms can also clear out the airshed of ozone precursors, leading to an improvement of air quality. During the time of Norbert's passage, ozone concentrations drastically decreased in the Valley. Once sunny skies returned after Norbert's exit from central Arizona, ozone showed an increasing trend, even exceeding the federal health standard a few days later.

Tropical systems moving through Arizona can certainly lead to excellent air quality. However, the heavy rainfall and flooding associated with them can be menacing. These weather systems may look calm in images, but they're one of nature's most destructive weather phenomena on the planet. Tropical cyclones start out as just a simple cluster of thunderstorms in the tropics. But, under the right conditions, they can transform to a massive heat engine, capable of mass destruction. Even though tropical systems do not cross paths with Arizona often, they can be very dangerous when they do. Whether it's a Category 5 hurricane like Patricia or just remnants of a tropical system like Norbert, these weather systems should be taken seriously.

Tips for Being Prepared

- Know your flood risk.
- Make a flood emergency plan.
- Build or restock your emergency preparedness kit, including a flashlight, batteries, cash, and first aid supplies.
- Familiarize yourself with local emergency plans. Know where to go and how to get there should you need to get to higher ground, the highest level of a building, or to evacuate.
- Stay tuned to your phone alerts, TV, or radio for weather updates, emergency instructions, or evacuation orders.

Source: http://www.ready.gov/floods

We hope you have enjoyed this latest issue of *Cracking the AQ Code* on Arizona Tornadoes!

For our next topic, the ADEQ Forecast Team will look at Prescribed Burns.

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
Dec 2015: Temperature Profiles, Inversions, and NO BURN DAYS
Jan 2016: El Niño Southern Oscillation
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

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

- Arizona Tornadoes
- Prescribed Burns
-PM$_{2.5}$ in Arizona and Around the World

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