Cracking the AQ Code

ADEQ Arizona Department of Environmental Quality

Air Quality Forecast Team

July 2016

Volume 2, Issue 5

Tools of the Air Quality Forecasting Trade

Part 2: Predicting and Tracking Wildfire Smoke

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As an air quality agency, anytime a wildfire breaks out the first questions often asked of the Arizona Department of Environmental Quality (ADEQ) are where is the fire located and will smoke head toward populated areas? The ultimate concern is whether smoke production now or in the near future will become a health hazard for the public.

Focusing on the smoke and the air quality aspect, it's not always the size of wildfires, but proximity to populated areas that becomes an important consideration. The 2014 Slide Fire that burned between Sedona and Flagstaff represents a prime example of how a relatively small fire (about 20,000 acres) can still exert a tremendous influence on air quality. Using the Slide Fire as a case study, the ADEQ Forecast Team will once again showcase another installment of a "tools of the trade" version of Cracking the AQ Code.

In this latest issue we explore available technology benefiting prediction and real time tracking of wildfire smoke, with the overarching goal of anticipating health impacts. To start things off, though, we want to touch on factors that favor an Arizona wildfire season.

Setting the Wildfire Stage…

It's a scorching hot late June afternoon in the high country of Arizona. Rainfall has been absent since spring and the trees are relishing the idea of soaking rains brought by the monsoon season only a few weeks away, if not a bit earlier. Despite the heat, there is some moisture out there. It may be just enough to kick off one or two dry thunderstorms.

By evening, a lightning strike from a thunderhead forks to the ground in an open field of prairie grass that might as well be a tinder box. With little effort, a wildfire is born. The weather over the coming days will be pivotal for dictating if this wildfire becomes one

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…

- Air Quality Around the World – PM_{10}
- Tropical Storms
- Arizona Tornadoes

of the hundreds that go undocumented or whether it turns into a full-fledged monster worthy of mainstream media. In this instance, weather did not cooperate.

Creeping through grass for days, the wildfire is suddenly pushed by gusty winds toward trees and other pockets of heavier foliage stricken by recent drought. As these heavier fuels begin to ignite, more heat is released. The heat energy creates its own winds through thermodynamics, causing even stronger winds to feed into the base of the fire. Adding to the wildfire intensity, rising convective columns force the fire to extend vertically into taller brush and crowns of trees.

It doesn't take long for burning embers to get carried by prevailing winds. Embers quickly ignite vegetation ahead of the main flame front. This is what wildland firefighters refer to as "spotting". Consequently, rapid advancement of the wildfire perimeter is realized when the rate of fuel consumed surges. In no time, the volume of smoke increases considerably as massive smoke plumes become established. Besides the fire being a direct threat to life and infrastructure, a feedback loop such as this can become quite problematic for air quality. A vivid depiction of a developing wildfire is captured in Figure 1.

Figure 1: Image showing a wildfire progressing through mixed fuel types. Extreme fire behavior is noted by the presence of "torching" of trees (red circle) and a "spot" fire ahead of the main flame front (red arrow).

Image by John Newman (USFS) and modified by Jonny Malloy (ADEQ).

As of the release date of this Cracking the AQ Code topic, Arizona is already headlong into the traditional wildfire season, with multiple fires having affected regional air quality. The calendar months of May and June have historically been the state's driest stretch for any given year. These months also overlap with the region's hottest annual temperatures. Bring some wind to the equation and now you have a recipe for a raging wildfire. Figure 2 presents the climatological perspective behind precipitation and temperature across several cities in Arizona during this period.

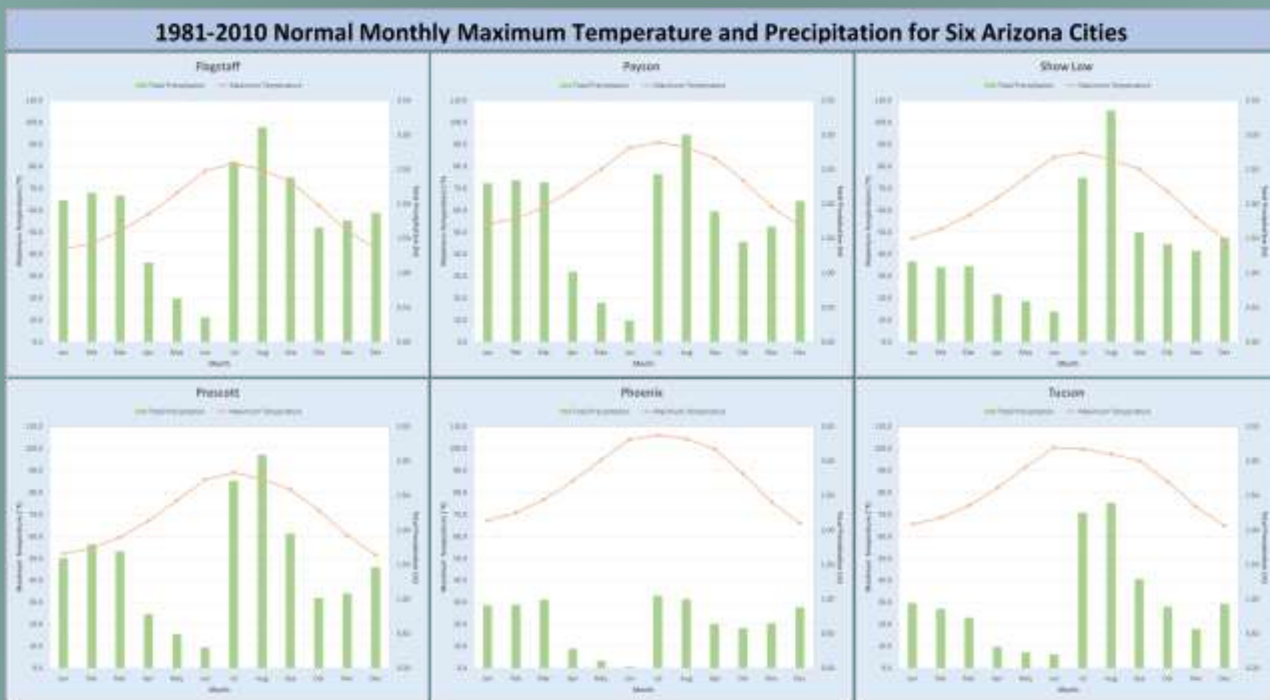


Figure 2: The National Climatic Data Center's (NCDC) 1981-2010 normal maximum temperature and precipitation for select Arizona cities. Note the hot and dry months of May and June experienced throughout the state. A clear monsoon signal showing a surge in precipitation is pronounced by July. The arrival of the monsoon usually heralds an end to a significant wildfire threat for our state. Data obtained from NCDC.

Graphic created by Michael Graves (ADEQ).

The two largest Arizona wildfires on record sprung to life during the hot, dry transition between early spring and the onset of wetter conditions brought on by the monsoon season in July. A mind-boggling amount of acres were eventually scarred between the two incidents: Rodeo-Chediski Fire in 2002 (468,638 acres) and Wallow Fire in 2011 (538,049 acres). For a better perspective, those acre tallies are equivalent to 732 and 840 square miles, respectively. Evacuations, property damage, smoke related health concerns, and blackening of forest land, all occurred. The Wallow Fire and its impressive smoke plume are shown in Figure 3.

Cool Tools for Predicting Smoke…

Smoke impacts can be tricky to anticipate for a few different reasons. First, the amount of smoke caused by a wildfire at any given time gets dictated by the types of fuel burning, quantity involved, and rate at which fire spreads. For instance, a small fire in a dense forest can generate the same amount of smoke as a much larger area burning only grassy vegetation. Types of fuels available to be consumed by a wildfire can vary greatly from year-to-year and by location. Figure 4 shows the wide diversity of landscapes found in Arizona that are susceptible to wildfire. Smoke output from wildfire incidents is complicated by 1) mixed fuel types, 2) how dry a given fuel type is, and 3) if any abrupt changes in fire behavior occur.

Figure 3: Significant smoke plumes stemming from the Wallow Fire visible on June 4, 2011, burning over much of the White Mountains region of Arizona (red outlined area). At times smoke was transported over long distances well into the Great Plains with prevailing winds.

Source: NASA Earth Observatory.

Figure 4: Pictures depicting examples of heavy timber fuels (left), desert brush fuels (middle), and fine grassy fuels in an open prairie (right) that are at risk to wildfire in Arizona.

Image source: Wikipedia.

Unlike fine grassy fuels, large trees may not be completely consumed when a wildfire progresses through an area and may instead remain smoldering. Smoldering causes smoke that can linger for days, if not longer. Such smoke needs to be taken into account for air quality since it may not have enough heat to lift on its own. The result is relatively cooler smoke flowing into low lying areas and valleys, similar to how water would flow. This type of smoke tends to "fill" low lying areas and valleys. These locations are most at risk for what are known as "drainage smoke impacts" during overnight and early morning hours. The Verde Valley experienced this during the 2014 Slide Fire (see Figure 5). Daytime heating and breezy winds were required to flush out this trapped smoke.

Once fuel conditions and fire behavior are assessed, projected smoke impacts are forecasted based on how weather conditions evolve. Key weather variables affecting smoke dispersion are **temperature**, **wind**, and **moisture** (Figure 6). The interplay between these variables, coupled with local topography, makes smoke dispersion complex.

Figure 5: Bird's eye view of early morning smoke trapped in the Verde Valley. Smoke impacts and visibility impairment are greatest for lower elevations. Smoke originated from the 2014 Slide Fire (pictured top left) and flowed down Oak Creek Canyon during the overnight hours to accumulate in and around Sedona.

Photo taken by Ted Grussing.

Hot summer temperatures provide lift for smoke; however, at the same time they can accelerate drying of fuels providing more material to burn, leading to increased wildfire smoke production. On the flipside, colder temperatures moderate fire behavior and decrease smoke output; however, cooler air would strengthen inversions to holds smoke closer to the ground.

Moisture has to be beneficial then, right? Not always. Rain obviously reduces the threat of fire if enough moisture is present for precipitation to hit the ground. However, there is a high risk of **dry lightning** right before the onset of monsoon moisture. Lightning without rain leads to more wildfire starts. Another problem with dry thunderstorms are gusty outflow winds. These winds either fan the flames of a wildfire already underway or force smoke into areas that normally would not have received smoke impacts.

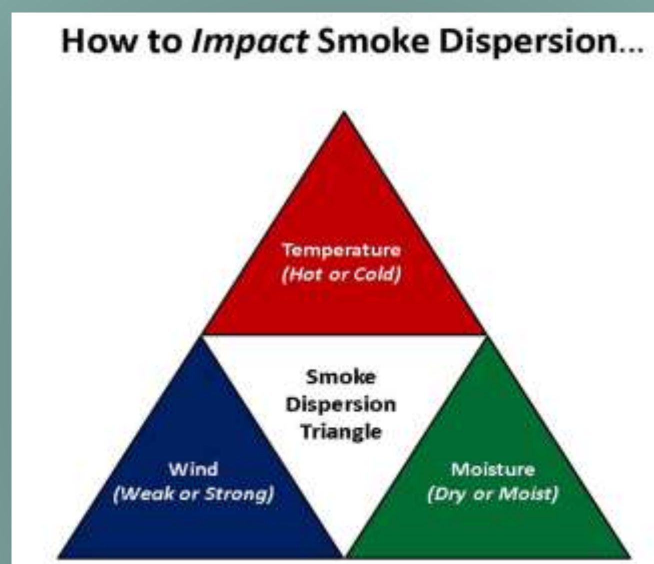


Figure 6: Graphic showing critical meteorological variables (e.g., wind, temperature, and moisture) dictating smoke dispersion.

Created by Jonny Malloy (ADEQ).

Even without thunderstorms, cloud cover itself can influence air quality indirectly. Cloud cover limits surface heating, which moderates fire behavior. This is good for reducing smoke output from a fire, but without strong daytime heating to breakup morning inversions in valleys smoke impacts can linger longer than what would be typically expected.

The BlueSky Model

The BlueSky model is an excellent tool for smoke prediction. The model was developed by the U.S. Forest Service AirFire Research Team. Forecasted values are based on both fuels and weather data (see Figure 7), representing a necessary relationship to improve accuracy for projected smoke output.

During the 2014 Slide Fire, this tool was used to gauge PM-2.5 concentrations on an hourly basis for the Verde Valley and populated areas along the Mogollon Rim. An example of a BlueSky forecasted smoke prediction for this region during the wildfire event and what actually was observed for Sedona is highlighted in Figure 8. ADEQ's portable particulate monitors showed the prediction adequately captured recorded conditions, giving us confidence for future BlueSky model applications.

Figure 7: Data types contributing to BlueSky model output.

Source: AirFire.

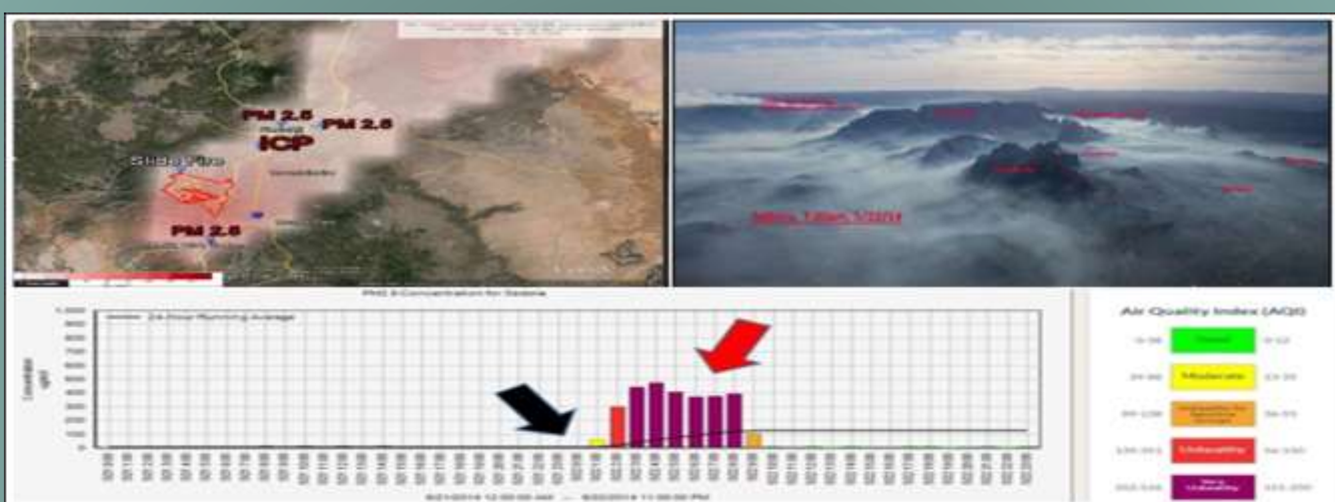


Figure 8: BlueSky modeled PM-2.5 concentrations at midnight May 22, 2014, during the 2014 Slide Fire (top left). Slide Fire perimeter (bold red outlined area), locations of three ADEQ PM-2.5 portable particulate monitors, and the fire incident command post (ICP) are noted (blue icons). Predicted low concentrations at midnight were verified near Sedona using a PM-2.5 monitor (bottom graph: black arrow). However, smoke quickly entered the Verde Valley from surrounding higher terrain by early morning the 22nd, as can be seen by the "Very Unhealthy" AQI hourly PM-2.5 values being recorded (bottom graph: red arrow). Smoke impacts that morning created widespread visibility restrictions (top right picture).

Photo by Ted Grussing.

HYSPLIT

Another available tool is the Air Resource Laboratory's Hybrid Single Particle-Lagrangian Integrated Trajectory Model (HYSPLIT). This model is great at indicating paths that smoke particles may take over time. Of particular use is its ability to forecast where a wildfire plume will go once it reaches certain altitudes. Even long-range transported smoke can eventually create air quality issues downwind of fires when smoke aloft begins to cool and settle toward the surface.

The tool gives an indication of areas which may experience smoke that are well removed from the actual fire. HYSPLIT forecast trajectories for May 30, 2014 indicated that smoke from the Slide Fire reaching heights around 3,000 feet above the ground could have been carried into central Colorado over the next 24 hours (Figure 9).

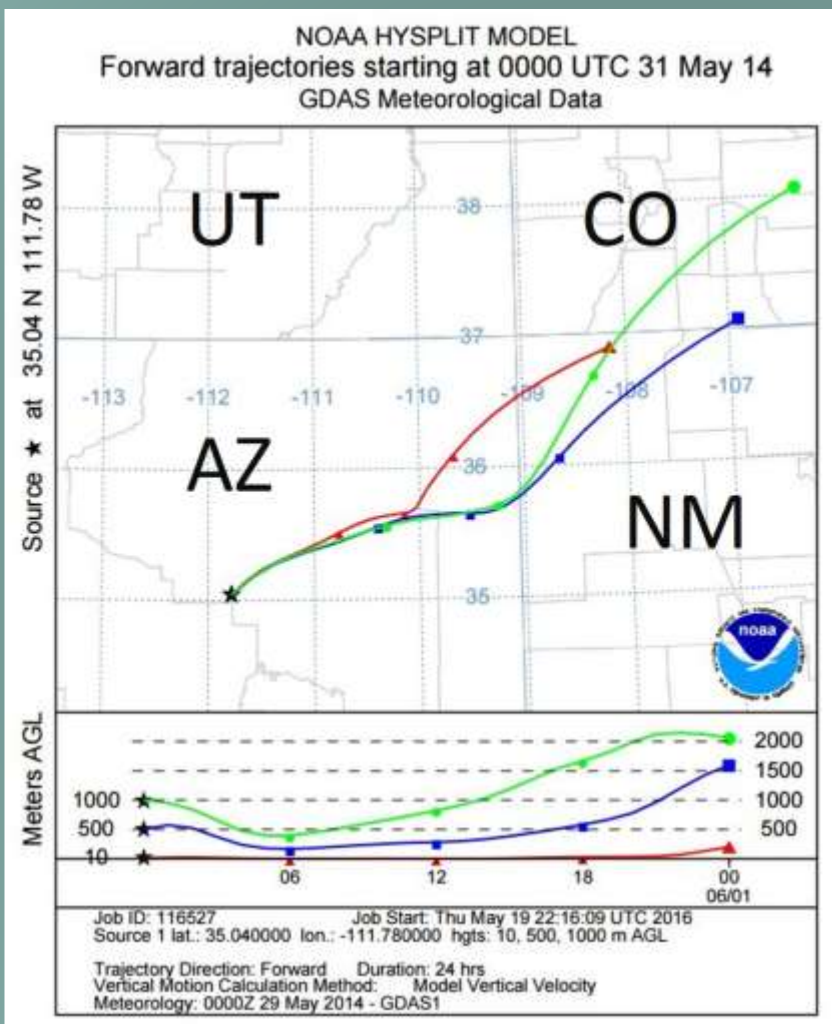


Figure 9: HYSPLIT model output for a 24-hour forward trajectory (in six hour increments) of smoke produced by the Slide Fire on May 30, 2014 at 5 PM. Trajectories were created for heights of 10 meters (30 feet), 500 meters (1,500 feet), and 1,000 meters (3,000 feet) above ground level. Note how long-range transport of smoke into Colorado and New Mexico is possible and that smoke particles at different elevations may not necessarily travel the same path with time.

Source: NOAA's Air Resources Laboratory.

What's great about HYSPLIT is both forward (predicted) and backward (observed) trajectories can be run. The purpose of a backward trajectory is to identify where the air at a particular location may have originated from. Backward trajectories help answer the question, "could air quality impacts be traced back to a wildfire or other point pollutant source?"

Tracking Smoke in Real-Time

Visible Satellite

We just went over two methods for anticipating where future smoke can go and accumulate. Another available tool is satellite surveillance. Visible satellite instrumentation provide an "eye in the sky". Its high resolution imagery can even help pick out smoke caught up in drainages and what areas that smoke is affecting (Figure 10). The most vivid indication of smoke is usually from daytime smoke plumes. They are often seen as long ribbons stretching along the landscape.

Figure 10: 2014 Slide Fire perimeter is outlined in red. Morning smoke filling lower elevations near Sedona, Cottonwood, Cornville, and Camp Verde (left) versus daytime plume movement southwest to northeast directly over Flagstaff (right). In either case, the presence of smoke has a lighter color in contrast to the darker terrain. Plumes, unlike drainage smoke, tend to be better defined and easier to discern.

Graphics provided by Ron Sherron of the USFS and Arizona Interagency Smoke Program.

The tremendous release of water vapor from an active wildfire often spawns pyrocumulus clouds, which shows as very bright regions on satellite. Refer back to Figure 2 to see how satellite captured pyrocumulus plumes from the 2011 Wallow Fire near the towns of Nutrioso and Alpine. Under the right atmospheric conditions pyrocumulus clouds may lead to actual thunderstorm development, causing rain, gusty winds, and lightning near the wildfire. A similar phenomenon regularly occurs with volcanic eruptions. Figure 11 shows an example of pyrocumulus forming as a direct result of smoke from the 2012 Sunflower Fire which burned northeast of Metro Phoenix.

Figure 11: The 2012 Sunflower Fire generating pyrocumulus clouds (bright white tops) that could be mistaken for distant thunderstorms.

Photo by Melissa Hincha-Ownby.

Doppler Radar

Our last tool we will discuss is Doppler radar. The versatility of radar extends beyond wildfire smoke applications. We first featured radar last year in Cracking the AQ Code's, "[Tools of the Air Quality Forecasting Trade: Capturing Dust Storms on Doppler Radar]." The goal was show how to locate thunderstorms, track outflow wind boundaries, and find if dust was picked up along the way. That issue can provide a quick refresher on that topic or give you a brief review of the technicalities of radar.

Similar to dust, radar can pick up smoke if it's dense enough. This is great for finding new wildfire starts or observing ones already in progress. Figure 12 depicts the nearest available Doppler radar site to observe Slide Fire's evolution.

Figure 12: Closest Doppler radar site (KFSX) available to track the daily progression of the 2014 Slide Fire smoke plume (red boxed area).

Graphics made using GR2Analyst software program and modified by Jonny Malloy (ADEQ).

Using radar during the 2014 Slide Fire was useful in explaining smoke plume behavior and tracking daytime smoke impacts. The operation of radar for wildfire smoke purposes is really restricted to diagnosing fire plumes. Recall that overnight drainage smoke would be low to the ground and is often missed by regional radars because they only scan above the horizon. Once plumes become high enough off the ground for radar to intercept, many characteristics can be known: 1) location of a wildfire, 2) confirming presence of smoke, 3) determining aerial coverage and shape of plume, 4) finding the peak altitude of a plume, 6) assessing smoke transport speed, and 6) identifying whether a wildfire is becoming more active.

Figure 13 and 14 walks through applications of three key radar modes used to track smoke: Base Reflectivity, Base Velocity, and Spectrum Width. Figure 15 then demonstrates a link between radar and air quality impacts.

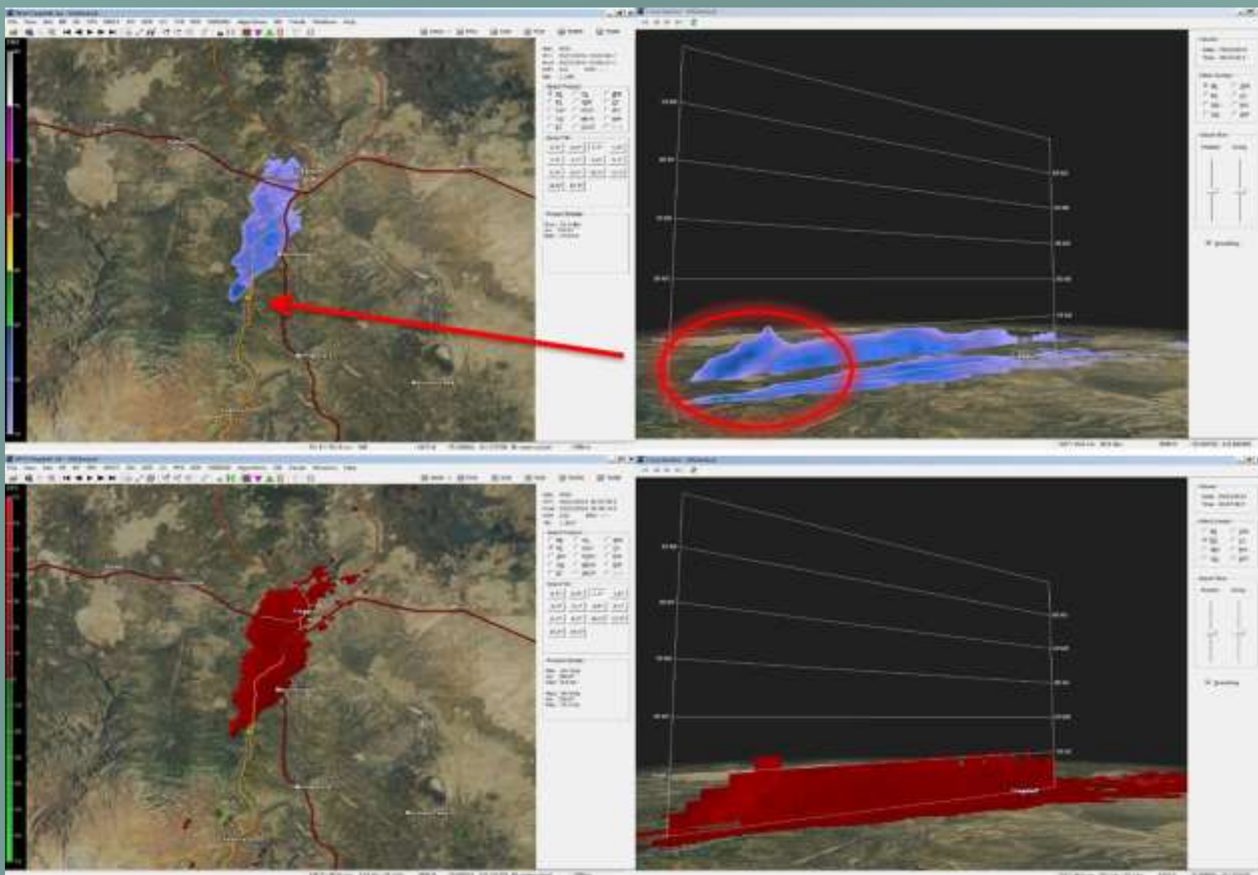


Figure 13: The 2014 Slide Fire's smoke plume as depicted by Doppler's Base Reflectivity (top panels) and Base Velocity (bottom panels) products. Heavier fuels consumed by wildfire produce denser smoke. Base Reflectivity reveals this as higher dBZ values (red arrow and red circle: top panel). In this example, note how "blues" become lighter (lower dBZs) further away from the main fire, meaning smoke is getting better dispersed. Base Velocity images taken at the same time show how fast the smoke plume is moving. Radar showed the Slide Fire smoke plume contained below 10,000 feet in altitude (bottom right panel) and moving toward Flagstaff between 20 and 40 knots (23 to 46 mph). Having transport wind speed known allows us to identify at risk communities downwind of the fire and anticipate when smoke impacts may occur. Verifying altitude of smoke plumes also means we can fine tune the HYSPLIT model to achieve similar goals.

Graphics made using GR2Analyst software program and modified by Jonny Malloy (ADEQ).

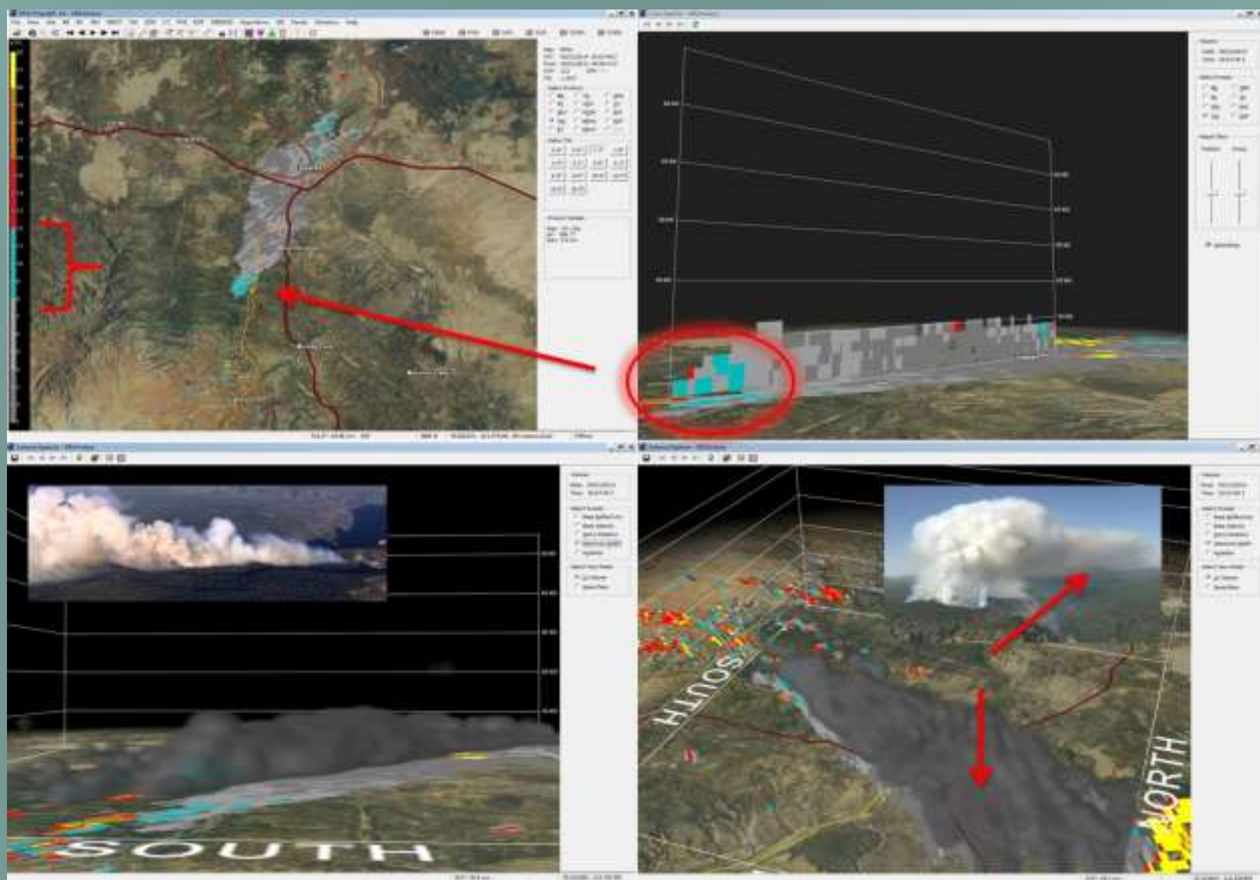


Figure 14: Doppler radar's Spectrum Width can measure the standard deviation of smoke particulate speeds in knots that are reflecting a radar beam. In other words, the greater the standard deviation, the greater the turbulence or "chaotic" motion of smoke. Turbulence increases closer to the wildfire due to fire induced updrafts. The cyan shaded area (red arrow: top left panel) is how Spectrum Width recorded the location of the 2014 Slide Fire. Higher Spectrum Width values imply increased fire behavior and more smoke output. Spectrum Width also reveals the shape of a smoke plume (bottom left and right panels), which is comparable to actual photos taken of Slide Fire's plume (see insert images). Red arrows in the bottom right panel show where Flagstaff is located relative to the fire. During this time, smoke would have been very noticeable to residents.

Graphics made using GR2Analyst software program and modified by Jonny Malloy (ADEQ).

InciWeb
Incident Information System

For the latest information on area wildfires, go to: inciweb.nwcg.gov

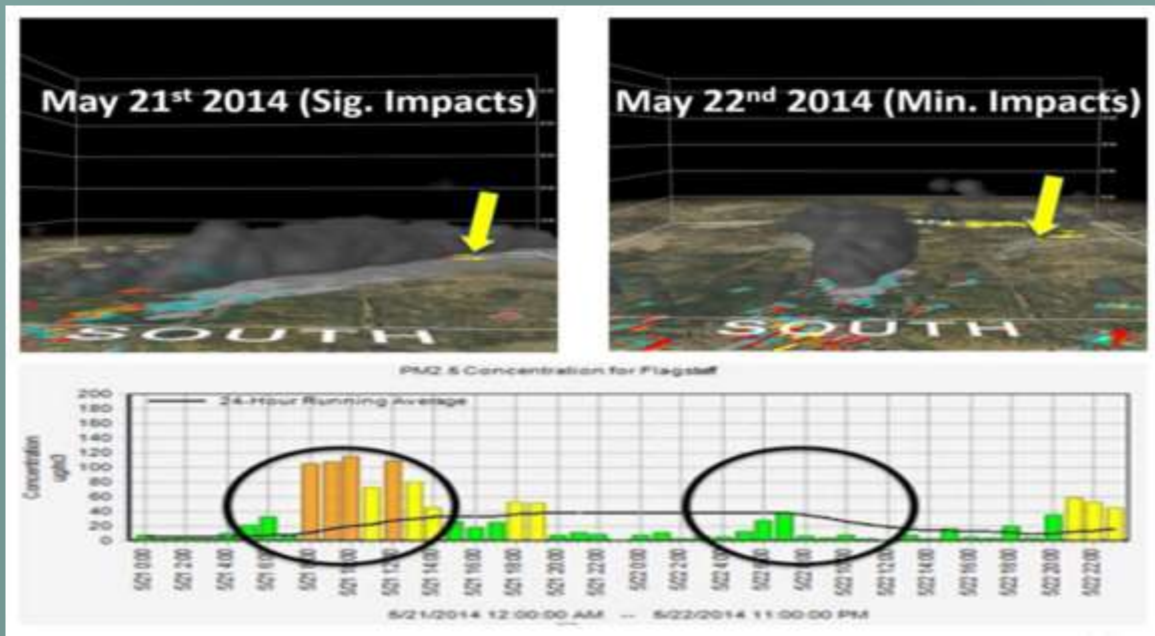


Figure 15: Unfortunately, a direct correlation between radar and actual smoke concentration is not yet well understood. Even so, determining the presence of smoke in a community is possible. During the 2014 Slide Fire, the community of Flagstaff was often hit by daytime smoke. However, wind shifts can make all the difference. Between May 21st (top left) and May 22nd (top right), prevailing winds changed from southwesterly toward Flagstaff to southerly, forcing the main smoke plume just west of the town. An ADEQ-operated portable particulate monitor in Flagstaff observed a striking difference in PM-2.5 concentrations (bottom). Essentially, air quality impacts were averted in Flagstaff on the 22nd. This kind of information, if forecasted accurately, could aid the public for planning day-to-day outdoor activities during a wildfire situation.

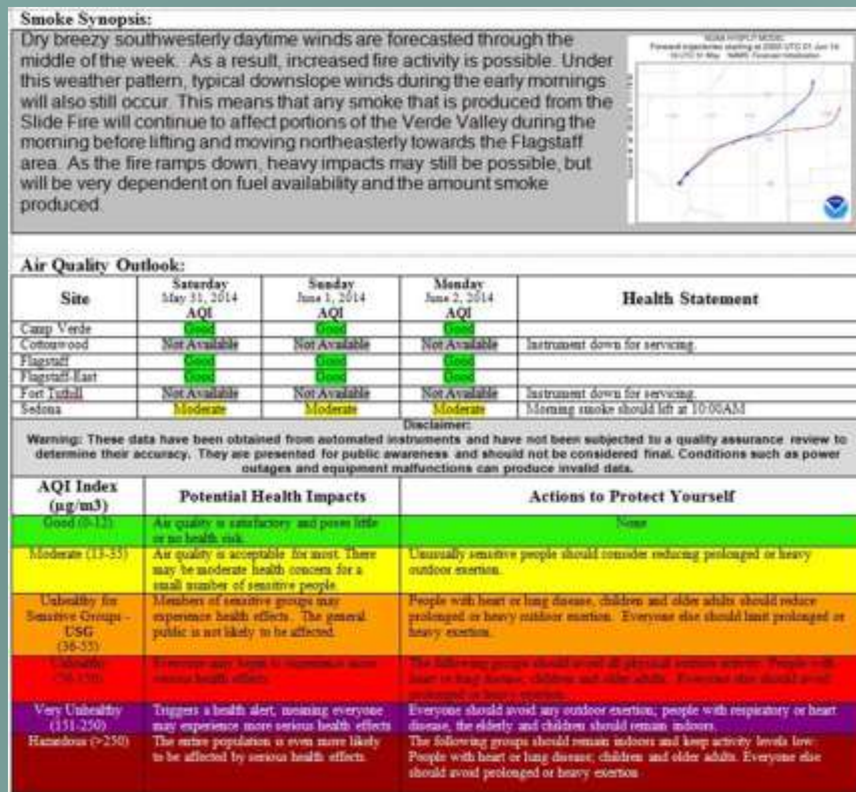
Graphics made using GR2Analyst software program and modified by Jonny Malloy (ADEQ).

Wildfire Air Quality Response - What's ADEQ's Role?

ADEQ's Air Quality Division participates in an air quality response capacity when smoke begins to affect the public adversely during a wildfire. When this occurs, ADEQ may get involved in one or all of the following activities: 1) deploy portable particulate monitors to measure smoke impacts, 2) request additional monitor support through the Arizona Interagency Smoke Program; 3) communicate directly with the public to provide pertinent health-related information pertaining to smoke and proactive measures to take for minimizing or eliminating smoke exposure; 4) be made available to health officials (county and/or local) to help draft accurate air quality messaging for public use; 5) inform those agencies engaged in fighting wildfire of developing air quality concerns, and/or 6) use all the tools we've talked mentioned in this issue of Cracking the AQ Code, assessing weather conditions to create smoke outlooks. An example of a smoke outlook that was issued during the 2014 Slide Fire is shown in Figure 16.

It's important to note that while ADEQ is aware of most wildfires and the resulting smoke, the agency **does not have jurisdiction over treatment of wildfires, nor is the agency authorized to permit wildfire duration or suppression**. Every wildfire is considered to be an emergency incident requiring the expertise, personnel, and resources available to land managers who address wildland fires directly (e.g., United States Forest Service, Arizona State Forestry, Bureau of Indian Affairs, etc.).

Wildfires are distinctly different from prescribed burn projects (also referred to as controlled burns), where the latter ADEQ does have a permitting process governed by an official Arizona Revised Statute (we plan on discussing prescribed burns in a future topic of Cracking the AQ Code).



Smoke Synopsis:

Dry breezy southwesterly daytime winds are forecasted through the middle of the week. As a result, increased fire activity is possible. Under this weather pattern, typical downslope winds during the early mornings will also still occur. This means that any smoke that is produced from the Slide Fire will continue to affect portions of the Verde Valley during the morning before lifting and moving northeasterly towards the Flagstaff area. As the fire ramps down, heavy impacts may still be possible, but will be very dependent on fuel availability and the amount smoke produced.

Air Quality Outlook:

Site	Saturday May 31, 2014 AQI	Sunday June 1, 2014 AQI	Monday June 2, 2014 AQI	Health Statement
Camp Verde	Good	Good	Good	
Cottonwood	Not Available	Not Available	Not Available	Instrument down for servicing.
Flagstaff	Good	Good	Good	
Flagstaff-East	Good	Good	Good	
Fort Tuthill	Not Available	Not Available	Not Available	Instrument down for servicing.
Sedona	Moderate	Moderate	Moderate	Morning smoke should lift at 10:00AM

Disclaimer:

Warning: These data have been obtained from automated instruments and have not been subjected to a quality assurance review to determine their accuracy. They are presented for public awareness and should not be considered final. Conditions such as power outages and equipment malfunctions can produce invalid data.

AQI Index (µg/m3)	Potential Health Impacts	Actions to Protect Yourself
Good (0-12)	Air quality is satisfactory and poses little or no health risk.	None
Moderate (13-35)	Air quality is acceptable for most. There may be moderate health concern for a small number of sensitive people.	Unusually sensitive people should consider reducing prolonged or heavy outdoor exertion.
Unhealthy for Sensitive Groups - USG (36-55)	Members of sensitive groups may experience health effects. The general public is not likely to be affected.	People with heart or lung disease, children and older adults should reduce prolonged or heavy outdoor exertion. Everyone else should limit prolonged or heavy exertion.
[illegible]	[illegible]	[illegible]
Very Unhealthy (151-250)	Triggers a health alert, meaning everyone may experience more serious health effects	Everyone should avoid any outdoor exertion; people with respiratory or heart disease, the elderly and children should remain indoors.
Hazardous (>250)	The entire population is even more likely to be affected by serious health effects.	The following groups should remain indoors and keep activity levels low: People with heart or lung disease, children and older adults. Everyone else should avoid prolonged or heavy exertion.

Figure 16: A smoke and air quality outlook issued during the 2014 Slide Fire.

Smoke outlooks were created by Ron Sherron of the USFS/Arizona Interagency Smoke Program with ADEQ meteorological staff support.

Regardless of whether smoke impacts come from wildfire or prescribed burns, measures everyone can take to protect themselves from exposure are similar.

Useful Tips for anyone being impacted by smoke…

- Reduce your physical activity.
- Check particulate levels near your location by visiting ADEQ's portable particulate monitor website.
- If you are not near a portable particulate monitor, then use to 5-3-1 visibility guidelines to assess potential smoke impacts.
- Stay indoors with doors and windows closed.
- Run the air conditioning on recirculate with a clean filter, or the fan feature on your home heating system with the heat turned off. The filtration systems on home systems can provide some benefit.
- Run room air filtration units that use HEPA filters.
- Finally, if you are experiencing symptoms with little to no relief from the suggestions above, consider temporarily locating to another area as long as it is safe for you to do so.

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

For our next topic, the ADEQ Forecast Team will look at PM-10 around the world.

Thanks for reading!

Sincerely,
Jonny Malloy
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…

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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
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