State of Delaware Final Report: Ozone Observations and Forecasts in 2022

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Delaware Department of Natural Resources and Environmental Control
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State of Delaware Final Report: Ozone Observations and Forecasts in 2022

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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 68% of days and Moderate category on 32% of days. No Unhealthy for Sensitive Groups (USG) days were observed.
- Based on daily air quality record keeping that started back in 1980, summer 2022 was the first summer on record without any USG (Code Orange) or higher ozone days in the First State. Additionally, no Unhealthy (Code Red) or Very Unhealthy (Code Purple) ozone days were observed for the sixth consecutive summer.
- Similar to 2021, long-range smoke transport from fires across the U.S. and Canada likely contributed to elevated ozone and particle levels in Delaware.
- Likely as a result of both wildfire smoke and emissions returning to pre-COVID levels, there were slightly fewer days with Good AQI values in 2022 than in 2020 or 2021.
- At the Good-to-Moderate threshold, next-day forecasts issued during the weekdays (Monday-Friday) were correct 76% of the time during summer 2022, with a probability of detection (POD) of 71% and a false alarm rate (FAR) of 48%.
- Looking ahead to the 2023 ozone season, above-normal temperatures may enhance ozone production, which may also be offset by above-normal precipitation in Delaware. However, given the ongoing 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 fine particulate matter ($PM_{2.5}$) AQI levels.

1. Ozone Climatology 2017-2021

Pollution resulting from ground-level ozone formation has improved over the years in the state of Delaware, driven in part by an overall reduction in regional emissions, as well as stricter regulations for ozone attainment.[1] Dating back to 2012, the overall trend toward cleaner air has led to fewer occurrences of days with Unhealthy for Sensitive Groups (USG) Air Quality Index (AQI) levels, or Code Orange days (daily maximum 8-hr average ozone concentrations between 71 ppb and 85 ppb) and days with Unhealthy AQI levels, or Code Red days (daily maximum 8-hr average ozone concentrations between 86 ppb and 105 ppb).

To account for the continuing shift toward improving air quality and to assist with daily forecasting operations, Sonoma Technology forecasters produced a 5-yr climatology of ozone levels across the state prior to the 2022 ozone forecasting season. This climatology was based on data from the seven ozone monitoring sites across the state (Figure 1), with data recorded between 2017 and 2021. The following climatology highlights the monthly and day-of-week patterns of ozone AQI levels, as well as the frequency of multi-day high-ozone events.

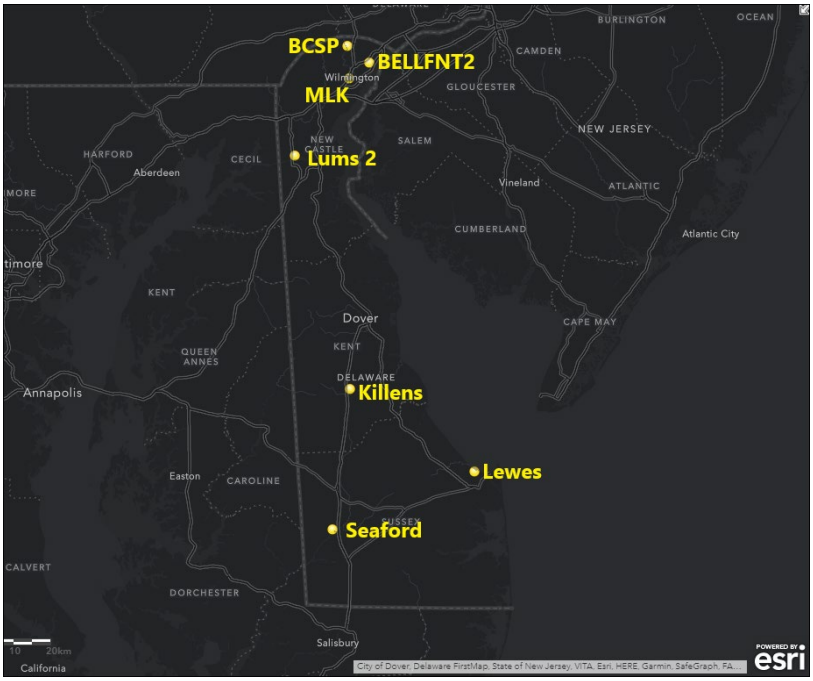

Figure 1. Active ozone monitoring sites in the State of Delaware.

[1] https://www.federalregister.gov/documents/2015/10/26/2015-26594/national-ambient-air-quality-standards-for-ozone

1.1 Monthly Climatology of Ozone

Ground-level ozone formation depends on a variety of meteorological factors, with the primary catalysts being sunlight and surface temperatures. In the spring, increasing daylight and warmer temperatures begin to enhance ozone production. This relationship is reflected in Figure 2, as days with Moderate or higher AQI levels increase in frequency from March through July. By August, shorter days and the gradual, seasonal reduction in temperatures result in improved ozone levels, with Good AQI levels being recorded on most days.

Days with Moderate or higher AQI values primarily occurred from April through September, while most USG days were observed between May and July. During July, occurrences of Good air quality were less frequent compared to the rest of the year, with 45% of July days between 2017-2021 recording Moderate or higher AQI values. This trend of reduced air quality in July coincides with historical weather records, which indicate July as the warmest month of the year in Delaware.

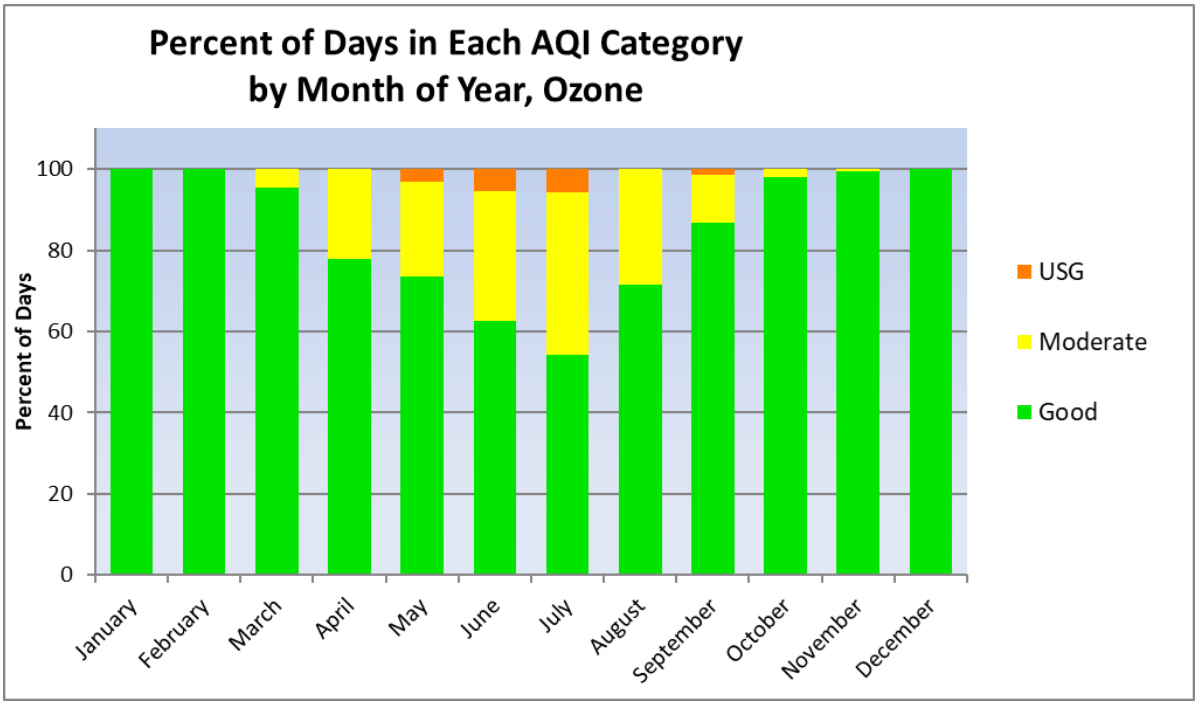

Figure 2. Monthly distribution of each AQI category based on 2017-2021 ozone data.

1.2 Daily Distribution of Moderate or Higher Ozone Days

While ozone development depends on meteorological conditions like sunlight and temperature, ozone formation on certain days can be strongly influenced by emissions from industrial facilities and vehicular traffic. With these emissions sources in mind, a day-of-week distribution pattern can

illustrate when Moderate or higher AQI levels are most likely to occur. As shown in Figure 3, days with Moderate or higher AQI ozone values were most frequent on Wednesdays and Thursdays in Delaware, based on 2017-2021 data. On weekend days, reduced regional emissions likely led to improved air quality, with Sundays featuring 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, which is likely the result of regional pollutant carryover from latter portion of the work week into Saturday. When examining the 2017-2021 period, the current day-of-week distribution of Moderate or higher AQI levels is similar to previous climatology studies done by Sonoma Technology.

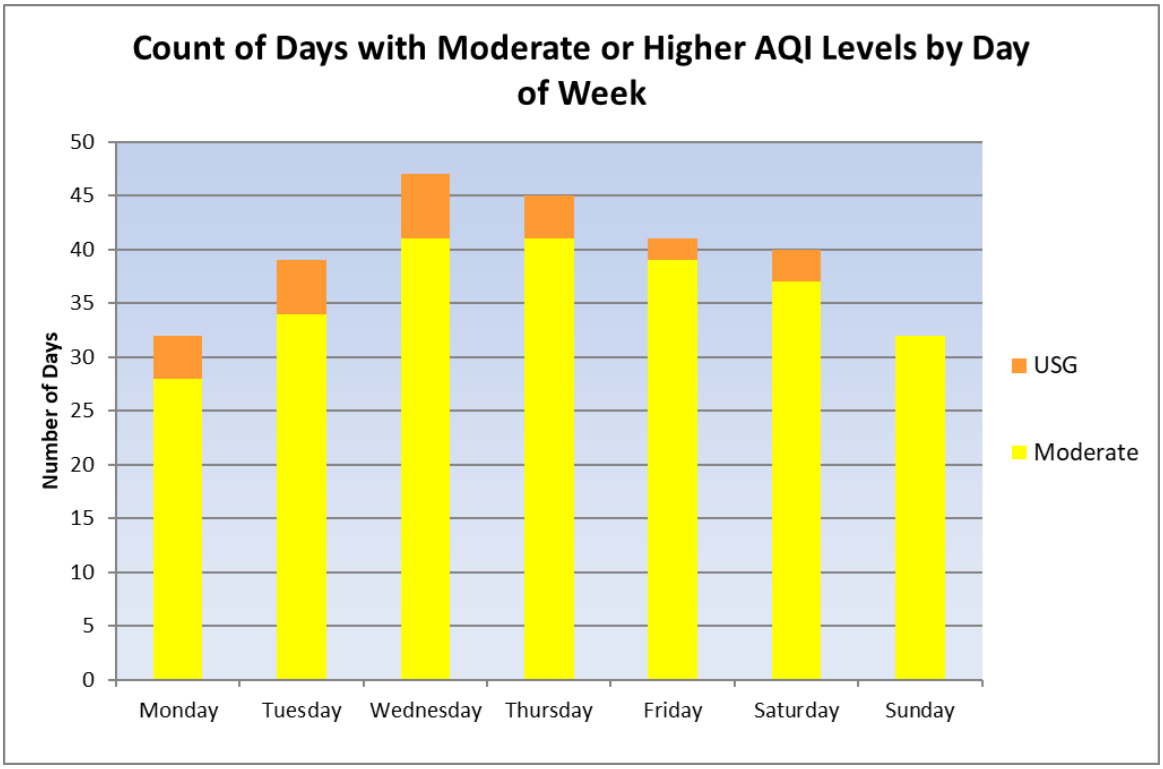

Figure 3. Number of days with Moderate or higher AQI levels by day of the week based on 2017-2021 ozone data.

1.3 Frequency of Multi-Day Ozone Exceedance Events

Due to the region-wide reduction in nitrous oxide (NO_x) emissions since 2012, air quality in Delaware has improved. Because of this reduction, occurrences of multi-day ozone exceedances (two or more consecutive Code Orange or higher days) have become less frequent and more dependent on emission sources outside of the Mid-Atlantic region, such as wildfire smoke.

According to 2017-2021 data, there were 24 Code Orange days in Delaware, with 11 instances of one-day ozone exceedance (Figure 4). Two-day ozone exceedance events occurred five times over

the previous five years, accounting for ten days, while only one three-day ozone exceedance event was recorded from July 9-11, 2018.

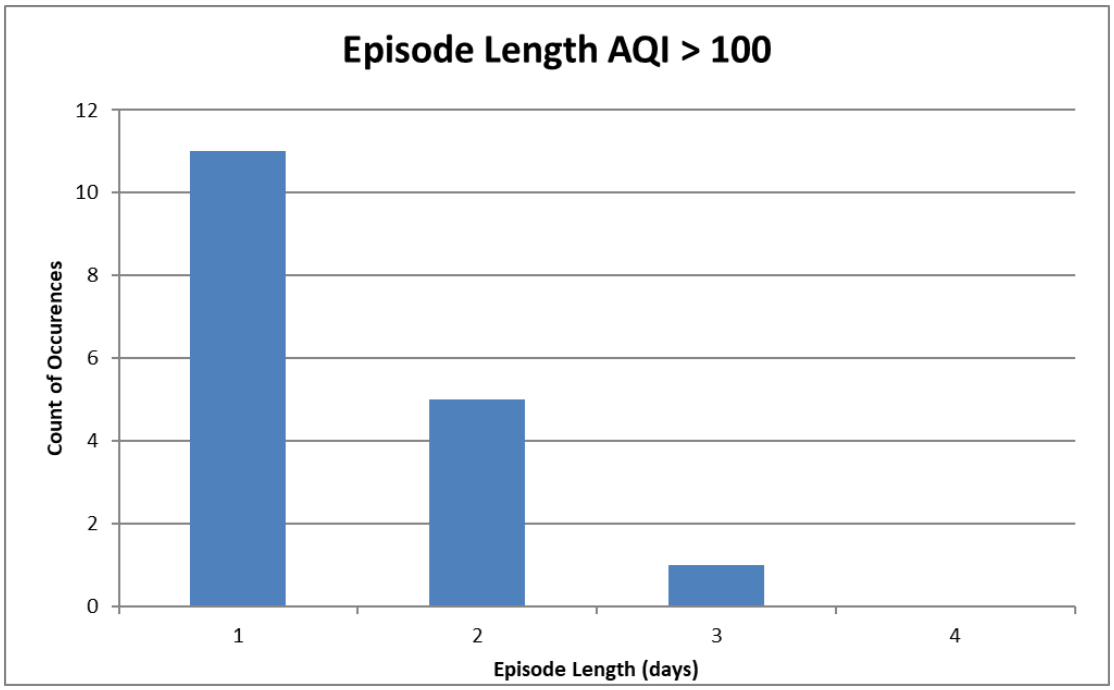

Figure 4. Frequency of long-duration Code Orange or higher AQI events, based on 2017-2021 ozone data.

2. Ozone and Meteorological Observations in 2022

The summer ozone forecasting season in Delaware is defined as the period from May 1 to September 30. During this period in 2022, daily maximum ozone levels (highest among all sites) in Delaware were in the Good AQI category on 68% of days and the Moderate AQI category on 32% of days (Figure 5). No USG AQI values were recorded, despite four Code Orange (USG) next-day forecasts being issued during the season.

Figure 6 provides a time series of statewide observed daily maximum 8-hr average ozone AQI levels throughout the 2022 ozone forecast season, while Table 1 shows a month-by-month breakdown of daily observed ozone values by AQI category.

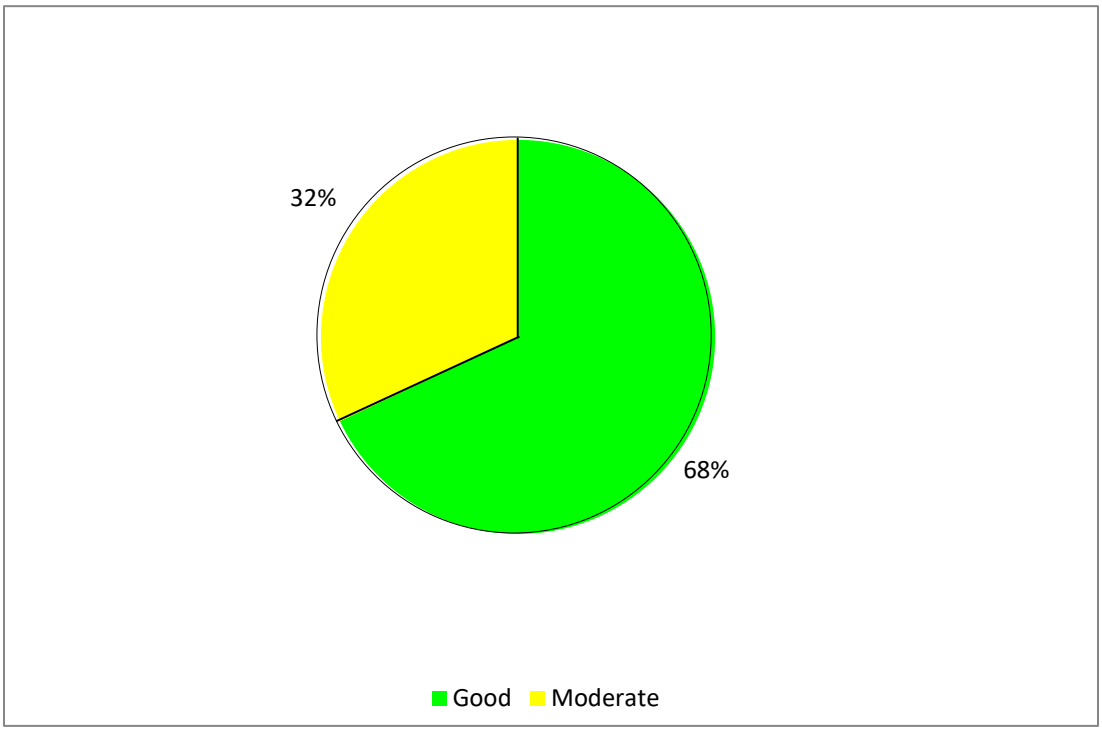

Figure 5. Delaware observed daily maximum ozone AQI values between May 1 and September 30, 2022. Data courtesy: AirNow-Tech

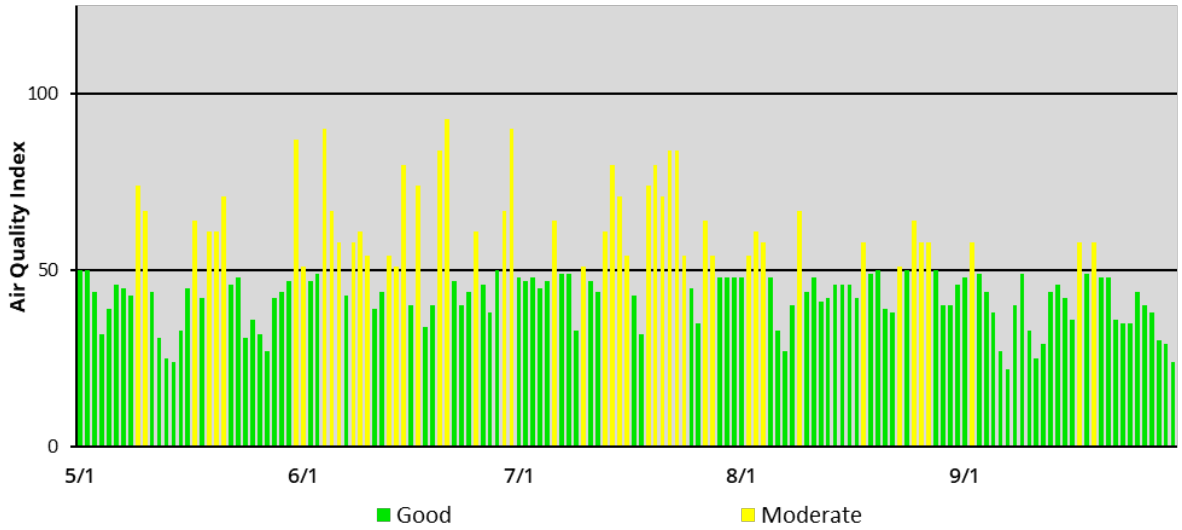

Figure 6. Delaware daily maximum ozone AQI values between May 1 and September 30, 2022. Data courtesy: AirNow-Tech

Table 1. Percent of days at each ozone AQI category by month for summer 2022.

Month	Good days	Moderate days
May	77%	23%
June	47%	53%
July	55%	45%
August	71%	29%
September	90%	10%

2.1 Site-By-Site Ozone Observations for 2022

Ozone observations for Delaware are measured at seven different monitoring sites across the state (Figure 7). Four monitoring sites are in New Castle County, one site is in Kent County, and two sites are in Sussex County. Both Figure 7 and Table 2 show the distributions of daily maximum ozone AQI values measured at each of the seven monitoring sites during summer 2022.

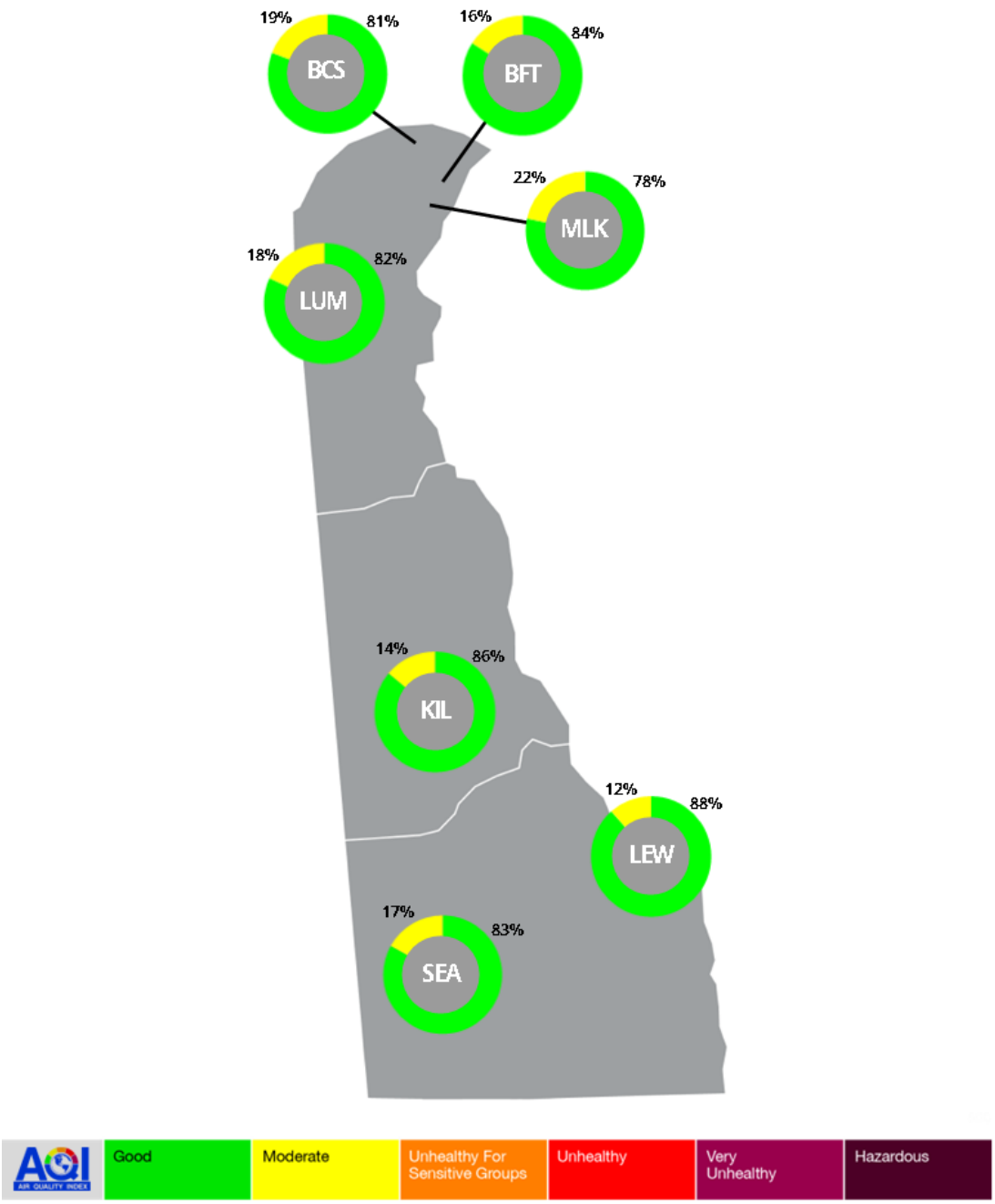

Figure 7. Delaware daily maximum ozone AQI distributions between May 1 and September 30, 2022. Courtesy: AirNow-Tech

Table 2. Percent of days at each AQI category for ozone by site for summer 2022. Station abbreviations from Figure 7 are in parentheses.

Monitoring Site	Good days	Moderate days
MLK Boulevard (MLK)	78%	22%
Bellevue State Park (BFT)	84%	16%
BCSP (BCS)	81%	19%
Lums (LUM)	82%	18%
Killens (KIL)	86%	14%
Seaford (SEA)	83%	17%
Lewes (LEW)	88%	12%

Days with Good AQI levels were frequent statewide throughout summer 2022, with most monitoring sites registering Good AQI levels over 80% of the time. The cleanest site during the summer was Lewes, due to its proximity to the Atlantic Ocean. Compared to other monitoring sites across the First State, the Lewes area is affected by cleaner marine air impacts on a more frequent basis.

Monitoring sites near or downwind of major metropolitan areas generally record more Moderate or higher AQI levels because of pollutant transport from numerous local emission sources. In summer 2022, the MLK monitoring site in Wilmington recorded the fewest days with Good AQI levels compared to other sites across the state. Between May and September 2022, 78% of days at MLK had Good AQI levels, and 22% of days had Moderate AQI levels.

2.2 Air Quality Comparison Between Summer 2022 and Previous Years

To assess year-to-year ozone trends, Sonoma Technology meteorologists compared summer 2022 ozone levels to the previous nine summers, dating back to 2013 (the first year with notable reductions in regional NO_x emissions).

Figure 8 provides the yearly distribution of daily maximum ozone AQI levels for Delaware between 2013 and 2022. While the general trend of improved air quality continued, Good ozone AQI values decreased in frequency in Delaware for the second straight year. Ozone levels in summer 2022 were Good 68% of the time, compared to 72% in summer 2021 and 81% in summer 2020. It is worth noting that summer 2020 ozone levels were anomalously low, due to a sharp reduction in emissions

related to COVID-19 shelter-in-place orders across the Mid-Atlantic region (see the 2020 air quality report[2] for more details).

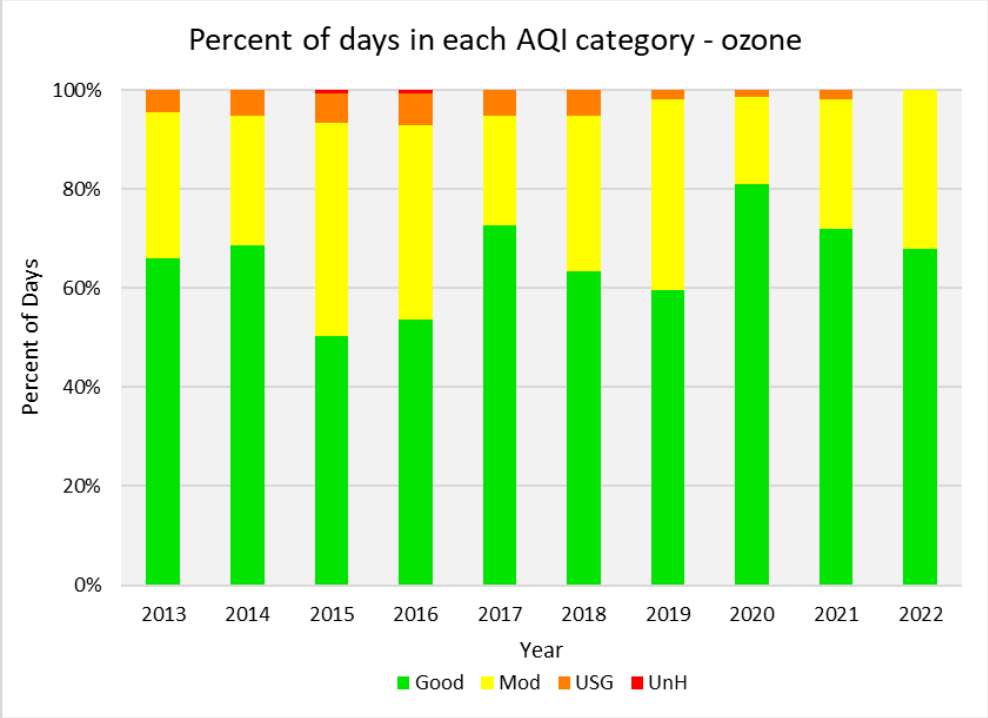

Figure 8. Distribution of daily maximum ozone AQI values during the defined summer ozone forecasting season.

Ozone exceedances of the National Ambient Air Quality Standards (NAAQS) have become less frequent in Delaware. According to daily air quality record keeping that started back in 1980, summer 2022 was the first summer on record with a day that recorded no USG or higher ozone AQI levels in the First State. Figure 9 highlights the occurrence of ozone exceedances for each of Delaware's three counties, dating back to 2000.

[2] https://documents.dnrec.delaware.gov/Air/ozone-reports/DE-Ozone-2020.pdf

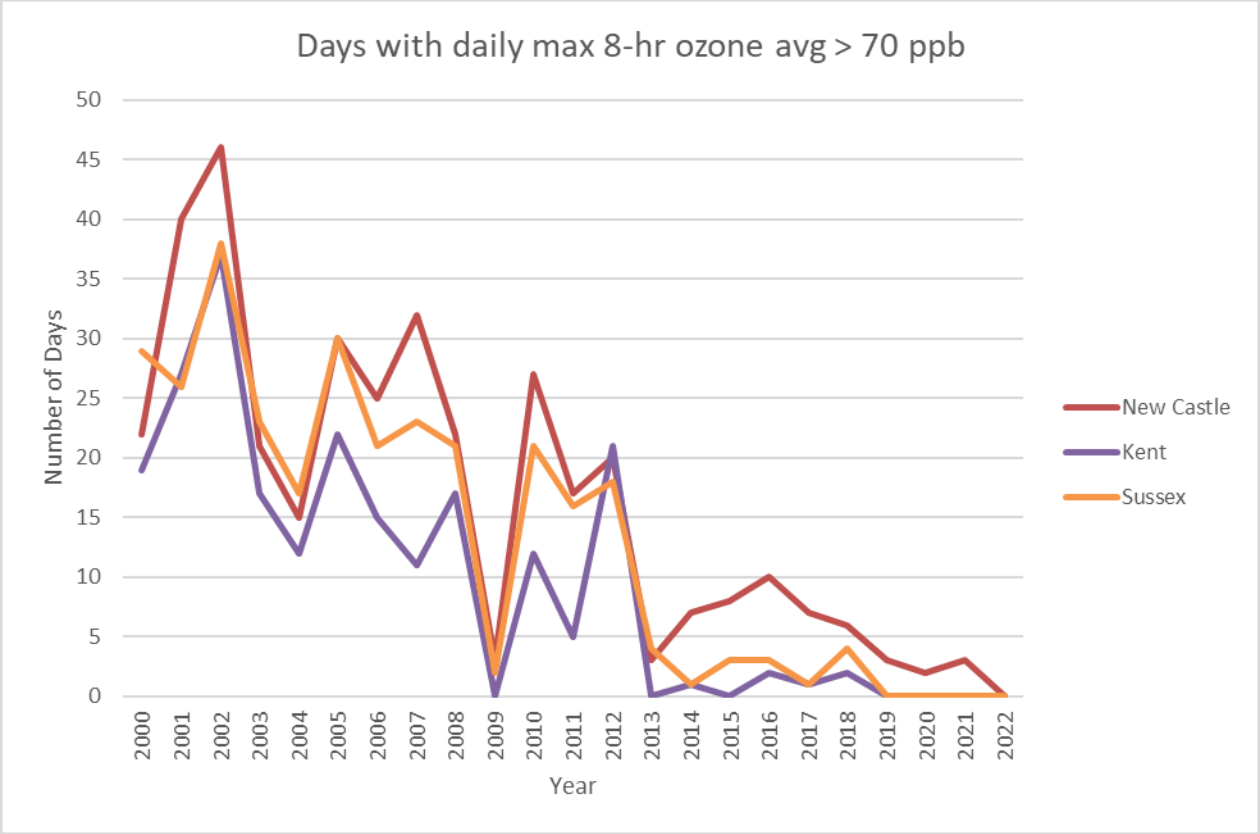

Figure 9. Year-to-year frequency of ozone exceedances between May and September by county. Source: U.S. EPA Air (**https://www.epa.gov/outdoor-air-quality-data**)

Since 2012, the number of days when the daily maximum ozone AQI value exceeded 100 has sharply declined, with this trend continuing in summer 2022. Kent and Sussex Counties marked their fourth consecutive year without an ozone NAAQS exceedance.

2.3 Summer 2022 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, cooler temperatures, rainfall, and enhanced vertical mixing - all of which hinder ozone development.

When compared to the 1991-2020 climatological averages, temperatures across the Mid-Atlantic and Northeast regions for the summer 2022 ozone forecast season were warmer than normal (**Figure 10**). In general, the average temperature departure from normal was 1-2°F above average, with the warmest places located across the Tri-State area of New Jersey, New York, and Connecticut.

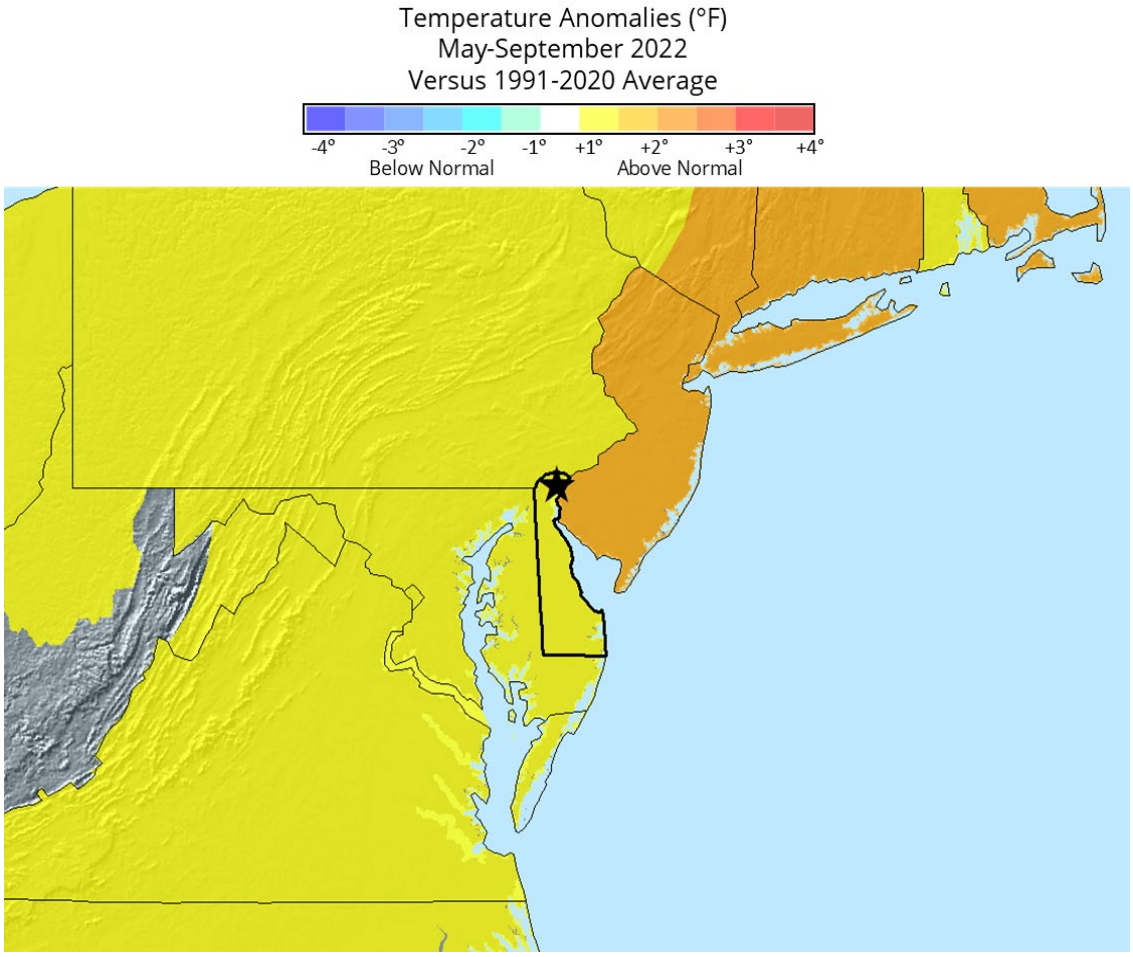

Figure 10. May-September 2022 average temperature departure from normal. Yellow and orange indicates areas where temperatures were around 1-2°F above normal. Courtesy: National Oceanic and Atmospheric Administration (NOAA)

Table 4 provides a complete meteorological summary for the summer 2022 ozone forecasting season for both Delaware NOAA climate sites. During the May-September period, the Wilmington and Georgetown climate sites recorded average temperature anomalies 1.0-1.5°F above the 1991-2020 climatological average. While Wilmington had a higher temperature anomaly (+1.5°F for the May-September period), Georgetown recorded a higher average temperature (73.8°F) for the summer ozone forecast season.

Table 3. May-September 2022 meteorological summary for Delaware climate locations.

Variable	Wilmington (KILG)	Georgetown (KGED)
Average Temperature (°F)	73.2	73.8
Average Temperature Departure from Normal (°F)	+1.5	+1.0
Total Precipitation (inches)	16.88	16.57
Precipitation Departure from Normal (inches)	-4.13	-3.80
Average Wind Speed (mph)	7.6	6.5
Average Wind Speed Departure from Normal (mph)	-0.3	+0.1
Number of Clear Days	94	99

Wind speeds for the Wilmington and Georgetown climate sites were near normal during the May-September period. Wilmington's average wind speed was 7.6 mph, which is 0.3 mph below average. In contrast, Georgetown's average wind speed was near normal during the season, averaging 6.5 mph.

Along with average temperature readings, observed precipitation anomalies during the May-September 2022 period were similar for Georgetown and Wilmington. During the summer ozone forecasting season, there was less rainfall was normal. The larger precipitation anomaly for the First State was in Wilmington, where seasonal rainfall was over 4 inches below normal. In Georgetown, observed rainfall between May-September 2022 was 3.8 inches below average.

Below-average rainfall was observed across many coastal regions in the Mid-Atlantic during the May-September 2022 period (Figure 11). In these areas, measured rainfall was approximately 3 to 6 inches below seasonal normal, with the driest locations being located from Delaware northward to the Tri-State area. Farther inland, seasonal rainfall totals for the May-September 2022 period were near or above average.

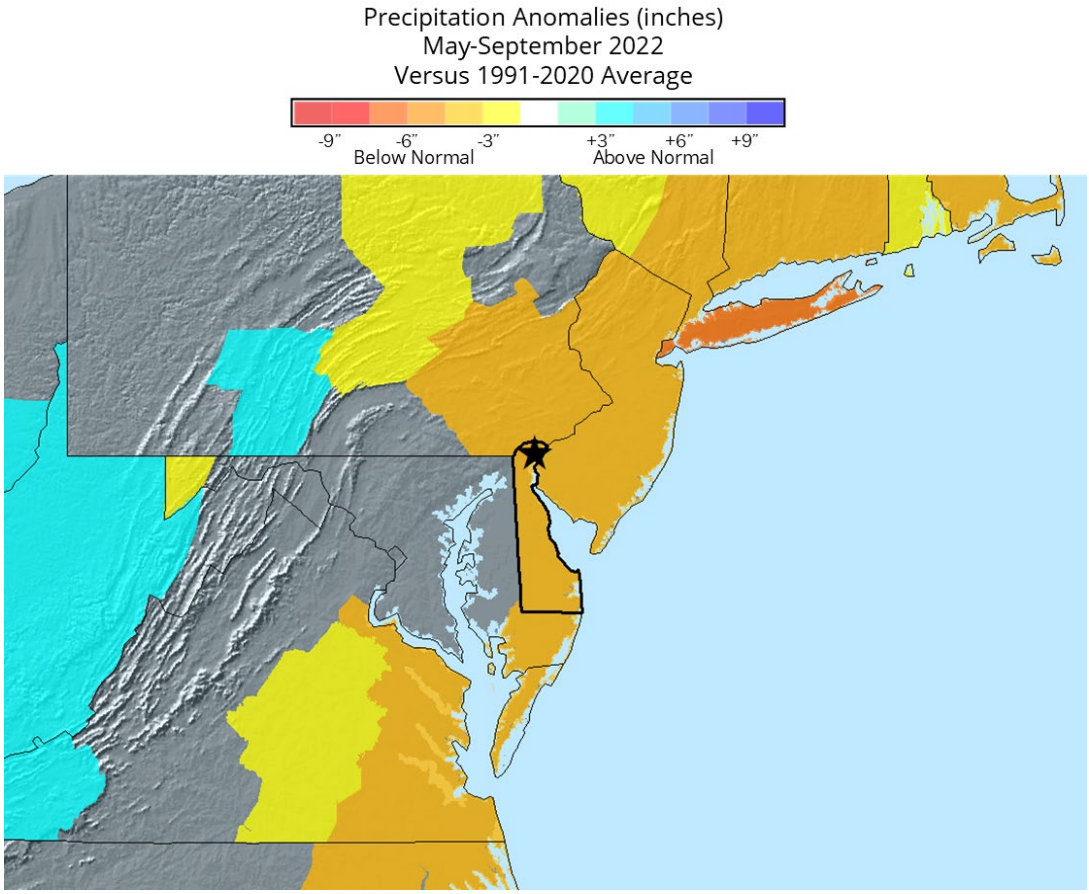

Figure 11. Precipitation anomalies for May-September 2022. Areas in yellow and orange denote below-normal rainfall, while areas absent of color or shaded light blue indicate near- or above-normal rainfall. Courtesy: NOAA

Table 4 shows a month-by-month summary of weather at the Wilmington climate site, and Table 5 contains a month-by-month summary of weather at the Georgetown climate site. Among the general trends found at both climate sites, most days recorded clear skies between June through September. Additionally, most months featured temperatures above the climatological averages, with the lone exception being June.

Based on temperature versus climatology, August had the largest positive temperature anomaly, with the average temperature running 2.5°F warmer than normal in Georgetown and 3.1°F warmer than normal in Wilmington. The warmest monthly average temperature in both cities during the summer ozone forecast season was July.

August was the driest month for both climate sites in terms of measured rainfall and departure from the climatological normal. Wilmington recorded 2.39 inches of precipitation in August, which was nearly 1.6 inches below average. Farther south in Georgetown, measured rainfall in August was 2.09 inches, running nearly 2 inches drier than normal.

Table 4. 2022 monthly meteorological summary for Wilmington-New Castle Airport (KILG).

Wilmington (KILG)	May	June	July	August	September
Average Temperature (°F)	65.8	72.2	79.4	78.9	69.6
Average Temperature Departure from Normal (°F)	+2.3	-0.4	+1.8	+3.1	+0.7
Total Precipitation (inches)	2.96	4.58	4.10	2.39	2.85
Precipitation Departure from Normal (inches)	-0.61	-0.09	-0.31	-1.59	-1.53
Number of Clear Days	10	18	21	22	23
Number of 90°F+ Days	2	3	15	13	0
Average Wind Speed (mph)	8.8	7.5	7.1	7.2	7.6
Average Wind Speed Departure from Normal (mph)	0.0	-0.7	-0.5	0.0	-0.1

Table 5. 2022 monthly meteorological summary for Georgetown (KGED).

Georgetown (KGED)	May	June	July	August	September
Average Temperature (°F)	66.3	73.0	80.0	79.2	70.5
Average Temperature Departure from Normal (°F)	+1.8	-0.6	+1.4	+2.5	+0.1
Total Precipitation (inches)	3.84	3.05	3.66	2.09	3.93
Precipitation Departure from Normal (inches)	+0.21	-1.02	-0.48	-1.90	-0.61
Number of Clear Days	10	21	22	24	22
Number of 90°F+ Days	5	7	20	16	2
Average Wind Speed (mph)	9.0	6.3	6.1	5.4	5.5
Average Wind Speed Departure from Normal (mph)	+1.4	-0.2	0.0	+0.1	-0.6

From a seasonal perspective, warmer and drier conditions across the First State resulted in more frequent Moderate AQI days versus the previous two summers. An increase in surface temperatures can enhance ozone production, while lower rainfall is often associated with reduced atmospheric mixing and more sunny days, creating optimal conditions for ground-level ozone formation.

Along with surface meteorological indicators like temperature, wind, and rainfall, upper-level weather patterns can give clues to trends in ozone development. For instance, persistent upper-level high pressure promotes sunny skies and a stable atmosphere, which reduces vertical mixing and enhances

ozone development. On the other hand, persistent upper-level low pressure can lead to frequent storm systems and rainfall, both of which inhibit ozone formation.

In order to assess the impact of upper-level weather patterns on ozone development in Delaware, Sonoma Technology meteorologists examined mean 500-mb heights (approximately 18,000 feet above sea level) for the May-September 2022 period. During this period, mean 500-mb heights indicated the presence of a very weak upper-level trough of low pressure over the eastern half of the United States (Figure 12). West of Delaware, mean height patterns showed an upper-level ridge of high pressure across the Rocky Mountains. Despite the weak upper-level trough over the Mid-Atlantic, it is more likely that the upper-level ridge west of the region had a larger impact on prevailing summer weather and air quality in Delaware, due to the warmer and drier weather that was observed.

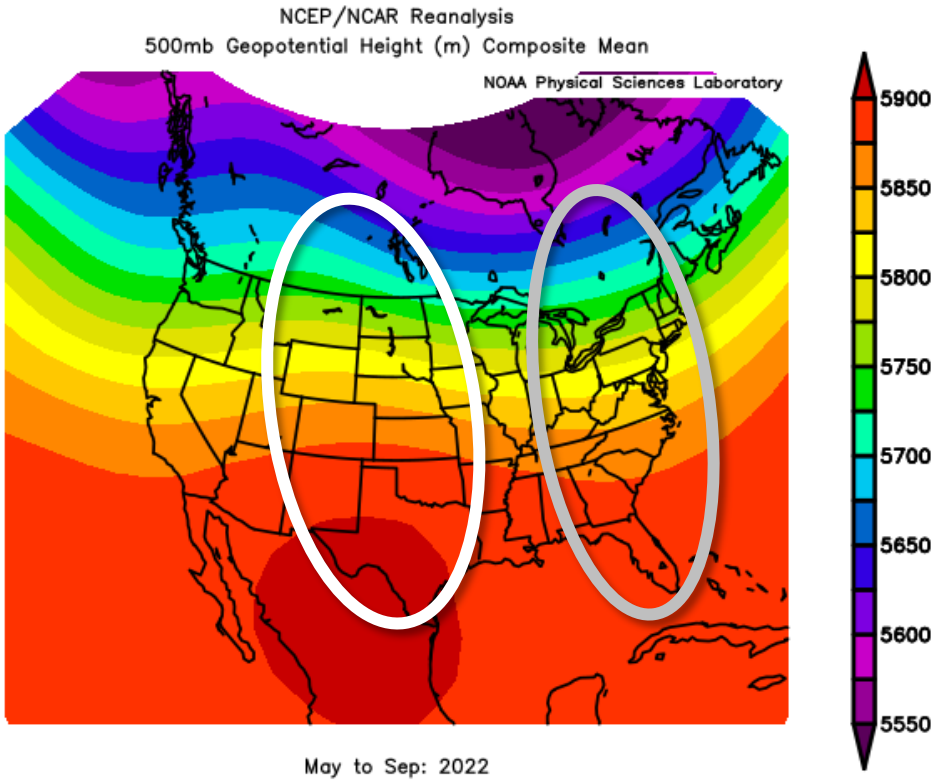

Figure 12. May-September 2022 mean 500-mb heights. An upper-level ridge of high pressure over the Rocky Mountains (circled in white) likely influenced ozone levels in Delaware, while the weak upper-level low pressure trough (circled in gray) had negligible impacts on air quality. Courtesy: National Center for Environmental Prediction (NCEP)

Observed 500-mb height anomalies were also assessed for the May-September 2022 period. Areas with positive height anomalies indicate stronger-than-normal upper-level high pressure, while negative height anomalies are synonymous with persistent upper-level low pressure. For the 2022 summer ozone forecasting season, height anomalies were slightly positive for a large swath of the

eastern United States (Figure 13). Although weak troughing was observed at upper levels on average, the mean 500-mb heights were still slightly higher than normal, resulting in greater stability than the 1991-2020 climatological average.

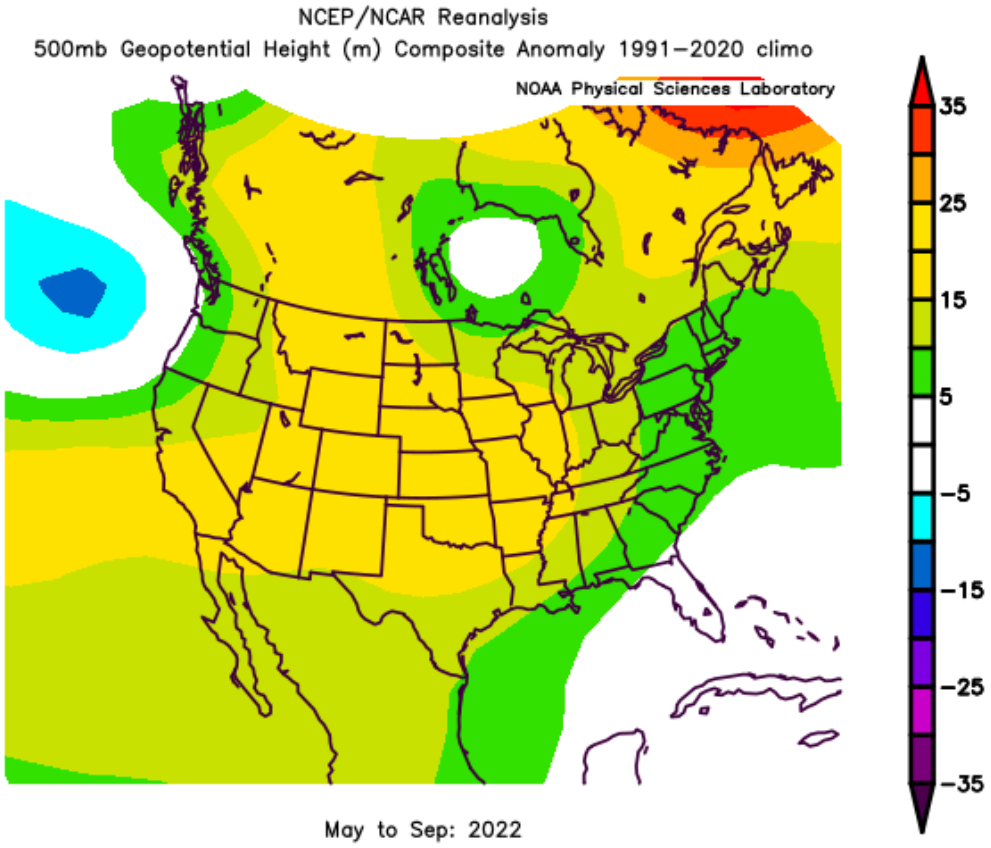

Figure 13. May-September 2022 500-mb height anomalies. Positive height anomalies in green indicate the presence of upper-level high pressure over the region. Courtesy: NCEP.

Another possible factor influencing ozone levels during the summer ozone forecasting season was long-range wildfire smoke transport. Wildfires emit a variety of pollutants, including $PM_{2.5}$ and volatile organic compounds (VOCs). These pollutants not only increase $PM_{2.5}$ levels, but can also interact with ozone chemistry and increase ozone production.

Sonoma Technology meteorologists explored the impacts of wildfire smoke on ozone during the May-September 2022 period, comparing daily observed ozone levels with NOAA Hazard Mapping System (HMS) smoke analysis. As shown in Table 6, smoke was observed over Delaware on 36 of the 49 Moderate ozone days between May and September 2022, accounting for 73% of all Moderate ozone days. Every month had at least half of its respective Moderate ozone days influenced by smoke.

Table 6. 2022 Moderate ozone days and NOAA HMS analyzed smoke days

	May	June	July	August	September	Season
Moderate ozone days	7	16	14	9	3	49
Moderate ozone days with smoke	4	11	11	7	3	36
Percent of ozone days with smoke influence	57%	69%	79%	78%	100%	73%

While monthly ozone concentrations in summer 2022 generally followed the historical trends in Figure 2, smoke was a lead factor in observed ozone levels in June 2022. Typically, July features the highest frequency of Moderate or higher ozone days, which coincides with the warmest temperatures of the year. However, Moderate ozone levels occurred on 16 days in June 2022, which was the most of any month during the summer 2022 ozone forecasting season. These ozone levels were achieved despite cooler-than-normal June temperatures across Delaware, along with no clear upper-level weather pattern that would support higher-then-normal ozone production.

Moderate ozone was present 53% of the time in June 2022, marking a 16% increase in Moderate or higher ozone days versus the 2017-2021 ozone climatology. Of the 16 Moderate ozone days in June 2022, NOAA HMS smoke analysis indicated varying degrees of smoke plumes in Delaware on 11 days. In conjunction with smoke, June 2022 ozone levels were also impacted by lighter-than-normal wind speeds, as shown in Tables 5 and 6. These light winds allowed smoke and other pollutants to accumulate across the First State, which led to more frequent Moderate ozone days.

As is typically the case, September 2022 recorded the fewest Moderate ozone days. Although smoke was analyzed over the state on all three Moderate ozone days for that month, the seasonal reduction of temperatures and daylight led to Good ozone levels on most days. It is also likely that increased mixing from a persistent upper-level low pressure trough west of the state resulted in improved air quality (**Figure 14**).

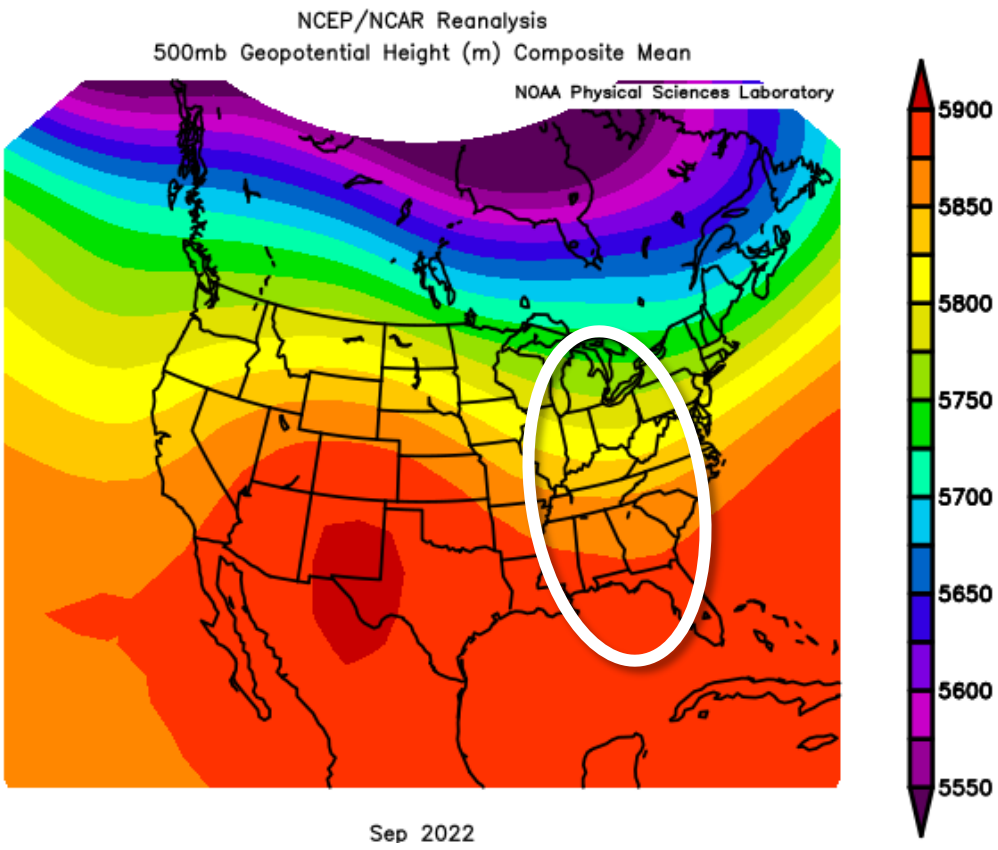

Figure 14. September 2022 mean 500-mb heights. An upper-level trough of low pressure (circled in white) promoted low-level mixing in Delaware, contributing to Good ozone levels. Courtesy: NCEP

While ozone levels were generally Good on most days during the summer 2022 ozone forecasting season, there were three days where ozone AQI levels met or exceeded 90 AQI. The following section will provide a review of the meteorological conditions leading to elevated ozone production on these days.

3. Meteorological Analysis of High Ozone Days in Summer 2022

3.1 Introduction

The summer 2022 ozone forecasting season was the first time daily observed ozone levels in Delaware did not exceed the USG threshold since the start of daily air quality record keeping in 1980. However, there were three occurrences this summer where observed ozone levels met or exceeded 90 AQI. All of these days happened in June, which was mentioned in the preceding section as the month with the highest frequency of Moderate ozone level days during the 2022 summer ozone forecasting season.

Table 7 lists the three days this summer with observed ozone AQI levels at or above 90, along with the next-day ozone forecast AQI issued by Sonoma Technology. Sections 3.2-3.4 will give a detailed review of the meteorological and air quality conditions for these days.

Table 7. Observed ozone AQI days ≥ 90 and next-day ozone forecasts for the May-September 2022 period.

Date	Observed Ozone AQI & Location	Next-Day Forecast Ozone AQI
June 4, 2022	90 – Bellefont	67
June 21, 2022	93 – Lums	50
June 30, 2022	90 – Bellefont and BCSP	97

3.2 June 4, 2022 – 90 AQI

Northwesterly winds tend to be a clean transport path for the First State due to few upwind emission sources and air that is generally cool across the eastern Great Lakes. However, this wind pattern was one of the factors behind high-Moderate ozone levels on June 4. On the day prior to this event, ozone levels were Good across Delaware, but low- to mid-Moderate across portions of the eastern Great Lakes. By June 4, northwesterly winds at and above the surface carried this plume of elevated ozone from the eastern Great Lakes into the First State, increasing ozone concentrations.

Along with pollutant transport from the eastern Great Lakes, abundant sunshine and afternoon temperatures in the mid-80s supported ozone formation. Surface weather stations across the northern portion of New Castle County also indicated a brief period of variable winds, with weak

surface convergence over the northern portion of the state, from 9 a.m. and 3 p.m. (Figure 15). This period of weak convergence likely allowed pollutants to accumulate north of Wilmington, increasing ozone levels at the Bellefont monitoring site. As a result of these conditions, ozone levels at many sites across the region were in the mid- to high-Moderate AQI category, and one site in southwestern New Jersey saw USG ozone AQI levels. The highest ozone concentrations in Delaware were observed in the northern portion of the state, where the daily ozone AQI value reached 90.

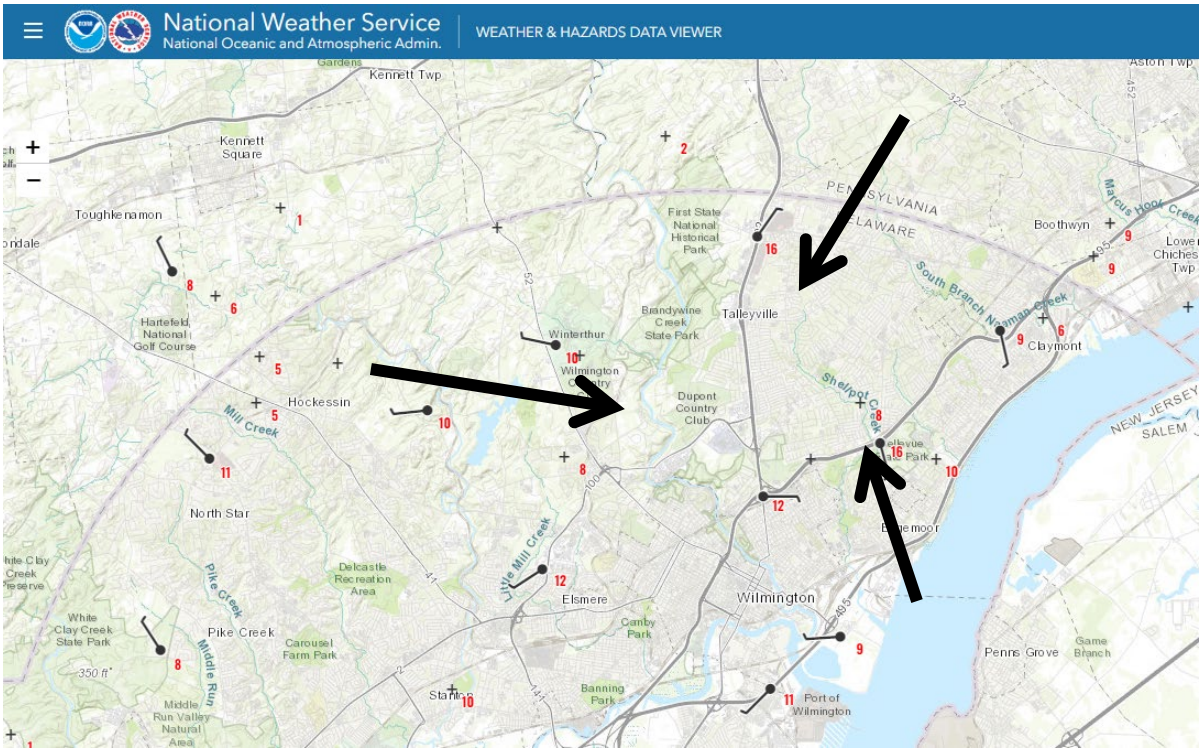

Figure 15. Surface wind plot, valid 12 p.m. EDT on June 4, 2022. Wind directions (black barbs and arrows) across northern New Castle County varied, which allowed for pollutant accumulation. Courtesy: National Oceanic and Atmospheric Administration (NOAA)

3.3 June 21, 2022 – 93 AQI

A few weeks after the June 4 high pollution event, the season's highest ozone levels occurred at the Lums monitoring site in New Castle County. The prevailing weather pattern on this day included a well-defined ridge of upper-level high pressure (Figure 16), extending from Hudson Bay, Canada, southward to the Lower Mississippi River Valley. This upper-level feature helped reduce low-level mixing across the Mid-Atlantic region.

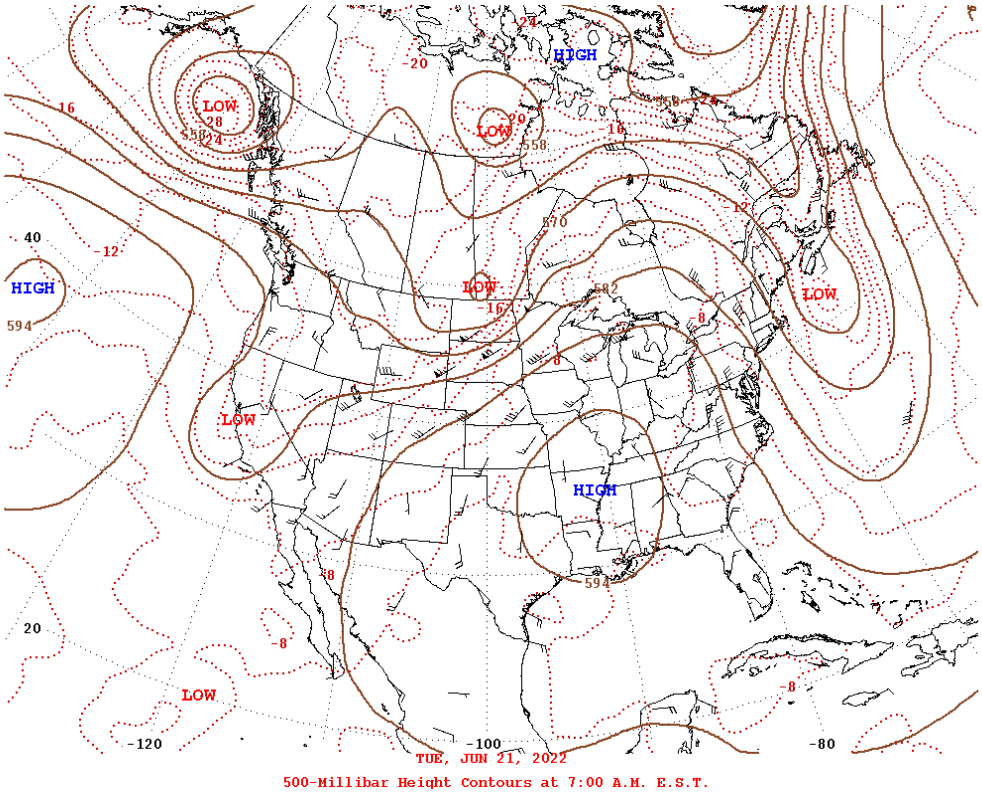

Figure 16. 500 mb map, valid 8 a.m. EDT on June 21, 2022. Upper-level high pressure west of Delaware reduced mixing, which helped promote ozone formation. Courtesy: NOAA

Although weather models on the previous day predicted partly to mostly cloudy skies on June 21, observed conditions were sunny to mostly sunny throughout the day, leading to higher-than-predicted ozone concentrations. Additionally, surface temperatures on this day reached 81°F in Wilmington, which was 3-7°F above the next-day predicted maximum temperature, further contributing to higher-than-predicted ozone levels. Furthermore, light west-southwesterly winds in the lower levels of the atmosphere transported regional pollutants into Delaware. It is also possible these winds transported thin smoke into the First State, which further enhanced ozone production. As a result of these conditions, the daily ozone AQI value reached 93, which is in the high-Moderate category. Additionally, all seven ozone monitoring sites across the First State recorded mid- to high-Moderate ozone AQI values.

3.4 June 30, 2022 – 90 AQI

The final day with an ozone AQI level at or above 90 occurred on the last day of June. Conditions leading up to this event included a weak upper-level ridge of high pressure west of the state, contributing to abundant sunshine and a reduction in atmospheric mixing. Surface temperatures on this day were warmer than normal, with a maximum high temperature of 91°F recorded in Wilmington (5°F above average).

Ozone levels were also enhanced by the presence of wildfire smoke. NOAA HMS analysis (Figure 17) indicated a plume of smoke hovering over the Mid-Atlantic region, with high concentrations of $PM_{2.5}$ and ozone precursors aiding ozone development.

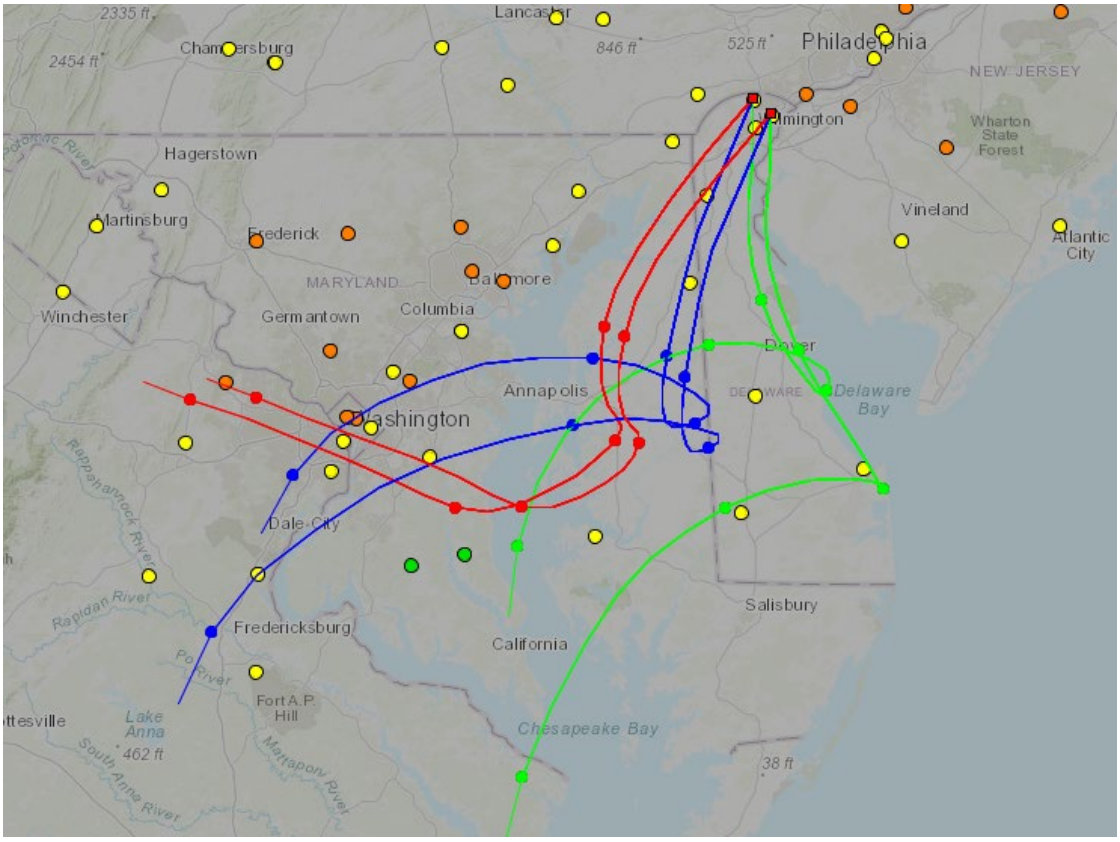

Figure 17. Daily maximum 8-hr average ozone AQI (dots), NOAA HMS smoke analysis (gray contour), and HYSPLIT 24-hr back trajectory analysis (green 100 m, blue 500 m, red 100 m above sea level) ending 11 p.m. EDT on June 30, 2022. Yellow and orange dots indicate Moderate to USG ozone levels across the region, due to smoke and low-level pollutant transport into Delaware from Washington D.C. Courtesy: AirNow-Tech

Low-level winds shown in Figure 17 also depict pollutant transport from regional sources. At 500 m (blue lines) and 1,000 m above sea level (red lines), back trajectory analysis shows westerly to southwesterly winds throughout much of the day. These winds were responsible for carrying additional ozone precursors and other regional pollutants into Delaware, further increasing ozone production on this day.

These conditions, along with pollutant carryover from the previous day, resulted in the Bellefont and BCSP monitoring sites recording a daily observed AQI value of 90. Much like the high-pollution event nine days prior, all seven ozone monitoring sites in Delaware recorded Moderate ozone AQI on June 30.

4. Skill of Ozone Forecasts in 2022

4.1 Introduction to Sonoma Technology Forecasts

During the summer 2022 ozone season in Delaware, Sonoma Technology meteorologists issued three-day forecasts during weekdays. On occasion, forecasts are issued on weekends when ozone concentrations approach Code Orange levels. However, the majority of next-day forecasts are issued between Mondays and Fridays and are valid for Tuesdays through Saturdays.

Due to true next-day forecasts being unavailable on Sundays and Mondays, and to assess forecast skill, observed ozone levels in summer 2022 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 2022 Ozone Forecast Statistics

A comparison between Sonoma Technology Forecasts and observed ozone levels in Delaware during summer 2022 is shown in Figure 18 below. Due to the low number of USG forecasts issued, the Good-to-Moderate threshold was used to verify forecast accuracy. As a result, Sonoma Technology Forecasts in Delaware were correct 76% of the time during summer 2022.

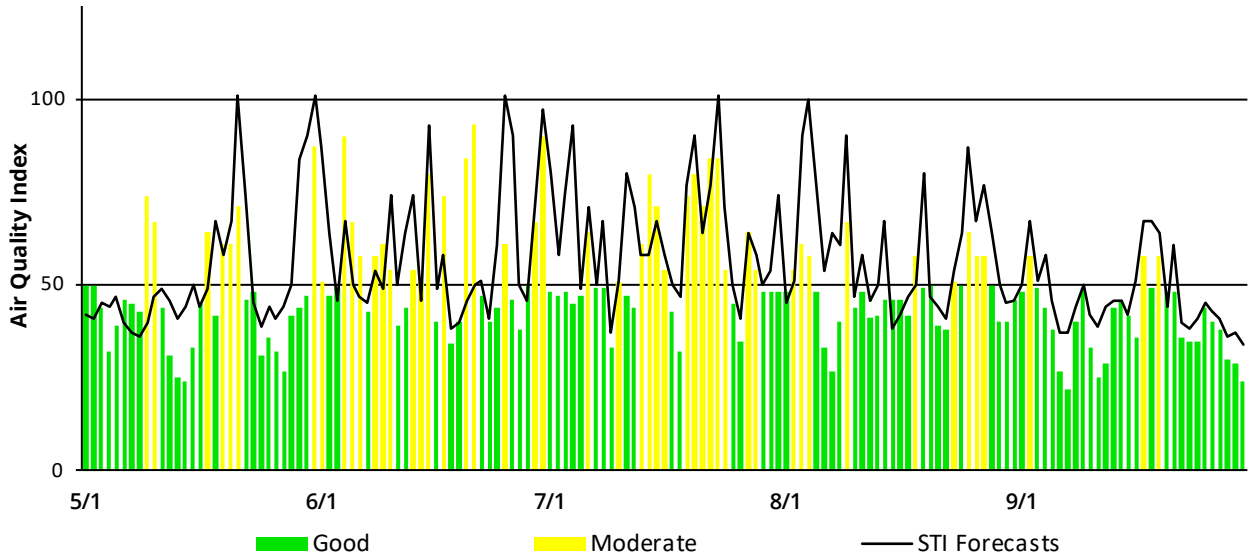

Figure 18. Daily observed ozone levels in Delaware versus Sonoma Technology Forecasts (STI Forecasts in the graph above).

Moderate ozone levels were observed on 49 out of 153 forecast days in summer 2022, which was a 5% increase over summer 2021. Sonoma Technology forecasters issued Moderate AQI level forecasts on 35 of the 49 observed days with Moderate AQI values. This resulted in a POD of 71% for days with Moderate AQI levels. AQI values did not reach the USG category during summer 2022 in Delaware, which is a decrease from 3 days with USG AQI levels during summer 2021.

Forecast false alarms occur when the forecast ozone AQI category is higher than the observed ozone AQI category. Of the 67 days during summer 2022 when Moderate ozone levels were forecast, there were 32 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 2022 was 48%. On average, actual AQI levels came within 5 ppb of the Moderate category on days with Moderate false alarms. USG ozone levels were forecast on four days this summer: May 21, May 31, June 25, and July 23. These USG ozone forecasts ended up as false alarms, with an average observed AQI of 76. Figure 19 shows a comparison of percent correct, POD, and FAR for Sonoma Technology Forecasts over the last three years. The statistics for each year are comparable, with the highest accuracy so far occurring during summer 2021.

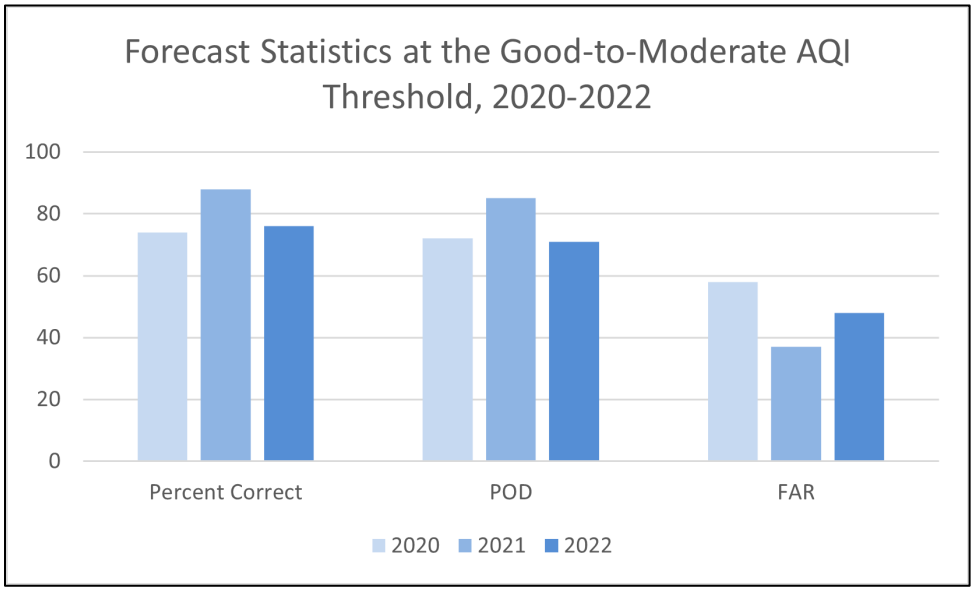

Figure 19. Percent Correct, Probability of Detection (POD), and False Alarm Rate (FAR) at the Good-to-Moderate AQI threshold 2020-2022.

Forecast skill can also be assessed by calculating forecast bias and mean absolute error (MAE), which is done through comparing the forecast ozone concentrations to observed concentrations. Bias is the average difference between forecast and observed concentrations. A positive bias indicates that the forecast concentrations tended to be higher than observed concentrations. Conversely, a negative bias indicates that the forecast 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 9 provides the forecast bias and MAE for all Sonoma Technology Forecasts during summer 2022 based on daily maximum 8-hr average ozone concentrations. For the May-September 2022 period, Sonoma Technology Forecasts exhibited a bias of +4.2 ppb over observed ozone values, with an MAE of 7.1 ppb. Sonoma Technology Forecasts were most biased in September 2022, at +5.5 ppb, and least biased in June 2022, at +1.7 ppb. Overall, Sonoma Technology Forecasts strive to be protective of public health while still maintaining accuracy, which often results in the positive forecast bias.

Table 8. Sonoma Technology forecast bias and MAE for next day forecasts for summer 2022.

Month	Bias (ppb)	Mean Absolute Error (ppb)
May	+4.4	10.0
June	+1.7	7.0
July	+4.2	5.3
August	+5.3	7.1
September	+5.5	5.9
Average	**+4.2**	**7.1**

5. Skill of Ozone Model Forecasts in 2022

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 forecasts for days 1-3.

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

- NOAA's raw and bias-corrected ozone model, run twice daily (https://digital.mdl.nws.noaa.gov/airquality/).
- BlueSky-Gateway (BSG) ozone model, run once daily. Developed by Sonoma Technology, this model also produces raw and bias-corrected output. The BSG ozone model was available for 85% of the days in the summer 2022 ozone season.

The following sections analyze the skill of each model's next-day forecast output and compare model performance to Sonoma Technology Forecasts during summer 2022.

5.1 Comparison of Sonoma Technology Forecasts to 2022 Ozone Model Forecasts

Table 10 provides each model run's next-day average forecast bias and MAE for the summer 2022 ozone forecast season in Wilmington, Delaware.

Table 9. May-September 2022 next-day forecast model statistics for Wilmington, Delaware.

Model	Bias (ppb)	Mean Absolute Error (ppb
NOAA Raw 06Z	-2.9	5.9
NOAA Raw 12Z	-2.7	5.9
NOAA Bias-Corrected 06Z	-3.6	7.0
NOAA Bias-Corrected 06Z	-3.4	6.9
BSG Raw 00Z	-2.2	6.3
BSG Bias-Corrected 00Z	-4.8	7.3

For the 2022 ozone forecast season, the model with the highest next-day forecast bias and MAE in Wilmington was the bias-corrected 0Z BSG model. In comparison, BSG's raw 0Z output had the least-biased predictions, while NOAA's raw 6Z and 12Z guidance had the lowest MAE.

Figures 20 and 21 compare the next-day forecast bias and MAE for each month during Delaware's ozone season. These figures include both modeled ozone predictions *and* Sonoma Technology Forecasts (blue bars at the left of each grouping) issued for the summer 2022 ozone season. Additionally, the average annual bias and average annual MAE for the entire May-September 2022 period is shown at the far right of each figure.

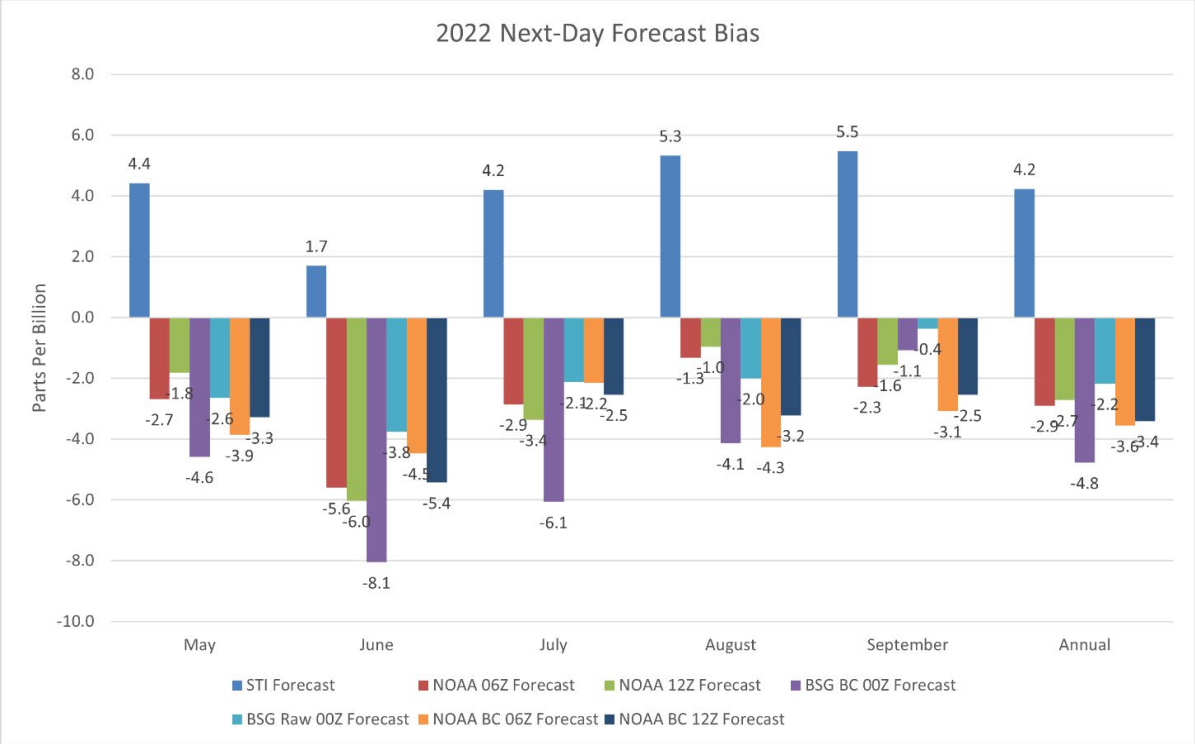

Figure 20. Monthly model forecast and Sonoma Technology Forecast bias during the summer 2022 ozone season in Wilmington, Delaware.

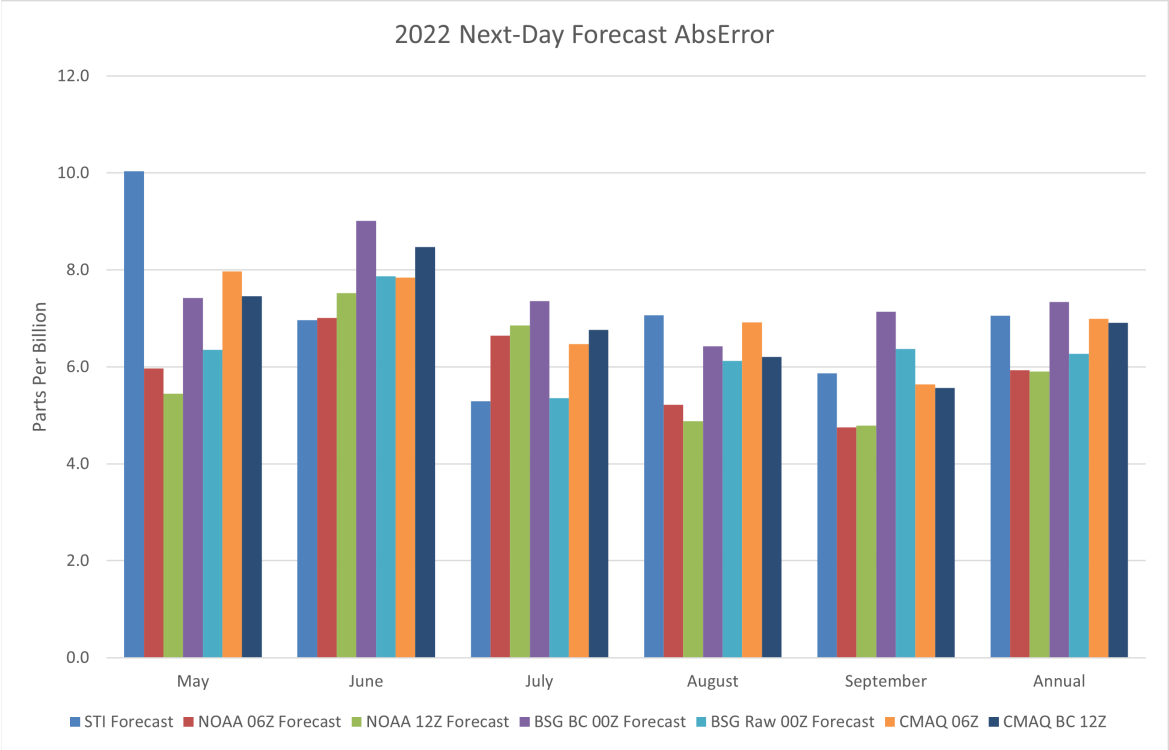

Figure 21. Monthly model forecast and Sonoma Technology Forecast MAE during the summer 2022 season in Wilmington, Delaware.

All of the ozone forecast models maintained a negative bias throughout the summer, indicating forecast concentrations were lower than observed concentrations in Wilmington. The BSG BC 00Z forecast consistently had the largest negative bias, while the remaining models were generally under predicting ozone by 2-4 ppb. In comparison, Sonoma Technology Forecasts had a persistent positive bias. This is partially due to these forecasts representing predictions of the statewide maximum, not specific to Wilmington. 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 2022 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.

Forecast MAE was similar for the ozone forecast models and Sonoma Technology Forecasts, with highest values in May and June. MAE generally decreased to between 4-7 ppb July through September across all forecasts.

6. Forecast Review and Outlook

6.1 Review of Sonoma Technology's Summer 2022 Outlook

In the 2021 end-of-season report for Delaware, Sonoma Technology meteorologists produced a temperature and precipitation outlook focusing on June, July, and August 2022. 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 climate forecast from NOAA's Climate Prediction Center (CPC) was also reviewed. With official forecasts, model output, and trends predicting a similar summer weather pattern, Sonoma Technology forecasters predicted a good chance of slightly above-average temperatures with near-average to above-average precipitation. The observed temperature and precipitation anomalies for the United States during summer 2022 are shown in Figures 22 and 23.

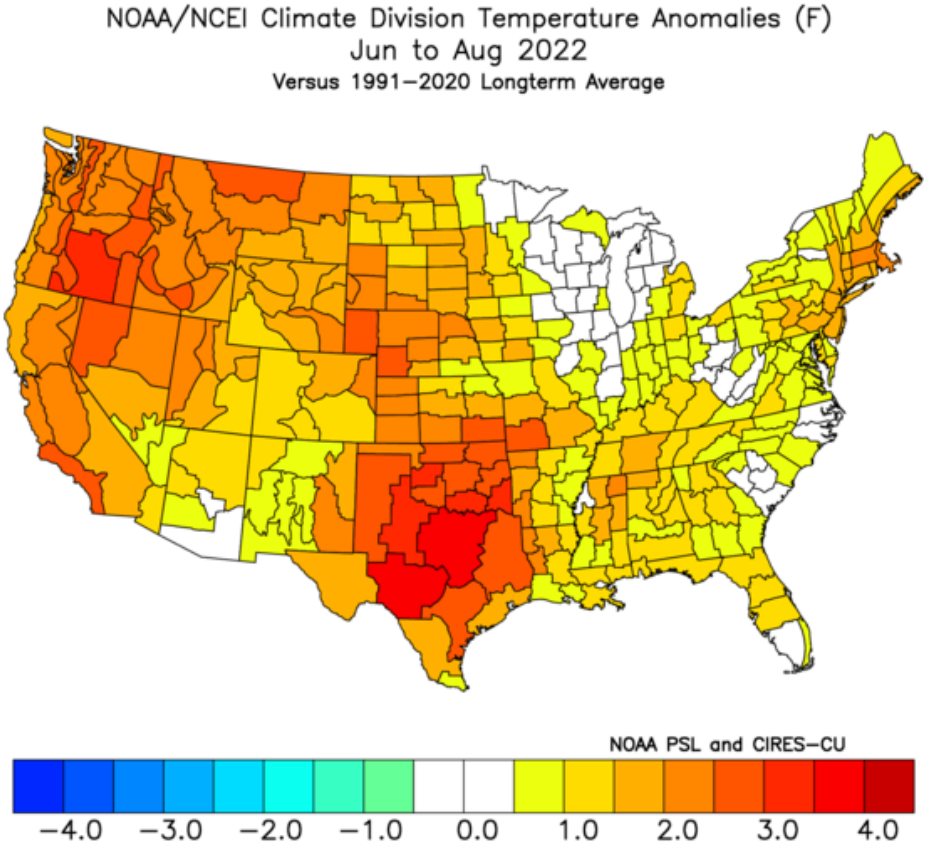

Figure 22. NOAA/NCEI temperature anomalies for summer 2022.

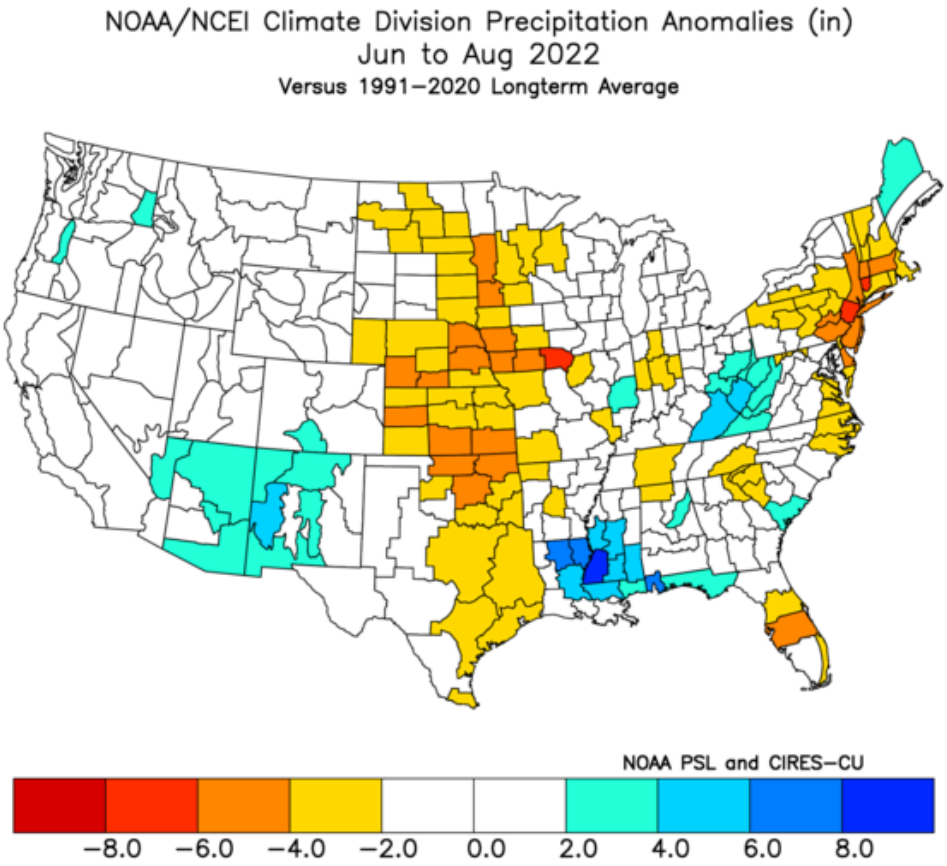

Figure 23. NOAA/NCEI precipitation anomalies for summer 2022.

These maps show that Delaware's average temperatures during summer 2022 were slightly above average, as predicted, while precipitation was below normal. The temperature map compares 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 2022 (**Figure 24**). However, below-normal precipitation was not forecast for Delaware in any of those products. This may be partly due to a lack of accuracy in ENSO predictions. While ENSO was forecast to become neutral over the summer, La Niña conditions persisted through summer 2022, which historically has favored below-normal precipitation along the East Coast.

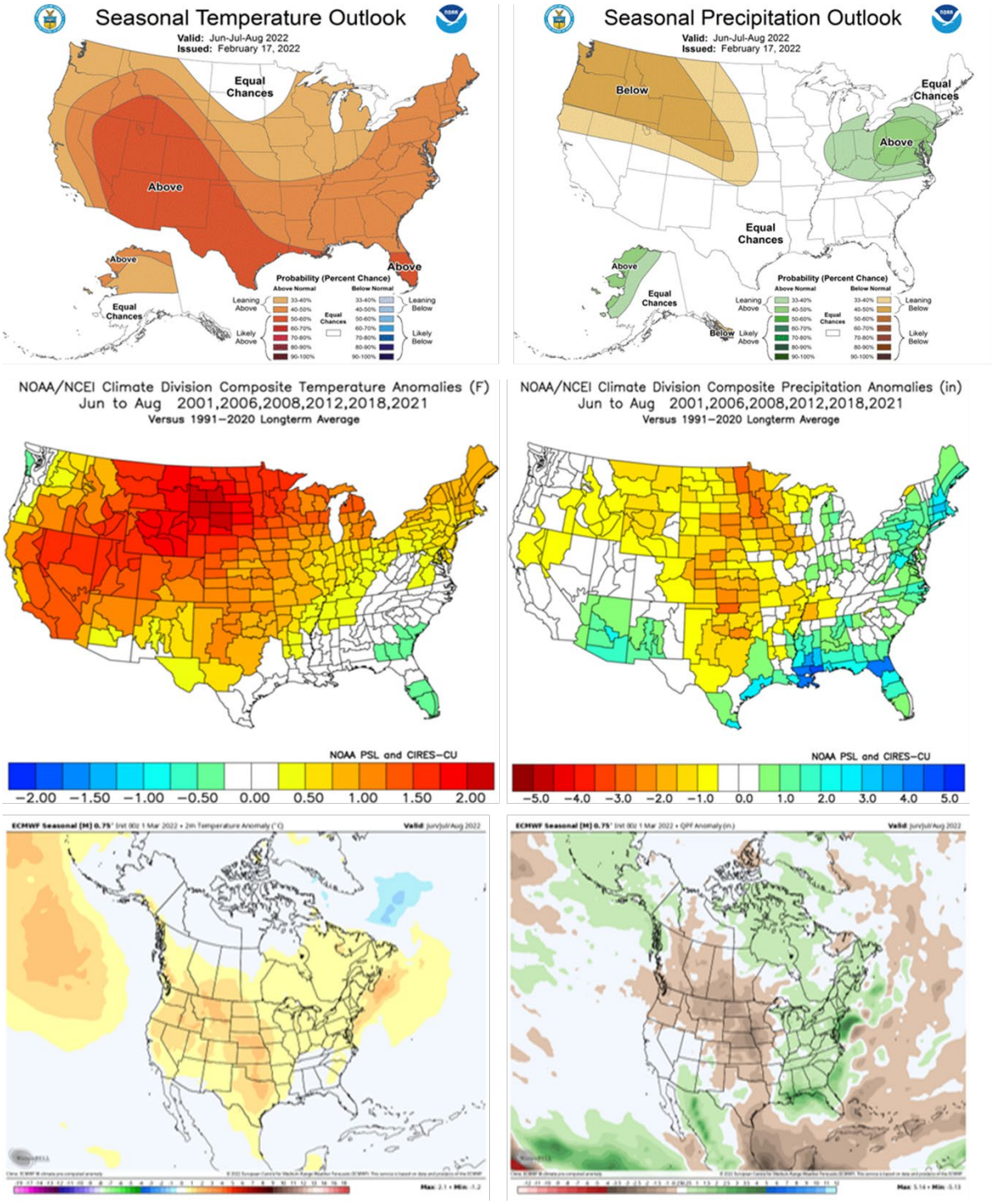

Figure 24. 2022 summer outlooks for temperature (left column) and precipitation (right column) from the CPC, ENSO analogs, and the ECMWF (top to bottom).

6.2 Summer Outlook 2023

To gauge the potential for ozone development during the upcoming 2023 summer season, Sonoma Technology meteorologists reviewed seasonal forecasts by NOAA's Climate Prediction Center (CPC), composites of temperature and precipitation anomalies for years with similar ENSO conditions, and model outputs from the CanSIPS multi-model ensemble. Current trends in summer temperatures and precipitation were also considered. The analysis focused on the forecast for June, July, and August 2023, as these months represent the peak of ozone season in Delaware.

CPC's forecast for temperature and precipitation anomalies for summer 2023 are shown below (Figures 25 and 26).

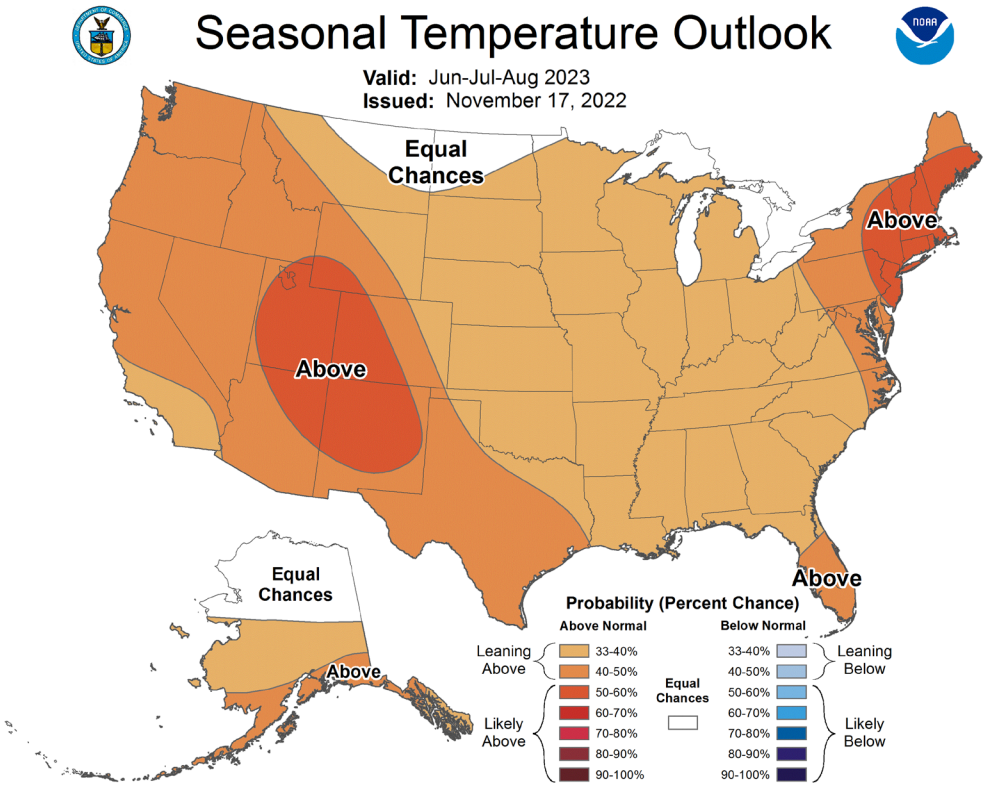

Figure 25. CPC forecast probability of surface temperature anomalies for June, July, and August 2023.

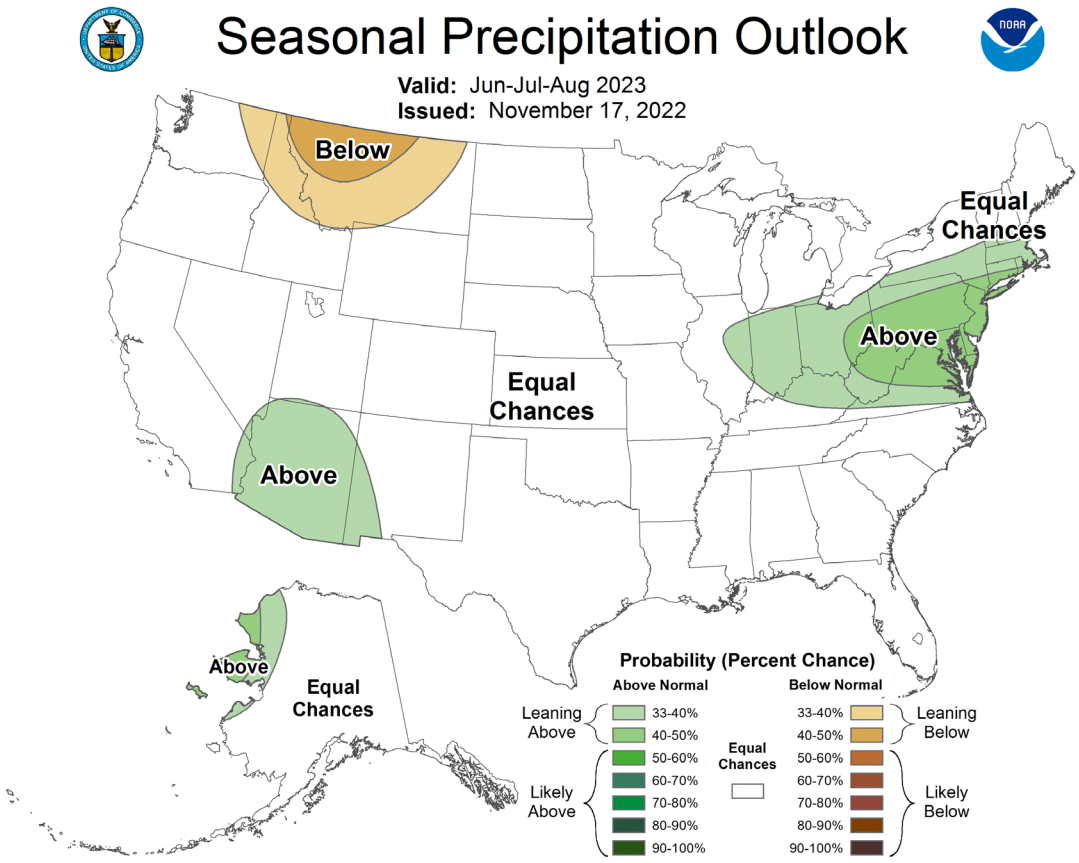

Figure 26. CPC forecast probability of precipitation anomalies for June, July, and August 2023.

Figures 25 and 26 indicate that the CPC is predicting a 40%-50% chance of above normal temperatures and a 40%-50% chance of above normal precipitation over the mid-Atlantic for summer 2023. 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 during summer 2023.

6.3 El Niño Southern Oscillation (ENSO)

Similar to the previous two summers, the CPC's ENSO outlook called for a transition from La Niña to ENSO-Neutral conditions by Northern Hemisphere summer 2023. As discussed in Section 6.1, last year's ENSO forecast did not end up verifying, as La Niña conditions persisted through the summer. This is only the third time since observations began in 1950 that La Niña conditions have persisted for three years in a row. The previous two occurrences of this phenomenon occurred from 1973-1976 and from 1998-2001. ENSO-neutral summers followed both of those long-duration La Niña episodes. The duration of the most recent La Niña passed the average duration of La Niña conditions (1-2 years), but based on NOAA's analysis, conditions have already transitioned out of La Niña, and summer 2023 will be ENSO-neutral.

Although ENSO is just one of many variables 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. 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 27 and 28** are composites of the temperature and precipitation anomalies that occurred during those years.

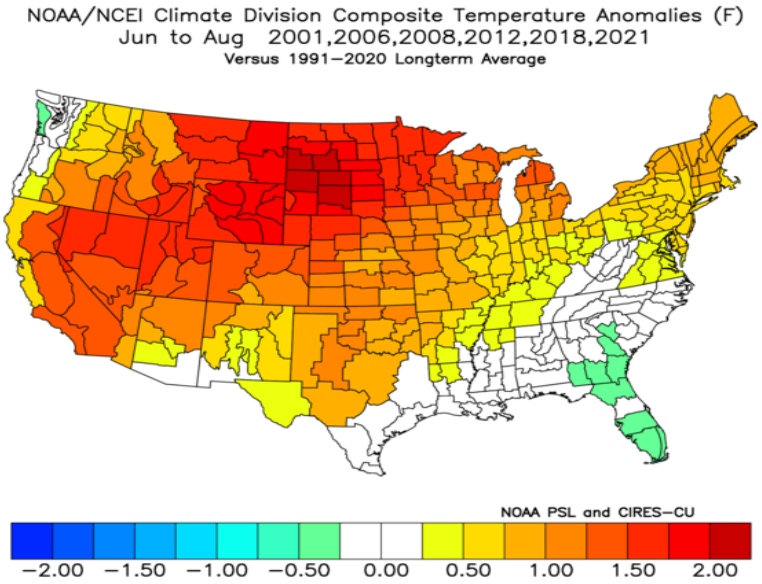

Figure 27. Temperature anomalies (°F) for ENSO-Neutral summers after La Niña subsided.

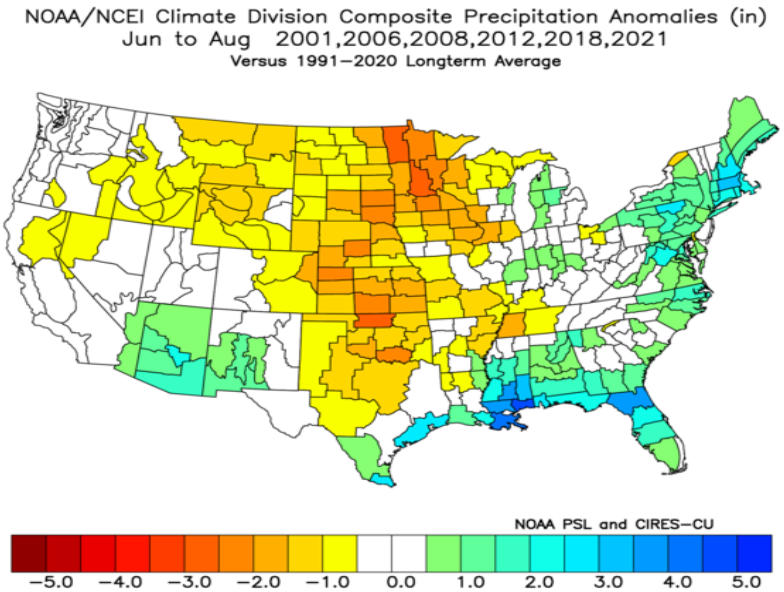

Figure 28. Precipitation anomalies (in.) for ENSO-Neutral summers after La Niña subsided.

Focusing on the Mid-Atlantic, the CPC's temperature forecast in Figure 25 is similar to historical temperature anomalies during ENSO-neutral summers in Figure 27, with both patterns indicating the potential for above-normal temperatures in Delaware. The precipitation forecast for Delaware from the CPC in Figure 26 also agrees with historical precipitation anomalies in Delaware in Figure 28, with above-normal rainfall occurring along much of the East Coast during ENSO-neutral summers.

While ENSO conditions and forecasts are an important component of the summer outlook, forecast models can resolve additional complexity between the different atmospheric systems that affect weather patterns around the globe. The following section examines the seasonal forecast from a climate model to see how it compares with the overall forecast.

6.4 Model Forecasts

The seasonal temperature and precipitation forecasts from the Canadian Seasonal to Inter-annual Prediction System (CanSIPS) model are shown in **Figures 29 and 30**. The CanSIPS model is an ensemble of two climate models developed by the Canadian Centre for Climate Modelling and Analysis and the Canadian Meteorological Centre. The model considers some of the complex interactions among the atmosphere, oceans, ice, and land surfaces across the globe to produce seasonal long-range forecasts.

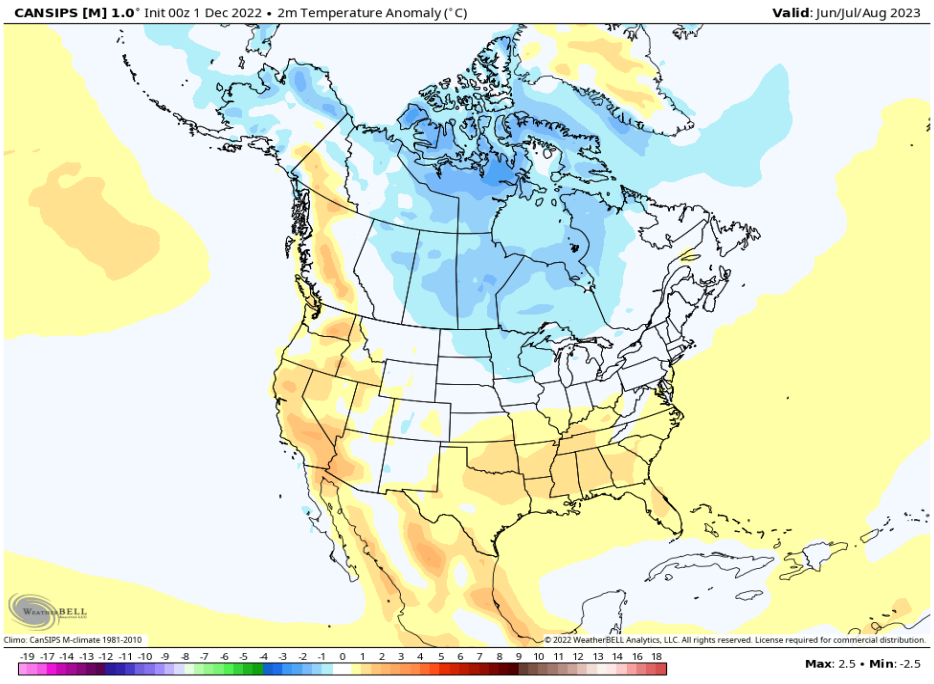

Figure 29. CanSIPS forecast temperature anomalies for June-August 2023.

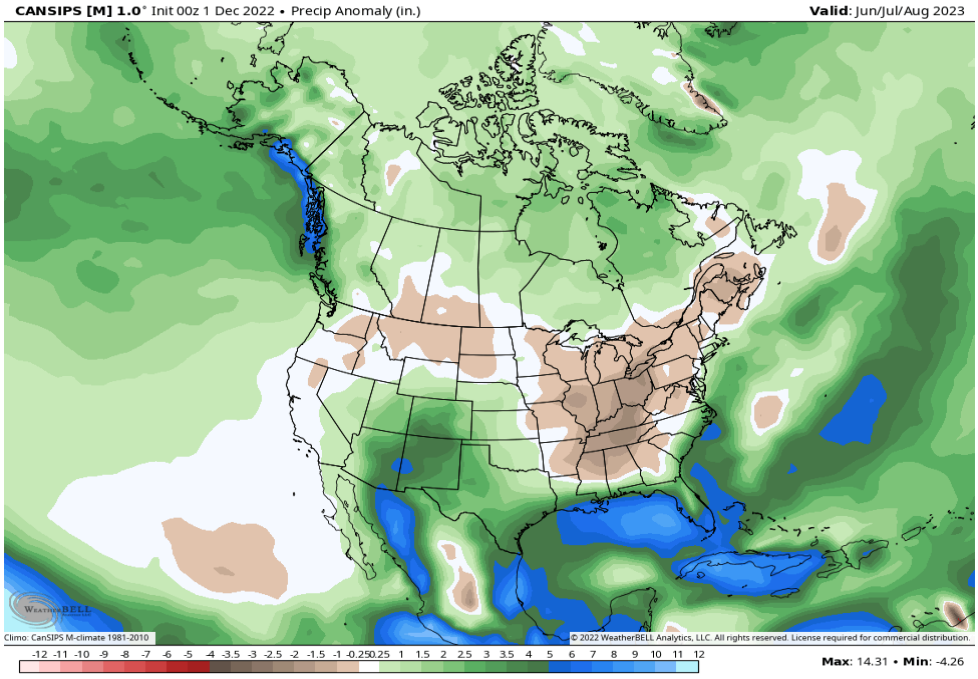

Figure 30. CanSIPS forecast precipitation anomalies for June-August 2023.

Similar to the CPC's forecast and the ENSO analogs, the CanSIPS model is forecasting slightly above-normal temperatures for Delaware during summer 2023. However, the precipitation pattern along the East Coast differs from the other products. CanSIPS is forecasting above-normal precipitation from the Gulf Coast into the Carolinas, with Delaware situated in a transition zone between above normal precipitation to the south and drier conditions to the north.

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 3-month periods throughout the year. Temperature trends reflect the difference between the average temperatures during a selected 3-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 3-month period over the last 15 years and the precipitation climatology from 1981-2010. The trend maps are shown in **Figure 31**.

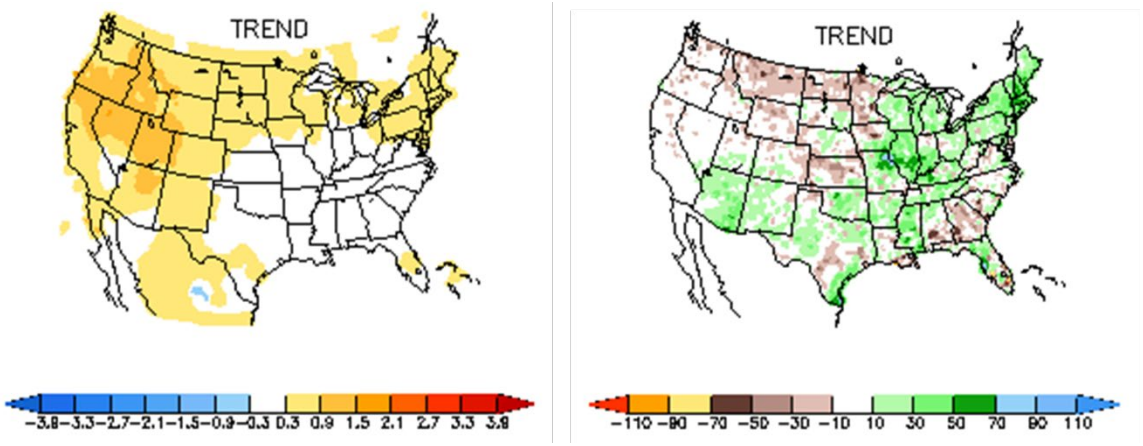

Figure 31. Recent trends in temperature in degrees Celsius (left) and precipitation in millimeters (right) for June, July, and August. The recent trend is estimated by the Optimal Climate Normal (OCN) of Huang et al. (1996).[3]

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 2023 Ozone Season in Delaware

Long-range forecasting is inherently challenging due to the complexity of the interactions among the atmosphere, oceans, ice, and land. In addition, there are no linear relationships between certain climate regimes and air quality impacts. However, considering the outlooks and products discussed so far in section 6, some general observations can be made to help inform a long-range air quality outlook.

Based on NOAA's analysis, conditions officially transitioned to ENSO-neutral in March 2023. Historically, this would imply a tendency toward above-normal precipitation along the East Coast. In addition, trends in summertime precipitation over the last 15 years are supportive of above-normal precipitation in much of the eastern U.S. If a wetter pattern is realized this summer, that could indicate a more active upper-level weather regime over Delaware and enhanced atmospheric mixing. Furthermore, an increase in rainfall could be related to increased humidity levels. Generally, increased humidity results in improved low-level mixing due to the buoyancy of moist air. Finally, a wetter summer could indicate increased cloudiness. Each of these factors has the potential to reduce ozone development.

[3] 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.

As far as temperatures are concerned, trends, models, and neutral-ENSO conditions are all supportive of above-normal temperatures during the summer months in Delaware. During a dry period, an increase in temperatures would support greater ozone formation. However, given the potential for above-average precipitation, any potential ozone increases could be mitigated by the more active weather pattern. Last summer, conditions were warmer and drier than average in Delaware, which resulted in Moderate AQI levels 32% of the time. If the wetter weather conditions materialize next summer, Sonoma Technology meteorologists expect a decrease in the frequency of days with Moderate AQI levels compared to summer 2022.