Cracking the AQ Code

ADEQ Arizona Department of Environmental Quality

Air Quality Forecast Team

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Weather Chaos: Model Uncertainty

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There was a lot of uneasiness brewing before hurricane Irma made her infamous turn toward Florida in early September this year. Where was Irma going to go? That was the million dollar question. To answer it, meteorologists relied on hurricane track forecast models. However, you may recall that Irma was initially expected to move along Florida's eastern coast, but later was forecast to favor the Sunshine State's western coast. Why the shift? It all comes down to *uncertainty* (Figure 1).

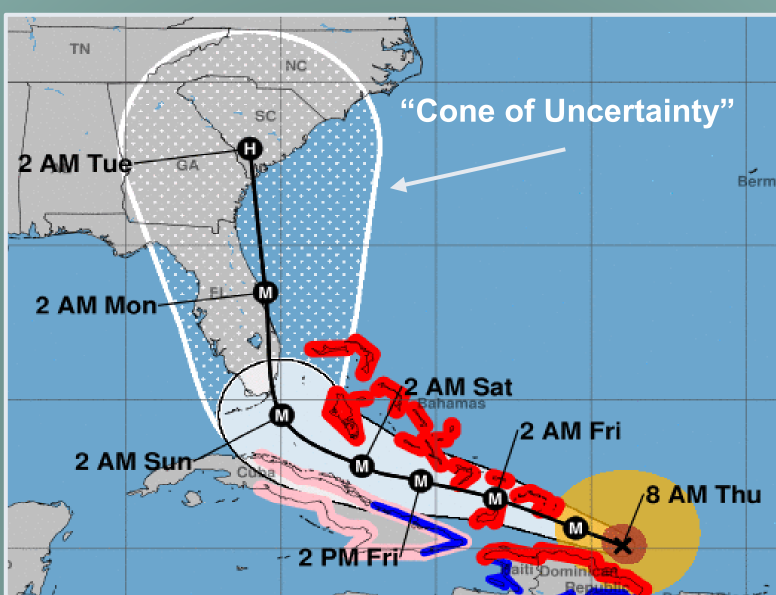

Figure 1. A 5-day forecast track for hurricane Irma issued by the National Hurricane Center Tuesday morning, September 5, 2017. The "cone of uncertainty" represents the probable path of the storm. The cone increases in size further out in time due to growing uncertainty in the storm's track.

Source: National Hurricane Center

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…

- Measuring the World above Us

In this issue of *Cracking the AQ Code*, we'll continue the conversation about weather forecast models that we began two issues ago, but now, with a focus on uncertainty. Simply put, uncertainty is inescapable, and it can affect confidence in both weather and air quality forecasts.

An Accidental Discovery

In the early 1960s, a research meteorologist by the name of Edward Lorenz happened upon a "characteristic" of nature that had gone unnoticed by scientists previously (Cox 222-223). While testing a weather model, Lorenz discovered that the model was extremely sensitive to its initial conditions (i.e. known weather observations such as temperature, pressure, etc. from which the forecast is made) (222). Before, Lorenz ran the model with initial conditions that went out to six decimal places (i.e. very exact). This time, Lorenz stopped the model halfway through its simulation, rounded the intermediate results to three decimal places (less exact), and then plugged those values back into the model (221-222).

Figure 2. One way to visualize the butterfly effect is to consider a mogul ski slope, as pictured above. Imagine yourself standing at the top of a mogul ski slope with a ball in each hand. You set both balls on the ground near each other and then push them so that they start rolling down the slope at the same time. For a time, both balls might travel down the slope with similar routes. However, further down, the balls could gradually separate and arrive at the bottom far apart from each other. In this case, a small difference in the ball's positions at the top ultimately resulted in a large difference in their positions at the bottom.

Source: Mrtrek1701 at English Wikipedia (CC-BY-SA 3.0)

When the model was finished with its simulation, it produced weather patterns that were greatly different from what it had produced before, without the rounding (Cox 222). In other words, very small differences in the weather variables that went into the model (six decimal places vs. three decimals places) led to "large differences" in its final output (222). Lorenz later called this sensitivity to initial conditions the "butterfly effect" (Figure 2), which is an essential piece of a larger aspect of nature known as "chaos" (222). Eventually, scientists in other disciplines such as physics, biology, astronomy, etc. realized the implications of chaos in their own fields as well (223).

Chaos in the Atmosphere

Meteorologists need to be aware of chaos in the atmosphere because it affects the predictability of the weather. Already at the start, any given weather model has a degree of imperfection (and therefore, uncertainty) because of the intrinsic error in its equations and initial conditions. This small difference from reality (and small uncertainty) then grows with each forecast interval further into the future. If allowed to run long enough, the model would eventually become useless as error grows too large. Ultimately, this places a limit on how far a model can accurately forecast into the future. Let's now explore some ways in which meteorologists can measure uncertainty in weather model forecasts and therefore, determine the atmosphere's predictability.

Ensemble Forecast Models

One tool meteorologists use to assess uncertainty is called an "ensemble" weather forecast model (Figure 3). An ensemble model is a set of multiple separate weather model forecasts (called "ensemble members"), where each has initial conditions that are slightly different from the original weather observations. If we return to our mogul ski slope, this would be like lining up

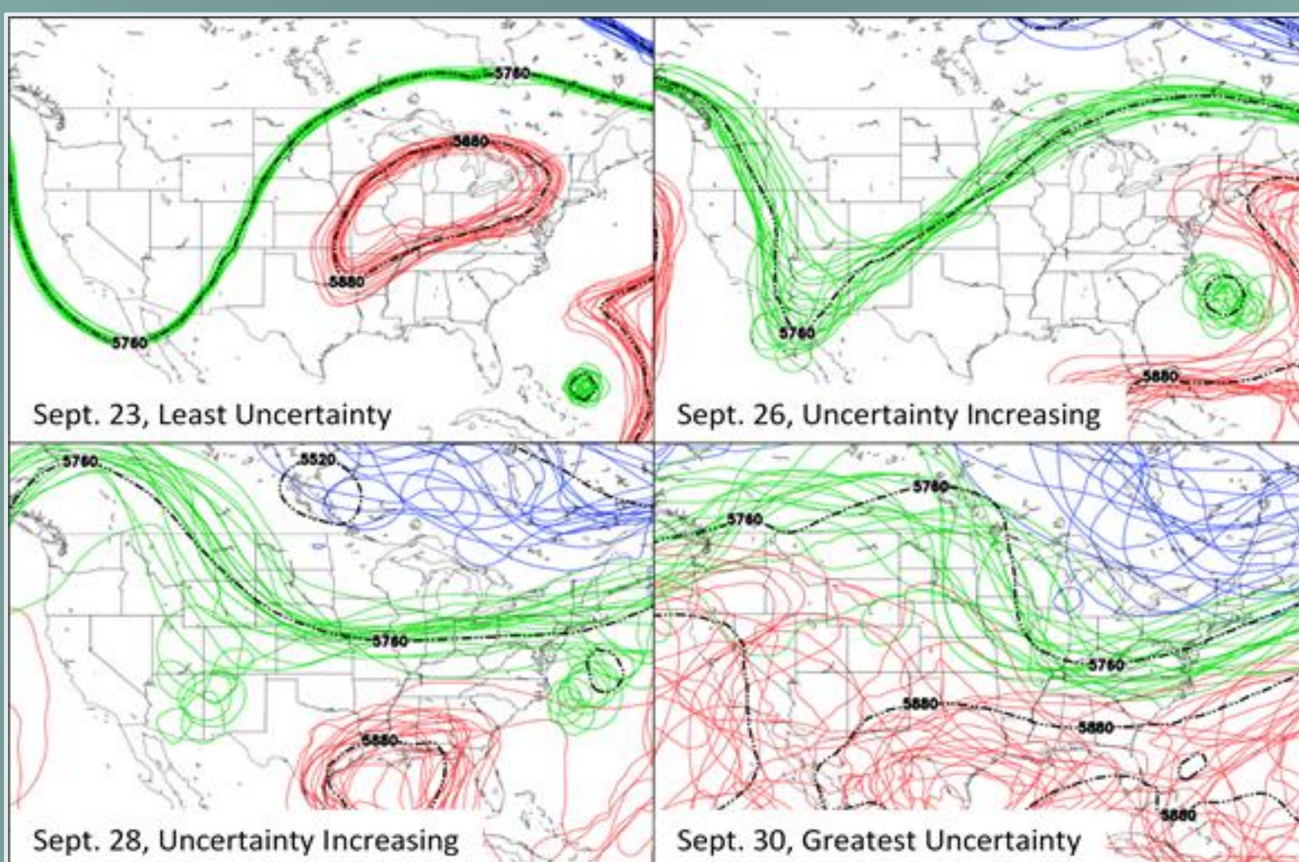

Figure 3. The progression of a weather pattern in the upper-levels of the atmosphere by an ensemble forecast model. This ensemble consists of 21 "members", or separate forecasts. This model began Friday morning (AZ), September 22. Notice how the members become more and more dissimilar with each map—this means that uncertainty in the forecast increases further into the future. Meteorologists often call these types of ensemble forecasts, "spaghetti plots."

Source: College of DuPage

several balls next to each other at the top and simultaneously pushing them down the slope. If all the balls remain close to one another as they roll down the slope, we could conclude that the path a given ball would take would be predictable. However, if the balls tend to roll in different directions, then the path of a given ball would be more uncertain.

Similarly, as an ensemble model forecasts further out in time, we can quantify uncertainty in the weather observations based on how closely aligned each ensemble member is to the others. The more spread (larger difference) there is between the ensemble members' forecasts, the more uncertainty there is ([NOAA](#)).

Comparing Models

Another way meteorologists can assess uncertainty is to compare different forecast models to one another (Figure 4). This is useful because different models have differences in their equations that represent atmospheric processes. Similar to an ensemble model, if multiple models have similar forecasts for a particular weather pattern, there is more confidence in their forecasts being closer to reality (this assumes they have reliable initial conditions). For example, in Figure 4, two separate models agree on the general placement of the greatest rainfall over the U.S. Southwest, due to a strong cold front. In the end, their consensus turned out to be pretty accurate.

However, if models don't agree very well, it may indicate that there is more

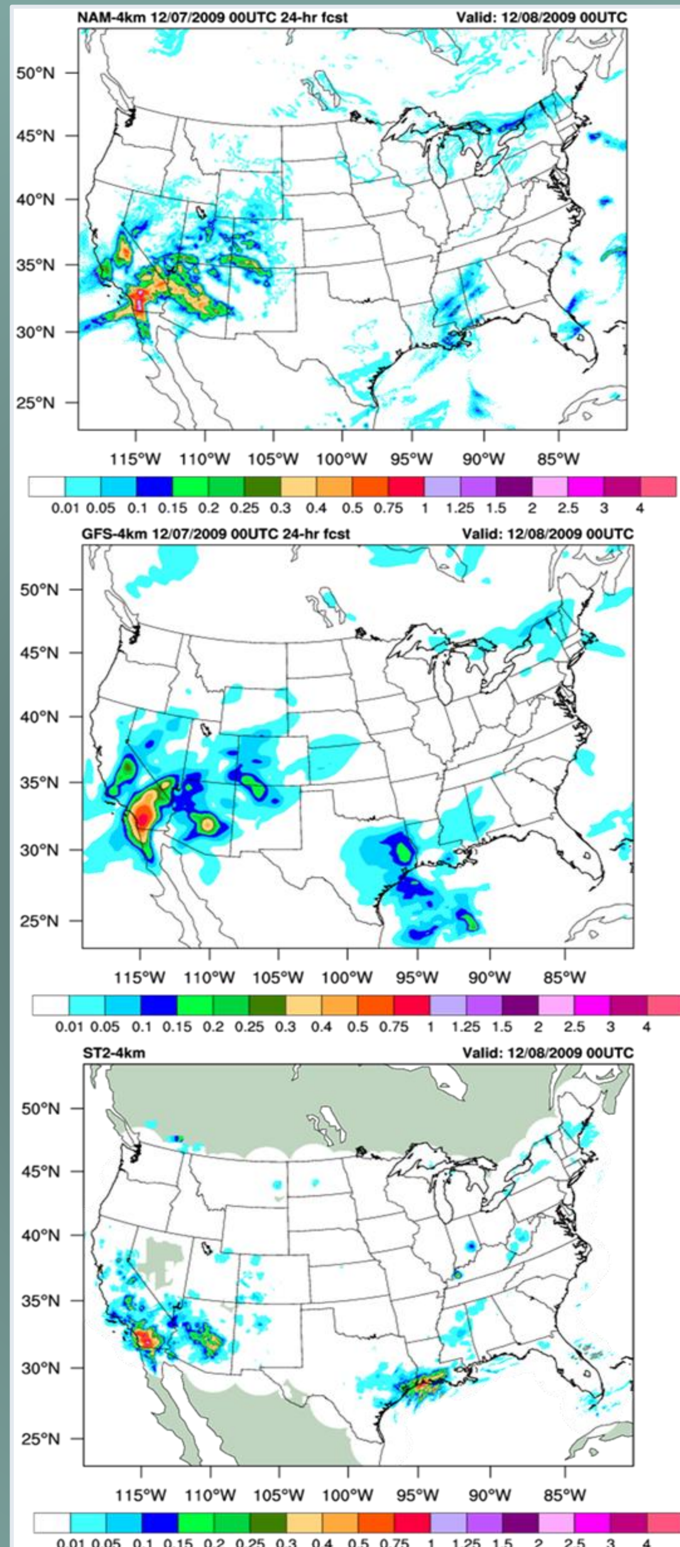

Figure 4. A comparison of two different forecast models' predictions of total rainfall throughout the U.S. over a 24-hour period in early December 2009 (top and middle) and what actually happened (bottom).

Source: UCAR [Developmental Testbed Center](#)

uncertainty in their forecasts. It is the meteorologist's job to sift through the model data and weather observations to determine which models (if any) are useful for making a forecast.

Chaos and Air Quality

Now that we have a basic understanding of where uncertainty in models comes from and how we can measure it, let's look at a couple real-life examples of how it affects the prediction of air quality.

Thunderstorms and Ozone

During the monsoon season, models can help shed light on where thunderstorms might form later in the day. However, this is not an easy task. Thunderstorms depend on a lot of atmospheric variables, and these variables are always changing and not always accurately measured. As a result, models may not handle thunderstorm movement and behavior very well.

Below in Figure 5 are two different model forecasts, produced in the morning on July 22 this year, of what the radar could have looked like at 1:00 PM that day throughout most of Arizona. It was an active monsoon day. The model on the left wanted to bring thunderstorms (reds and yellows) into central Arizona, and closer to the Valley. However, the model on the right kept thunderstorm activity limited to the eastern third of the state. This discrepancy in timing matters because each forecast leads to a completely different air quality outcome. If the forecast on the left is more accurate, thunderstorms would arrive in the Valley earlier in the afternoon. This would help to interfere with the daily ozone cycle and prevent ozone from achieving its full potential. If the forecast on the right is better, then ozone would have more time to reach higher levels. In all, the differences in the thunderstorm forecasts results in more uncertainty in the ozone forecast.

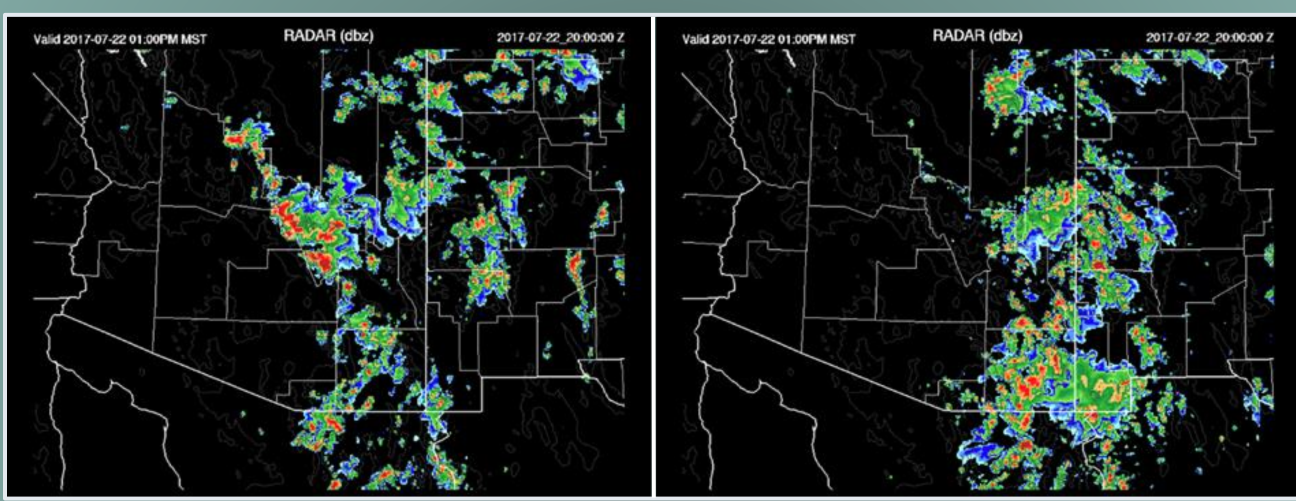

Figure 5. A comparison between two high resolution weather models predicting what the radar could have looked like at 1:00 PM on July 22, 2017. Both forecast model runs began at 5:00 AM. Notice how each model favors thunderstorm activity in different parts Arizona. The model on the left has activity reaching Maricopa County; the model on the right has a lot more activity in southeast Arizona. These differences result in uncertainty in the forecast.

Source: University of Arizona Weather Research and Forecasting Model

Wind and Ozone

Let's now zoom out a little bit and compare two larger scale model forecasts of near-ground wind over the Southwest U.S. in early October this year (Figure 6). Both forecasts are about three days into the future, valid for 11:00 AM on October 2. The main difference to key into here is the difference in the winds over Arizona and New Mexico. The model on the left predicts 15-20 mph winds in Phoenix, while the model on the right predicts, at most, 10 mph. In addition to stronger winds, the left model also predicts a greater extent of elevated winds than the one on the right.

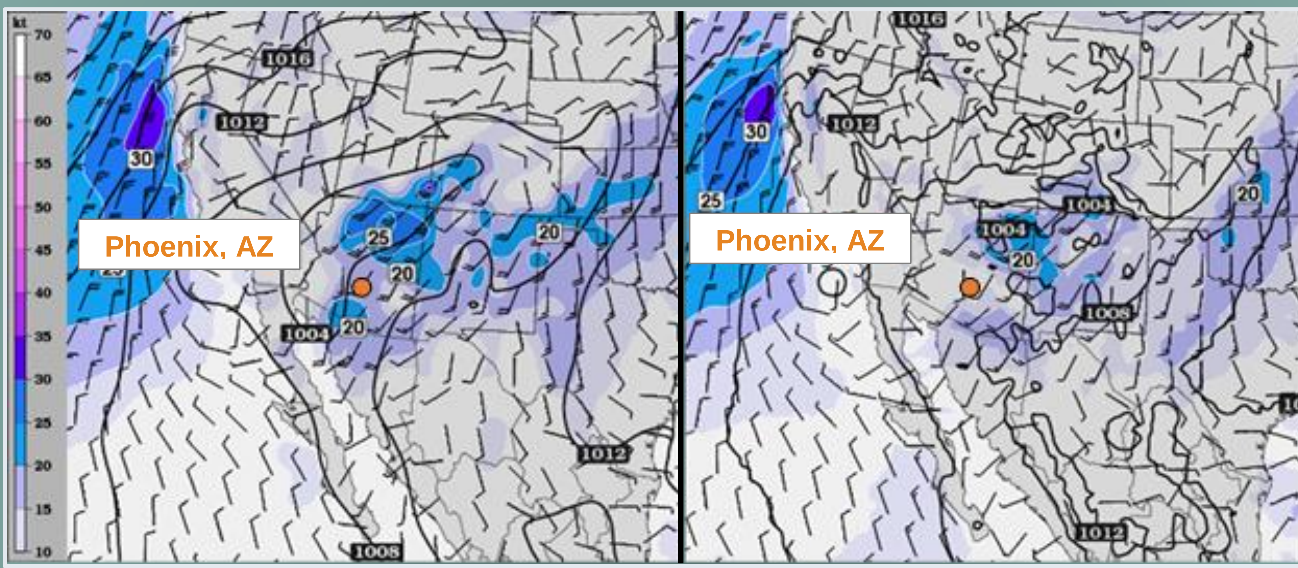

Figure 6. A comparison between the GFS (left) and NAM (right) weather models' forecasts for mean sea level pressure and wind speed/direction near the ground over the U.S. Southwest. Both models were run at 5:00 AM (AZ), Friday, September 29 and the forecasts were valid for 11:00 AM (AZ), Monday, October 2, 2017. The orange dot represents the location of Phoenix, AZ.

Source: TwisterData.com

Obviously, both models are telling a different story. If winds turn out to be breezy as the model on the left suggests, we would expect ozone levels to be lower as winds promote better dispersion. But, if winds turn out to be lighter, as in the model on the right, ozone would have a greater potential to reach higher levels during the day.

To visualize the uncertainty here, we can look at an ensemble forecast model for the wind speed in Phoenix. Figure 7 shows an ensemble forecast with 27 members (lines), each representing a different outcome of the near-ground winds for 5:00 PM October 1 through 11:00 PM October 2. The higher a member/line is on the graph, the stronger its forecast wind speed. Notice the fairly large spread in wind speeds at 11:00 AM on October 2 (the same time as Figure 6) and how the spread increases even more by 5:00 PM. This tells us that, as winds are forecast to increase in strength later in the day, the uncertainty in what will actually happen also increases.

Not an Exact Science

In an ideal world, the weather would be perfectly predictable. Weather observations would be perfectly measured, every location would be perfectly represented, and forecast models would be perfect in their representations of reality. But alas, we do not live in such a world. Instead, imperfections permeate the whole weather model process, and this gives birth to chaos. Fortunately, the meteorologists of the ADEQ Forecast Team do their best to navigate the murky waters of chaos and provide Arizona residents with the most accurate air quality forecasts possible. Perhaps we will move closer to perfection in the years to come.

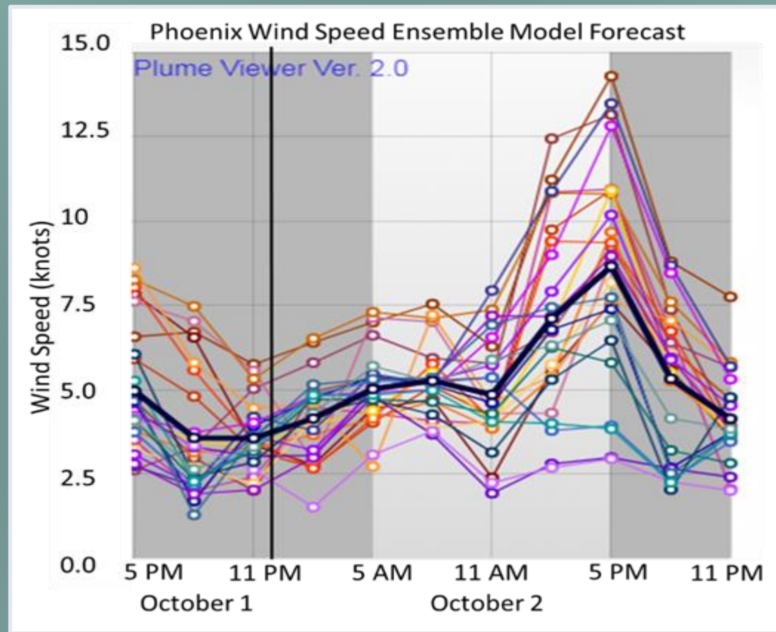

Figure 7. An ensemble model forecast of wind speed (knots) over time in Phoenix, AZ. Each colored line represents a separate model forecast. The black trend line is the average of all the 27 separate members' forecasts. The vertical black line separates the days. This particular ensemble forecast began Friday morning, September 29.

Source: NWS Storm Prediction Center

Works Cited

Cox, John D. *Storm Watchers*. Hoboken: John Wiley & Sons, Inc., 2002. Print.

We hope you enjoyed learning about chaos in the atmosphere and what that means for weather and air quality prediction here in Arizona!

Sincerely,

The ADEQ Forecast Team

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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…

May 2017: You Ask, We Answer: Part 1
June 2017: Patterns in Phoenix Air Pollution
July 2017: Tools of the Air Quality Forecasting Trade Part 4: Weather Forecast Models
September 2017: Organized Thunderstorms in Arizona
For Full Archive (2015-2017): Click Here

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

-Measuring the World above Us

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