State of Delaware Final Report: Ozone Observations and Forecasts in 2021

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STi Sonoma Technology

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State of Delaware Final Report: Ozone Observations and Forecasts in 2021

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Final Report

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Executive Summary

Key Findings

- Between May and September, ozone levels in Delaware were in the Good Air Quality Index (AQI) category on 72% of days, Moderate on 26% of days, and Unhealthy for Sensitive Groups (USG) on 2% of days.
- Three USG (Code Orange) ozone days were observed during the summer 2021 ozone forecasting season. No Unhealthy (Code Red) or Very Unhealthy (Code Purple) ozone days were observed for the fifth consecutive summer.
- Long-range smoke transport from fires across the U.S. and Canada likely contributed to elevated ozone and particle levels in Delaware, especially during the month of July. As a result of the smoke transport, Sonoma Technology issued $PM_{2.5}$ forecasts (as well as ozone forecasts) from late July through mid-August.
- With COVID-19 restrictions being reduced in 2021, emissions may have rebounded to near pre-pandemic levels.
- As a result of both wildfire smoke and increased emissions, there were fewer days with Good AQI values in 2021 than in 2020.
- At the Good-to-Moderate threshold, next-day forecasts issued during the weekdays (Monday-Friday) were correct 88% of the time during summer 2021, with a probability of detection (POD) of 85% and a false alarm rate (FAR) of 37%.
- Looking ahead to the 2022 ozone season, above-normal temperatures may enhance ozone production, which may also be offset by above-normal precipitation in Delaware. However, given the current drought conditions and above-normal temperatures predicted for the western U.S. this summer, wildfire smoke may be a continued concern in Delaware for both ozone and $PM_{2.5}$ AQI levels.

1. Ozone Climatology 2016-2020

Ozone levels in the state of Delaware have improved since the mid-1990s. Despite a slightly greater number of days with Moderate or higher AQI levels in 2021 than in 2020, the overall trend toward improved air quality continued as the occurrence of Code Orange days (daily max 8-hour average ozone concentrations greater than or equal to 71 ppb and below 86 ppb) and Code Red days (daily max 8-hour average ozone concentrations greater than or equal to 86 ppb and below 106 ppb) has decreased since 2012.

To account for the recent shift in improved air quality and to assist with forecasting efforts, Sonoma Technology forecasters produced a five-year climatology of ozone levels across the state prior to the 2021 ozone forecasting season. This climatology was based on data from the seven ozone monitoring sites across the state (Figure 1) recorded between 2016 and 2020. The following climatology highlights the monthly patterns of ozone AQI levels, the day-of-week patterns in ozone AQI levels, and the frequency of multi-day high-ozone events.

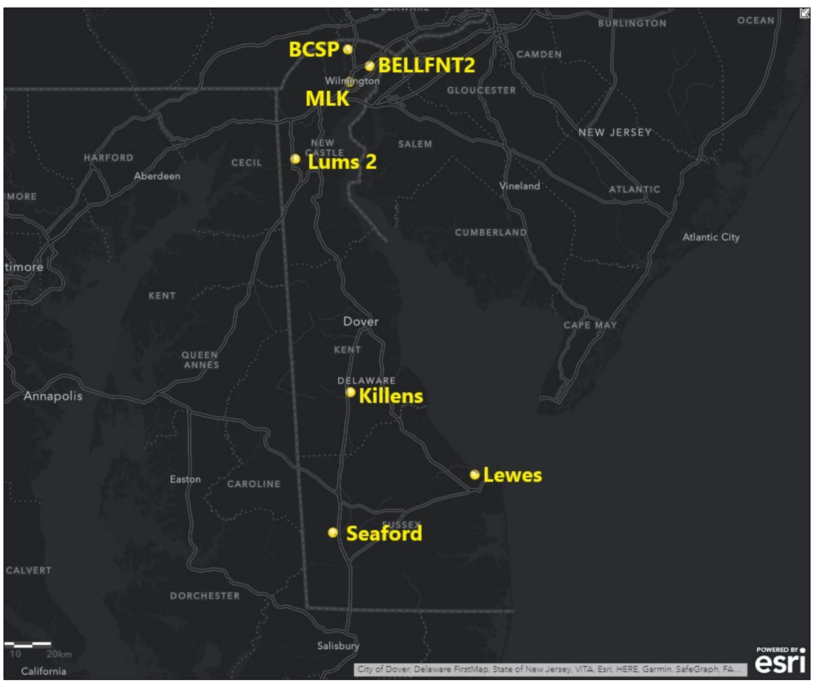

Figure 1. Active ozone monitoring sites in the State of Delaware.

1.1 Monthly Climatology of Ozone

Ground-level ozone formation is highly dependent on sunlight and surface temperatures. Each spring, increasing sunlight and warmer temperatures begin to enhance ozone formation. This relationship is reflected in Figure 2, as days with Moderate or higher AQI levels increased in frequency from March through July, based on 2016-2020 data.

According to Figure 2, days with Moderate or higher AQI values primarily occurred from April through September, while USG or higher days were observed each month from May through September. Good ozone days were the least frequent in July, when 52% of days during that month between 2016-2020 featured Moderate or higher AQI levels. Compared to the 2015-2019 climatology, the percentage of days with Moderate or higher ozone AQI values decreased slightly for most months, with June being the only month that remained nearly the same.

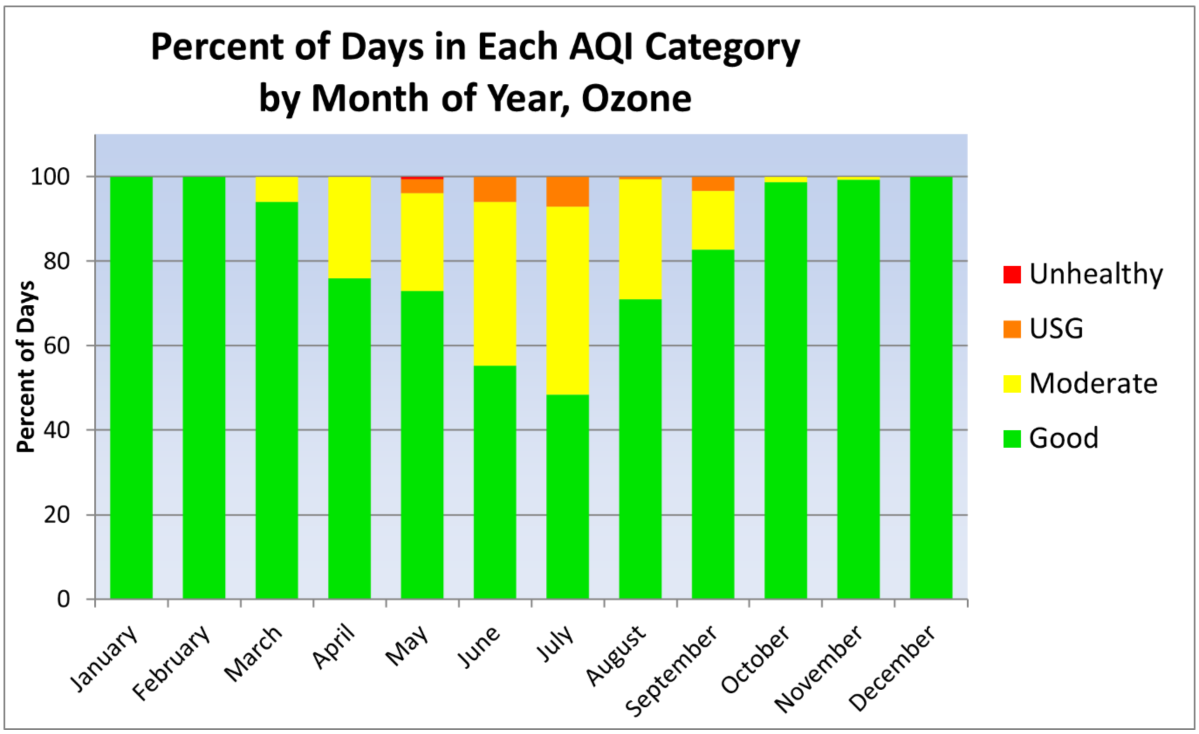

Figure 2. Monthly distribution of each AQI category based on 2016-2020 ozone data.

1.2 Daily Distribution of Moderate or Higher Ozone Days

While ozone development depends on daylight and temperature, emissions from industrial facilities and vehicular traffic can also strongly influence ozone formation on certain days. As shown in the day-of-week distribution in Figure 3, Moderate or higher AQI ozone days were most frequent on

Wednesdays and Thursdays, based on 2016-2020 data. Emissions decreased on weekend days, resulting in improved air quality. Between 2016-2020 in Delaware, Sundays featured the fewest days with Moderate or higher AQI levels for ozone. However, days with Moderate or higher AQI levels for ozone were more frequent on Saturdays than on Mondays and Tuesdays, perhaps due to regional pollutant carryover from Fridays. By comparison, the current distribution of days with Moderate or higher AQI levels is similar to the 2015-2019 climatology. However, the number of days with Moderate or higher AQI levels has decreased for each day.

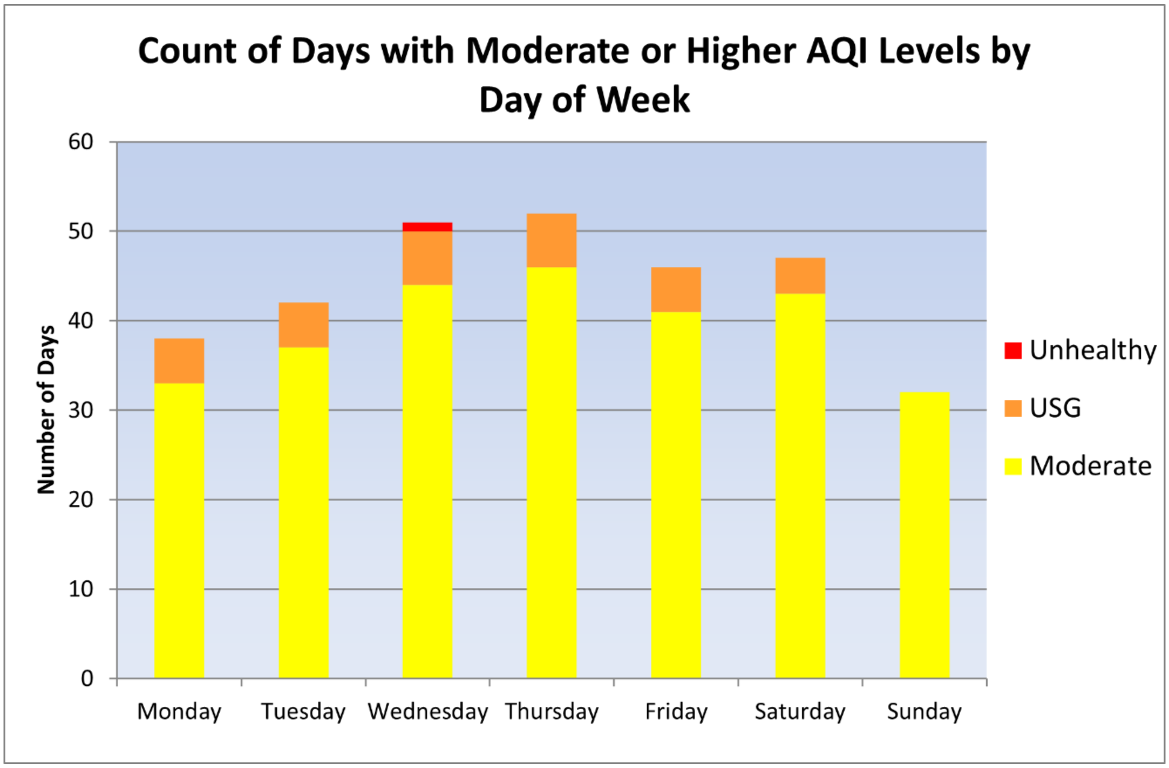

Figure 3. Number of days with Moderate or higher AQI levels by day of the week based on 2016-2020 ozone data.

1.3 Frequency of Multi-Day Ozone Exceedance Events

The region-wide reduction in nitrous oxide (NO_x) emissions since 2012 has generally improved the air quality in Delaware. This reduction has not only decreased the number of observed Code Orange or higher days, but it has also made multi-day ozone exceedances (two or more consecutive Code Orange or higher days) less frequent.

Based on 2016-2020 data, there were 32 ozone exceedances greater than 70 ppb in Delaware. The majority of these ozone exceedances were one-day events (**Figure 4**). Two-day ozone exceedance events occurred seven times, accounting for 14 days. Of the 32 ozone exceedances observed in the five-year period, there was only one event with three consecutive Code Orange or higher days. This event accounted for three of the 32 observed ozone exceedances between 2016 and 2020.

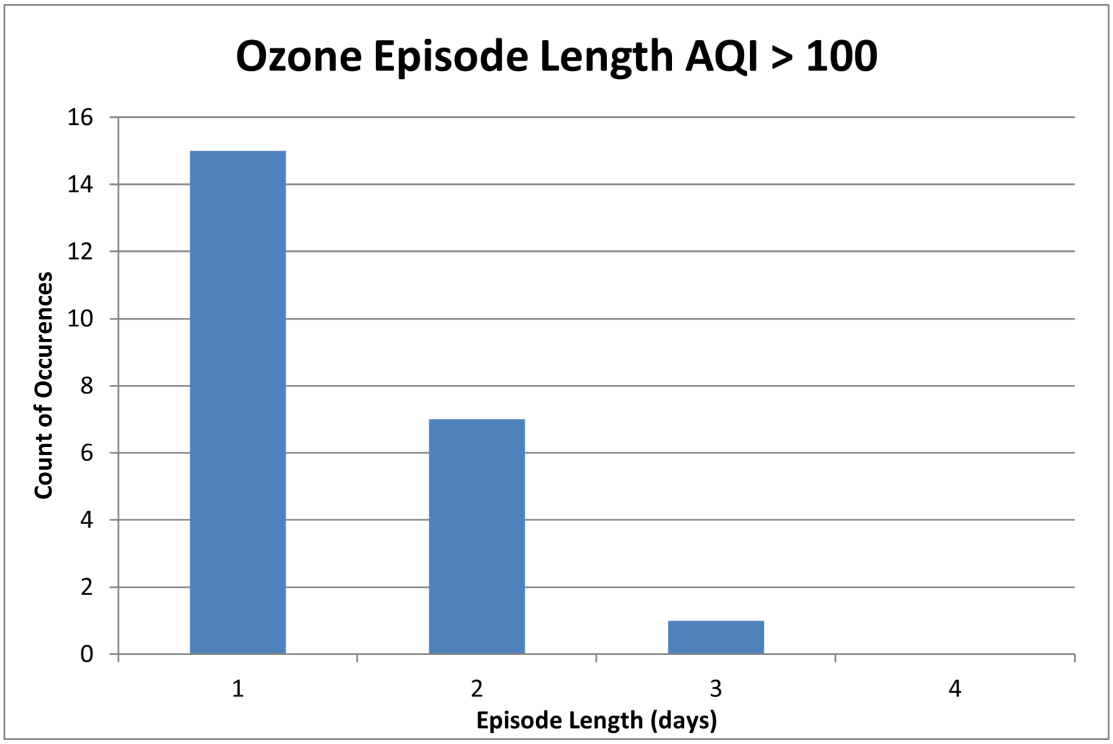

Figure 4. Frequency of long-duration Code Orange or higher AQI events, based on 2016-2020 ozone data.

2. Ozone and Meteorological Observations in 2021

The summer ozone forecasting season in Delaware lasts from May 1 to September 30. During this period in 2021, statewide daily maximum air quality levels (highest among all sites) in Delaware were in the Good AQI category on 72% of days and the Moderate AQI category on 26% of days (**Figure 5**). Three days with USG AQI values were recorded, accounting for 2% of days during the summer 2021 ozone season. Two Code Orange (USG) next-day forecasts were issued.

Figure 6 provides a daily time series of statewide observed daily maximum 8-hour average ozone AQI levels throughout the 2021 ozone forecast season, while **Table 1** shows a month-by-month breakdown of daily observed ozone values by AQI category.

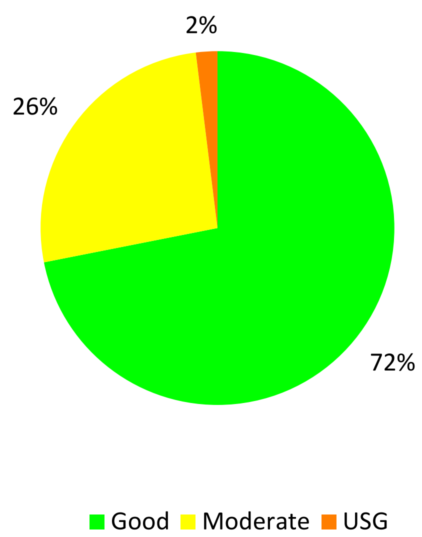

Figure 5. Delaware observed daily maximum ozone AQI values between May 1, 2021, and September 30, 2021. Courtesy: AirNow-Tech

Figure 6. Delaware daily maximum ozone AQI values between May 1, 2021, and September 30, 2021. Courtesy: AirNow-Tech

Table 1. Percent of days at each ozone AQI category by month for summer 2021.

Month	Good days	Moderate days	USG days
May	65%	32%	3%
June	77%	20%	3%
July	61%	36%	3%
August	68%	32%	0%
September	90%	10%	0%

2.1 Site-By-Site Ozone Observations for 2021

Ozone observations for Delaware are measured at seven different monitoring sites across the state (Figure 1). Four monitoring sites are in New Castle County, one monitoring site is in Kent County, and two monitoring sites are in Sussex County. Figure 7 and Table 2 show the distributions of daily maximum ozone AQI values measured at each of the seven monitoring sites during summer 2021.

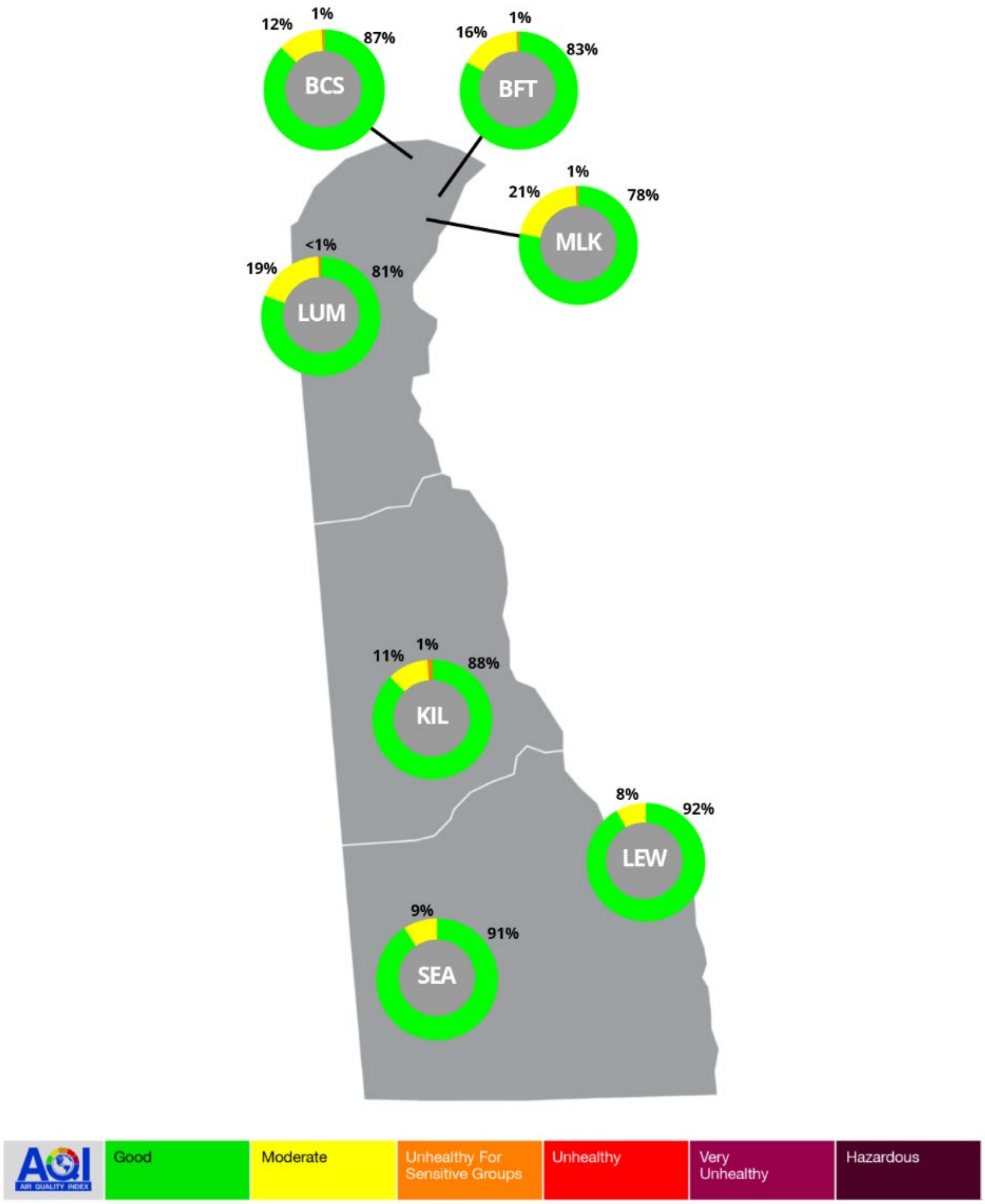

Figure 7. Delaware daily maximum ozone AQI distributions between May 1, 2021, and September 30, 2021. Courtesy: AirNow-Tech

Table 2. Percent of days at each AQI category by site for summer 2021. Station abbreviations from Figure 7 are in parentheses.

Monitoring Site	Good days	Moderate days	USG days
MLK Boulevard (MLK)	78%	21%	1%
Bellevue State Park (BFT)	83%	16%	1%
BCSP (BCS)	87%	12%	1%
Lums (LUM)	81%	19%	<1%
Killens (KIL)	88%	11%	1%
Seaford (SEA)	91%	9%	0%
Lewes (LEW)	92%	8%	0%

Days with Good AQI levels were frequent statewide throughout summer 2021. For most monitoring sites, at least 80% of days registered had Good AQI levels. The cleanest site during the summer was Lewes, where only 8% of days between May and September 2021 recorded Moderate AQI levels, and no USG days were observed. The better air quality at that site may have been due to its proximity to the ocean, as cleaner marine air impacts the area more frequently there than at other sites.

Monitoring sites near or downwind of major metropolitan areas tend to record fewer days with Good AQI levels, which is primarily due to pollutant transport from emission sources. In summer 2021, the MLK monitoring site in Wilmington recorded the fewest days with Good AQI levels when compared to other sites across the state. Between May and September 2021, 78% of days at MLK had Good AQI levels, followed by Moderate on 21% of days and USG on 1% of days. Table 3 breaks down the three Code Orange air quality days that were observed summer 2021. The following section provides a meteorological summary of the summer's three Code Orange air quality days.

Table 3. Observed ozone exceedance days in 2021. Forecast error row indicates the difference between the next-day forecast concentrations and the observed ozone concentrations.

Date	May 19	June 5	July 28
Daily max 8-hr average O_3 concentrations (ppb)	71	74	71
Forecast error (ppb)	-5	-11	-6
Location of ozone exceedance	Lums	MLK Boulevard	Killens
Max temperature at KILG (°F)	89	91	89
Daily average wind speed at KILG (mph)	5.4	7.0	6.0
Daily average wind direction at KILG	North	Southwest	South-Southeast

2.2 Summary of Code Orange Ozone Days in Summer 2021

2.2.1 May 19, 2021

The season's first Code Orange day was recorded at the Lums monitoring site, and was the earliest first occurrence of a Code Orange day in over three years. On this day, an upper-level ridge of high pressure west of Delaware (Figure 8) inhibited vertical mixing in the lower levels of the atmosphere, which aided ground-level ozone formation across the mid-Atlantic region.

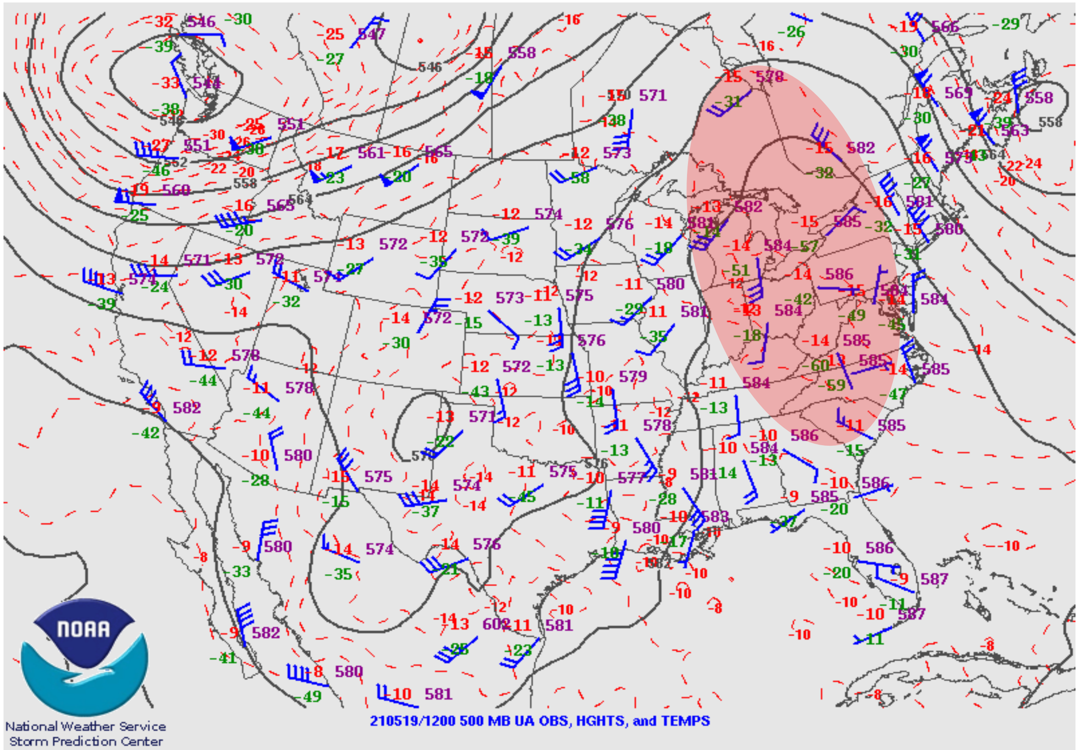

Figure 8. 500 mb map, valid 8 a.m. on May 19. Upper-level high pressure (red shading) limited atmospheric mixing in Delaware, aiding ozone formation. Courtesy: National Weather Service – Storm Prediction Center

At the surface, winds were northwesterly over much of New Castle County, which kept ozone levels below Code Orange around the Wilmington area. However, near the Lums monitoring site, lower-level winds became westerly in the late afternoon and evening (Figure 9). This wind pattern allowed pollutants from the Washington D.C. and Baltimore areas to be transported into far northeastern Maryland and far western New Castle County. Due to the transport of regional pollutants, ozone levels at the Lums site were higher than those at other monitors in the state.

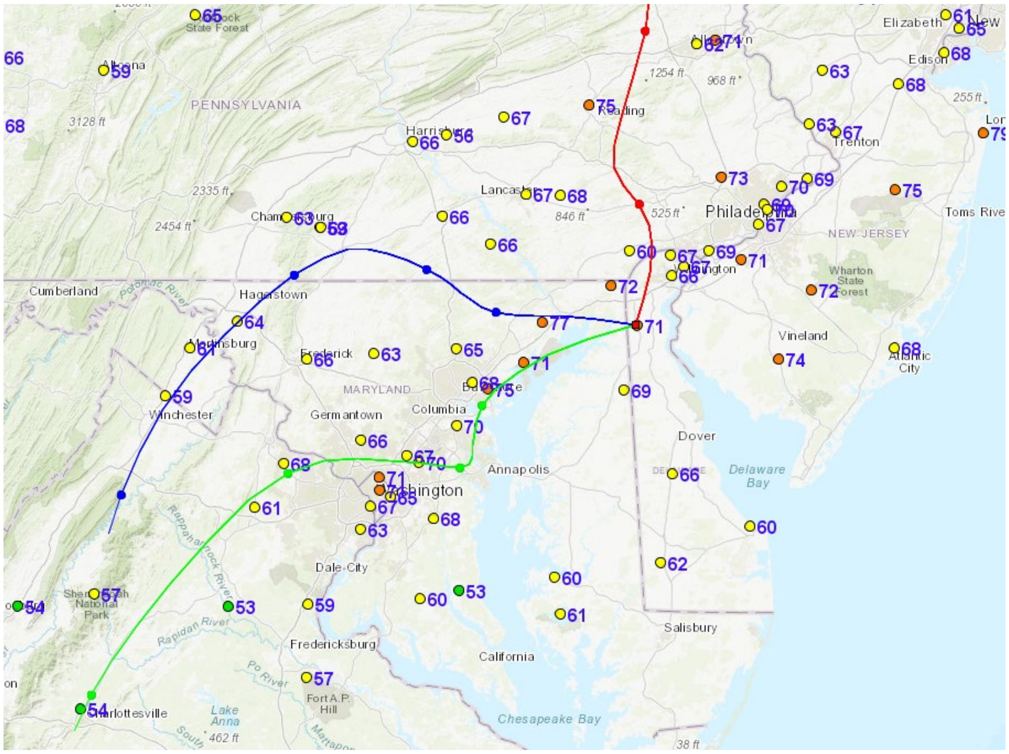

Figure 9. Observed 8-hr daily maximum ozone concentrations (dots) and 24-hour back trajectories, ending at 12 a.m. on May 20, 2021, at 250 m (green), 500 m (blue), and 1,000 m (red). The green and blue lines indicate transport of pollutants at low levels from the Baltimore and Washington D.C. areas into the Lums monitoring site. Courtesy: AirNow-Tech

In addition to the upper-level pattern and low-level winds, ozone production was aided by abundant sunshine and temperatures around 90°F. Temperatures on this day were well above average for mid-May 2021, as indicated by Figure 10.

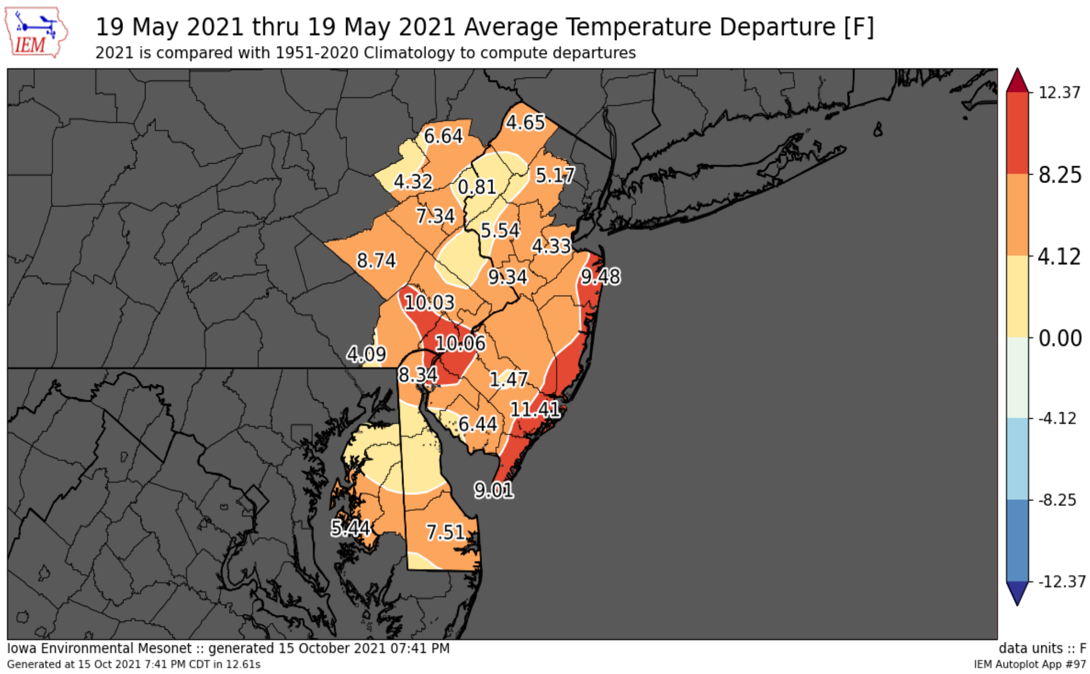

Figure 10. Average temperature departure from normal on May 19, 2021. Compared to 1951-2020 climatology, the average temperature around New Castle County and at the Lums site was around 4-8°F above normal for this day (orange shading). Courtesy: Iowa State Mesonet

Furthermore, light winds in the two days prior to this event allowed pollutants to accumulate over the region. The pollutant carryover (Figure 11), combined with the aforementioned weather conditions, led to an observed AQI value of 101 at Lums, which was the only site on this day to reach Code Orange levels.

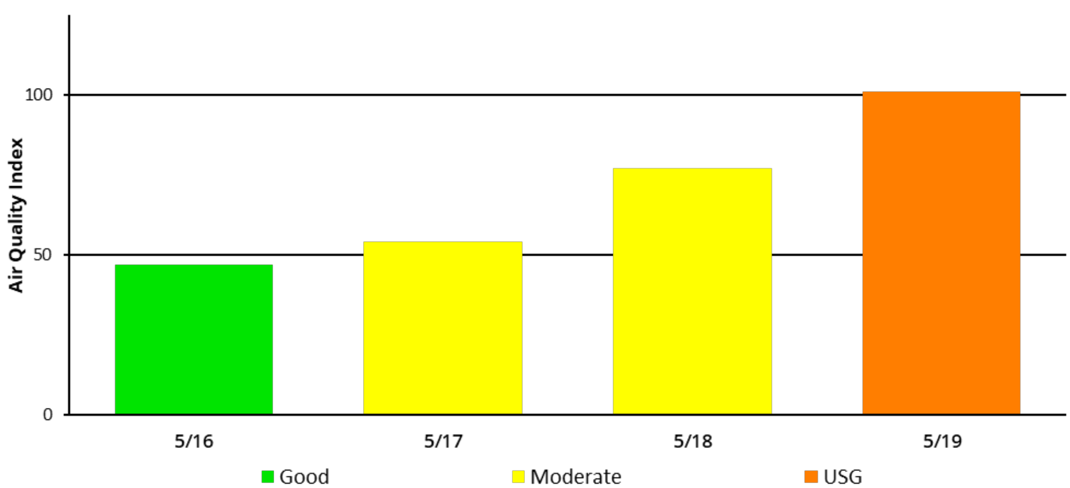

Figure 11. Observed AQI values at the Lums monitoring site May 16-19, 2021. Data courtesy: AirNow-Tech

2.2.2 June 5, 2021

The season's second Code Orange day was the highest ozone AQI value recorded for the summer. On this day, five of the eight ozone monitoring sites in Delaware recorded USG AQI levels, and the highest reading was observed at the MLK site in Wilmington (Figure 12).

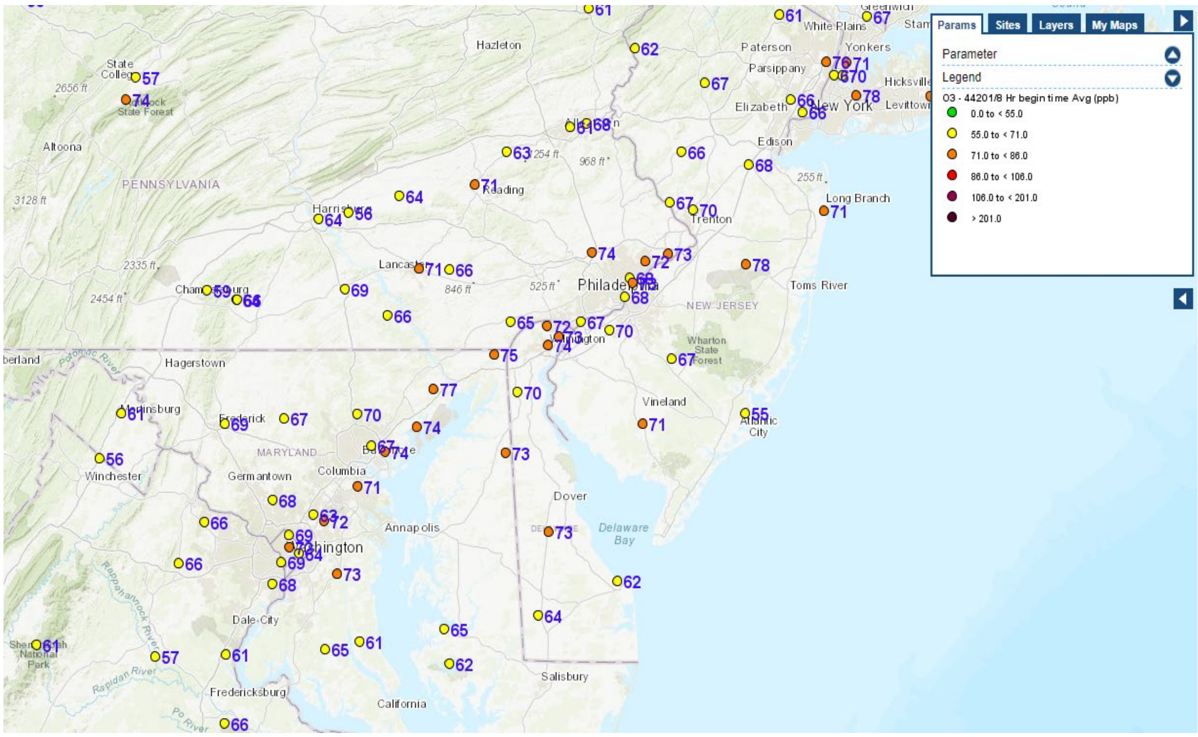

Figure 12. Observed 8-hour daily maximum ozone concentrations across the mid-Atlantic region on June 5, 2021. Orange dots represent monitoring sites with USG AQI levels. Courtesy: AirNow-Tech

There were several factors in the lowest levels of the atmosphere that influenced ozone formation. First, sunny skies and temperatures in the low-90s supported ozone formation. In addition, surface high pressure west of the state limited pollutant dispersion across the region. Furthermore, light westerly to southwesterly winds throughout much of the day (Figure 13) limited dispersion and gradually transported regional pollutants into Delaware, increasing ozone levels.

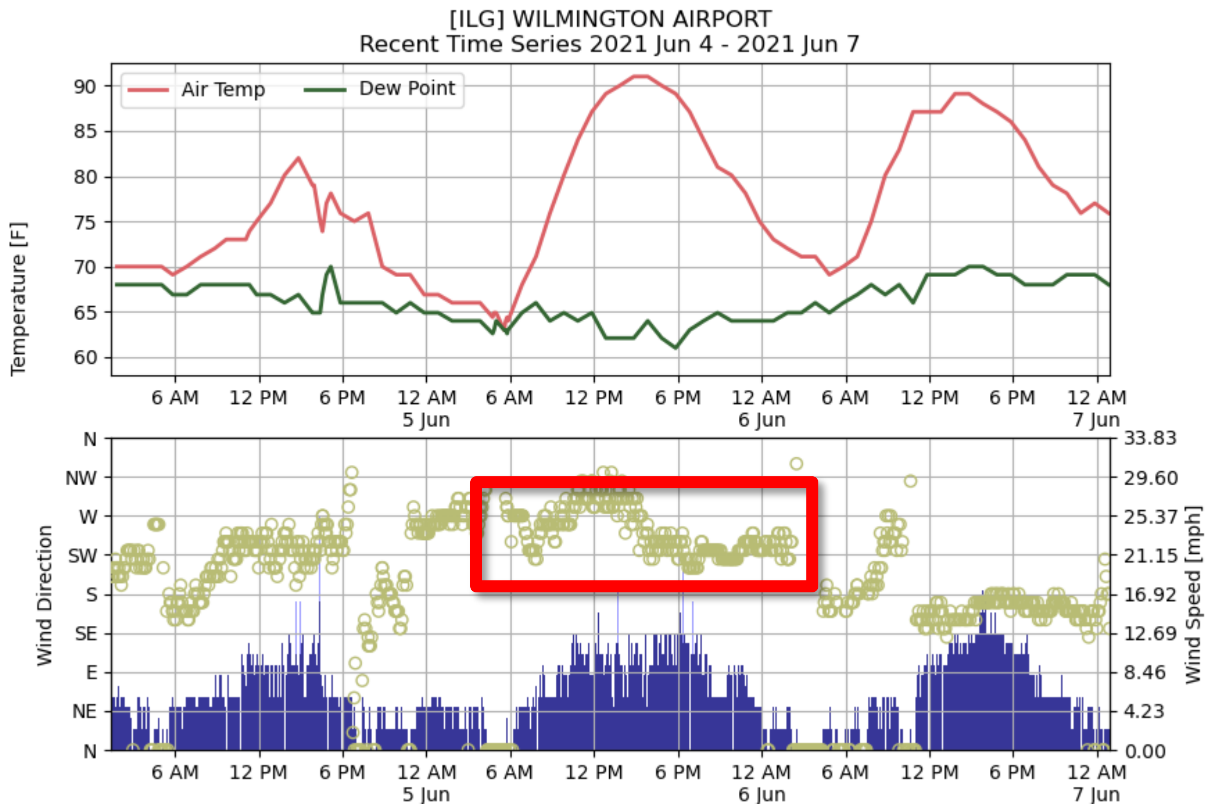

Figure 13. Wilmington ASOS meteogram valid June 4-6, 2021. On June 5, winds were predominantly westerly to southwesterly (tan dots within the red rectangle). These winds carried regional pollutants into the First State. Courtesy: Iowa State Mesonet

Ozone levels on this day may have also been influenced by long-range transport of wildfire smoke. As noted by McClure and Jaffe in *Investigation of high ozone events due to wildfire smoke in an urban area*[1], wildfires emit a variety of pollutants, including fine particulate matter ($PM_{2.5}$) and volatile organic compounds (VOCs), which can enhance the formation of ground-level ozone downwind from the wildfire.

On June 4, 2021, a thin plume of remnant smoke from Canadian wildfires was analyzed by the National Oceanic and Atmospheric Administration (NOAA) over the Ohio Valley and Great Plains (Figure 14). While smoke was not analyzed directly over Delaware on June 5, 2021, 48-hour back trajectory analysis indicates the possibility that the smoke plume present on June 4, 2021, was transported into the mid-Atlantic region on June 5, 2021.

[1] https://www.sciencedirect.com/science/article/abs/pii/S1352231018306137

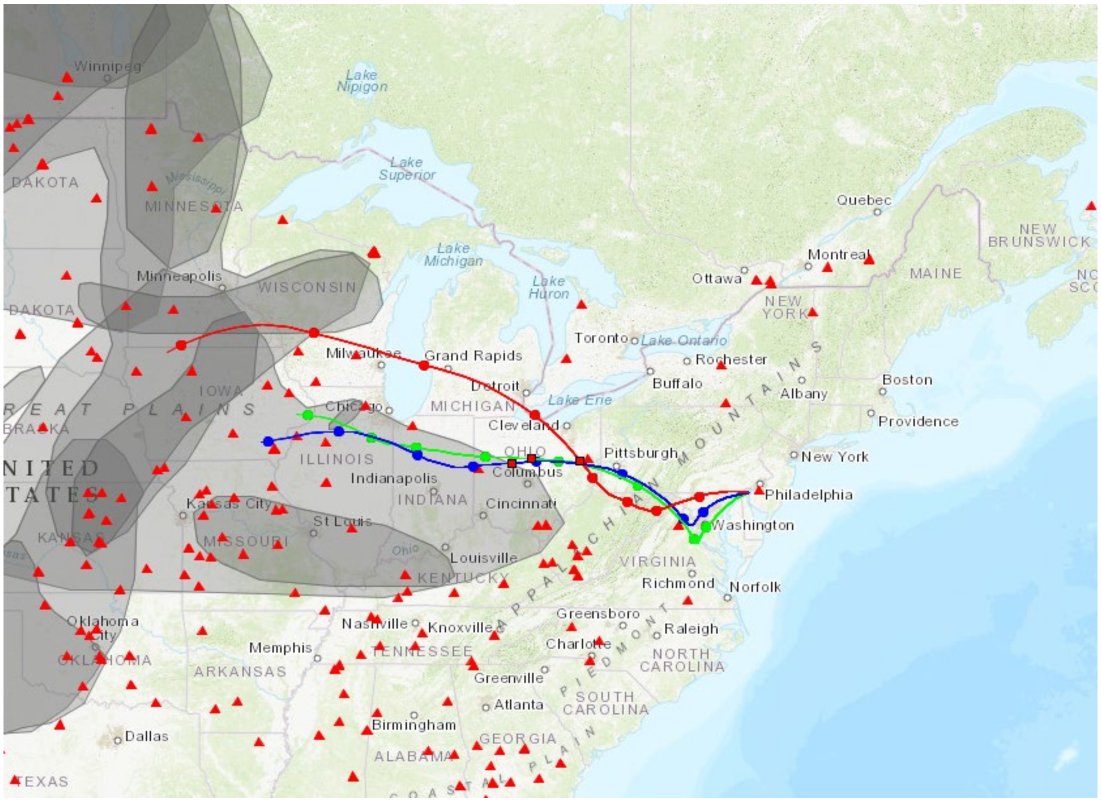

Figure 14. NOAA smoke plume analysis (gray) and satellite fire detections (red triangles) on June 4 (gray), and 48-hour back trajectory analysis ending 12 a.m. ET June 6, 2021. Winds at 500 m (green line), 1,000 m (red line), and 1,500 m (blue line) indicate possible transport of remnant wildfire smoke into Delaware. Courtesy: AirNow-Tech

While AQI values for $PM_{2.5}$ were Good statewide on June 5, transport of VOCs contained within the thin smoke plume might have further increased ozone formation. Due to the aforementioned local and regional conditions, the daily max ozone AQI value reached 112 at the MLK monitoring site on June 5, 2021.

2.2.3 July 28, 2021

The third and final Code Orange ozone day in summer 2021 occurred on July 28. Unlike the June 5, 2021, ozone event, long-range wildfire smoke transport had a more definitive impact on ozone levels in Delaware on this day.

In the days prior to the July 28, 2021, northwesterly winds allowed low-level transport of a dense smoke plume from Canadian wildfires and associated ozone precursors into Delaware. It should also be noted that northwesterly winds were averaging less than 10 mph each day (Figure 15), which limited dispersion and allowed pollutants to accumulate across the region from day to day. Because of the light winds and lingering smoke, $PM_{2.5}$ AQI levels were Moderate every day from July 24-28, 2021.

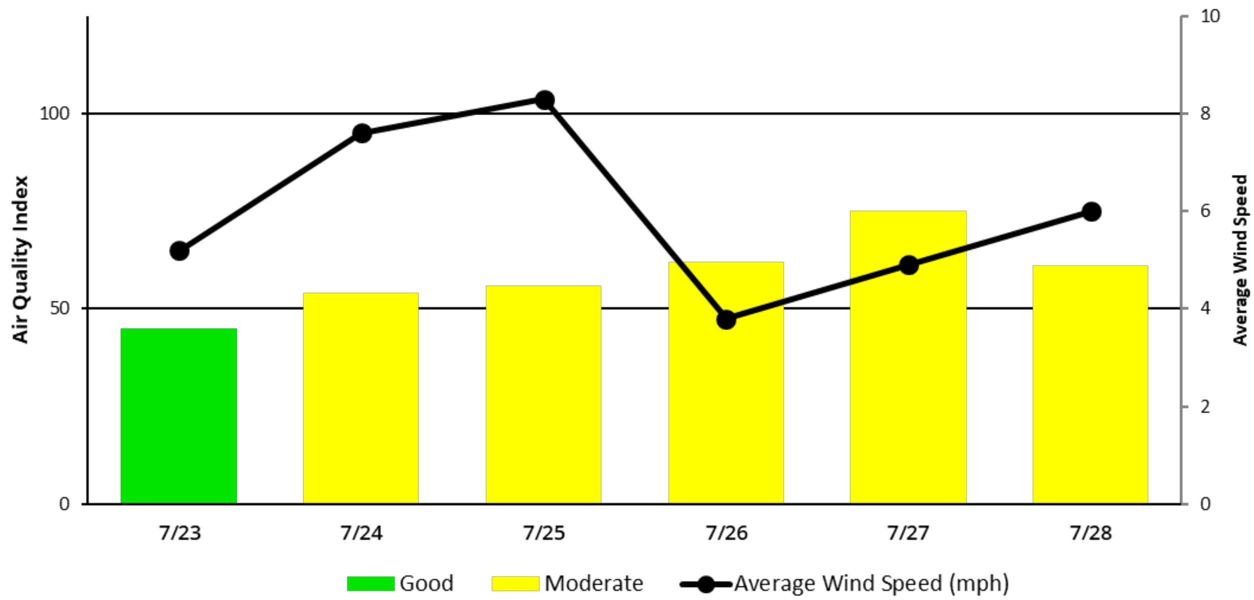

Figure 15. Daily state maximum average 24-hour $PM_{2.5}$ AQI levels and KILG daily 24-hour average wind speed for July 23-28, 2021. Data courtesy: AirNow-Tech

By the afternoon of July 28, abundant sunshine and temperatures in the upper-80s promoted ozone formation. Along with these weather conditions, lingering wildfire smoke over the state (**Figure 16**) further enhanced ozone production. Therefore, despite late afternoon clouds and thunderstorms inhibiting ozone development, the daily ozone AQI level reached the USG category.

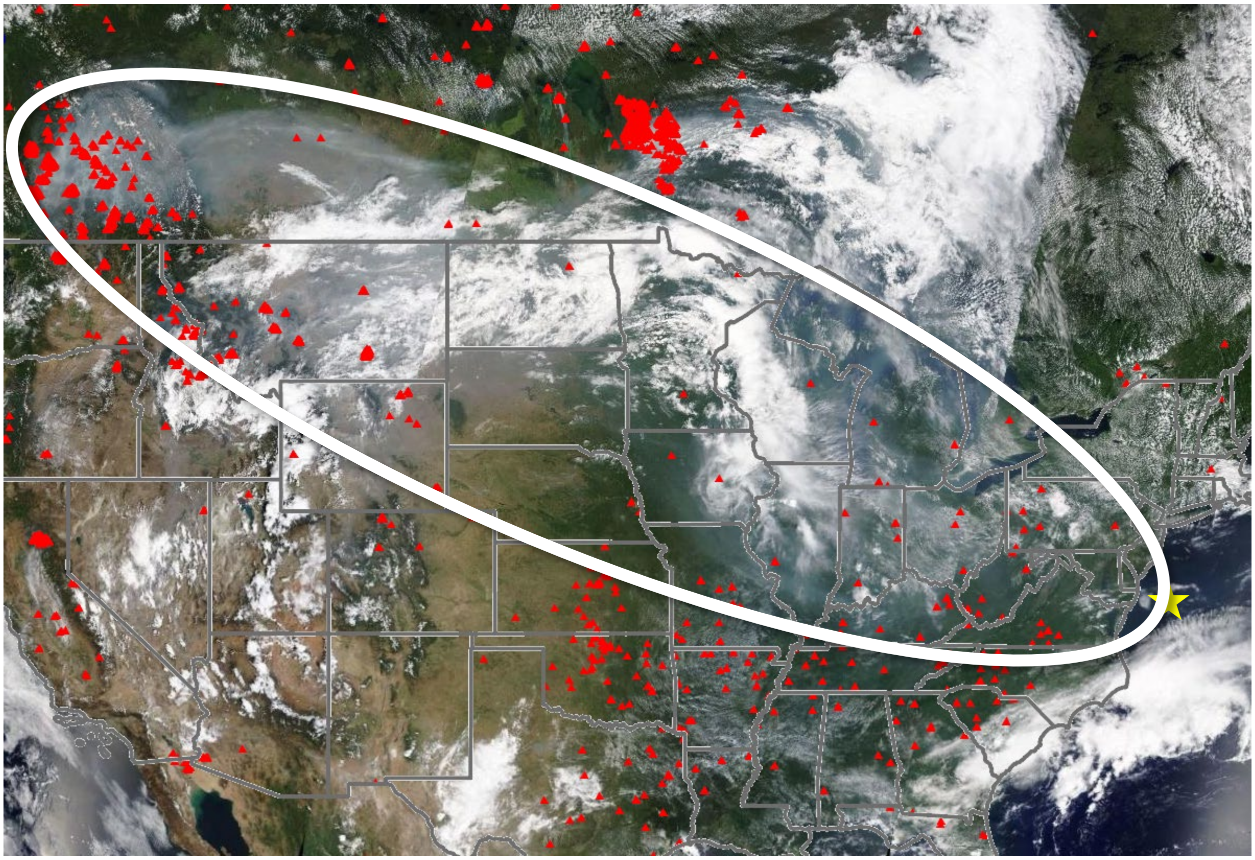

Figure 16. MODIS Terra satellite imagery and satellite fire detections (red triangles) on July 28, 2021. Smoke from Canadian wildfires (outlined in white) elevated ozone and $PM_{2.5}$ AQI values in Delaware (yellow star). Courtesy: AirNow-Tech

The highest AQI value on this date was 101, which was registered at the Killens monitoring site. Surrounding monitoring sites in Delaware generally recorded mid- to high-Moderate AQI ozone levels on this day.

2.3 Air Quality Comparison Between Summer 2021 and Previous Years

Ozone levels in Delaware have improved since 2012, driven largely by a reduction in NO_x emissions across the mid-Atlantic region. To accurately compare year-to-year trends in ozone levels, Sonoma Technology meteorologists compared summer 2021 ozone levels to the previous eight summers, dating back to 2013.

Figure 17 provides the yearly distribution of daily maximum ozone AQI levels for Delaware between 2013 and 2021. While days with Moderate and higher AQI values increased in 2021 from the previous year, the general trend in improved air quality continued. The 153-day period between

May 1, 2021, and September 30, 2021, featured Good AQI levels 72% of the time. Including summer 2021, Good AQI levels were observed on at least 70% of summer days in three of the past five years, with 2018 and 2019 both falling below the 70% threshold for the Good AQI category.

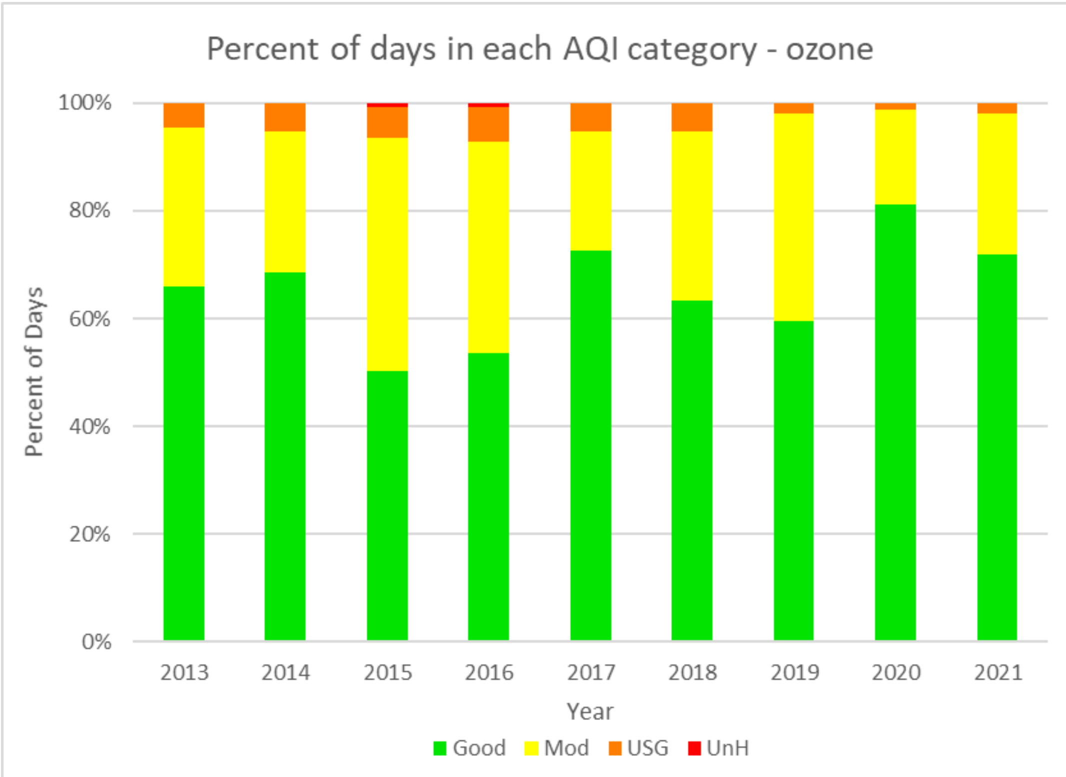

Figure 17. Distribution of daily maximum ozone AQI values between May 1, 2021, and September 30, 2021.

Ozone exceedances of the National Ambient Air Quality Standards (NAAQS) have become less frequent in Delaware. Figure 18 highlights the occurrence of ozone exceedances for each of Delaware's three counties going back to 2000.

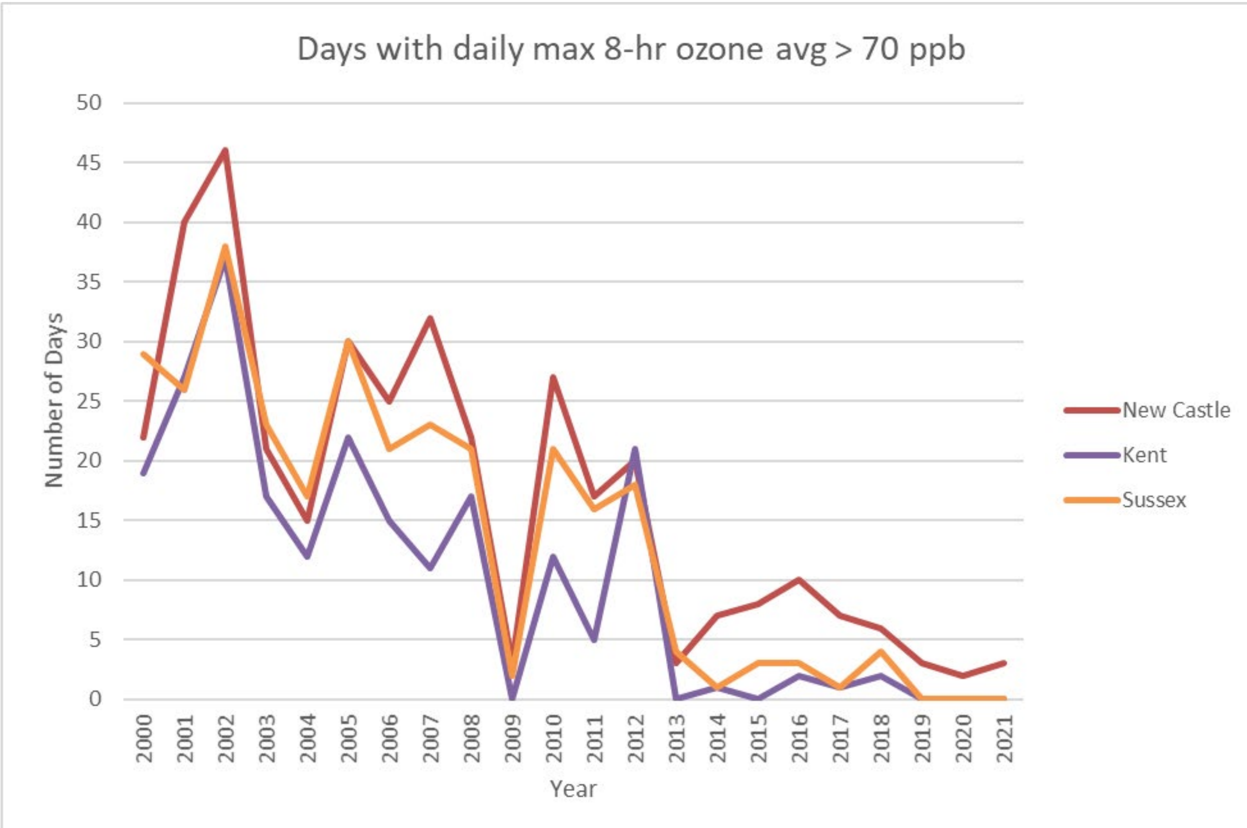

Figure 18. Frequency of ozone exceedances between May 2021 and September 2021 by county. Source: U.S. EPA Air Data (**https://www.epa.gov/outdoor-air-quality-data**)

Since 2012, the number of days when the daily maximum AQI value exceeded 100 has sharply declined. After a brief increase in New Castle County in 2016, due in part to anomalously warm temperatures, ozone exceedances during the summer ozone forecast season have continued to be infrequent. Additionally, summer 2021 marks the third straight year without an ozone exceedance recorded in either Kent or Sussex counties.

2.4 Summer 2021 Meteorological Summary

Weather patterns can have a strong impact on ozone formation in Delaware. Generally, warmer-than-normal temperatures and below-normal wind speeds can enhance ozone formation during the summer months. On the other hand, frequent frontal passages can result in increased cloud cover, above-average precipitation, and enhanced vertical mixing, which all reduce ozone development.

For the summer 2021 ozone forecasting season, temperatures across the mid-Atlantic region were near or slightly above average between May 1 and September 30 (**Figure 19**). In general, the average temperature departure from normal ranged from 0.0°F to 1.0°F above normal, with the largest temperature anomalies occurring across central and southern Delaware and portions of southeastern Pennsylvania and New Jersey.

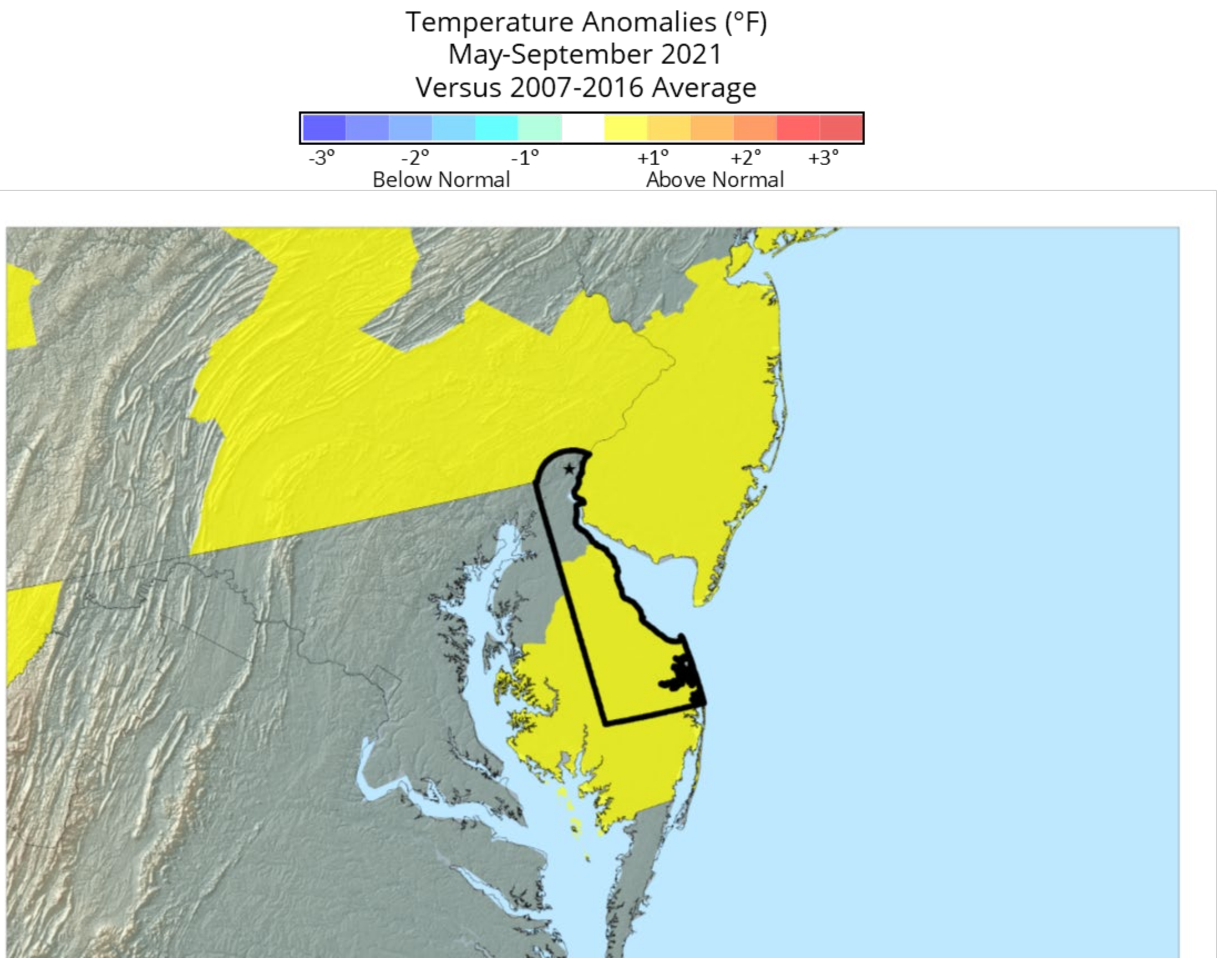

Figure 19. May-September 2021 average temperature departure from normal. Yellow indicates areas where temperatures were around 0.5-1.0°F above normal.

With respect to the two Delaware NOAA climate sites, Table 4 provides a complete meteorological summary for the summer 2021 ozone forecasting season. Both Delaware NOAA climate sites were above average for temperatures between May and September 2021. The Georgetown climate site recorded an average temperature of 73.9°F during this period, which is 1.2°F above normal. For the Wilmington climate site, the average May-September 2021 temperature was 75.6°F, which is 0.9°F above average.

Table 4. May-September 2021 meteorological summary for Delaware climate locations.

Variable	Wilmington (KILG)	Georgetown (KGED)
Average Temperature (°F)	75.6	73.9
Average Temperature Departure from Normal (°F)	+0.9	+1.2
Total Precipitation (inches)	17.88	20.97
Precipitation Departure from Normal (inches)	-3.13	+0.60
Average Wind Speed (mph)	7.3	6.1
Average Wind Speed Departure from Normal (mph)	-0.6	-0.2
Number of Clear Days	87	100

Wind speeds for the Wilmington and Georgetown climate sites were near or slightly weaker than normal during the May-September 2021 period. Wilmington's average wind speed was 7.3 mph, which is 0.6 mph below average. In contrast, Georgetown's average wind speed was near normal during the season, averaging 6.1 mph.

Observed precipitation during the May-September 2021 period differed for the two climate sites. While Wilmington's precipitation was below average, Georgetown's measured precipitation for the summer 2021 ozone forecast season was more than a half-inch above average.

Region-wide, precipitation during the May-September 2021 period was generally near or slightly above-normal (Figure 20). The wettest areas during the summer ozone forecast season were located across a wide swath of Maryland, Pennsylvania, Washington D.C., and New Jersey. On the other hand, the driest areas were in the Delmarva Peninsula and portions of northern Virginia, where average precipitation for the season was generally near normal.

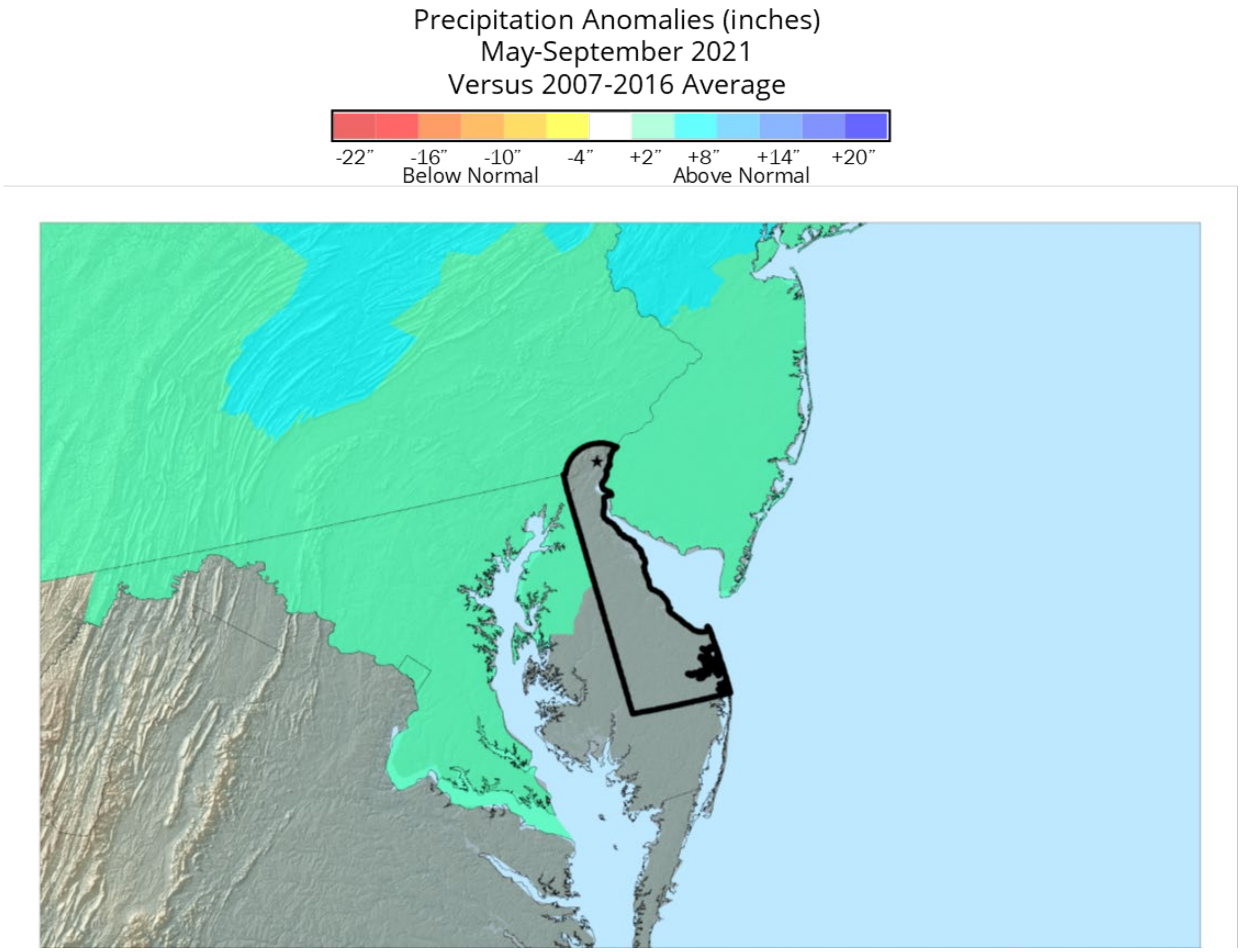

Figure 20. Precipitation anomalies for May-September 2021. Areas in green and light blue indicate above-normal rainfall for the season. Areas absent of color denote near-normal rainfall. Courtesy: NOAA/NCEI

Table 5 shows a month-by-month summary of weather at the Wilmington climate site, and Table 6 contains a month-by-month summary of weather at the Georgetown climate site. Clear conditions were most prevalent in July for the summer 2021 forecast season, despite above-normal precipitation. The frequency of sunny days, combined with warm temperatures, partially contributed to 12 days with Moderate or higher ozone AQI levels during the month, which was the most recorded for any month during the summer 2021 ozone forecasting season. As temperatures gradually cooled in September 2021, ozone production decreased, and days with Good AQI values became more prevalent.

Table 5. 2021 monthly meteorological summary for Wilmington-New Castle Airport (KILG).

Wilmington, (KILG)	May	June	July	August	September
Average Temperature (°F)	62.7	73.8	77.8	78.1	70.3
Average Temperature Departure from Normal (°F)	-0.8	+1.2	+0.2	+2.3	+1.4
Total Precipitation (inches)	3.03	1.96	4.77	2.76	5.36
Precipitation Departure from Normal (inches)	-0.54	-2.71	+0.36	-1.22	+0.98
Number of Clear Days	15	18	22	16	16
Number of 90°F+ Days	2	9	11	13	0
Average Wind Speed (mph)	8.2	7.4	6.6	6.7	7.8
Average Wind Speed Departure from Normal (mph)	-0.6	-0.8	-1.0	-0.5	+0.1

Table 6. 2021 monthly meteorological summary for Georgetown (KGED).

Georgetown (KGED)	May	June	July	August	September
Average Temperature (°F)	65.2	76.1	79.3	77.9	71.1
Average Temperature Departure from Normal (°F)	+0.7	+2.5	+0.7	+1.2	+0.8
Total Precipitation (inches)	2.35	3.39	6.34	5.78	3.11
Precipitation Departure from Normal (inches)	-1.28	-0.68	+2.20	+1.79	-1.43
Number of Clear Days	19	18	24	18	21
Number of 90°F+ Days	3	12	15	10	0
Average Wind Speed (mph)	6.5	7.1	6.2	5.0	5.9
Average Wind Speed Departure from Normal (mph)	-1.1	+0.6	0.0	-0.3	-0.2

Monthly ozone trends in summer 2021 generally followed the 2016-2020 climatology in Figure 2, where days with Moderate or higher AQI levels were most frequent in July and least frequent in September. However, the first two months of the summer 2021 forecast season produced ozone levels that differed from climatology. In May 2021, 35% of days featured Moderate or higher AQI values, which is an 8% increase compared to the 5-year climatology. The following month, days with

Moderate and higher AQI levels occurred only 23% of the time, marking a 22% decrease compared to June 2016-2020 statistics.

To further evaluate the weather's impact on ozone levels in May and June 2021, Sonoma Technology meteorologists reviewed daily anomalies for mixing ratio, which is a measure of how much water vapor is present in the atmosphere. An atmosphere that contains more water vapor tends to be more unstable, resulting in increased vertical mixing and lower ground-level ozone values. On the other hand, an atmosphere containing little water vapor can increase ozone values, due to reduced vertical mixing in the lower atmosphere.

In the case of May 2021, mixing ratios at both climate sites were drier-than-normal on most days (Figures 21 and 22). Reduced mixing ratios during the month might have led to higher AQI levels when compared to climatology. For June 2021, mixing ratios at both climate sites were higher-than-normal, as indicated by Figures 21 and 22. Due to the anomalously high mixing ratio values, atmospheric mixing over Delaware likely increased in June 2021, contributing to fewer days with Moderate and higher AQI values than in the 2016-2020 climatology.

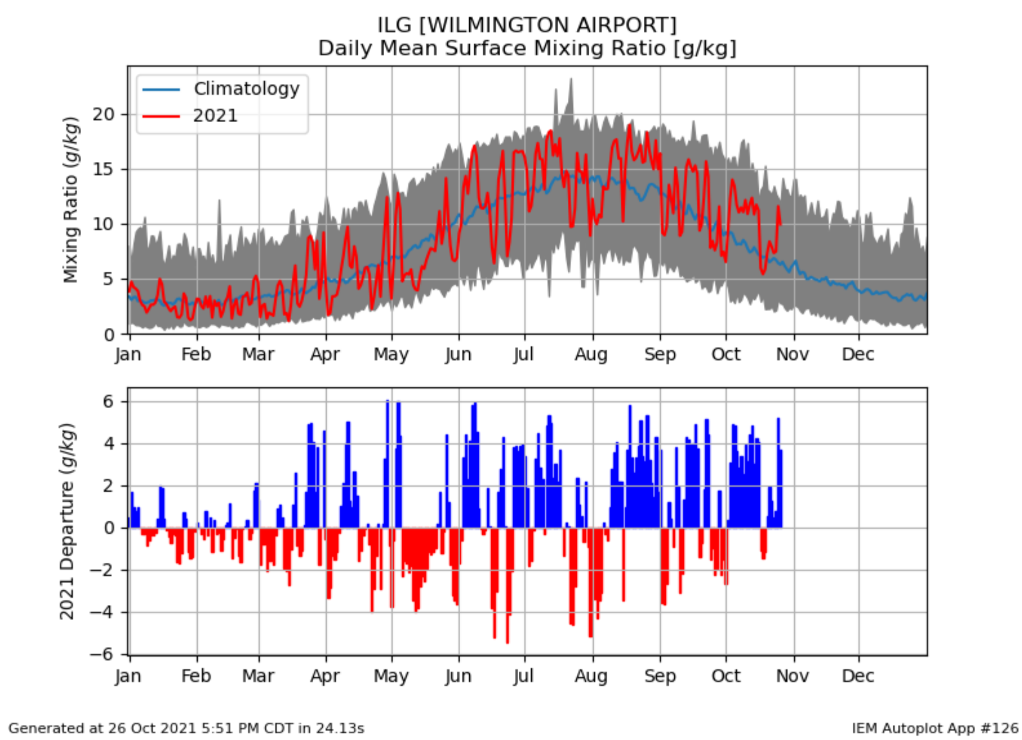

Figure 21. Daily mean surface mixing ratio values and departure from normal for Wilmington. In the bottom graph, red bars indicate below-normal mixing ratio values and a drier atmosphere. Conversely, blue bars depict above-normal mixing ratio values, which means a more humid, unstable atmosphere. Courtesy: Iowa State Mesonet

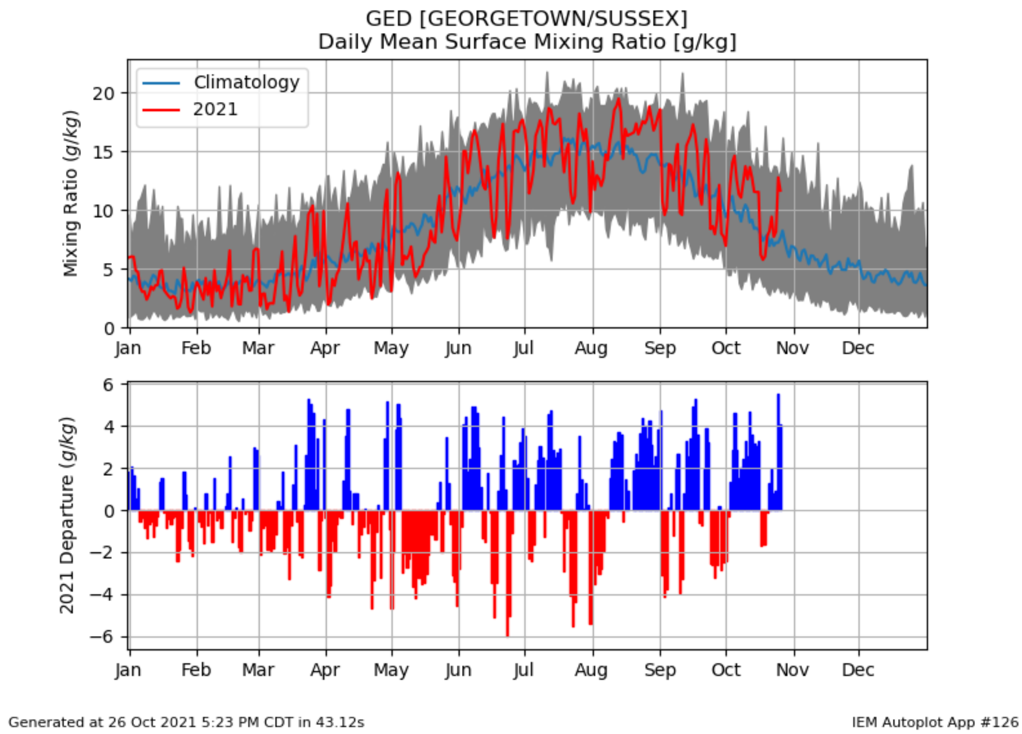

Figure 22. Daily mean surface mixing ratio values and departure from normal for Georgetown. In the bottom graph, red bars indicate below-normal mixing ratio values and a drier atmosphere. Conversely, blue bars depict above-normal mixing ratio values, which means a more humid, unstable atmosphere. Courtesy: Iowa State Mesonet

Upper-level weather patterns can also influence ozone formation. For example, persistent upper-level high pressure over a region typically results in clear skies, warm surface temperatures, drier air, and limited vertical mixing in the lower levels of the atmosphere – all of which can enhance ground-level ozone development. Conversely, persistent upper-level low pressure can lead to a more humid air mass, cloudier skies, and increased vertical mixing, all of which can inhibit ozone production.

To analyze these patterns, Sonoma Technology meteorologists examined the height anomalies at the 500-mb level (roughly 18,000 feet above sea level). Above-normal height anomalies are consistent with upper-level high pressure, while below-normal height anomalies are related to upper-level low pressure.

During the May-September 2021 period, the 500-mb height anomalies (Figure 23) indicated strong upper-level high pressure along the northern California and Pacific Northwest coast. Height anomalies were slightly above normal in the mid-Atlantic region and southeastern United States (U.S.). The weak height anomalies present over Delaware and the surrounding area suggests a near-normal upper-level weather pattern during summer 2021.

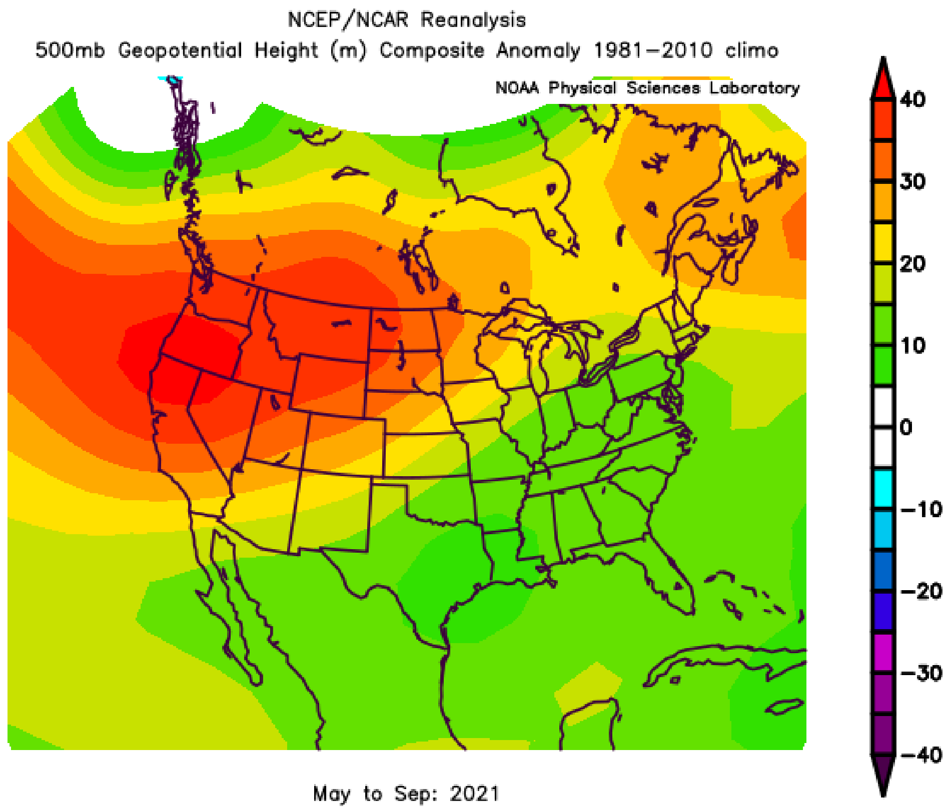

Figure 23. 500-mb height anomalies for May-September 2021. Courtesy: NCEP/NCAR

Throughout the summer 2021 ozone forecast season, the correlation between these upper-level signals and subsequent effects on air quality varied monthly. Delaware's highest 500-mb height anomalies during the season were in June 2021 (Figure 24), due to upper-level high pressure off the eastern Canadian coast. In addition, surface temperatures in June at both Delaware climate sites were 1.0°F to 2.5°F above average (Tables 4 and 5). However, despite warm conditions and upper-level high pressure over the region, anomalously high mixing ratio values in June 2021 (Figures 21 and 22) aided vertical mixing, which partially contributed to more frequent days with Good AQI values for ozone during the month in Delaware.

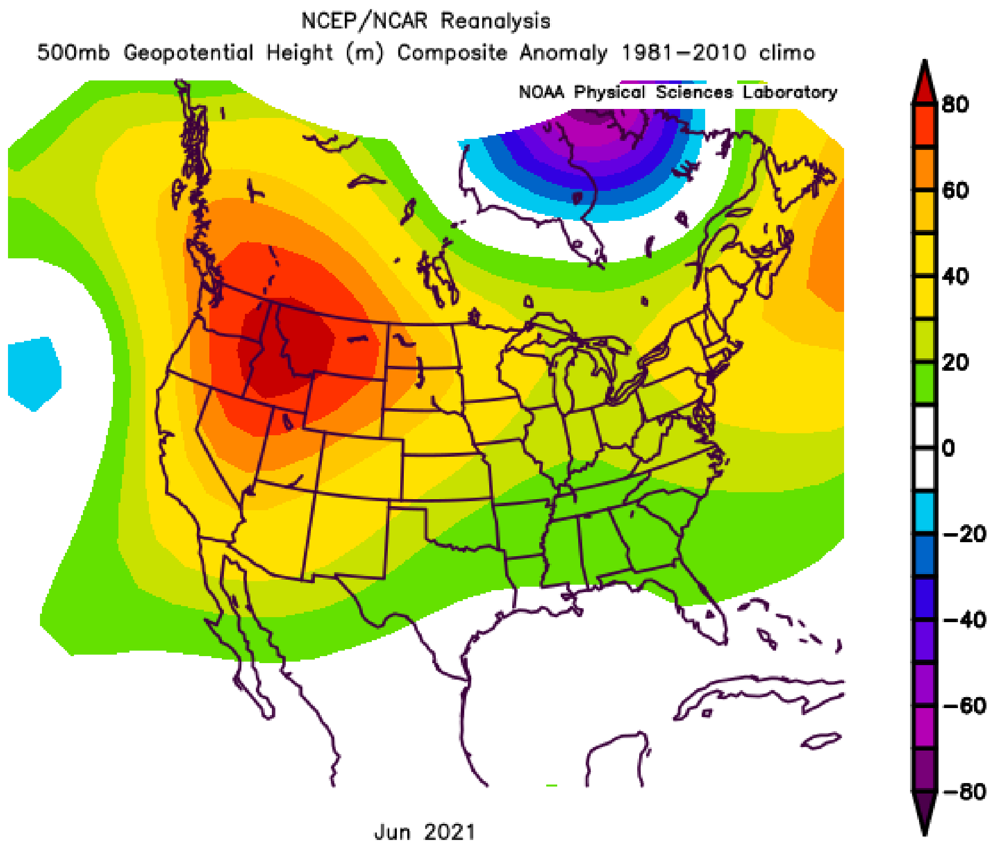

Figure 24. 500-mb height anomalies for June 2021. Courtesy: NCEP/NCAR

500-mb height anomalies were slightly positive again in August 2021 (**Figure 25**) in the mid-Atlantic region, caused by a persistent upper-level high pressure center anchored over the Canadian Maritimes. In conjunction with this upper-level pattern, surface temperatures at both Delaware climate sites were warmer than normal, which helped promote ozone formation despite above-normal mixing ratios for most of the month.

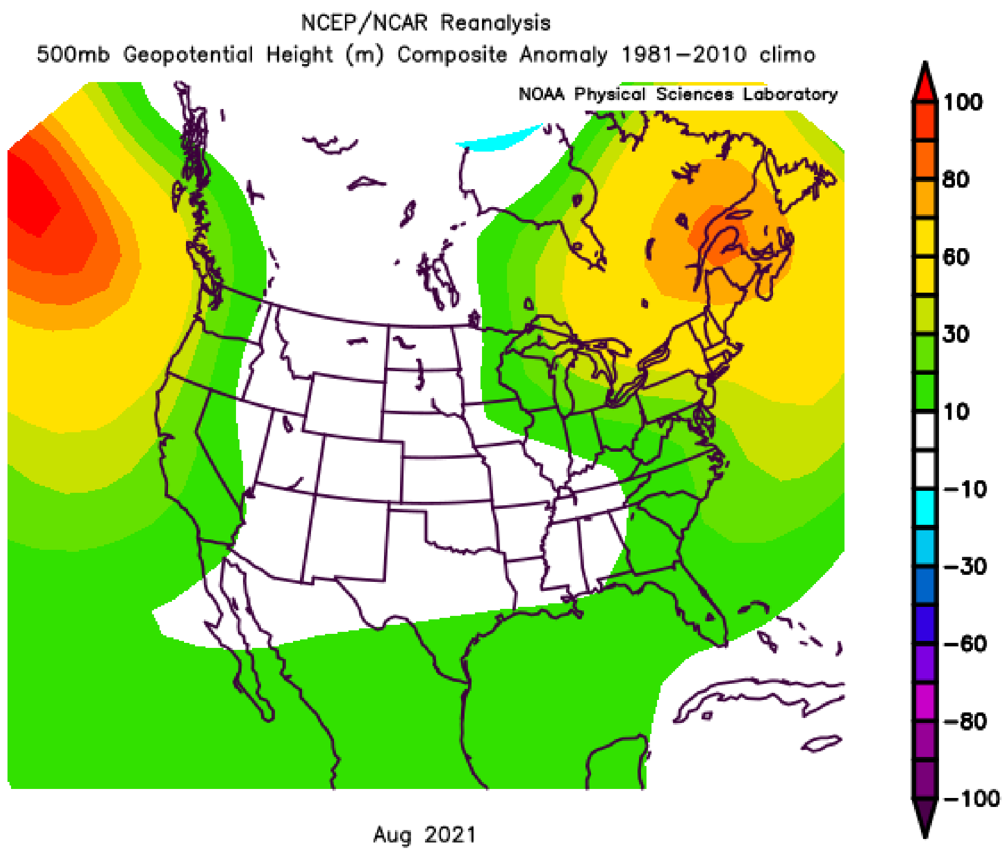

Figure 25. 500-mb height anomalies for August 2021. Courtesy: NCEP/NCAR

Along with the upper-level pattern throughout August 2021, surface winds speed anomalies were analyzed over Delaware. The surface wind speed anomaly data in **Figure 26** shows that winds were slightly weaker than normal over the region in August 2021, suggesting reduced pollutant dispersion. These wind speed anomalies are also corroborated by the wind speed data recorded at the two climate sites (**Tables 4 and 5**).

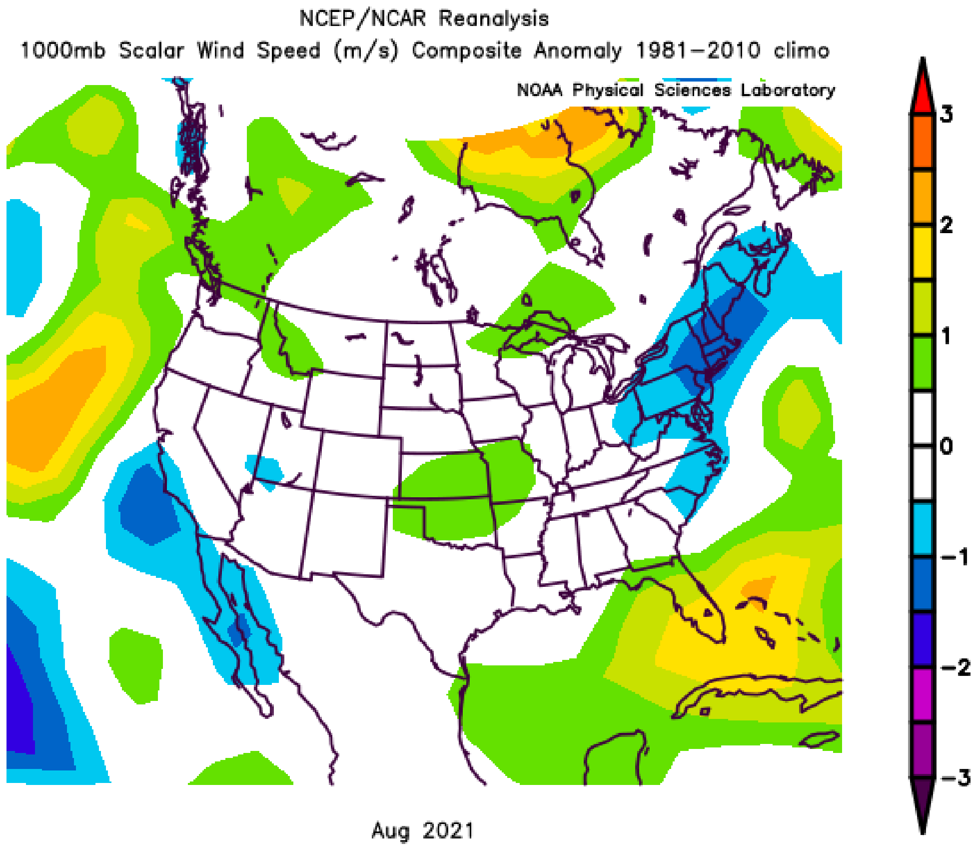

Figure 26. Surface wind speed anomalies for August 2021. Blue colors signal weaker than normal winds, while green, yellow, and orange colors indicate stronger than normal winds. Courtesy: NCEP/NCAR

In total, 32% of days in August 2021 featured Moderate or higher ozone AQI levels in Delaware, with light winds, warm temperatures, and upper-level high pressure each affecting air quality to some degree.

Ozone development is not solely dependent on surface and aloft weather conditions, and the varying weather patterns at the surface and aloft throughout summer 2021 suggest that other factors played an important role in air quality levels as well. One of these factors was long-range transport of wildfire smoke. The following section provides insight into how smoke impacted ozone and $PM_{2.5}$ levels in the First State during summer 2021.

3. Wildfire Smoke Impacts on Air Quality in Delaware Summer 2021

3.1 Introduction

Throughout summer 2021, a series of devastating wildfires broke out across the western U.S. and southern Canada. These fires generated vast plumes of smoke, which affected air quality for a large portion of the contiguous U.S. (CONUS). These impacts included Delaware, which experienced smoky skies and reduced air quality.

Wildfires emit a variety of pollutants, including fine particulates known as $PM_{2.5}$. These fine particles are dangerous to human health, as they can be lodged deep into the lungs or enter the blood stream after inhalation. According to the U.S. Environmental Protection Agency (EPA), health impacts from $PM_{2.5}$ include (but are not limited to) coughing, shortness of breath, and an irregular heartbeat. In some cases, repeated exposure to $PM_{2.5}$ can lead to premature death in individuals with heart or lung disease.

The following sections provide insight into the conditions that led to these wildfires, the magnitude of the fires and acres burned over the summer, and how smoke influenced both ozone and $PM_{2.5}$ levels in the First State.

3.2 Weather Influence on US/Canadian wildfires

Several factors influenced the abundant wildfire activity in the western U.S. and southern Canada. In the months prior to and in the early portion of the summer ozone forecasting season, the upper-level weather pattern, temperatures, and precipitation all led to above-average fire risk and subsequent fire activity.

Figure 27 depicts precipitation anomalies between mid-April and mid-July 2021, as calculated from the Climate Prediction Center's gauge-based analysis. This analysis indicated a wide swath of drier-than-normal conditions from (1) the U.S. West Coast to the Northern Rockies, (2) southern Canadian prairie provinces, and (3) Northern Plains. In some areas, rainfall was 65-95% below normal levels, which is shown in red and pink colors on Figure 27.

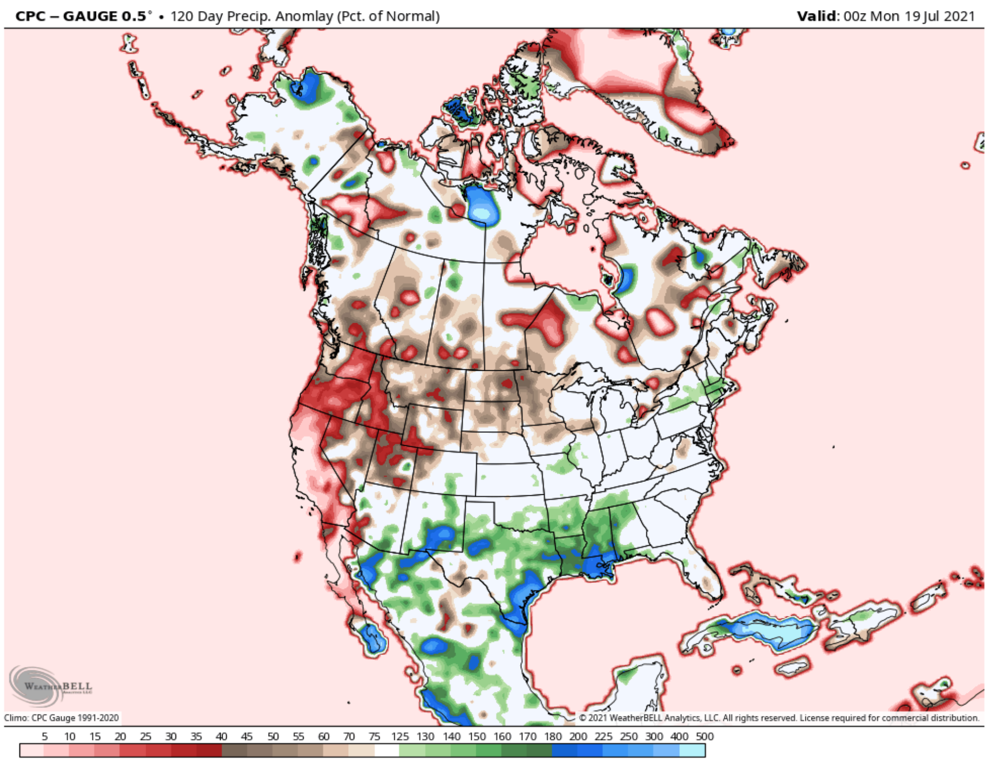

Figure 27. North America 120-day precipitation anomalies, ending 00Z July 19, 2021. Courtesy: Climate Prediction and WeatherBell

Due to the abnormally dry conditions that persisted in these locations, widespread drought conditions developed. Prior to the start of the summer 2021 ozone forecast season, the North American Drought Monitor (Figure 28) classified severe to extreme drought across large sections of the western and north-central U. S., along with portions of south-central Canada. Drier trees and vegetation in these areas allowed for accelerated wildfire growth.

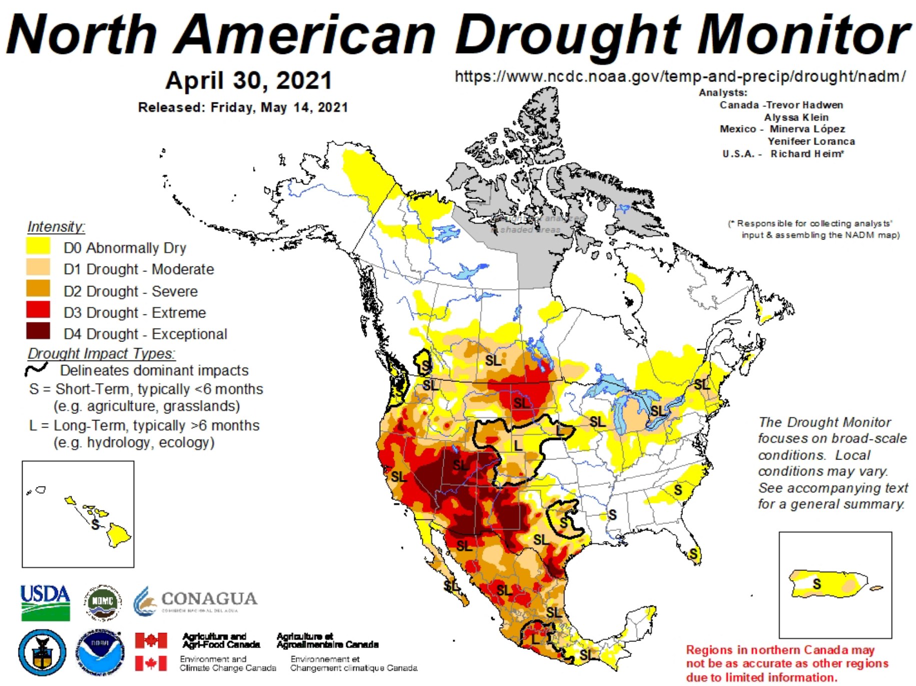

Figure 28. North American Drought Monitor, valid April 30, 2021. Courtesy: National Climatic Data Center (NCDC)

As the summer ozone season commenced in Delaware, the upper-level weather pattern across the western U.S. and Canada allowed drought conditions to remain. 500-mb height anomalies between May and July 2021 (Figure 29) were strongly positive in the Pacific Northwest, Northern Rockies, and southern Canada. With persistent high pressure in place aloft, storm systems were unable to provide beneficial rains to these areas.

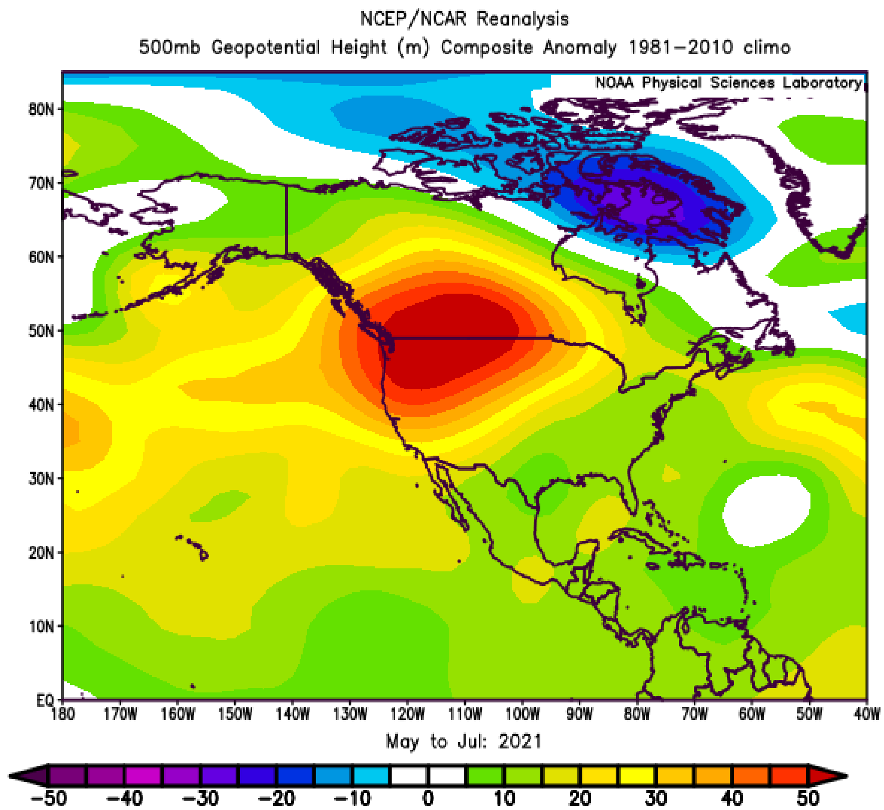

Figure 29. 500-mb height anomalies for May-July 2021. Courtesy: National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR)

With the lack of clouds and rainfall, persistent upper-level high pressure generated clear skies and warm surface temperatures. Monthly average temperature anomalies in June and July across the western U.S. and southern Canada were strongly positive (**Figure 30**), running almost 9°F above average in some locations. Warmer-than-normal temperatures, in conjunction with dry fuels resulting from drought conditions, further exacerbated wildfire behavior and allowed fires to grow at a rapid pace.

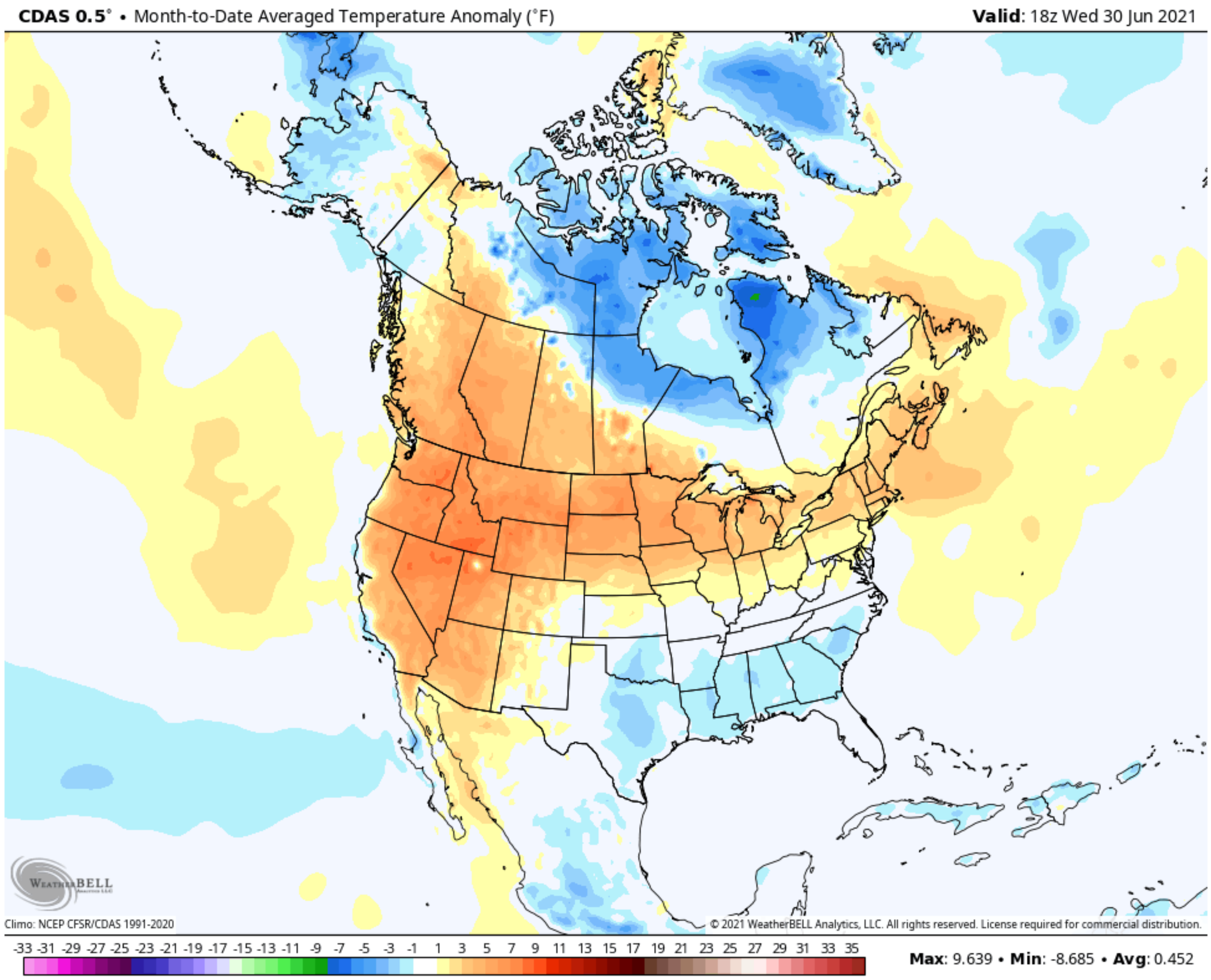

Figure 30. Monthly average temperature anomaly for June and July 2021. Courtesy National Center for Environmental Prediction (NCEP)

3.3 Summary of 2021 wildfire statistics

The combination of drought and hot temperatures generated an abundance of wildfire activity outside of Delaware during the summer 2021 ozone forecast season. To account for the number of acres burned during throughout the year, and to compare 2021 wildfire activity to other years, Sonoma Technology meteorologists reviewed wildfire statistics both domestically and in Canada.

In the U.S., wildfire acre statistics are kept by the National Climatic Data Center (NCDC), with records going back 22 years. Through the end of September 2021, 5.9 million acres of land were burned by 46,000 wildfires in the U.S. The 5.9 million acres burned between January and September accounted for the 10th-lowest acreage burned domestically and was roughly 124-thousand acres below the 10-year average. However, when factoring in the number of fires across the country, 128.2 acres of land were burned per fire, which was the 7th most on record and was 37.1 acres above the 10-year average.

In Canada, wildfire statistics are generated by the Canadian Interagency Forest Fire Center Incorporated (CIFFC), with calculations going back 25 years. Based off their final situational report filed on September 15, 2021, over 6,000 fires burned approximately 10.3 million acres of Canadian land during the year. When compared to the 10-year average, the acres burned in 2021 were roughly 4-million acres more than 10-year average. More notably, 1,660 acres of Canadian land burned per fire in 2021, which outpaced the 128.1 acres of land per fire burned in the U.S.

3.4 $PM_{2.5}$ levels in Delaware

As long-range transport of wildfire smoke likely impacted the First State in summer 2021, Sonoma Technology meteorologists issued $PM_{2.5}$ forecasts for late July to early August in addition to ozone forecasts. To understand past particle levels in the state, a five-year climatology for $PM_{2.5}$ was compiled.

In the winter, cold temperatures produce strong inversions, which hinder low-level mixing and trap pollutants near the ground. Emissions related to residential wood burning also factor into increased particle levels during the winter months. Between 2016-2020, days with Moderate or higher AQI values for $PM_{2.5}$ were most common during the winter months (**Figure 31**), with USG AQI levels for particles observed in November and December.

During the 2016-2020 summer ozone forecast seasons, 80% of days featured Good $PM_{2.5}$ air quality. However, the five-year climatology displayed a slight decrease in days with Good $PM_{2.5}$ AQI values in July, with roughly 24% of days recording Moderate AQI levels for particles. In the five years examined, AQI values for $PM_{2.5}$ did not reach the USG threshold during the summer months.

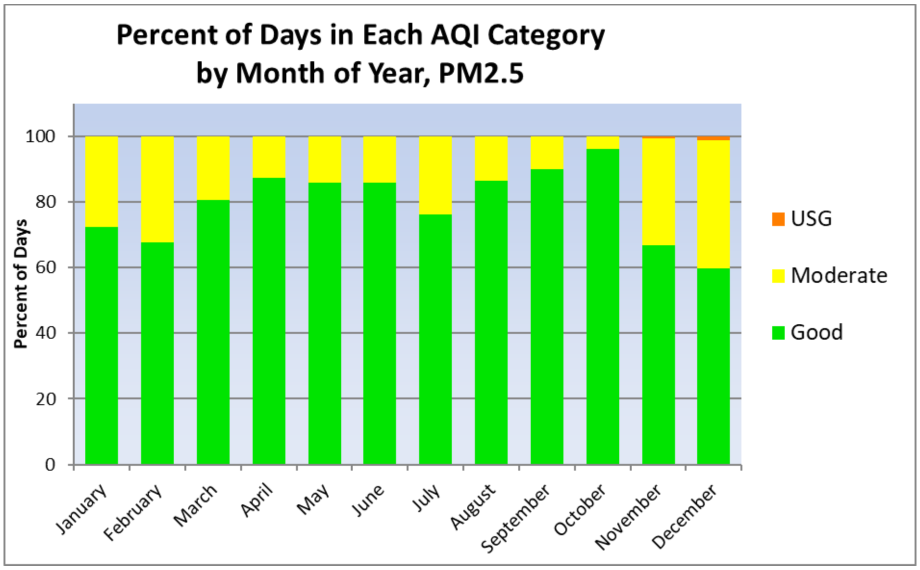

Figure 31. Percentage of days in each AQI category for $PM_{2.5}$ between 2016-2020.

By contrast, Figure 32 contains the percentage breakdown of days in each AQI category by month in summer 2021. While $PM_{2.5}$ AQI values were similar to the five-year climatological averages in May, June, August, and September, wildfire smoke in July 2021 brought a sharp increase to Delaware's $PM_{2.5}$ AQI levels. Compared to the five-year climatology in Figure 31, Moderate and higher AQI levels in July 2021 increased by 34%, which included 6% of days in the USG AQI category. This increase is a strong indicator of smoke influence.

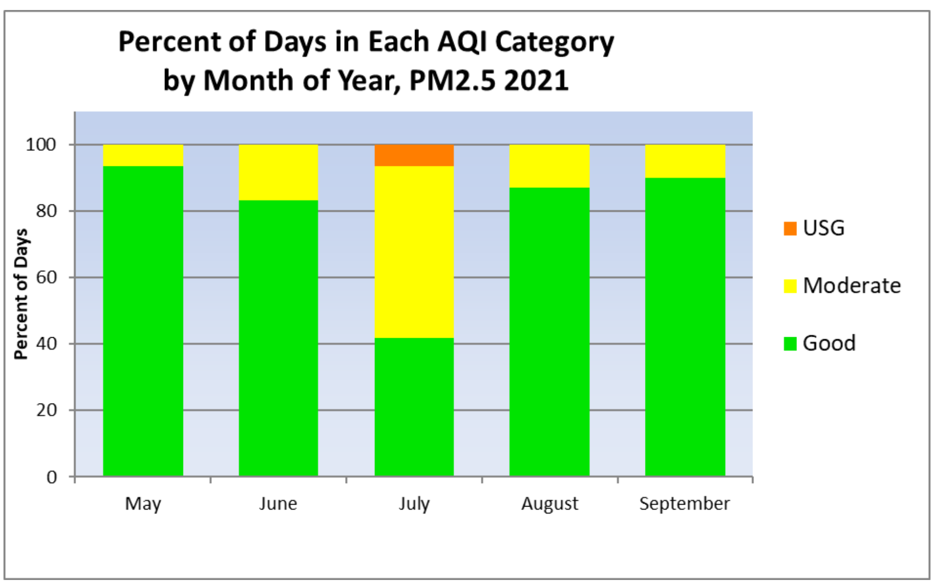

Figure 32. Percentage of summer 2021 days in each AQI category for $PM_{2.5}$.

The two days with USG AQI values for $PM_{2.5}$ measured in July 2021 marked the first summer USG $PM_{2.5}$ days in New Castle County since June 2011, based on regular daily $PM_{2.5}$ concentration record keeping that dates back to 1999 (**Figure 33**). A summary of these USG $PM_{2.5}$ days can be found in Section 3.5.

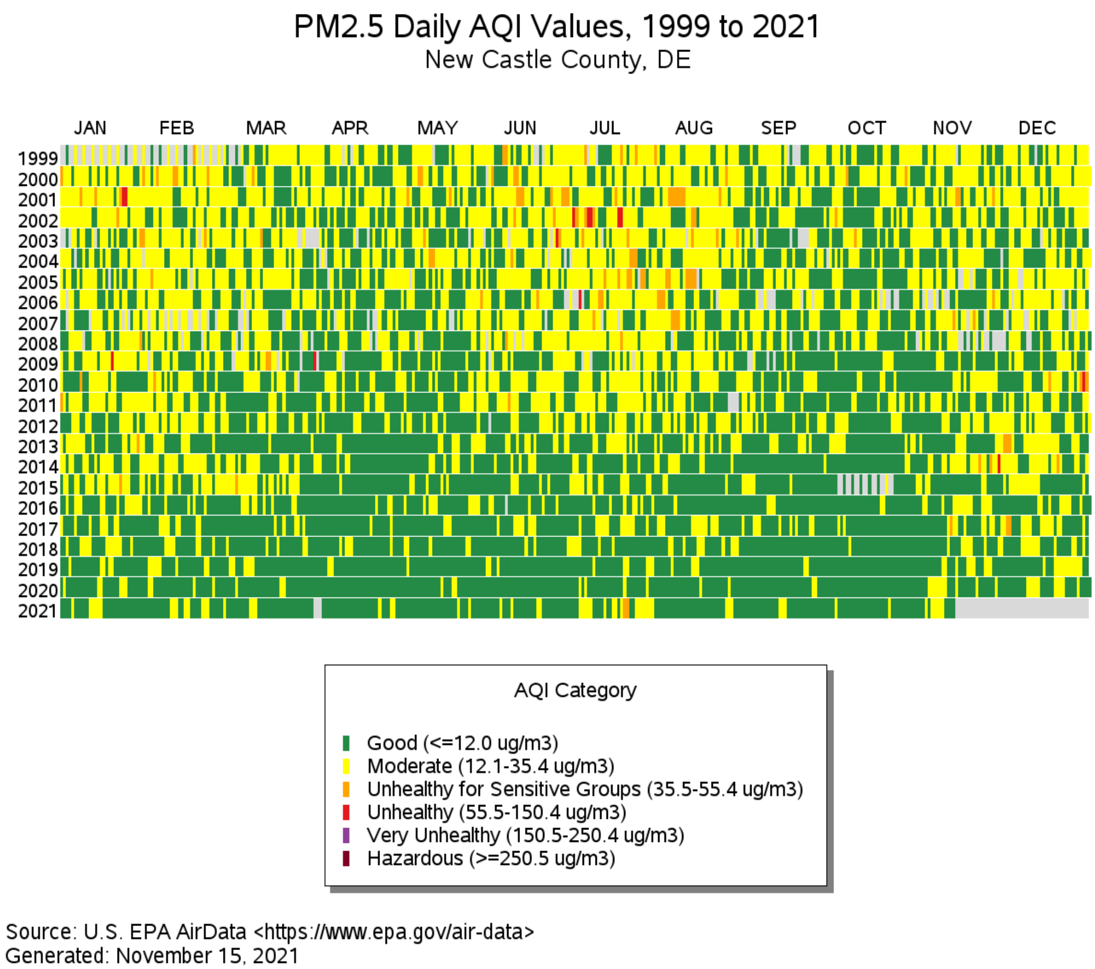

Figure 33. Daily maximum $PM_{2.5}$ AQI values for New Castle County. Courtesy: EPA AirData

Potential influence of wildfire smoke over a region can be inferred from assessing aerosol optical depth (AOD). Derived from weather satellites, AOD is a measure of aerosols within a column of air, from the ground to the top of the atmosphere. The larger the AOD value, the greater the amount of particles within the atmospheric column. While high AOD may indicate the presence of smoke in the atmosphere, it does not indicate whether that smoke is aloft or near the surface. A visual example of AOD output can be found in **Figure 34**.

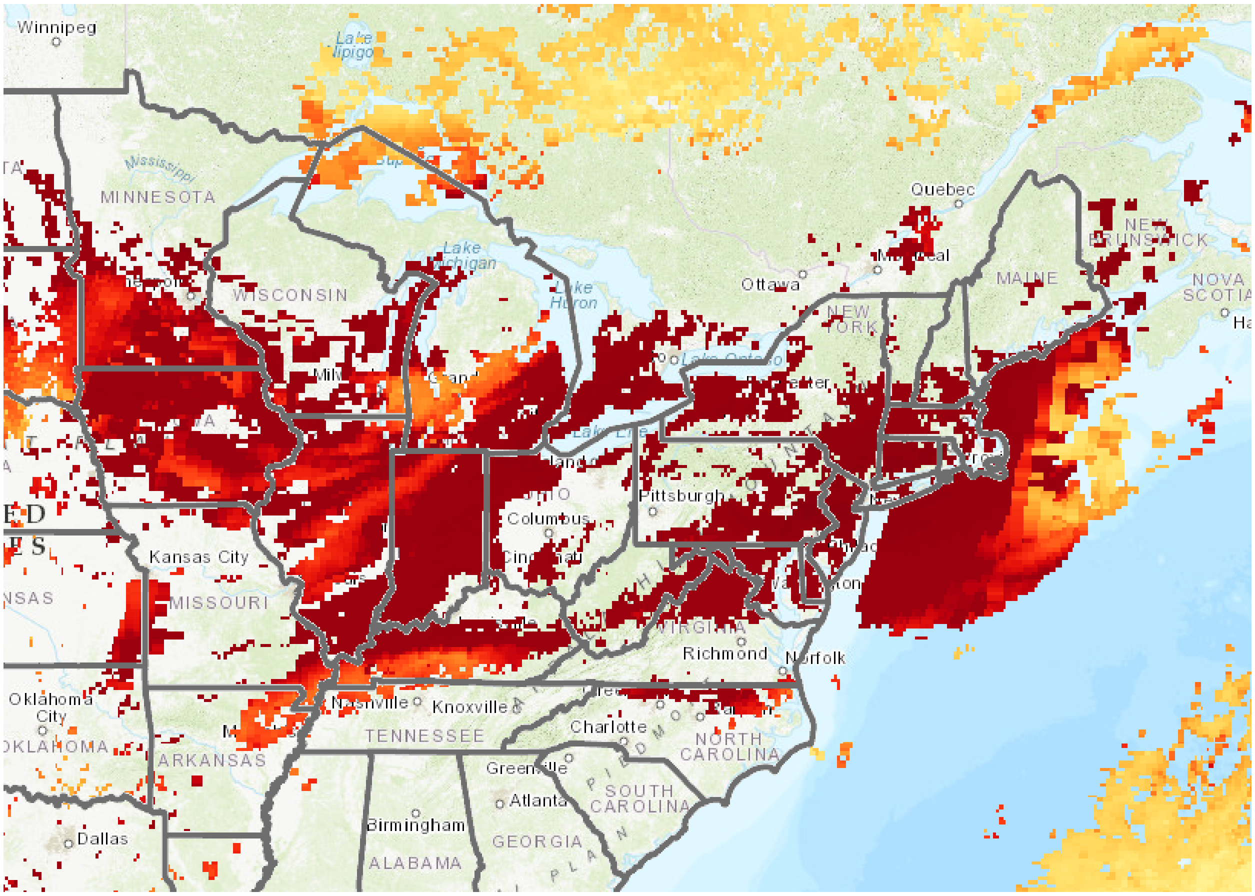

Figure 34. AOD visual output from the MODIS satellite from July 20, 2021. High AOD values are indicated in dark red, denoting high particle amounts throughout the entire column of the atmosphere. Courtesy: AirNow-Tech

To assess AOD, Sonoma Technology meteorologists obtained MODIS satellite data from the NASA Giovanni database. Using a bounding box to extract data for Delaware, AOD readings for May-September 2021 were compared to a calculated historical average of monthly AOD values. To account for recent air quality trends, and to be consistent with air quality climatology in this report, this calculated average spanned the five-year period from 2016-2020. Figure 35 shows the 2021 monthly average AOD values for summer 2021 versus the 5-year average monthly AOD.

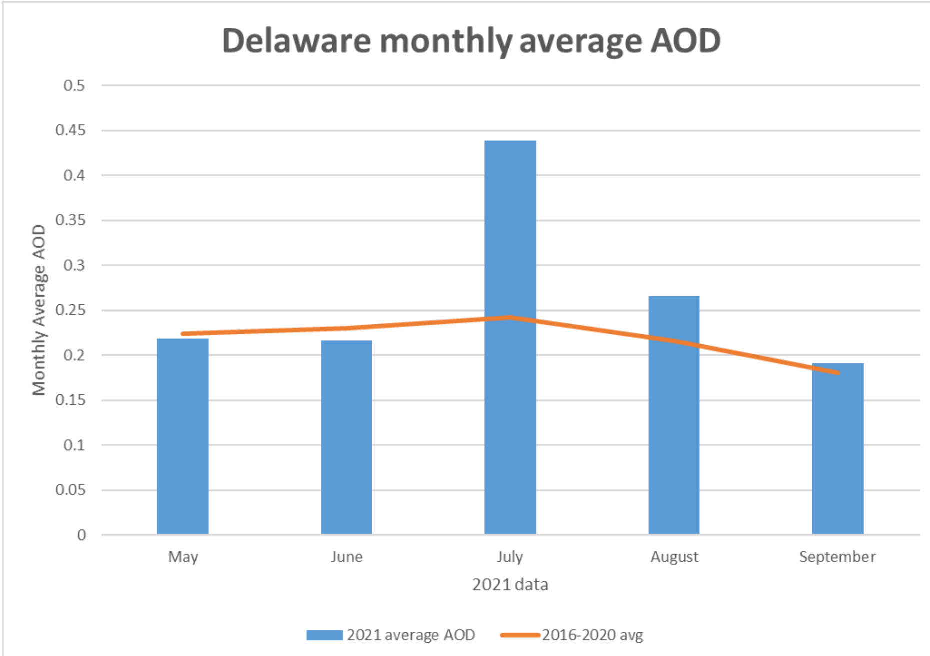

Figure 35. Monthly average AOD for summer 2021 (bars) and 2016-2020 (orange line).

In May and June 2021, AOD readings for Delaware were comparable to their respective five-year averages. However, the July 2021 AOD reading was much higher than normal. In addition, the July 2021 AOD reading over Delaware was the 5th highest recorded by MODIS satellite since record keeping started in 2003. Furthermore, the July 2021 AOD reading was the highest since July 2006 (**Table 7**).

Table 7. Highest monthly mean AOD values for Delaware, derived from MODIS satellite.

Date	Mean AOD Value (unitless)
8/2002	0.49
7/2006	0.48
7/2002	0.47
6/2003	0.45
7/2021	0.44

While an in-depth analysis would be needed to accurately assess the smoke's contribution to Delaware's AQI levels, this preliminary analysis suggests wildfire smoke was a considerable influence on observed air quality levels in summer 2021.

3.5 Summary of USG $PM_{2.5}$ days in summer 2021

As shown in Figure 33, two USG $PM_{2.5}$ days were recorded in New Castle County during summer 2021, marking the first occurrence of a USG $PM_{2.5}$ summer day since 2011. These USG readings occurred on consecutive days, July 20 and 21, 2021. This section summarizes the meteorological conditions during this period of poor air quality and the likely sources for high particle levels.

In early July 2021, prior to this two-day event, a series of large wildfires developed across the western U.S. and southern Canada. By the middle of the month, dense smoke emitted from these fires became lofted into the atmosphere and entrained within an upper-level ridge of high pressure positioned over the Intermountain West (**Figure 36**). As the ridge gradually strengthened and expanded eastward, upper-level winds over the eastern U.S. became westerly to northwesterly, allowing lofted smoke to be transported into the mid-Atlantic region.

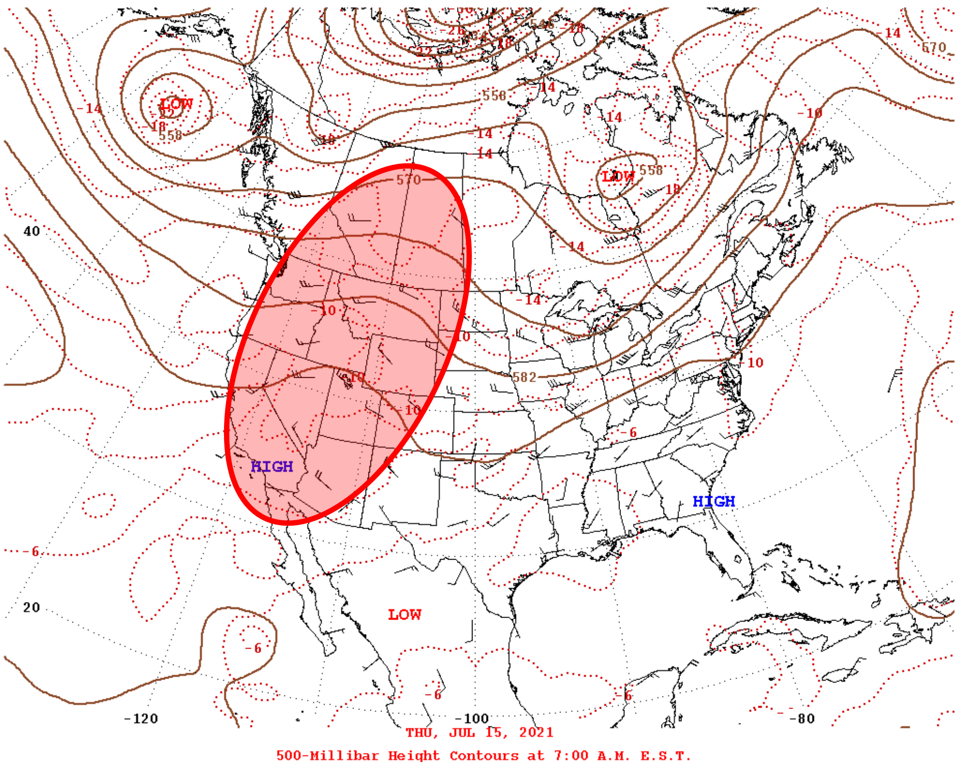

Figure 36. 500 mb map, valid July 15, 2021. Smoke from wildfires in the western U.S. and southern Canada became entrained in a developing upper-level ridge of high pressure (red shading). Courtesy: Weather Prediction Center (WPC)

Along with the upper-level pattern, low-level winds shifted to westerly to northwesterly starting on the afternoon on July 18, 2021 (**Figure 37**). These lower-level winds allowed smoke to be gradually carried into Delaware. After Good AQI values were recorded on July 18, smoke transport caused AQI levels to reach the high-Moderate category on July 19.

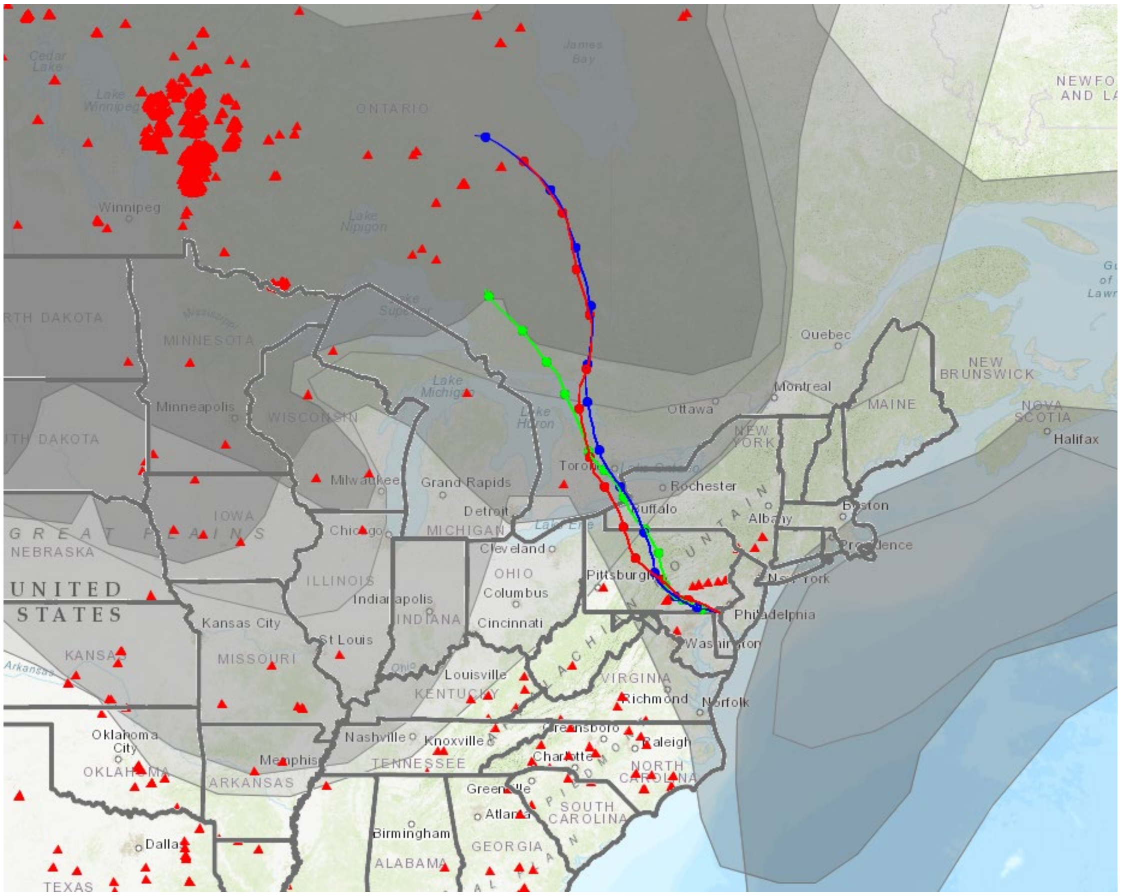

Figure 37. HMS smoke and fire detections, valid July 17, 2021, and 72-hour back trajectories ending at 12 a.m. ET on July 21, 2021. Low-level winds (green-250 m, blue-500 m, red-1,000 m) transported smoke (gray shading) from Canadian wildfires (red triangles) into Delaware. Courtesy: AirNow-Tech

By July 20 and 21, 2021, dense smoke was observed over the First State, with increasing particle levels due to transport and pollutant carryover from the day to day. Furthermore, surface high pressure west of the state limited dispersion, generating wind speeds that averaged around 5-10 mph throughout the day (Figure 38). Due to light westerly to northwesterly winds, smoke and regional pollutants accumulated across the mid-Atlantic region.

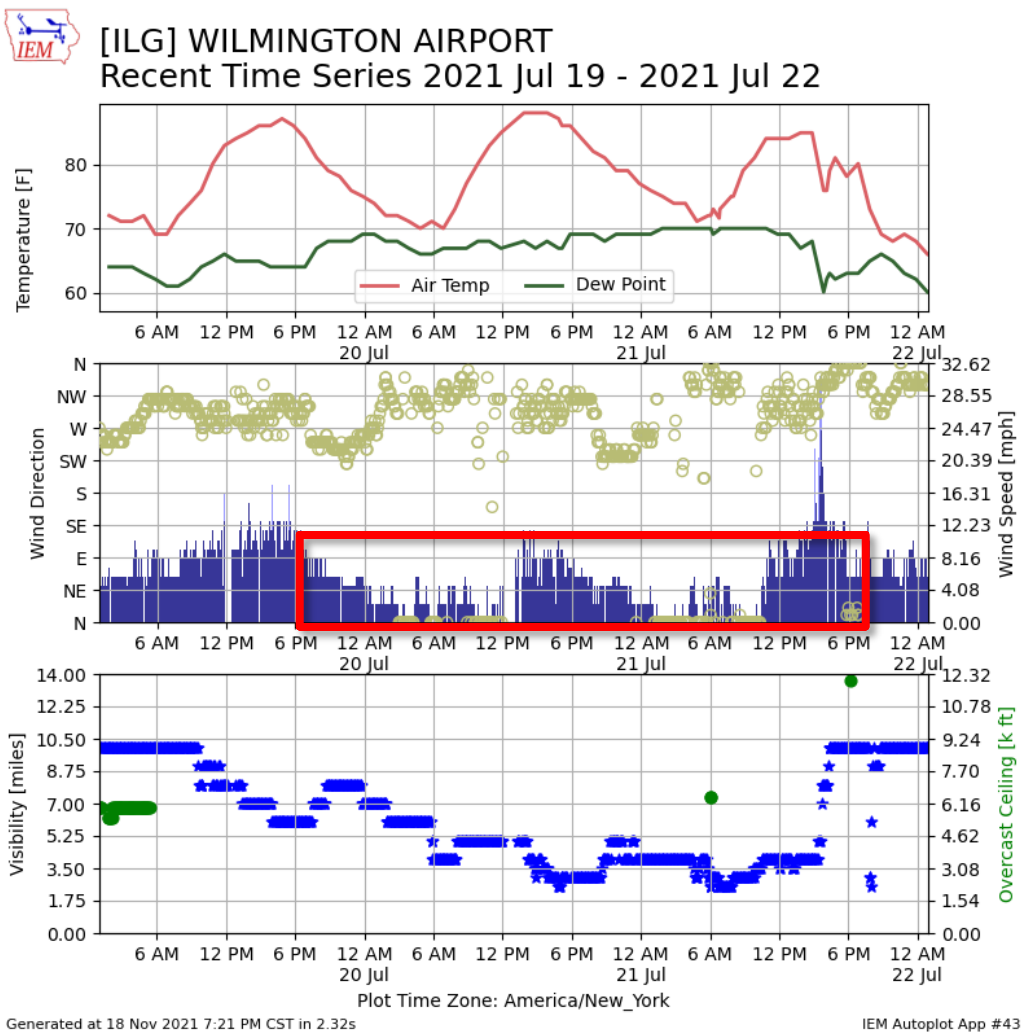

Figure 38. Meteogram from the New Castle County Airport, valid July 19-22, 2021. Surface winds speeds around 5-10 mph on July 20 and 21 (red rectangle) limited dispersion of smoke and allowed pollutants to accumulate. Courtesy: Iowa State Mesonet.

Localized weather conditions also influenced particle levels on these days. At the New Castle County airport each morning, low-level moisture associated with fog and mist enhanced particle production. Daytime high temperatures also impacted particle concentrations, with observed high temperatures on these days peaking in the upper-80s, which generated deep atmospheric mixing. Through this vertical mixing process, lofted smoke in the upper levels of the atmosphere was transported down to the surface, which further increased ground-level particle concentrations.

These factors, along with ambient regional emissions, resulted in all three $PM_{2.5}$ monitoring sites in New Castle County reaching USG AQI levels on July 20 (Figure 39), with a peak AQI value of 144 recorded at the MLK site. By July 21, 2021, the MLK site was the lone monitor in New Castle County to register USG AQI levels, reaching the 24-hour average AQI value of 106.

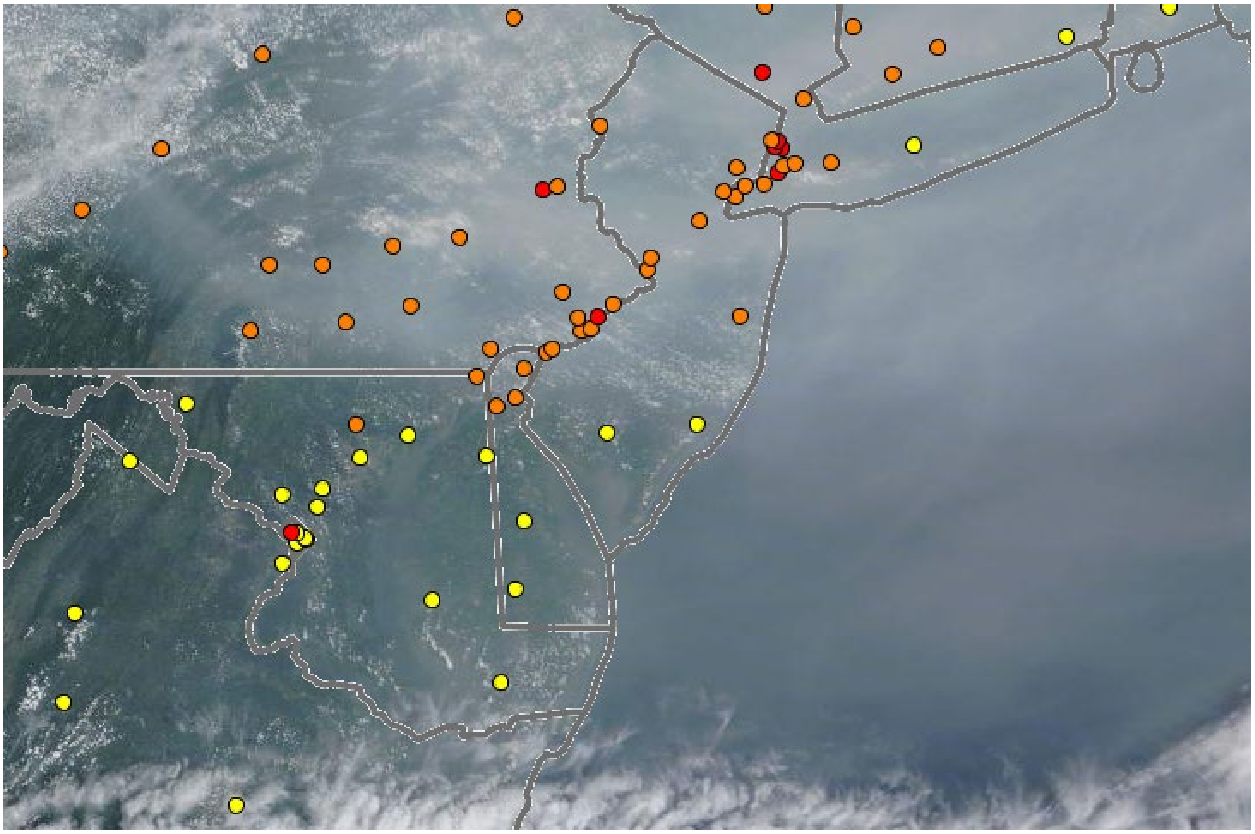

Figure 39. MODIS Terra satellite image and 24-hour observed $PM_{2.5}$ AQI values on July 20, 2021. Dense smoke (denoted in haze above) caused AQI values to peak in the USG category at all three New Castle County monitoring sites (orange dots). Courtesy: AirNow-Tech

Air quality models captured the general trend of increasing $PM_{2.5}$ levels during this period, with large contributions due to smoke transport. Two models used in operational forecasts by Sonoma Technology meteorologists include the NOAA NAQFC model and HRRR-Smoke model.

The NOAA NAQFC model utilizes the previous day's satellite fire detections to predict surface-based $PM_{2.5}$. The model runs twice daily at 12-km grid spacing, forecasting daily average AQI values out to 72 hours in the future.

For the HRRR-Smoke model, satellite fire detections are incorporated on an hourly basis, with four model runs per day predicting hourly $PM_{2.5}$ up to 60 hours in advance. While daily average AQI forecasts for $PM_{2.5}$ are not generated in the HRRR-Smoke model, these hourly $PM_{2.5}$ concentration forecasts are available from the ground level to the upper levels of the atmosphere, capturing lofted smoke transport. Compared to the NOAA NAQFC model, the HRRR-Smoke model is able to capture finer details in smoke spatially due to a 3-kilometer grid spacing.

Next-day forecasts from the NOAA NAQFC and HRRR-Smoke models indicated varying degrees of $PM_{2.5}$ concentrations over the First State during the period. The HRRR-Smoke model run from July

19, 2021, showed a narrow band of dense surface smoke (Figure 40) over far northern New Castle County on the evening of July 20, 2021, while lighter smoke was predicted in central and southern Delaware.

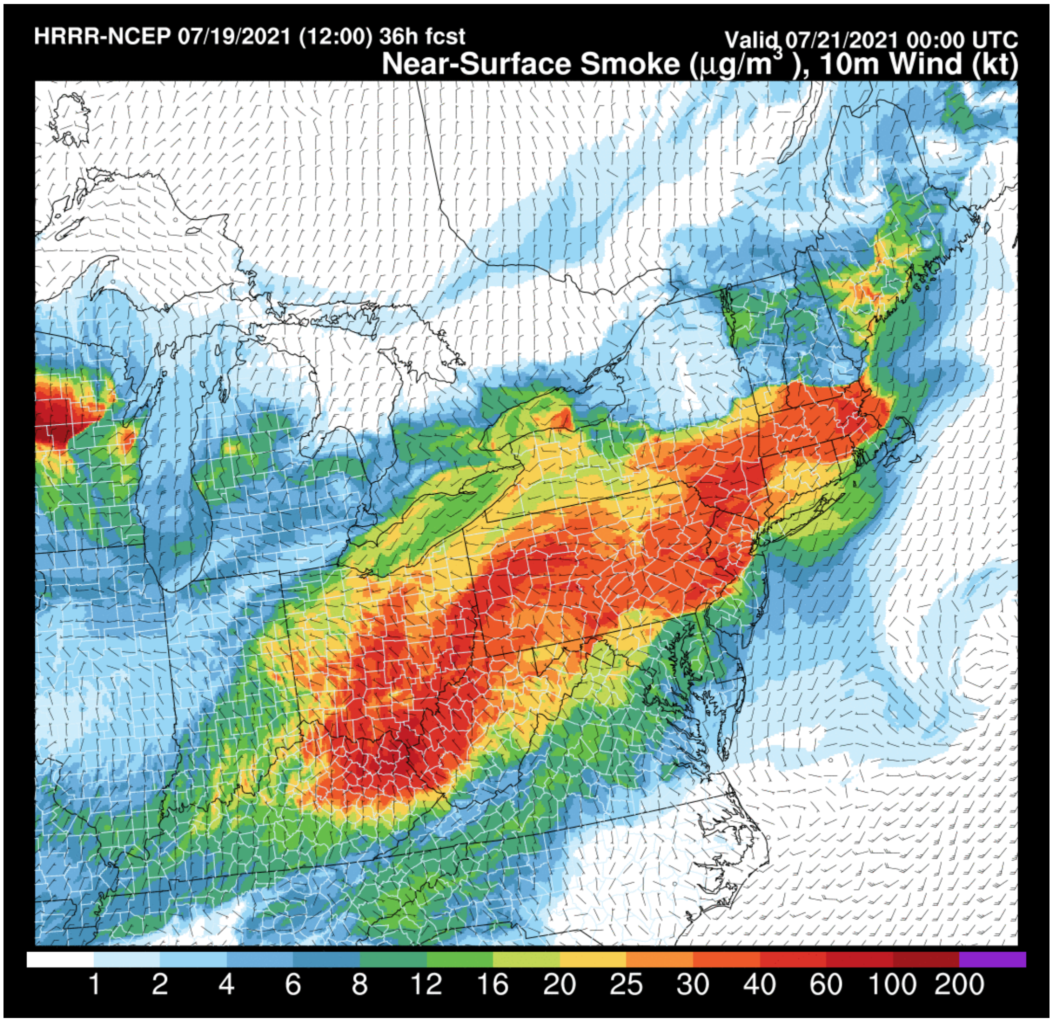

Figure 40. HRRR-Smoke near-surface model run from July 19, 2021, valid 8 p.m. ET on July 20, 2021. Courtesy: rapidrefresh.noaa.gov/hrrr/HRRRsmoke

On the other hand, the bias-corrected version of the NOAA NAQFC model run (Figure 41) from the morning of July 19, 2021, showed widespread smoke impacts on July 20 across Delaware and the entire mid-Atlantic region. 24-hour forecast AQI levels from the NOAA NAQFC model on July 20, 2021, were predicted to reach the Unhealthy category.

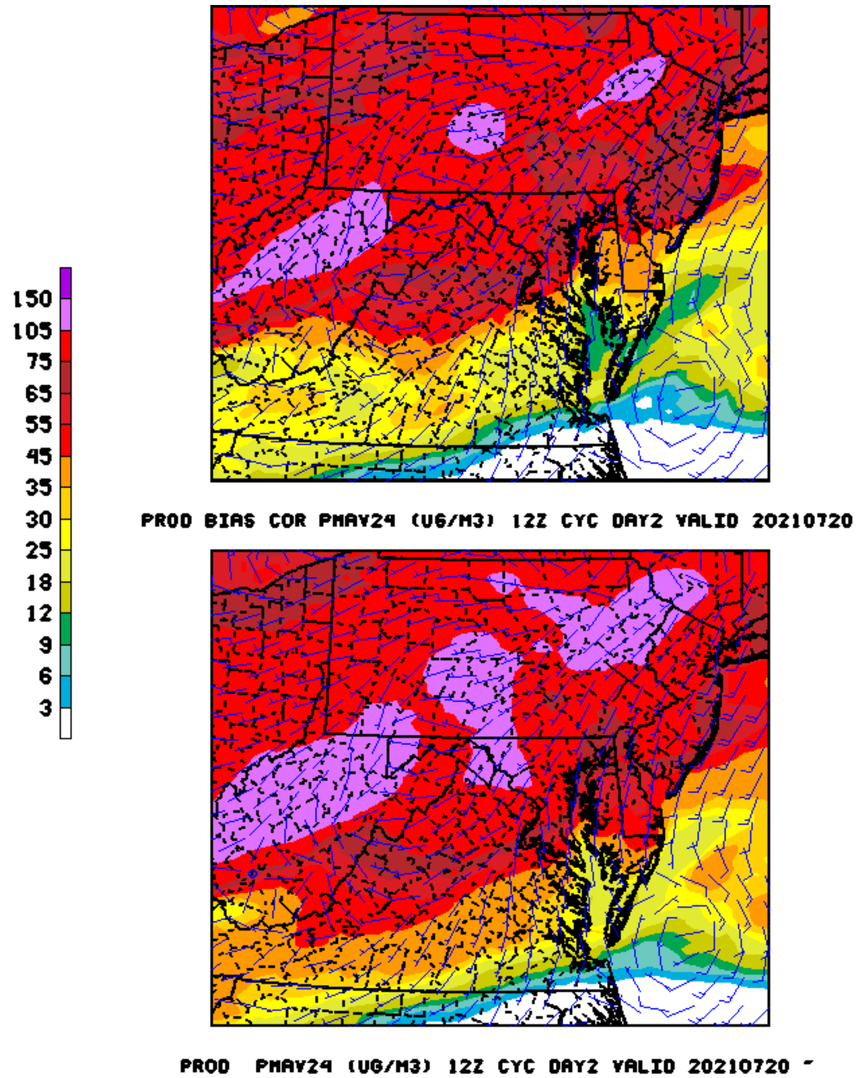

Figure 41. NOAA NAQFC daily average $PM_{2.5}$ AQI forecast for July 20, 2021, generated from the morning model run on July 19, 2021. Courtesy: www.emc.ncep.noaa.gov

Ultimately, the daily max AQI $PM_{2.5}$ value for July 20, 2021, was 146 at the MLK monitoring site, which is in the high-USG category. While the observed AQI value for the day was closer to the NOAA NAQFC prediction of Unhealthy AQI levels, the HRRR-Smoke model had predicted high $PM_{2.5}$ concentrations aloft. As previously mentioned, daytime heating associated with afternoon temperatures in the upper-80s likely increased vertical mixing, allowing aloft smoke to reach the surface.

Air quality models the morning of July 20 also predicted continued high $PM_{2.5}$ values for July 21, 2021. Next-day forecast accuracy from the NOAA NAQFC model decreased (Figure 42), with forecast 24-hour $PM_{2.5}$ AQI values predicted to reach the Moderate category over much of central and northern Delaware on July 21, 2021. Daily AQI data for the day reached low-USG AQI values in New Castle County.

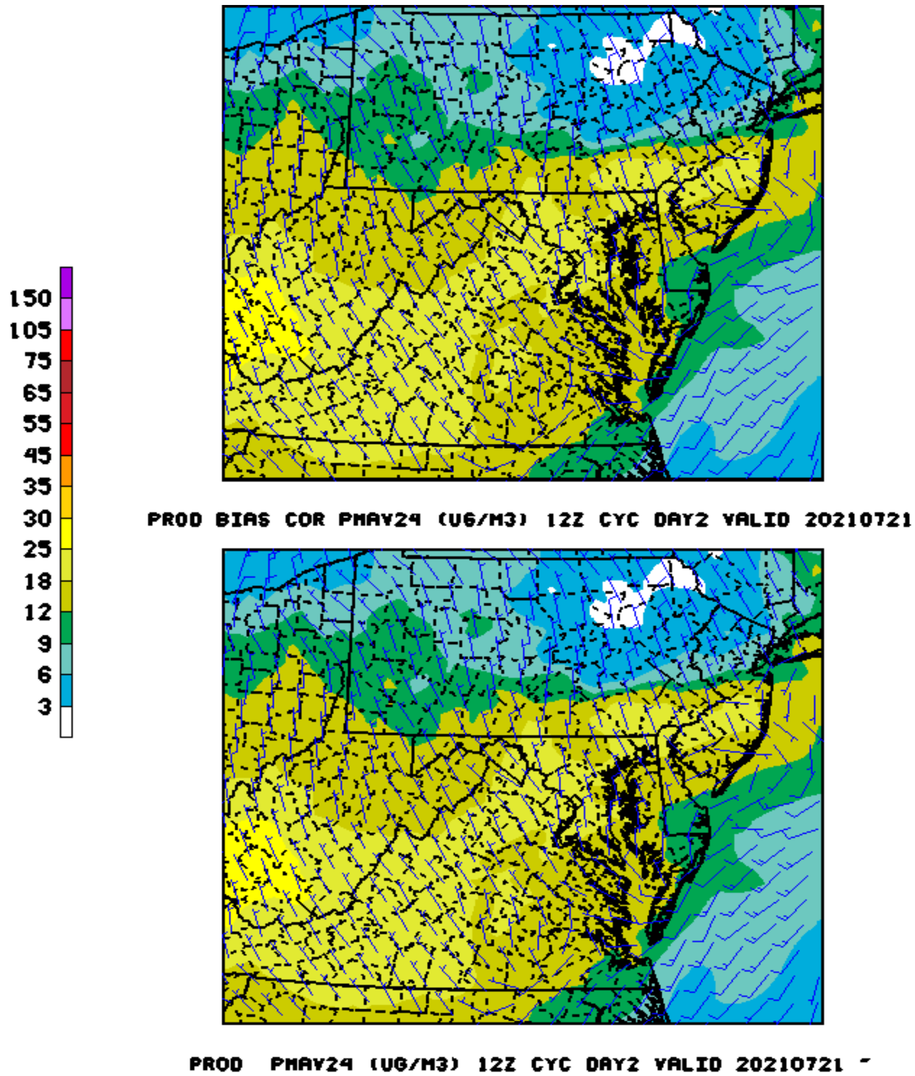

Figure 42. NOAA NAQFC daily average $PM_{2.5}$ AQI forecast for July 21, 2021, generated from the morning model run on July 20, 2021. Courtesy: www.emc.ncep.noaa.gov

By comparison, model performance was improved for the HRRR-Smoke model run (Figure 43) generated the morning of July 20, 2021. The forecast output for July 21, 2021, indicated periods of USG $PM_{2.5}$ levels at the surface, and the HRRR-Smoke model also correctly predicted that $PM_{2.5}$ concentrations would improve the evening of July 21, 2021, due to a cold front passing over the state.

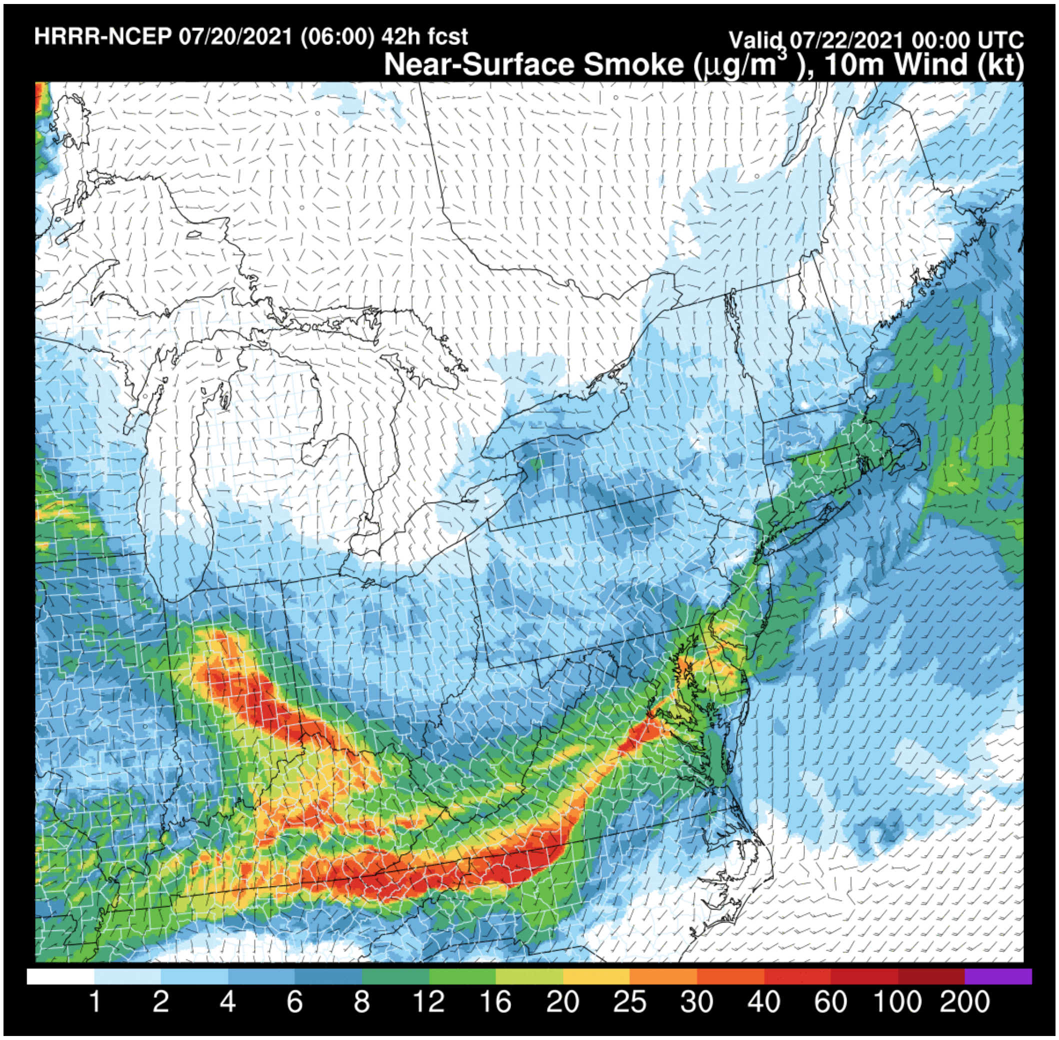

Figure 43. HRRR-Smoke model run from July 20, 2021, valid at 8 p.m. on July 21, 2021. Courtesy: rapidrefresh.noaa.gov/hrrr/HRRRsmoke

Observational data (**Figure 44**) from July 21, 2021, confirms the accuracy of the HRRR-Smoke forecast. High concentrations were observed in the morning and afternoon hours before the frontal passage. By the late afternoon and evening, $PM_{2.5}$ concentrations lowered across the state as the front departed to the east.

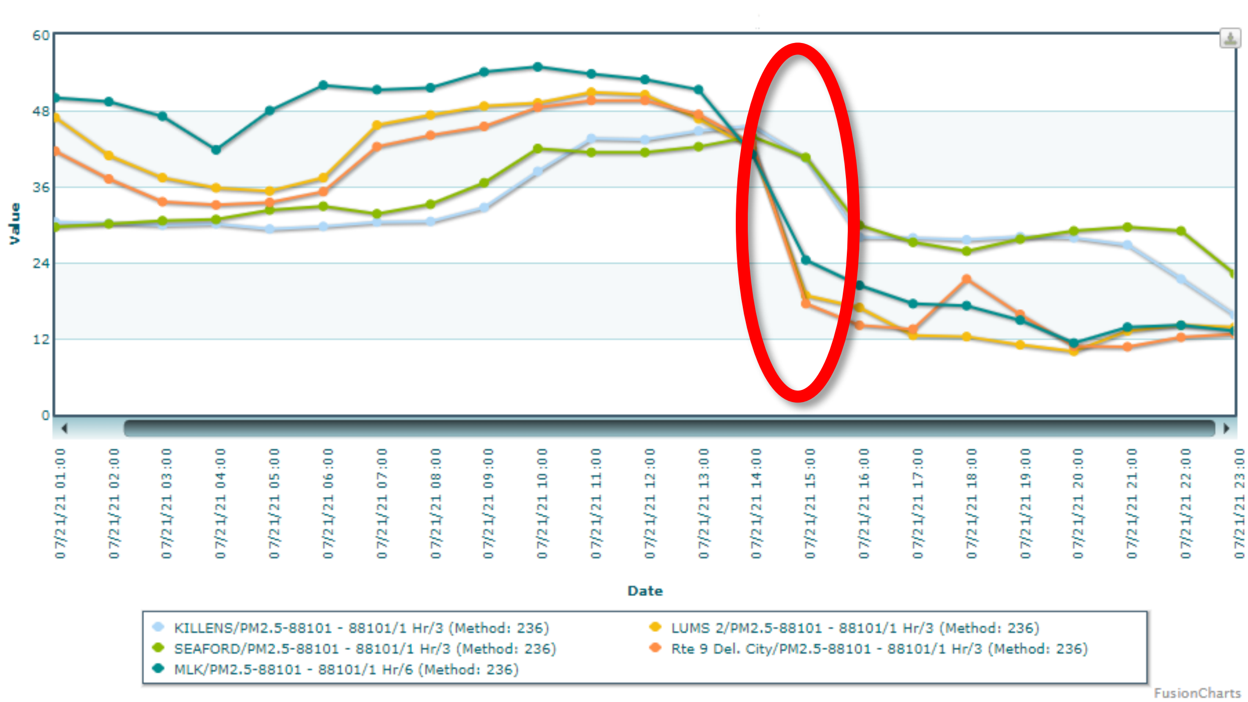

Figure 44. Hourly $PM_{2.5}$ concentrations from Delaware monitoring sites on July 21, 2021. Concentrations decreased in the late afternoon and evening (circled) as a cold front departed the state. Courtesy: AirNow-Tech

4. Skill of Ozone Forecasts in 2021

4.1 Introduction to Sonoma Technology Forecasts

During the summer 2021 ozone season in Delaware, Sonoma Technology meteorologists issued three-day forecasts during the weekdays. On occasion, forecasts were issued on the weekends when ozone concentrations were approaching Code Orange levels. However, the majority of next-day forecasts were issued between Mondays and Fridays, valid for Tuesdays through Saturdays.

Due to true next-day forecasts being unavailable on Sundays and Mondays, and to accurately assess forecast skill, observed ozone levels in summer 2021 were compared to next-day forecasts valid for Tuesdays through Saturdays, day-2 forecasts valid for Sundays, and day-3 forecasts valid for Mondays. These forecast values are referred to as "Sonoma Technology Forecasts" in the following sections.

4.2 2021 Ozone Forecast Statistics

Sonoma Technology Forecasts captured the general trend of observed ozone levels in Delaware during summer 2021 (**Figure 45**). Sonoma Technology only issued two forecasts in the USG category, and all other forecasts were in the Good and Moderate categories. Using the Good-to-Moderate threshold to verify forecast accuracy, Sonoma Technology Forecasts in Delaware were correct 88% of the time during summer 2021.

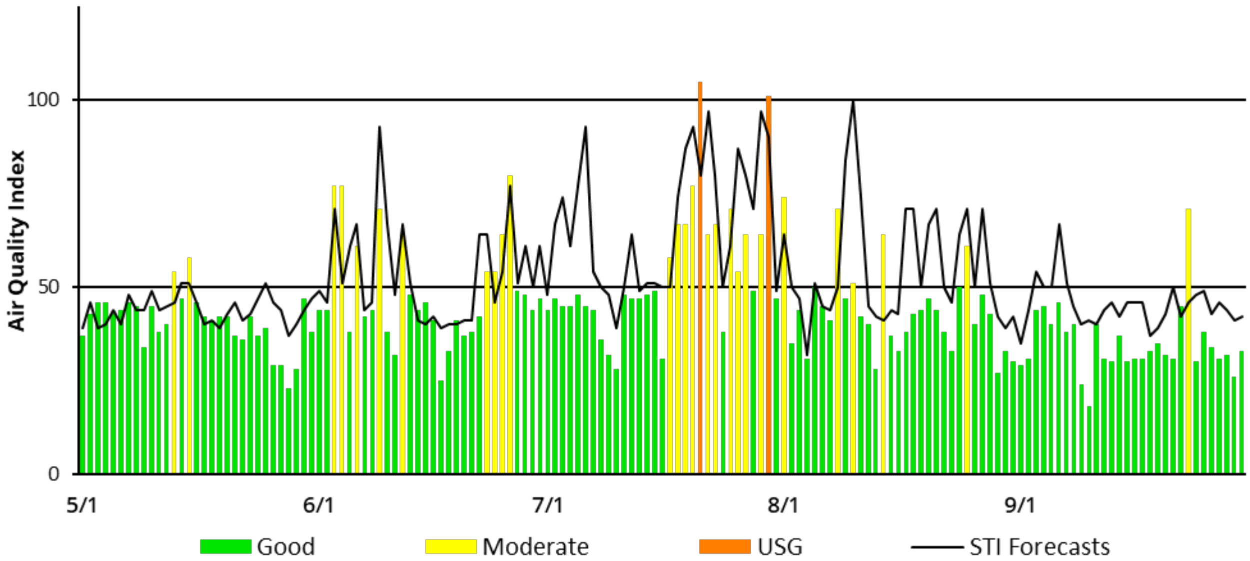

Figure 45. Daily observed ozone levels in Delaware versus Sonoma Technology, Inc. (STI in the graph above) Forecasts.

Moderate or higher ozone levels were observed on 43 days out of 153 forecast days in summer 2021, which was a 9% increase over summer 2020. Sonoma Technology forecasters issued a Moderate AQI-level forecast on 34 of the 40 observed days with Moderate AQI values. This resulted in a POD of 85% for days with Moderate AQI levels. While Sonoma Technology issued high-Moderate forecasts on two of the three USG ozone days, none of the observed USG days were forecasted at USG AQI levels. For more information on the meteorological conditions and other factors that lead to the season's highest AQI levels, refer to Section 2.2.

Forecast false alarms occur when the forecast ozone AQI category is higher than the observed ozone AQI category. Of the 59 days during summer 2021 when Moderate ozone levels were forecast, there were 22 instances when observed ozone AQI levels were lower than the forecast levels (i.e., in the Good AQI category). As a result, the False Alarm Rate (FAR) for Moderate forecasts during summer 2021 was 37%. USG ozone levels were forecast on only two days this summer: July 7, 2021, and August 25, 2021. While both USG ozone forecasts ended up as false alarms, the actual AQI value on August 25 was 100, while the forecast was 101. This amounts to a difference of only 1 ppb. Based on Percent Correct, POD, and FAR, forecast performance improved in 2021 compared to 2020 (Figure 46).

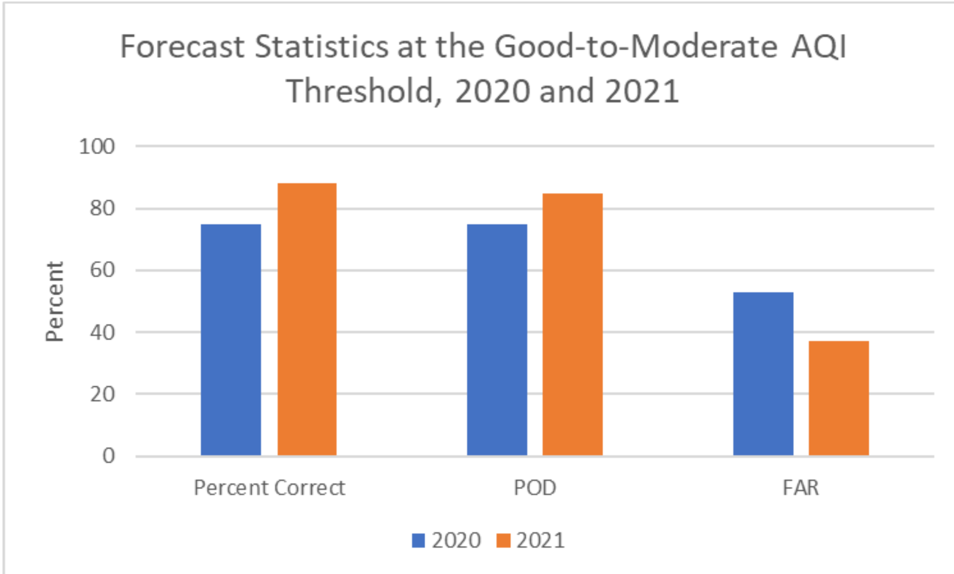

Figure 46. Percent Correct, Probability of Detection (POD) and False Alarm Rate (FAR) at the Good-to-Moderate AQI threshold in 2020 and 2021.

Forecast skill can also be assessed by calculating forecast bias and mean absolute error (MAE) through comparing the forecasted ozone concentrations to observed concentrations. Bias is the average difference between forecasted and observed concentrations. A positive bias indicates that the forecasted concentrations tended to be higher than observed concentrations. Conversely, a negative bias indicates that the forecasted concentrations tended to be lower than observed. MAE indicates the average absolute difference between forecast and observed concentrations. A low MAE suggests that forecasts were fairly accurate.

Table 8 provides the forecast bias and MAE for all Sonoma Technology Forecasts during summer 2021 based on daily maximum 8-hr average ozone concentrations. For the May-September 2021 period, Sonoma Technology Forecasts exhibited a bias of +4.7 ppb over observed ozone values, with a MAE of 6.8 ppb. Sonoma Technology Forecasts were most biased in June 2021 at 7.1 ppb, and least biased in May and September 2021. Overall, Sonoma Technology Forecasts strive to be protective of public health while still maintaining accuracy, which resulted in the positive forecast bias.

Table 8. Sonoma Technology forecast bias and MAE for next day forecasts for summer 2021.

Month	Bias (ppb)	Mean Absolute Error (ppb)
May	+2.8	5.0
June	+7.1	8.4
July	+4.7	8.0
August	+5.6	6.7
September	+3.3	6.0
Average	+4.7	6.8

4.3 2021 $PM_{2.5}$ Forecast Statistics

As discussed in Section 3.4, Sonoma Technology meteorologists issued $PM_{2.5}$ forecasts in addition to ozone forecasts for Delaware from late-July to early-August when long-range smoke transport brought a significant increase of fine particles to the East Coast. As shown in **Figure 47**, Sonoma Technology issued 10 forecasts in the Good AQI category, 11 forecasts in the Moderate AQI category, and 1 forecast in the USG AQI category. Using the Good-to-Moderate threshold to verify Sonoma Technology's forecast accuracy during this short period of time, Sonoma Technology Forecasts of $PM_{2.5}$ in Delaware were correct 87% of the time.

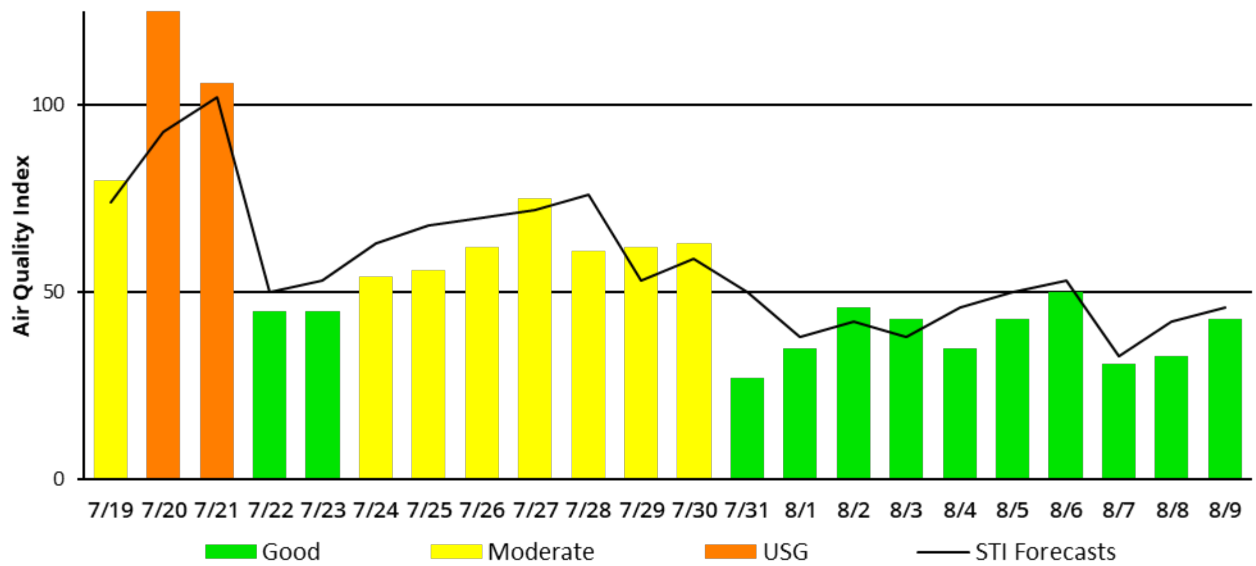

Figure 47. Daily observed ozone levels in Delaware versus Sonoma Technology Forecasts. The forecast for July 19, 2021, represents the same-day forecast, while all other forecasts represent next-day forecasts.

Out of the 22 $PM_{2.5}$ forecast days in summer 2021, Moderate or higher $PM_{2.5}$ levels were observed on 10 days. Sonoma Technology forecasters issued a Moderate AQI level forecast on all eight of the days with observed Moderate AQI values. This resulted in a POD of 100% for days with Moderate AQI levels. AQI levels reached the USG category on two of the 22 forecast days, and Sonoma Technology issued a USG forecast on one of those days, yielding a POD of 50%. Of the 11 days during summer 2021 when Moderate $PM_{2.5}$ levels were forecasted, there were two instances when observed $PM_{2.5}$ AQI levels were lower than the forecast (i.e., in the Good AQI category). As a result, the FAR for Moderate $PM_{2.5}$ forecasts during summer 2021 was 18%. USG ozone levels were forecasted on only one day this summer (July 21). On the only day when USG AQI levels were forecasted, USG AQI levels were observed, resulting in an FAR of 0% for USG forecasts.

Table 9 provides the forecast bias and MAE for the Sonoma Technology $PM_{2.5}$ forecasts during summer 2021 based on daily 24-hr average $PM_{2.5}$ concentrations. For the short period from late July to early August, Sonoma Technology Forecasts exhibited minimal bias at -.04 ug/m^3 under observed $PM_{2.5}$ values, with a MAE of 3.2 ug/m^3.

Table 9. Sonoma Technology forecast bias and MAE for next day $PM_{2.5}$ forecasts for summer 2021.

Forecast Period	Bias (ug/m^3)	Mean Absolute Error (ug/m^3)
July 19 – Aug 9	-.04	3.2

5. Skill of Ozone Model Forecasts in 2021

5.1 Introduction to Ozone Model Forecasts

Sonoma Technology meteorologists utilize a variety of tools to issue ozone forecasts for the state of Delaware. One useful tool that Sonoma Technology uses in day-to-day operations is ozone model guidance, which generally provides same- and next-day forecasts for cities across the U.S.

To aid in forecast decision-making, Sonoma Technology meteorologists use three different ozone computer models. These models include:

- NOAA ozone model, run twice daily (**https://digital.mdl.nws.noaa.gov/airquality/**)
- National Centers for Environmental Prediction (NCEP) Community Multiscale Air Quality (CMAQ) bias-corrected ozone model, run twice daily. However, accuracy metrics are only computed for the 12Z model run. (**https://www.emc.ncep.noaa.gov/mmb/aq/cmaqbc/web/html/max.html**)
- BlueSky-Gateway (BSG) ozone model, run once daily. This model was only available for 54% of the days in the summer 2021 ozone season, mainly during the spring and early summer.

The following sections analyze the skill of each model's next-day forecast output and compare model performance to Sonoma Technology Forecasts during summer 2021.

5.2 2021 Ozone Model Forecast Statistics

Table 10 provides each model run's next-day forecast bias and MAE for the summer 2021 ozone forecast season. Data for each model run are specific to Wilmington, Delaware.

Table 10. May-September 2021 next-day forecast model statistics for Wilmington, Delaware.

Model	Bias (ppb)	Mean Absolute Error (ppb
NOAA 06Z	-2.2	6.7
NOAA 12Z	-1.8	6.3
BSG Bias-Corrected 00Z	-4.3*	6.5*
BSG Ras 00Z	-1.9*	5.8*
NCEP CMAQ Bias-Corrected 12Z	-2.7	6.6

*The BSG model was only available for 54% of the days this ozone season, mainly during spring and early summer.

For the 2021 ozone forecast season, the magnitude of the next-day forecast bias was greatest for the Bias-Corrected 0Z BSG model run, while the highest MAE was observed on the 06Z NOAA model. In comparison, the NOAA 12Z run had the least biased predictions, while BSG's raw 0Z output had the lowest MAE, which is likely due in part to its limited time operating during the peak of the summer ozone season.

A month-by-month breakdown of next-day forecast bias and MAE is provided in Figures 48 and 49. Throughout the summer 2021 ozone season, most models had some degree of negative bias. These negative biases were most significant on the fringes of the season in May and September 2021, but there was also an increase in underpredictions during July 2021. Further inspection showed that for the first half of July, models averaged a slight positive bias. However, for the second half of July, all forecast models had large negative biases. This period corresponds to the timeframe when significant wildfire smoke was impacting Delaware. It is likely that the models underrepresented the increase in ozone precursors from the smoke during the second half of July, which led to underpredictions of ozone.

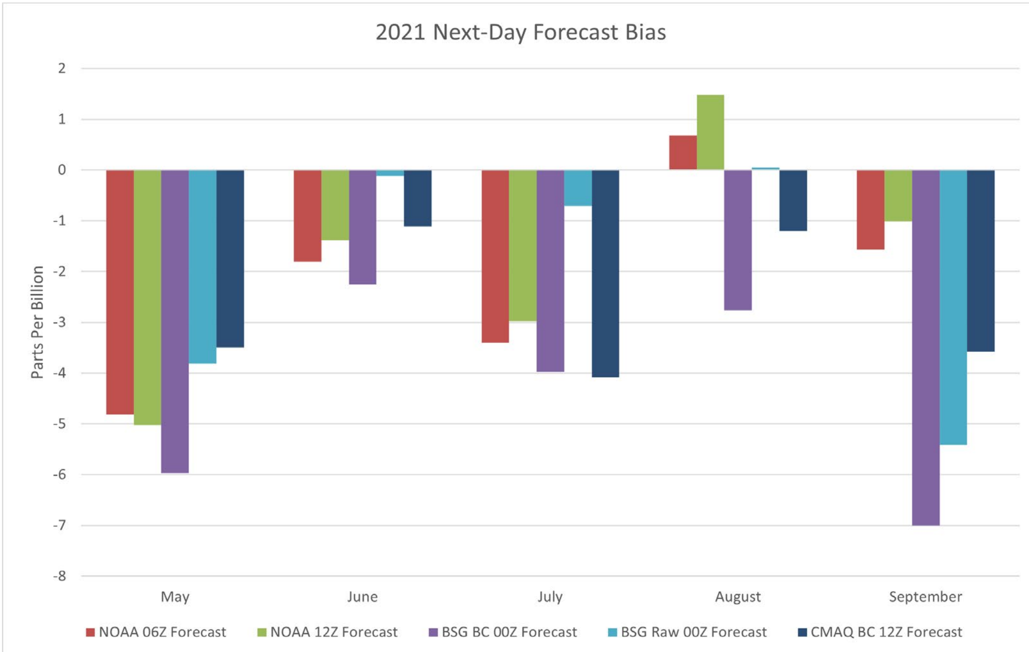

Figure 48. Monthly model forecast bias during the summer 2021 ozone season in Wilmington, Delaware.

The MAE across all models was generally between 4-8 ppb throughout the summer 2021 ozone season, although the MAE for the NOAA 06Z model approached 9 ppb in July 2021. Overall, the ozone models had similar performance throughout the ozone season, with no individual models consistently outperforming the others.

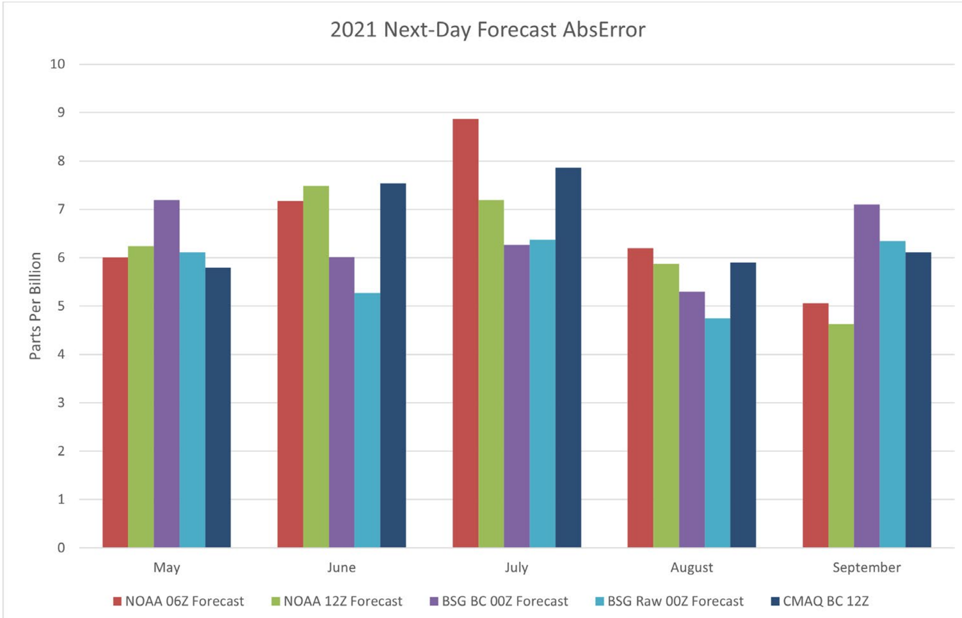

Figure 49. Monthly model MAE during the summer 2021 season in Wilmington, Delaware.

5.3 Comparison of Sonoma Technology Forecasts to 2021 Ozone Model Forecasts

Similar to Figures 48 and 49, **Figures 50 and 51** provide next-day forecast bias and MAE. However, these figures include both ozone model predictions *and* Sonoma Technology Forecasts issued for the summer 2021 ozone season (blue bars at the left of each grouping). Additionally, the average annual bias and MAE for the entire May-September 2021 period is shown at the far right of each figure.

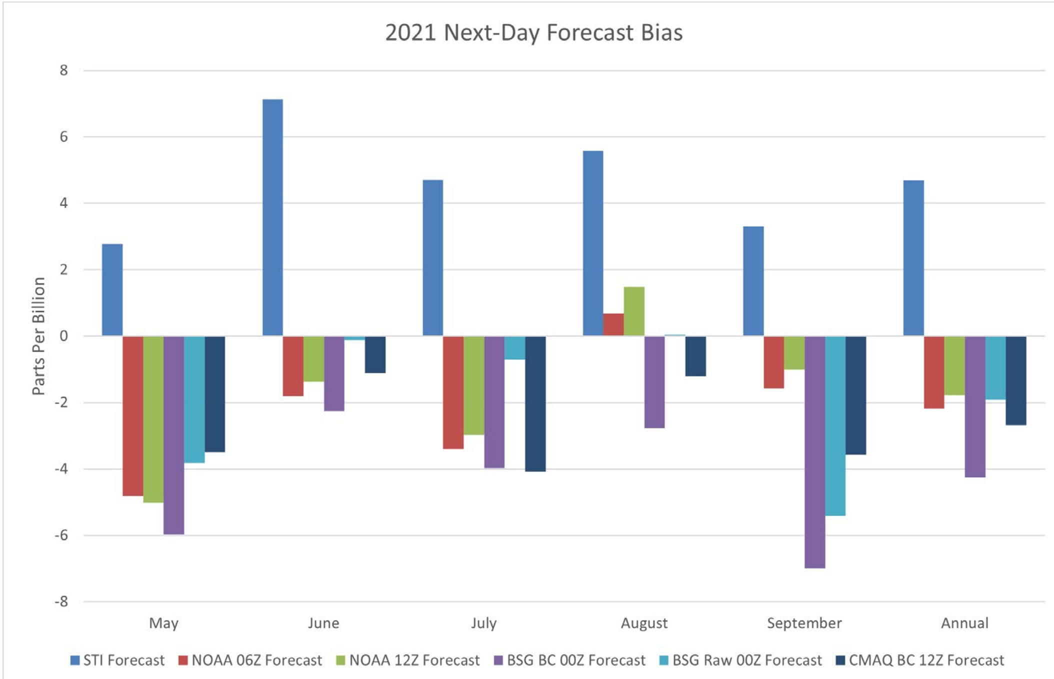

Figure 50. Monthly next-day forecast bias for air quality models and Sonoma Technology Forecasts during the summer 2021 ozone season in Wilmington, Delaware. Annual averages are shown on the far right.

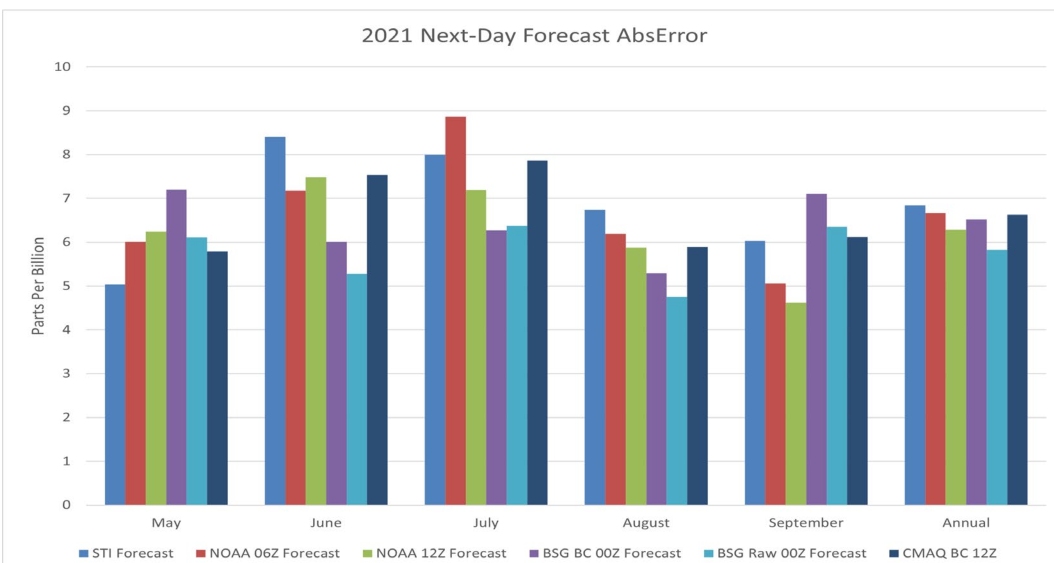

Figure 51. Monthly next-day forecast MAE for air quality models and Sonoma Technology Forecasts during the summer 2021 ozone season in Wilmington, Delaware. Annual averages are shown on the far right.

Sonoma Technology Forecasts had a positive bias every month, while ozone models generally had a negative bias. This difference is most likely due to Sonoma Technology's forecasts representing a forecast statewide maximum 8-hour average, while the models are only being evaluated for a specific location in Wilmington, Delaware. Sonoma Technology Forecasts also tend to be biased high to be protective of vulnerable populations whose health may be negatively impacted by poor air quality and to aid agencies with decision-making support for air quality outreach programs that are implemented on days with high AQI values. In addition, Sonoma Technology Forecasts in summer 2021 included next-day forecasts issued between Mondays and Fridays, along with day-2 forecasts for Sunday and day-3 forecasts for Monday. Long-range forecasts are statistically less accurate than their next-day forecast counterparts. Thus, the inclusion of the longer-range day-2 and day-3 forecasts in the Sonoma Technology Forecast statistics further increased forecast bias.

The MAE of the Sonoma Technology Forecasts was lower than all model MAEs in May 2021, while the MAE of Sonoma Technology Forecasts for June 2021 was slightly higher than the ozone models. On average, the MAE of Sonoma Technology Forecasts was similar to ozone model MAEs throughout the season.

6. Forecast Review and Outlook

6.1 Review of Sonoma Technology's Summer 2021 Outlook

In the 2020 end-of-season report for Delaware, Sonoma Technology meteorologists produced a state-level temperature and precipitation outlook focusing on June, July, and August 2021. Several long-range forecast methods were discussed, including composite analog maps of seasons with similar El Niño-Southern Oscillation (ENSO) conditions, long-range model forecasts, and climatological trends in Delaware's summer temperature and precipitation patterns. The official seasonal forecast from NOAA's Climate Prediction Center (CPC) was also reviewed, along with other methods. Due to strong agreement between each of the methods and the CPC's official forecast, Sonoma Technology meteorologists forecasted a good chance of above-normal temperatures and precipitation in Delaware during summer 2021. The observed statewide temperature and precipitation anomalies for the U.S. in summer 2021 are shown in Figures 52 and 53.

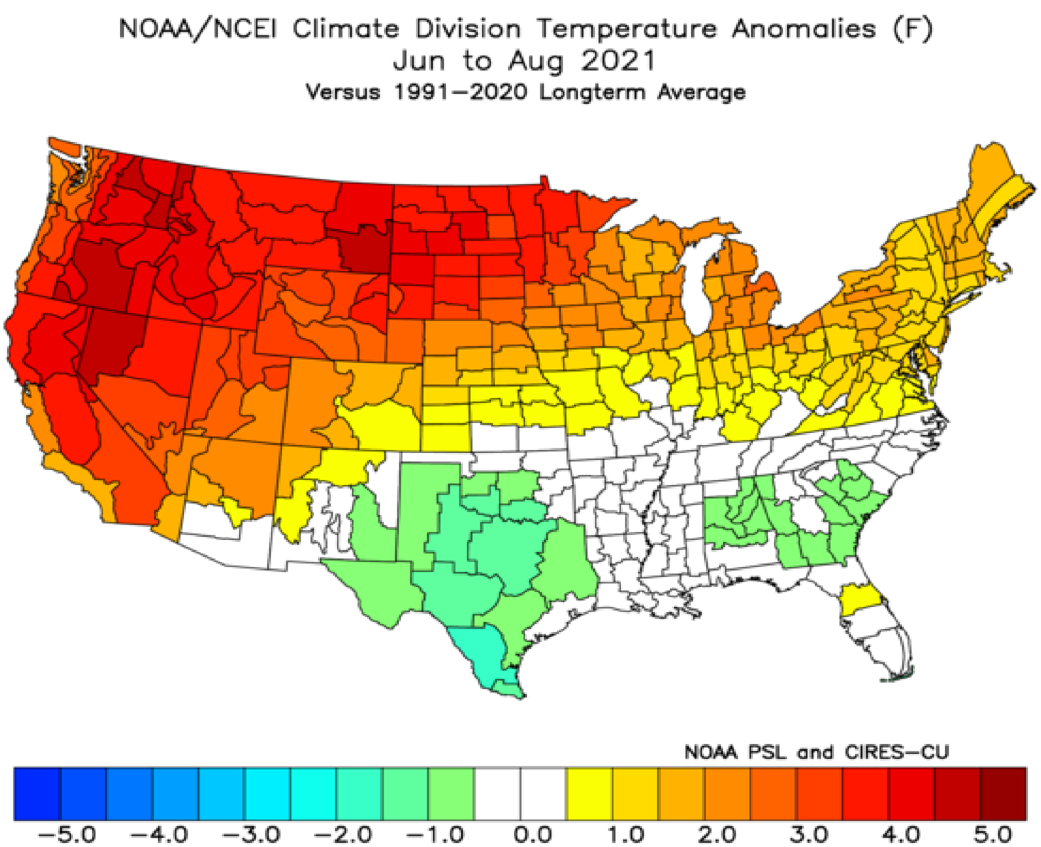

Figure 52. NOAA/NCEI temperature anomalies for summer 2021.

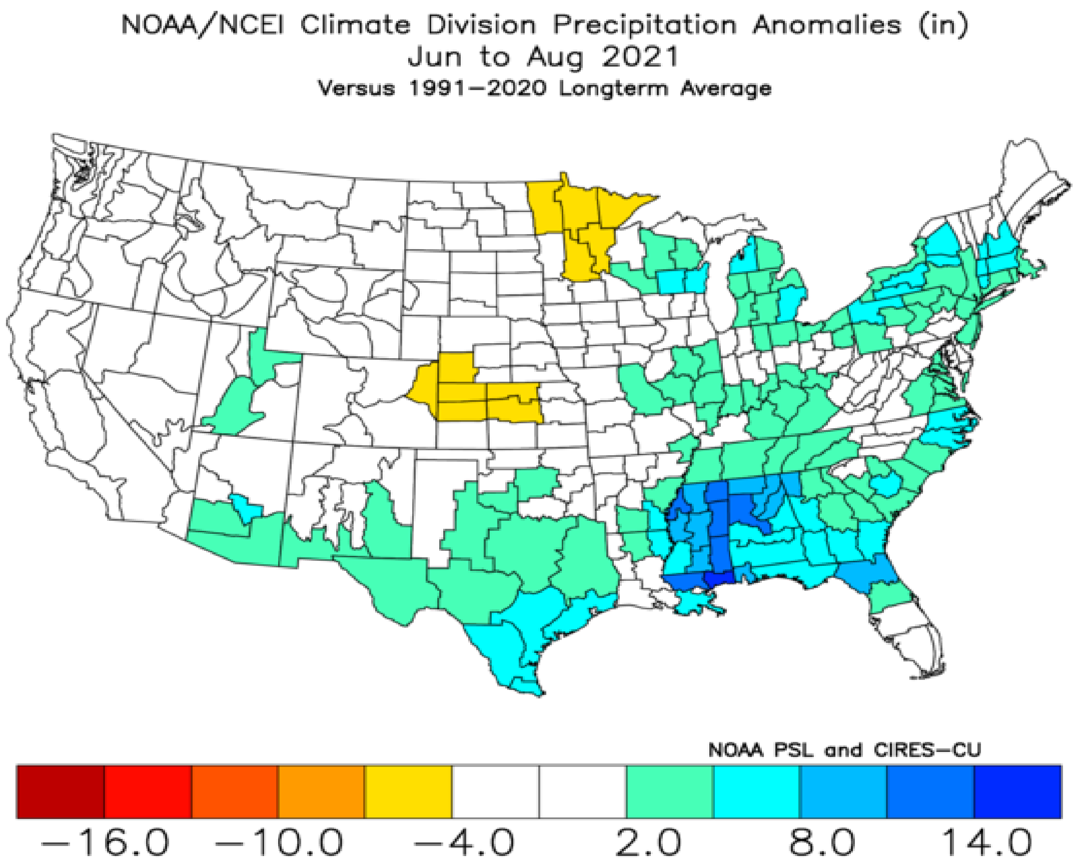

Figure 53. NOAA/NCEI precipitation anomalies for summer 2021.

These maps show that Delaware's average temperatures during summer 2021 were above average. Precipitation was also above average for a large portion of the eastern U.S. However, Delaware's precipitation ended up being near normal. These maps compare favorably with the projections from the CPC, ENSO analogs, and long-range model predictions that the European Centre for Medium-Range Weather Forecasts (ECMWF) generated in spring 2021 (**Figure 54**).

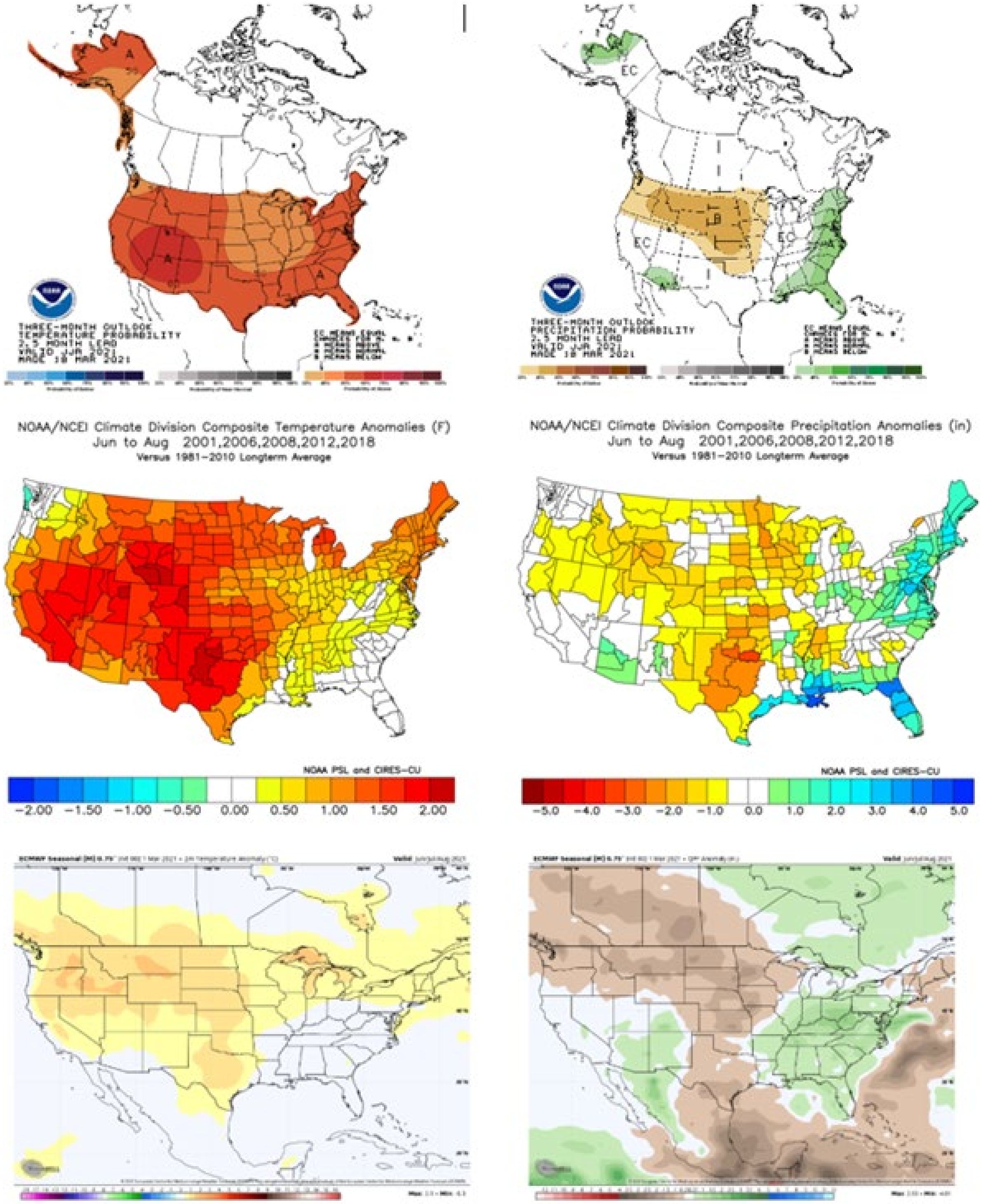

Figure 54. 2021 summer outlooks for temperature (left column) and precipitation (right column) from the CPC, ENSO analogs, and the ECMWF (top to bottom).

6.2 Summer Outlook 2022

To gauge the potential for ozone development during the upcoming 2022 summer season, Sonoma Technology meteorologists reviewed seasonal forecasts by NOAA's Climate Prediction Center (CPC), as well as analog composites of temperature and precipitation anomalies, model outputs from the ECMWF, and the CanSIPS multi-model ensemble. The CanSIPS ensemble is produced by the Canadian Centre for Climate Modelling and Analysis and the Canadian Meteorological Centre. Current trends in summer temperatures and precipitation were also considered. The analysis focused on the forecast for June, July, and August 2022, as these months represent the peak of ozone season in Delaware.

CPC's forecast for temperature and precipitation anomalies for summer 2022 are shown below (**Figures 55 and 56**).

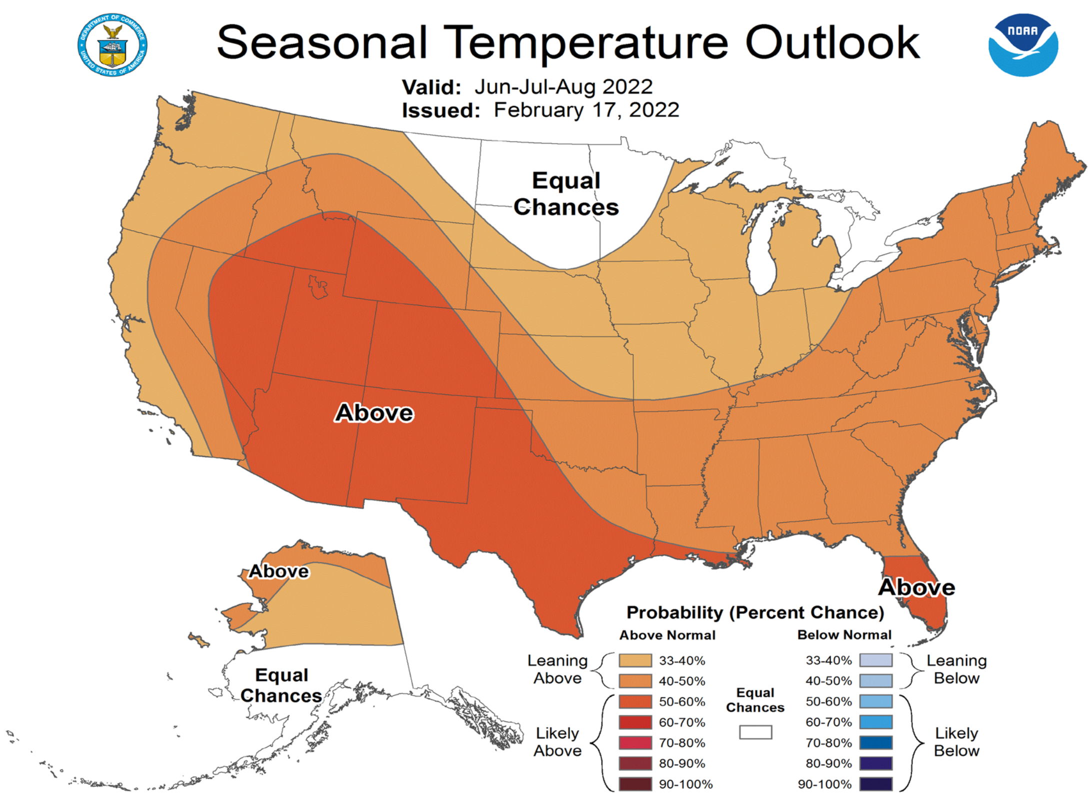

Figure 55. CPC forecast probability of surface temperature anomalies for June, July, and August 2022.

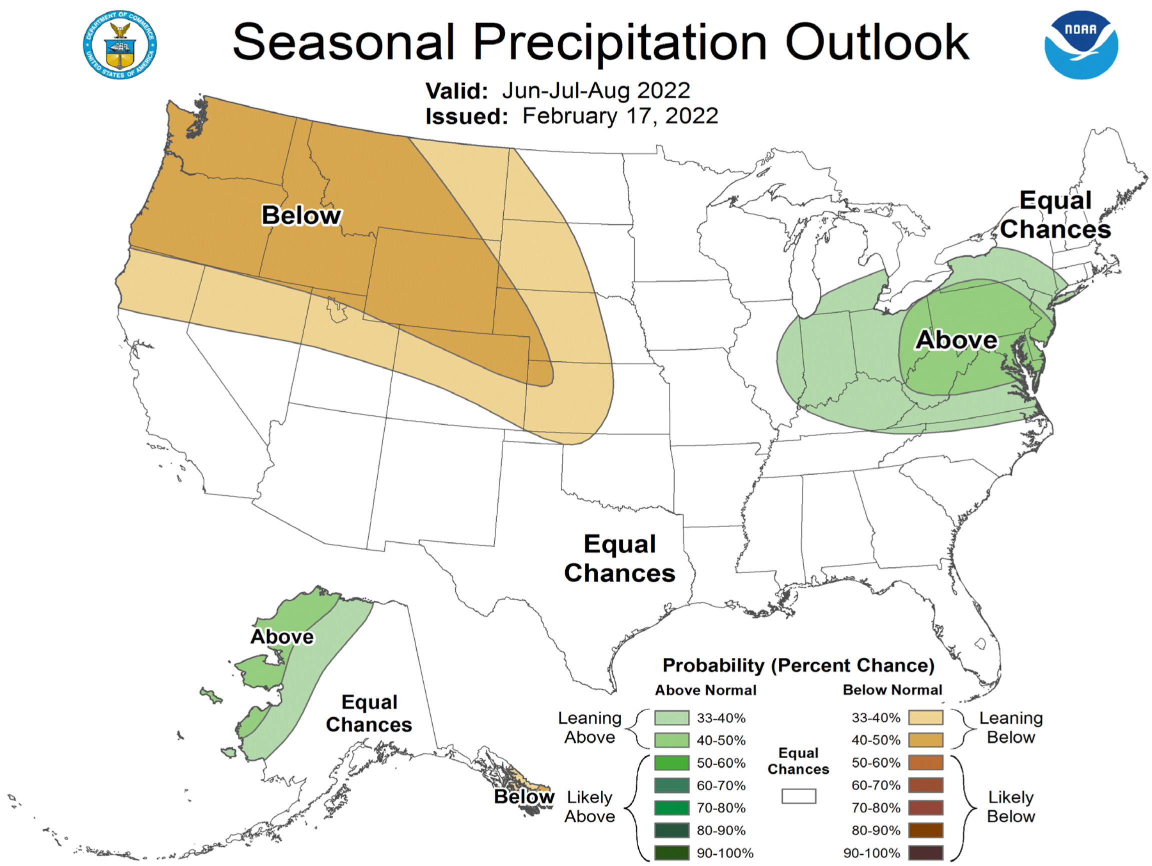

Figure 56. CPC forecast probability of precipitation anomalies for June, July, and August 2022.

Figures 54 and 55 indicate that the CPC is predicting a 40%-50% chance of above normal temperatures over the mid-Atlantic for summer 2022 and a greater than 40% chance of above normal precipitation. The following sections detail how other data sources compare to the official forecast, followed by a brief discussion on how meteorology could impact ozone in Delaware summer 2022.

6.3 El Niño Southern Oscillation (ENSO)

Similar to spring 2021, La Niña conditions are currently present over the eastern equatorial Pacific region. Also similar to spring 2021, the CPC's ENSO outlook calls for a transition from La Niña to ENSO-Neutral conditions by Northern Hemisphere summer 2022. Although ENSO may not be the primary driver when it comes to global oceanic and atmospheric circulations, current ENSO conditions and forecasts can provide useful insight into how weather conditions may respond over the continental U.S. in the months ahead. Sonoma Technology meteorologists investigated how temperature and precipitation anomalies were impacted by recent occurrences of similar transitions from La Niña to ENSO-Neutral conditions. Since the year 2000, similar transitions occurred in 2001, 2006, 2008, 2012, 2018, and most recently in 2021. Figures 57 and 58 are composites of the temperature and precipitation anomalies that occurred during those years.

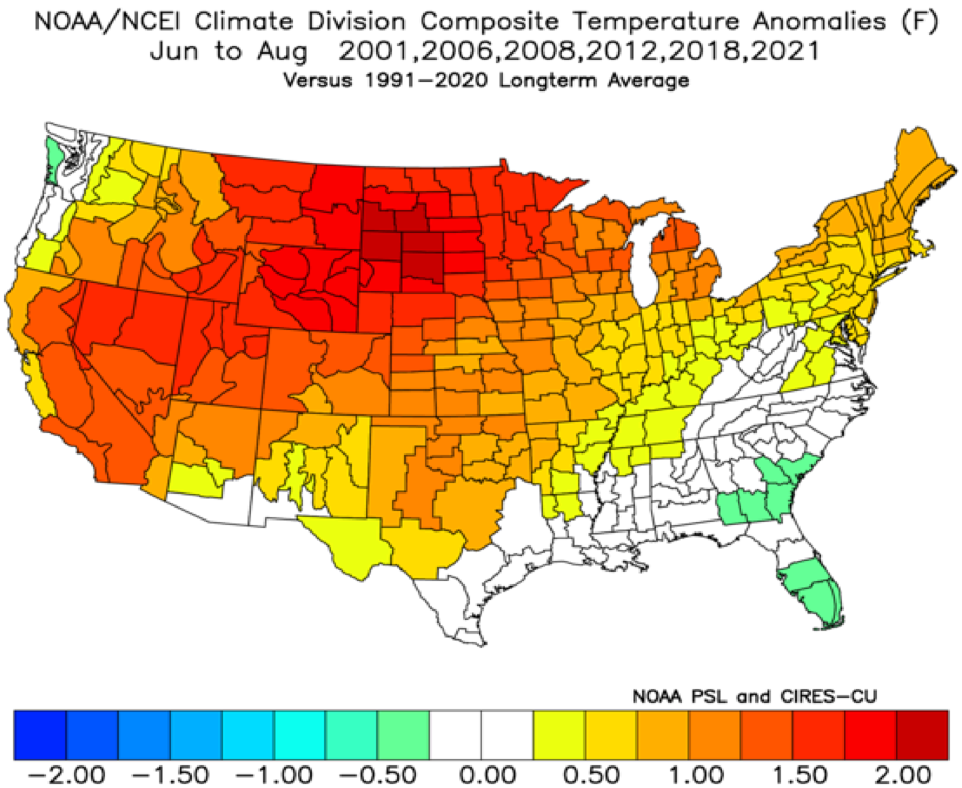

Figure 57. Temperature anomalies (°F) for ENSO-Neutral summers after La Niña subsided.

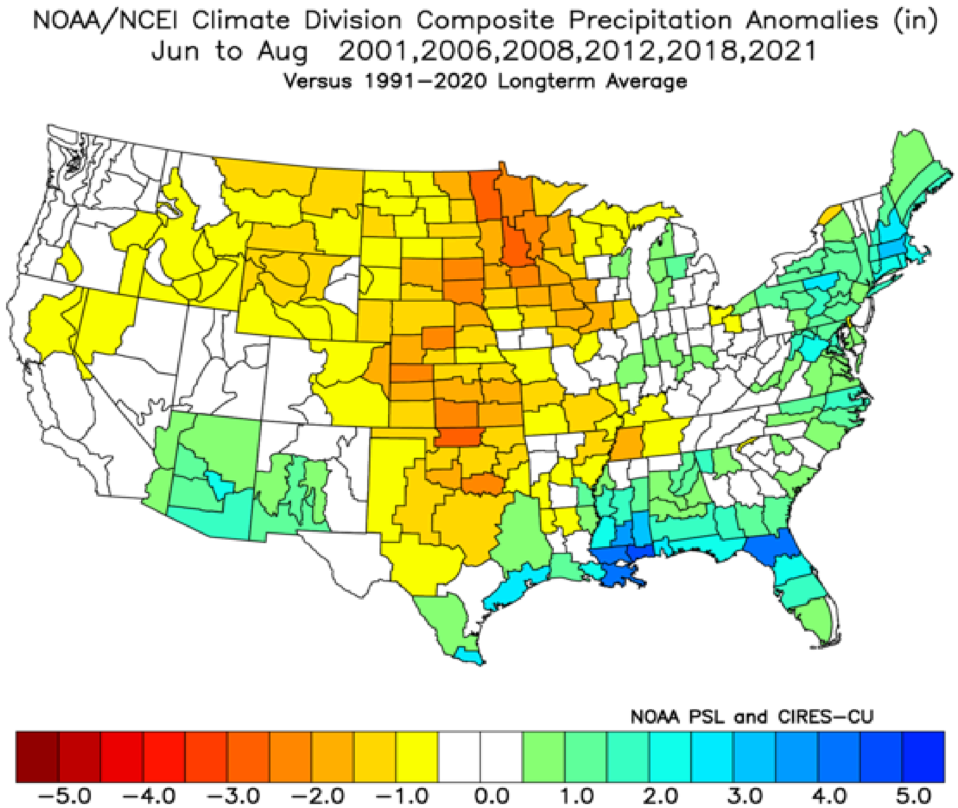

Figure 58. Precipitation anomalies (in.) for ENSO-Neutral summers after La Niña subsided.

While there are differences between CPC's forecast and the analog ENSO years across the northern Plains and Southeast, Figure 56 is largely similar to the CPC's forecast temperature anomalies in that much of the country experienced above average temperatures during these ENSO-Neutral summers. In addition, temperatures in Delaware averaged slightly above normal for the years with similar ENSO conditions. Precipitation anomalies in Figure 57 are slightly different when compared to the CPC's forecast, with drier-than-normal conditions extending farther into the central U.S. However, analog conditions from years with transitions from La Niña to ENSO-Neutral agree with the CPC's forecast of above-average precipitation in the northeastern U.S. for summer 2022.

While ENSO conditions and forecasts are only one piece of the climate story heading into the summer, forecast models can resolve more complexity between the different atmospheric systems that affect weather patterns around the globe. The following section examines seasonal model forecasts from the ECMWF and CanSIPS to see how they compare with the overall forecast.

6.4 Model Forecasts

The seasonal temperature and precipitation forecasts from the ECMWF are shown in Figures 59 and 60. The forecast temperature and precipitation anomalies are similar to the patterns shown in the maps for the analog ENSO years (Figures 57, 58). The temperature anomalies for Delaware differ in magnitude (0.5°C on the ECMWF vs. 0.5°F on the analog maps). However, the overall pattern is similar. The ECMWF is also forecasting above-normal precipitation across much of the eastern U.S. (Figure 59).

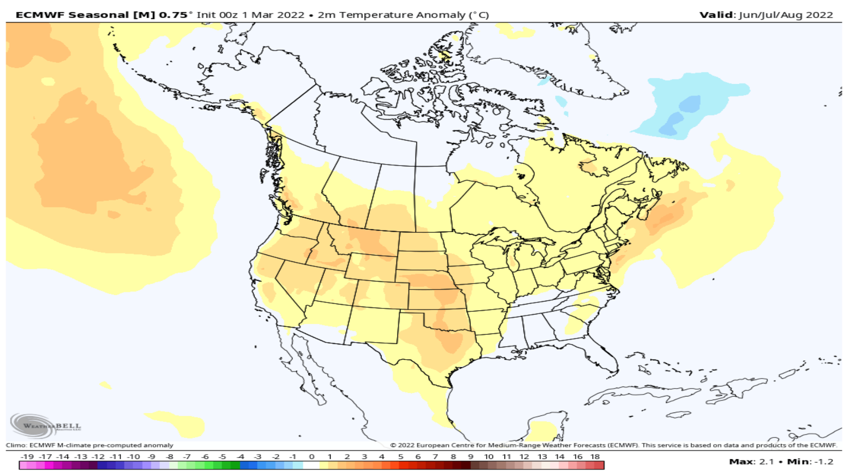

Figure 59. ECMWF forecast temperature anomalies for June-August 2022.

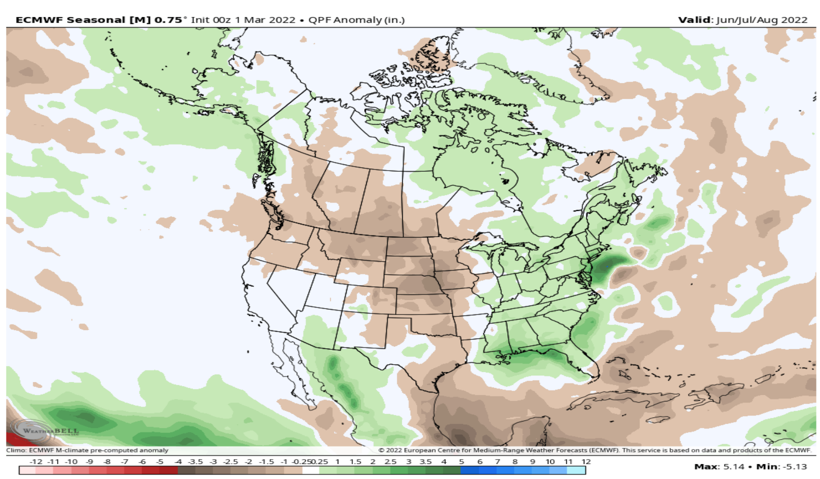

Figure 60. ECMWF forecast precipitation anomalies for June-August 2022.

The CanSIPS model forecast also predicts above-normal temperatures across much of the U.S. this summer (Figure 61). Similar to last spring, the CanSIPS model is forecasting a higher magnitude of warming over much of the U.S. compared to the ECMWF, but the forecast for Delaware is similar, with slightly above-average temperatures forecast for June through August 2022.

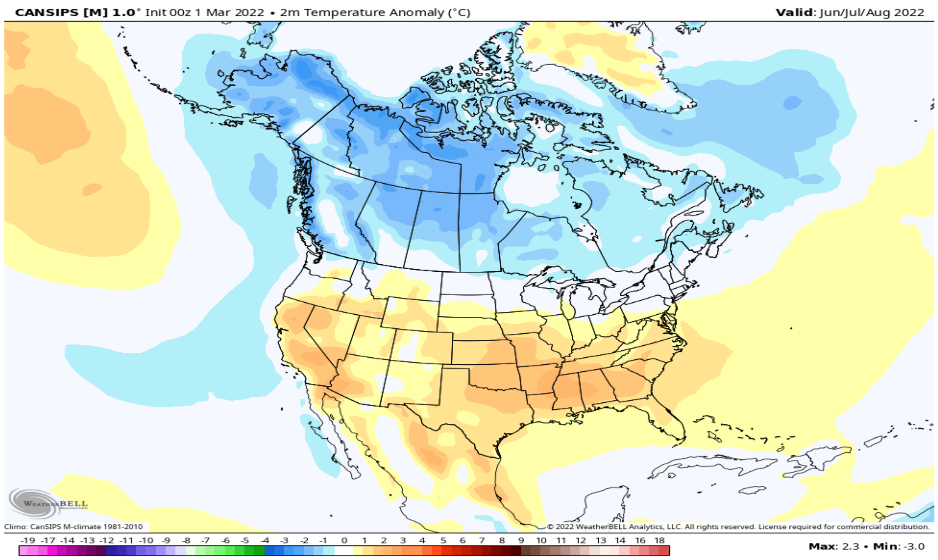

Figure 61. CanSIPS forecast temperature anomalies for June-August 2022.

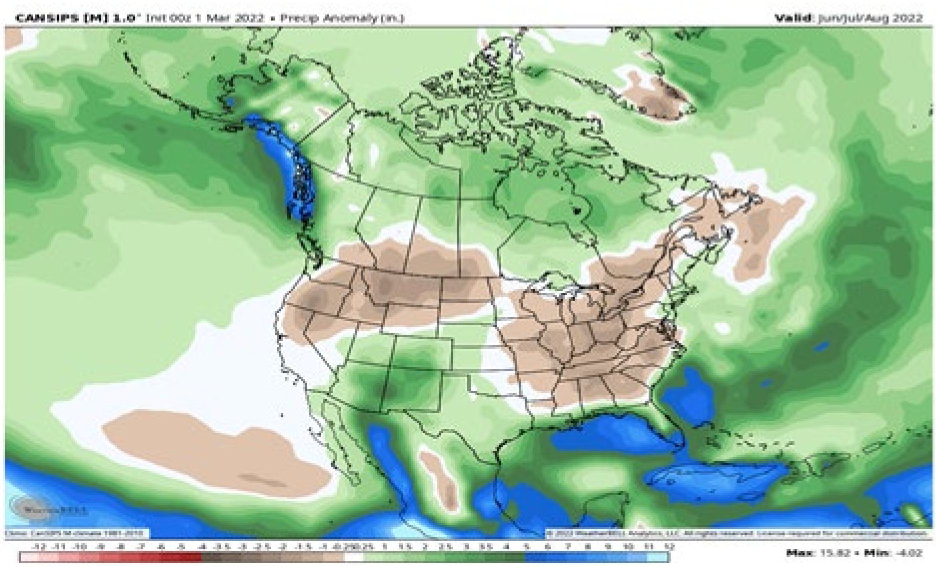

Figure 62. CanSIPS forecast precipitation anomalies for June-August 2022.

The largest disagreement between these models comes with the precipitation forecast (Figure 40). While the ECMWF is forecasting above normal precipitation for much of the eastern U.S., the CanSIPS model is predicting below-normal precipitation for the eastern U.S., with the exception of coastal New England. This dry bias was also present in the predictions for summer 2021 on the CanSIPS model, which did not end up being verified. As a result, less weight will be given to the CanSIPS precipitation forecast for summer 2022.

6.5 Trends in Summer Temperatures and Precipitation

Another factor to consider in seasonal weather predictions is recent weather trends compared to climatological norms. The CPC produces maps of temperature and precipitation trends for three-month periods throughout the year. Temperature trends reflect the difference between the average temperatures during a selected three-month period over the last 10 years and the temperature climatology from 1981-2010. Precipitation trends reflect the difference between the average precipitation during a selected three-month period over the last 15 years and the precipitation climatology from 1981-2010. The trend maps are shown in Figure 63.

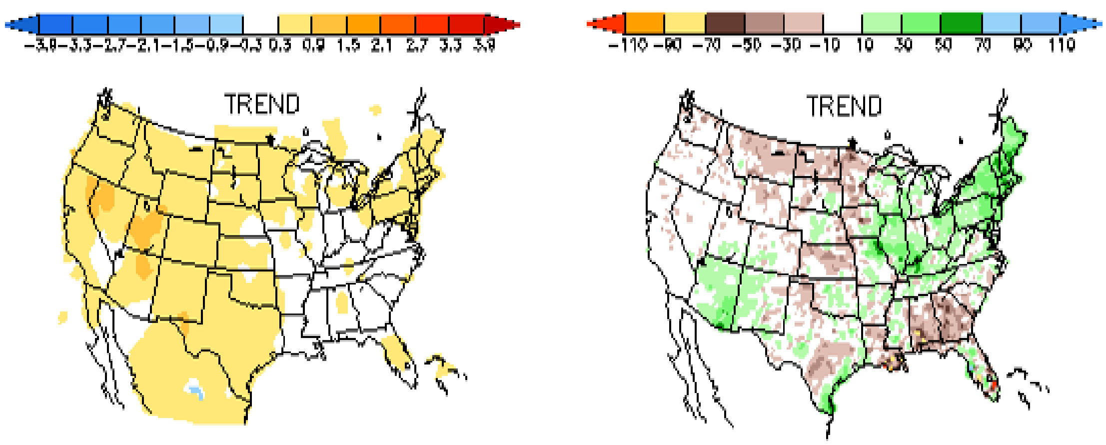

Figure 63. Recent trends in temperature in degrees Celsius (left) and precipitation in millimeters (right) for June, July, and August. The recent trend is estimated by the Optimal Climate Normal (OCN) of Huang et al. (1996)[2].

Trends in summertime temperatures and precipitation show that, in general, temperatures are slowly warming and precipitation is increasing in the northeastern U.S.

6.6 Implications for the Summer 2022 Ozone Season in Delaware

With official forecasts, model output, and trends largely showing a similar picture for summer 2022, there is a good chance that temperatures in Delaware will be slightly above average, with near-average to above-average precipitation. The potential for above-average temperatures alone would suggest an associated potential increase in ozone for the coming summer, with increases in both

[2] Huang, J., H.M. van den Dool, and A.G. Barnston, 1996: Long-Lead Seasonal Temperature Prediction Using Optimal Climate Normals. J. Climate, 9, 809,817.

average daily ozone levels and the frequency of high-AQI-level events. However, if the precipitation pattern is more active than normal through the summer, an increase in moisture and associated cloudiness would suggest a decrease in ozone production. Adding to the complexity of the forecast, the severity and extent of wildfire activity this summer has implications on summertime ozone in Delaware. Maps of the current drought extent across North America (**Figures 64 and 65**) would suggest another active wildfire season from the western U.S. into south-central Canada. Sonoma Technology meteorologists will monitor the potential for long-range smoke transport into Delaware and its potential impacts on ozone.

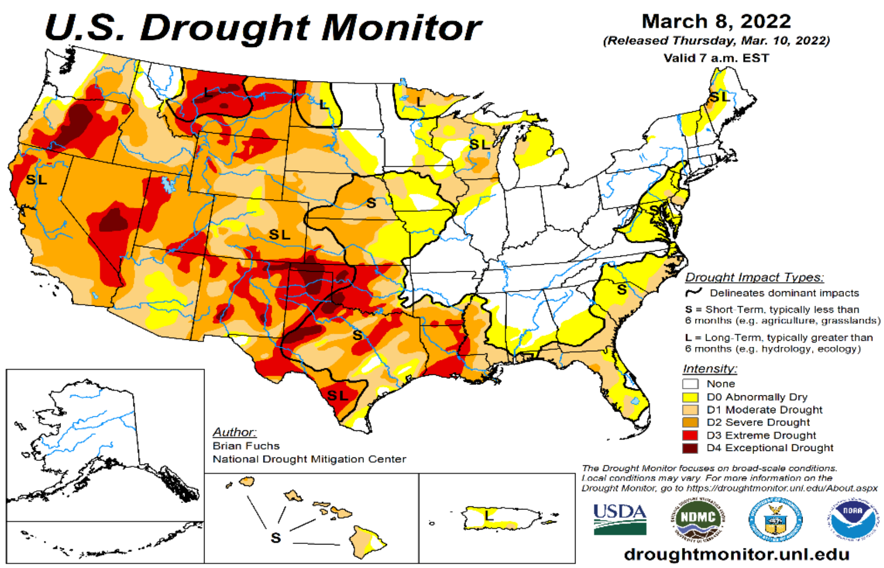

Figure 64. U.S. Drought Monitor depiction of current drought conditions across the country as of March 8, 2022. Much of the drought regions are predicted to persist.

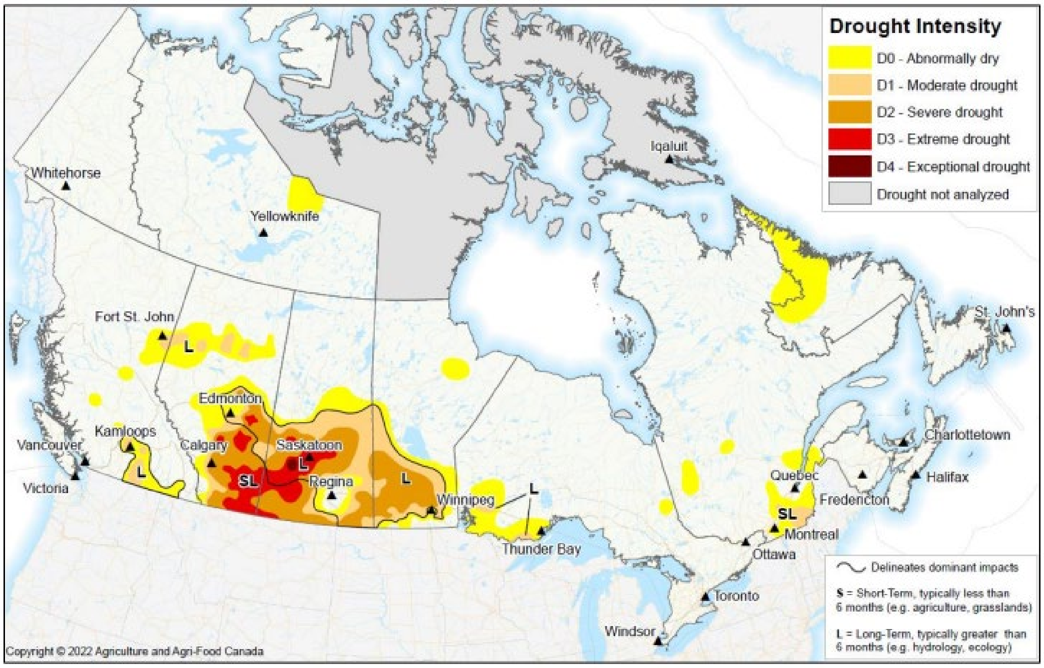

Figure 65. Canadian drought monitor shows the extent of drought in Canada as of February 28, 2022.

As with any meteorological forecast, specifics for Delaware will become clearer as summer approaches and the large-scale patterns begin to develop. Sonoma Technology meteorologists will track the latest developments and use the best tools available to produce our forecasts for the summer 2022 ozone season.