State of Delaware Final Report: Ozone Observations and Forecasts in 2020

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Final Report

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Key Findings

- Between May and September, ozone levels were in the Good Air Quality Index (AQI) category on 81% of days, Moderate on 18% of days, and Unhealthy for Sensitive Groups (USG) on 1% of days.
- Two USG (Code Orange) ozone days were observed during the summer 2020 ozone forecasting season. For the fourth consecutive summer, no Unhealthy (Code Red) or Very Unhealthy (Code Purple) ozone days were recorded.
- Despite warmer-than-normal temperatures, Good AQI days were more frequent than any summer dating back to 2013.
- Emissions reductions related to the COVID-19 pandemic likely contributed to better-than-normal air quality during summer 2020, especially during the month of August.
- At the Good-to-Moderate threshold, next-day forecasts issued during the weekdays (Monday-Friday) were correct 75% of the time during summer 2020, with a probability of detection (POD) of 76% and false alarm rate (FAR) of 53%.

1. Ozone Climatology 2015-2019

Ozone levels in the state of Delaware have drastically improved since the mid-1990s. With respect to Code Orange (days with daily max 8-hour average ozone concentrations greater than or equal to 71 ppb and below 86 ppb) and Code Red (days with daily max 8-hour average ozone concentrations greater than or equal to 86 ppb and below 106 ppb) days, the occurrence of these ozone levels has decreased since 2012. As noted by Ryan, Huff, et al. in *State of Delaware Final Report: Ozone Observations and Forecasts in 2018*[1], the decrease in Code Orange and Code Red days since 2012 can be attributed to a reduction in nitrous oxide (NO_x) emissions across the Mid-Atlantic region.

To account for the recent shift in improved air quality, Sonoma Technology (STI) forecasters produced a five-year climatology of ozone levels across the state prior to the 2020 ozone forecasting season. This climatology was based on data from the seven ozone monitoring sites across the state (**Figure 1**) recorded between 2015 and 2019. The following climatology highlights the seasonality of ozone AQI levels, the day-of-week patterns in ozone AQI levels, and the frequency of multi-day high-ozone events.

[1] http://www.dnrec.delaware.gov/Air/Documents/2018-Delaware-Annual-Air-Quality-Report.pdf

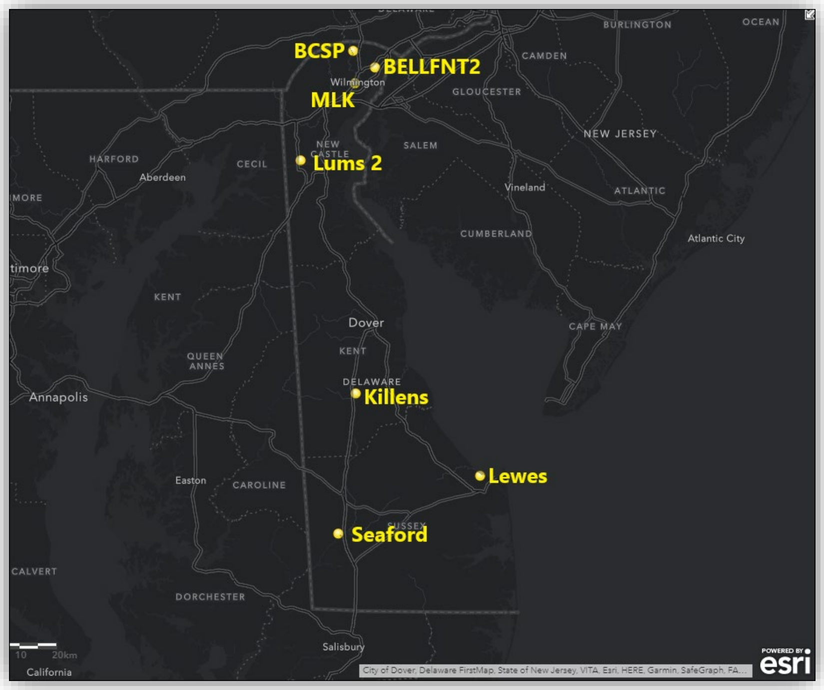

Figure 1. Active ozone monitoring sites in the State of Delaware.

1.1 Monthly Climatology of Ozone

Ground-level ozone formation is highly dependent on sunlight and surface temperatures. In early spring, increasing daylight and warmer temperatures enhance ozone formation. This relationship is shown in Figure 2, as Moderate or higher AQI days increased in frequency beginning in March, based on 2015-2019 data.

According to the 2015-2019 climatology in Figure 2, Moderate or higher AQI days primarily occurred in April through September, while USG or higher days were observed every month between May and September. Good ozone days were the least frequent in July, and 55% of days during that month between 2015-2019 featured Moderate or higher AQI levels.

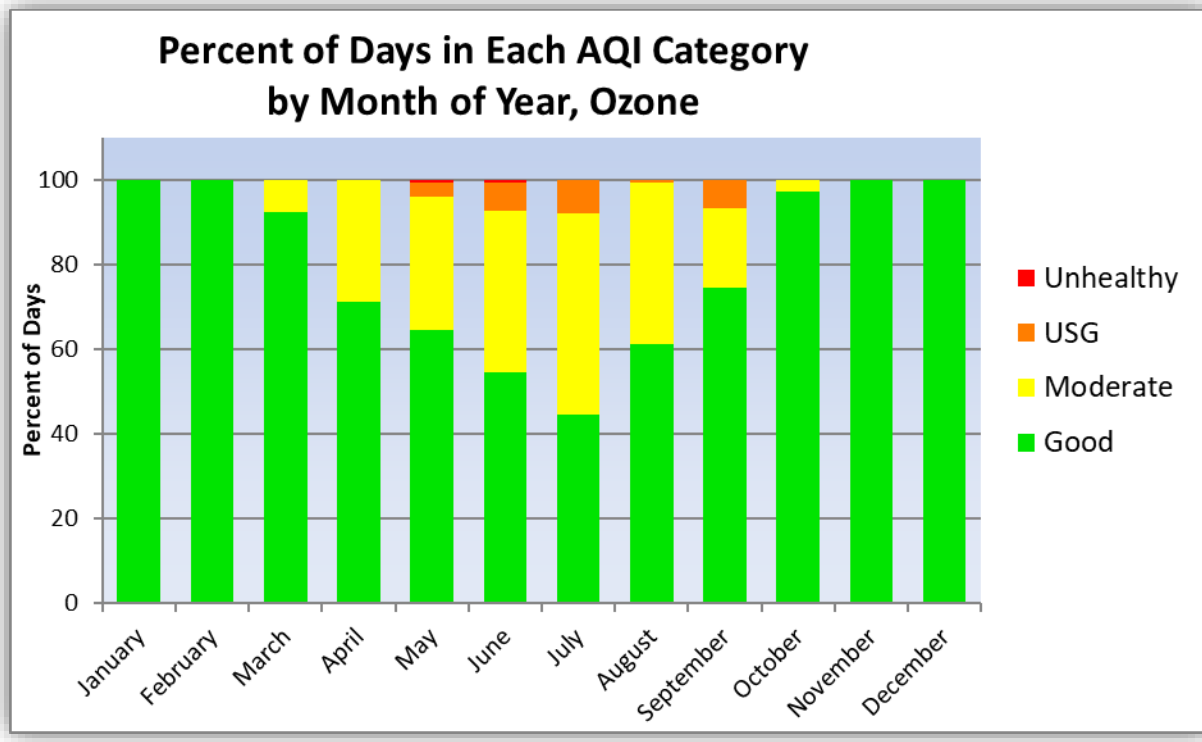

Figure 2. Monthly distribution of each AQI category, based on 2015-2019 ozone data.

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 occurred most frequently on Wednesdays and Thursdays, based on 2015-2019 data. In some regions, emissions decreased on weekend days, resulting in improved air quality. Between 2015-2019 in Delaware, Sundays featured the fewest Moderate or higher AQI ozone days. However, Moderate or higher AQI ozone days were more frequent on Saturdays than on Mondays and Tuesdays, perhaps due to pollutant carryover from Fridays. Further research is needed to understand the relationship between daily emissions and ozone levels in Delaware.

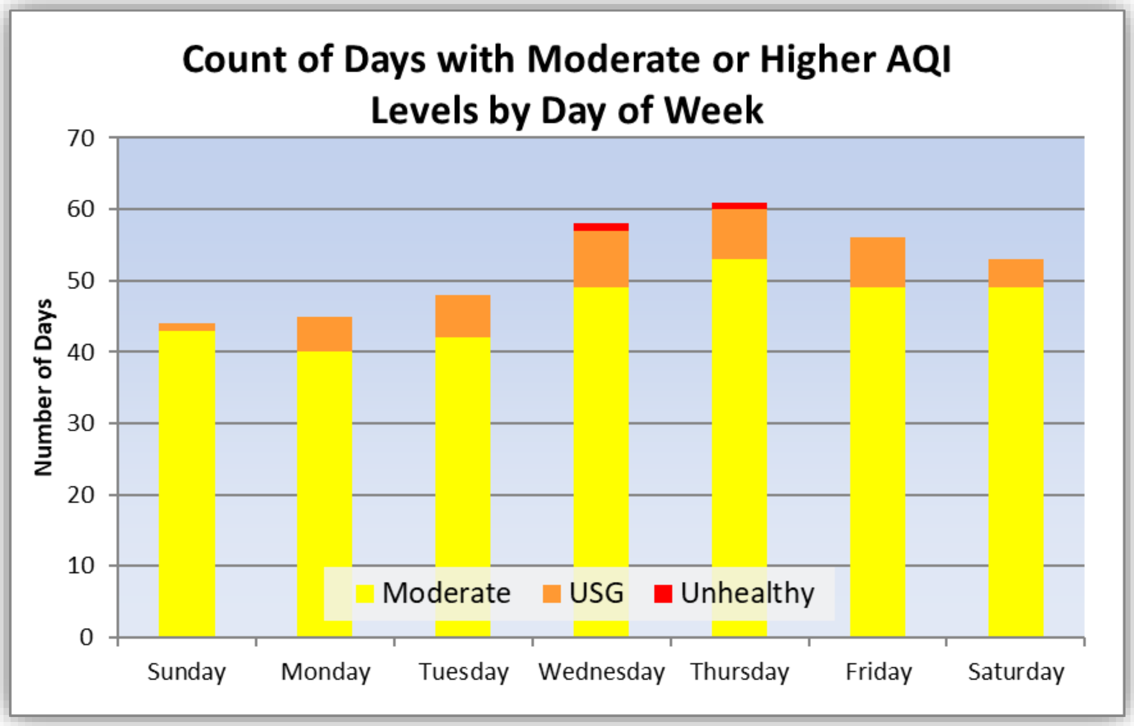

Figure 3. Number of days with Moderate or higher AQI levels by day of week, based on 2015-2019 ozone data.

1.3 Frequency of Multi-Day Ozone Exceedance Events

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

Based on 2015-2019 data, there were 40 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 8 times, accounting for 16 days. Of the 40 ozone exceedances observed in the five-year period, there were two separate events with three consecutive Code Orange or higher days. These events accounted for 6 of the 40 observed ozone exceedances between 2015 and 2019.

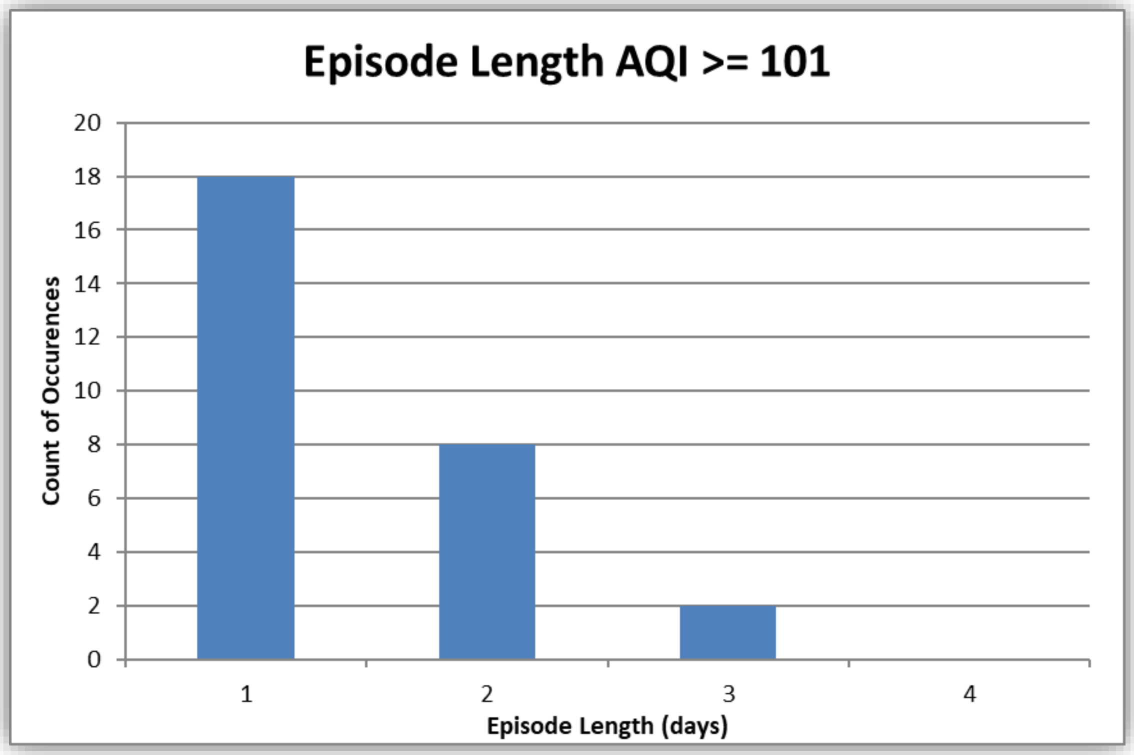

Figure 4. Frequency of long-duration Code Orange or higher AQI events, based on 2015-2019 ozone data.

2. Ozone and Meteorological Observations in 2020

The summer ozone forecasting season in Delaware lasts from May 1 to September 30. During this period in 2020, statewide daily maximum air quality levels in Delaware were in the Good AQI category on 81% of days and the Moderate AQI category on 18% of days (Figure 5). Two USG AQI days were recorded during the 2020 ozone forecasting season, and no Code Orange (USG) next-day forecasts were issued.

Figure 6 includes a daily breakdown of statewide observed daily maximum 8-hour average ozone AQI levels throughout the 2020 ozone forecast season.

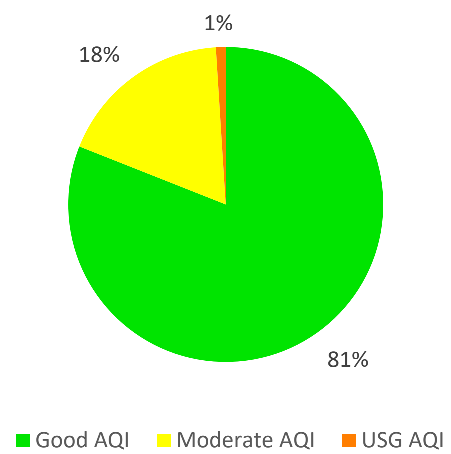

Figure 5. Delaware observed daily maximum ozone AQI values between May 1–September 30, 2020. Courtesy: AirNow-Tech.

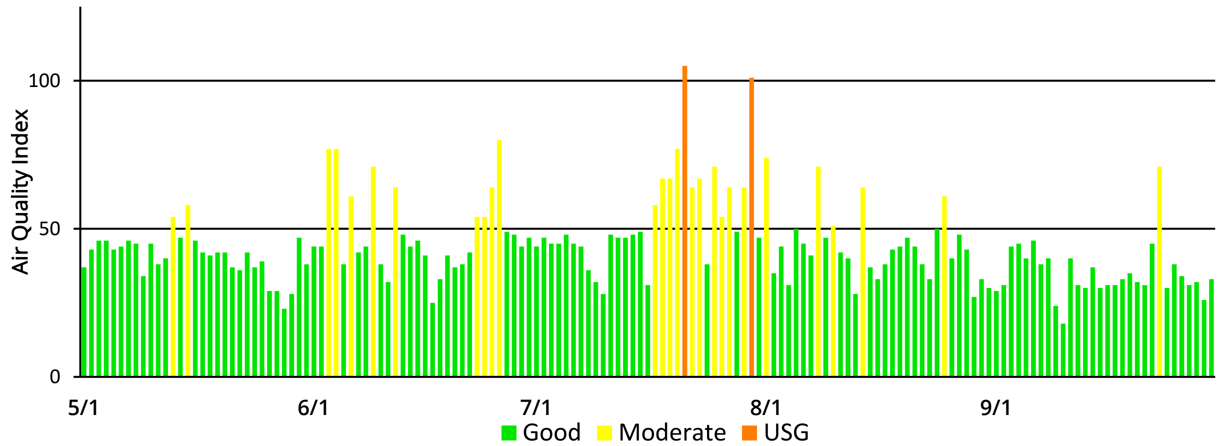

Figure 6. Delaware daily maximum ozone AQI values between May 1–September 30, 2020. Courtesy: AirNow-Tech

2.1 Site-By-Site Ozone Observations for 2020

Ozone observations for Delaware are measured at seven different monitoring sites across the state (Figure 1). Four monitoring sites reside in New Castle County, with one monitoring site in Kent County, and two monitoring sites in Sussex County. Figure 7 and Table 1 show the distributions of daily maximum ozone AQI value measured at each of the seven monitoring sites during summer 2020.

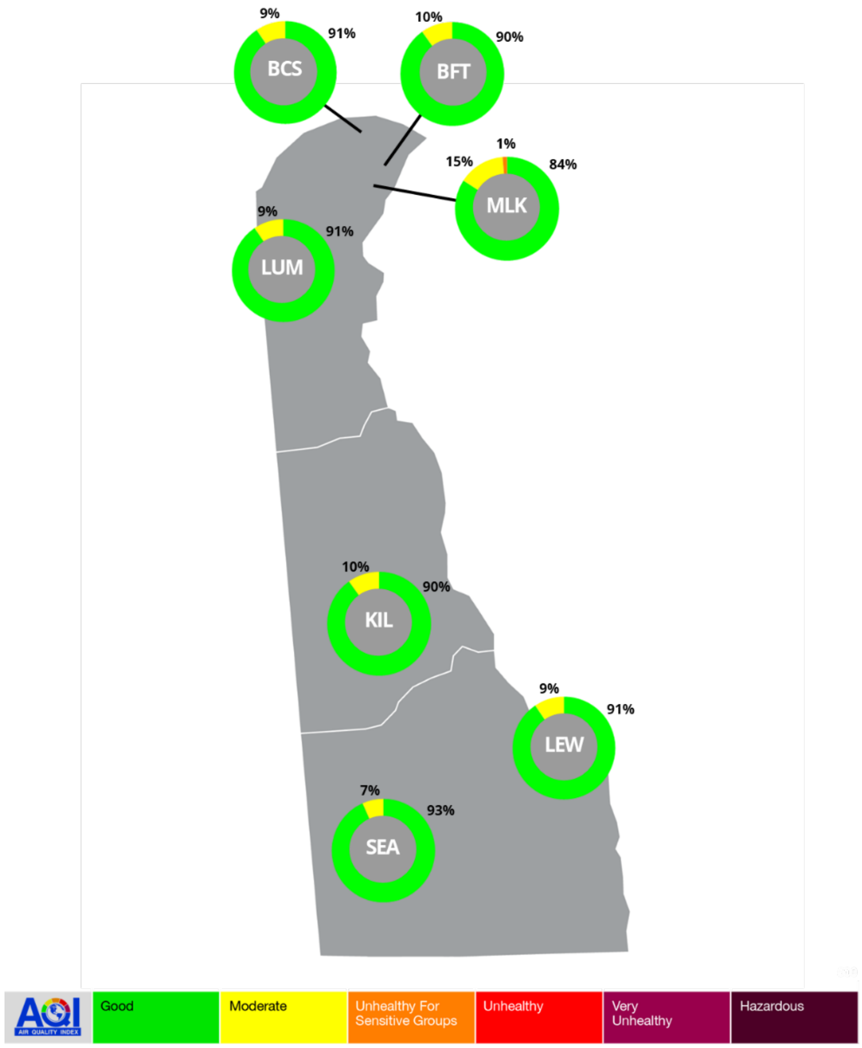

Figure 7. Delaware daily maximum ozone AQI distributions between May 1–September 30, 2020. Courtesy: AirNow-Tech.

Table 1. Percent of days at each AQI category for summer 2020. Station acronyms from Figure 7 are in parentheses.

Monitoring Site	Good days	Moderate days	USG days
MLK Boulevard (MLK)	84%	15%	1%
Bellevue State Park (BFT)	90%	10%	0%
BCSP (BCS)	91%	9%	0%
Lums (LUM)	91%	9%	0%
Killens (KIL)	90%	10%	0%
Seaford (SEA)	93%	7%	0%
Lewes (LEW)	91%	9%	0%

Good AQI levels were frequent in the state throughout summer 2020. For most monitoring sites, at least 90% of days registered Good AQI days across Delaware. The cleanest site during the summer was Seaford, where only 7% of days between May and September recorded Moderate AQI levels.

Monitoring sites near or downwind of major metropolitan areas tend to record fewer Good AQI days, which is primarily due to pollutant transport from emission sources. In summer 2020, the MLK monitoring site in Wilmington recorded the fewest Good AQI days when compared to other sites across the state. Between May and September, 84% of days featured Good air quality, followed by Moderate air quality on 15% of days. The MLK monitoring site was the only site in the state during summer 2020 to reach USG air quality, occurring on July 21 and 30 (Table 2).

Table 2. Observed ozone exceedance days in 2020. Under-forecast row indicates the difference between the next-day forecast concentrations and the observed ozone concentrations

Date	July 21	July 30
Daily Max 8-hr average O3 concentrations (ppb)	72	71
Under-Forecast (ppb)	9	5
Location of Ozone Exceedance	MLK	MLK
Max Temperature at KILG (°F)	92	93
Weather conditions present	Sunny skies, upper-level high pressure southwest of Delaware, weak surface convergence over Wilmington	Sunny skies, light morning winds, regional pollutant transport from southwest in afternoon/evening

2.2 Summary of Code Orange Ozone Days in Summer 2020

2.2.1 July 21, 2020

Summer 2020’s highest ozone AQI day occurred on July 21. On this day, upper-level high pressure over the southeastern United States (Figure 8) inhibited vertical motion in the lower levels of the atmosphere, which reduced mixing associated with a surface stationary front south of Delaware.

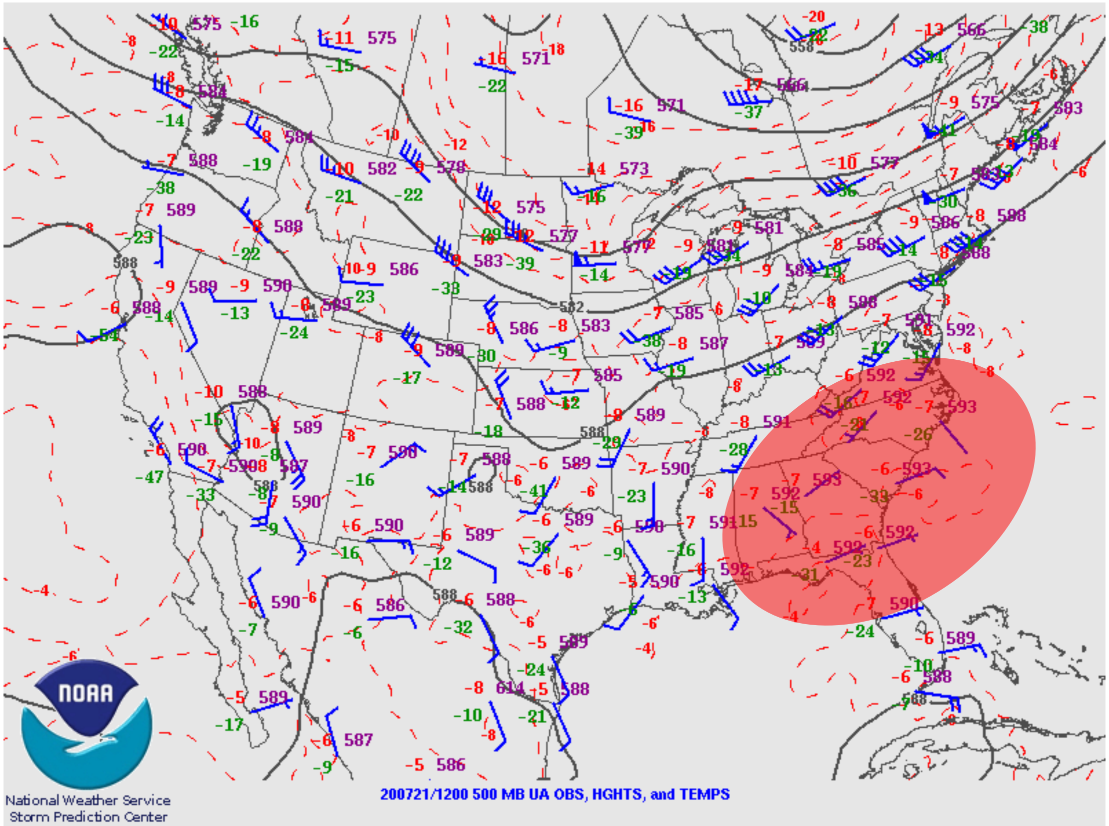

Figure 8. 500-mb map from 8:00 a.m. EDT on July 21, 2020. The red-shaded area denotes upper-level high pressure, responsible for hindering vertical mixing.

During the early afternoon hours, light southerly to southeasterly winds were observed at the New Castle County Airport, while northerly winds were observed north of downtown Wilmington (Figure 9). This wind pattern produced a weak surface convergence zone over the Wilmington area. Within surface convergence zones, pollutants from surrounding sources can be transported into a particular area, and winds directly over the site can become stagnant, allowing pollutants to accumulate and leading to increased ozone concentrations. Such was the case on this day, as hourly ozone concentrations at the MLK monitoring site were in the USG category from 12:00-5:00 p.m.

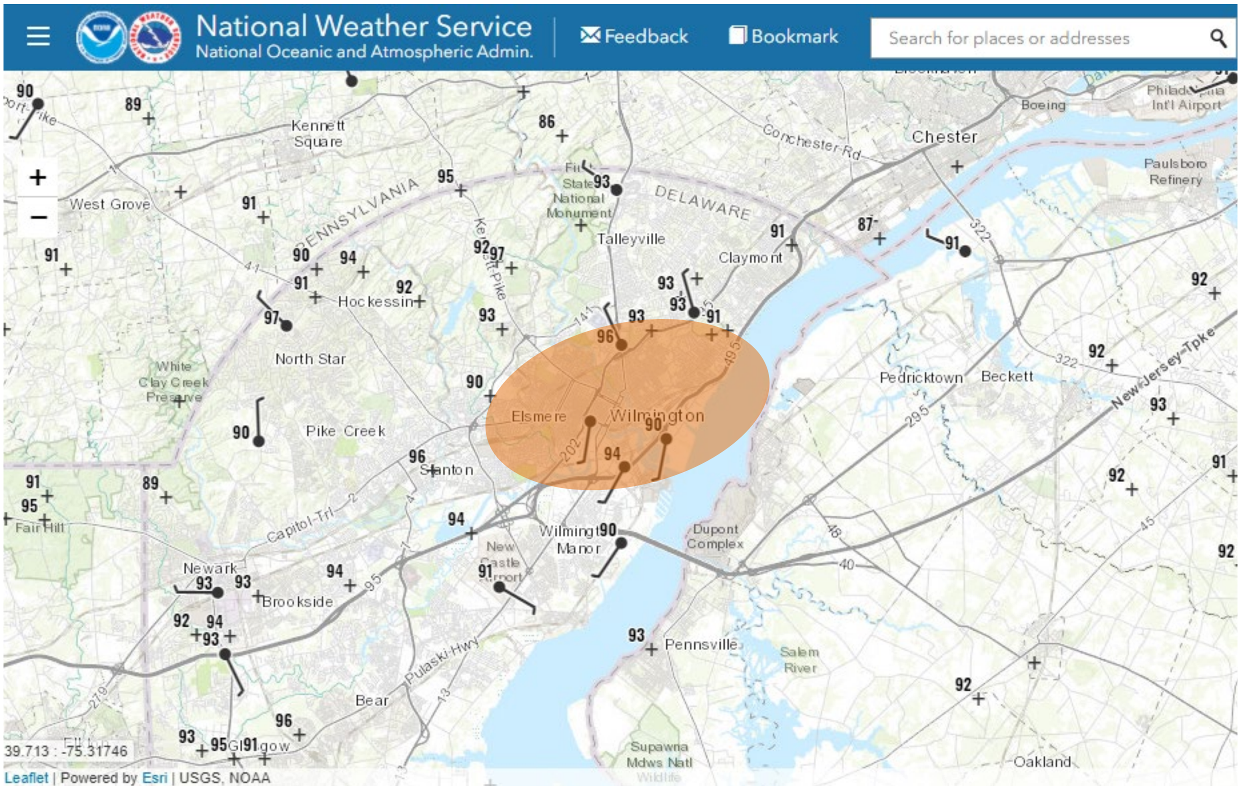

Figure 9. Surface weather map on July 21, 2020, at 1:00 p.m. Northwesterly winds in northern New Castle County, combined with southerly winds in southern New Castle County, produced a surface convergence zone (orange shading) near downtown Wilmington, Delaware. Note temperatures in the 90s Fahrenheit in the same area. Courtesy: National Oceanic and Atmospheric Administration (NOAA).

Ozone formation was further enhanced by sunny skies and temperatures in the low-90s. These conditions resulted in daily maximum 8-hour average ozone concentrations of 72 ppb at the MLK monitoring site, which is in the USG AQI category.

2.2.2 July 30, 2020

The final Code Orange ozone day of summer 2020 occurred at the MLK monitoring site on July 30. Despite an upper-level low-pressure trough west of Delaware aiding vertical mixing, a complex surface wind pattern drove two distinct periods of poor air quality (Figure 10).

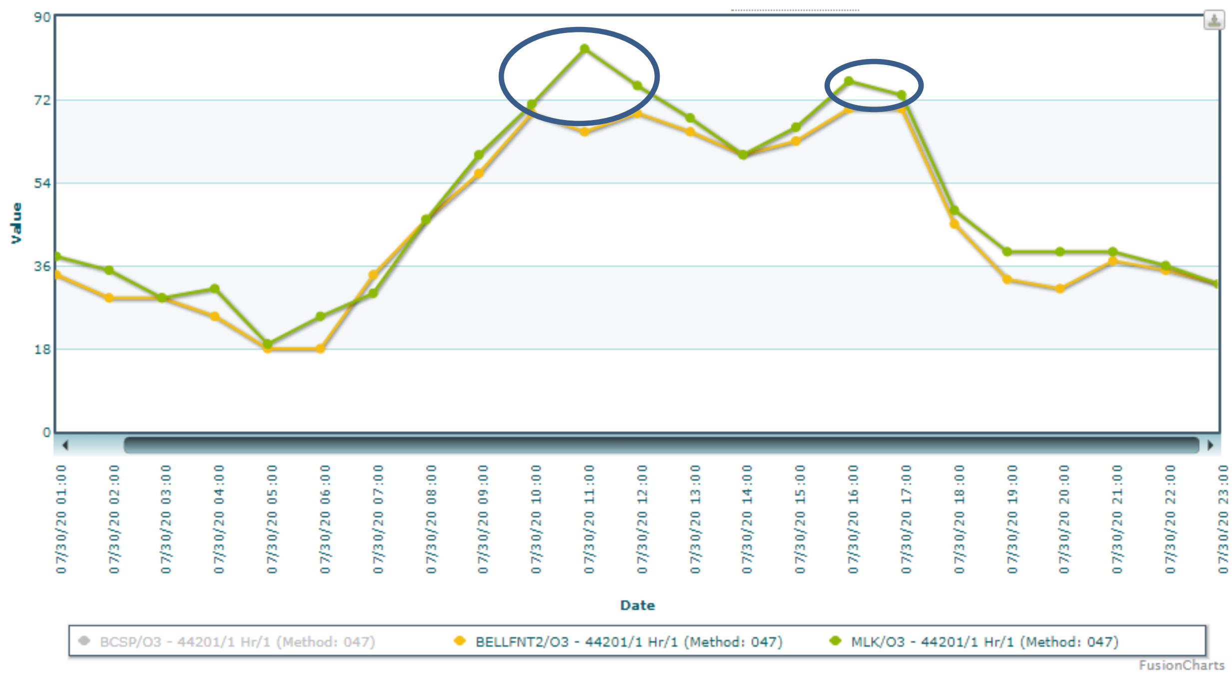

Figure 10. Hourly ozone concentration values for Bellevue State Park (yellow line) and MLK (green line) monitoring sites. Concentration values in the USG category are circled in blue. Courtesy: AirNow-Tech.

The two spikes in ozone concentrations were captured at two of the five monitoring sites within New Castle County. While the Bellevue State Park monitor recorded lower concentrations than the MLK monitor, both sites recorded similar hourly ozone spikes during the day.

The first period of poor air quality occurred in the late morning and early afternoon hours. At the New Castle County Airport, winds were southeasterly and prevailing from Delaware Bay (Figure 11). Farther inland at the MLK monitoring site in downtown Wilmington, surface winds were calm to light south-southwesterly. As wind speeds decreased, pollutants accumulated, and ozone levels increased. As a result, the day's peak hourly ozone value of 83 ppb was recorded at 12:00 p.m.

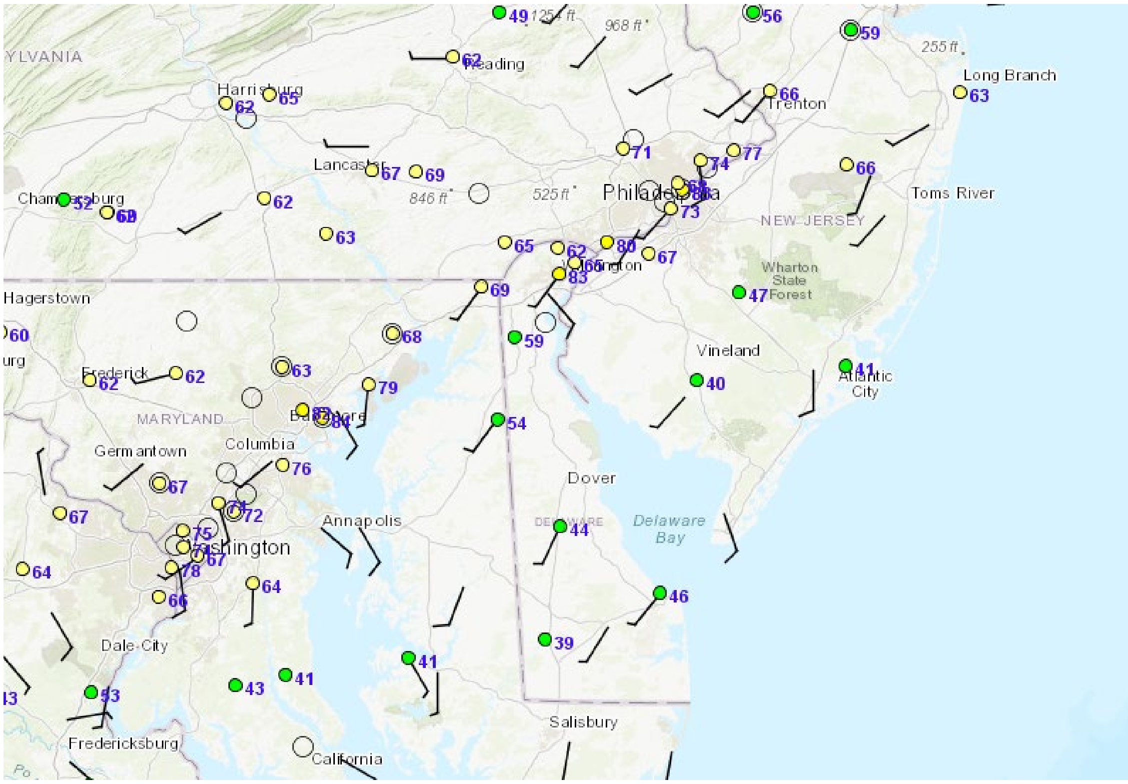

Figure 11. Ozone concentrations (green/yellow dots) in ppb and wind barbs at 12:00 p.m. on July 30. At this time, the hourly ozone concentration value at the MLK monitoring site reached 83 ppb. Courtesy: AirNow-Tech.

As the afternoon progressed, the surface wind pattern shifted to west-southwesterly (**Figure 12**). Initially, the wind shift aided pollutant dispersion, lowering ozone levels to the mid-Moderate range. However, during the late afternoon and early evening hours, additional pollutants were carried into the Wilmington region from the Baltimore-Washington D.C. metropolitan area. Therefore, a second spike in hourly ozone concentrations occurred from 5:00-7:00 p.m.

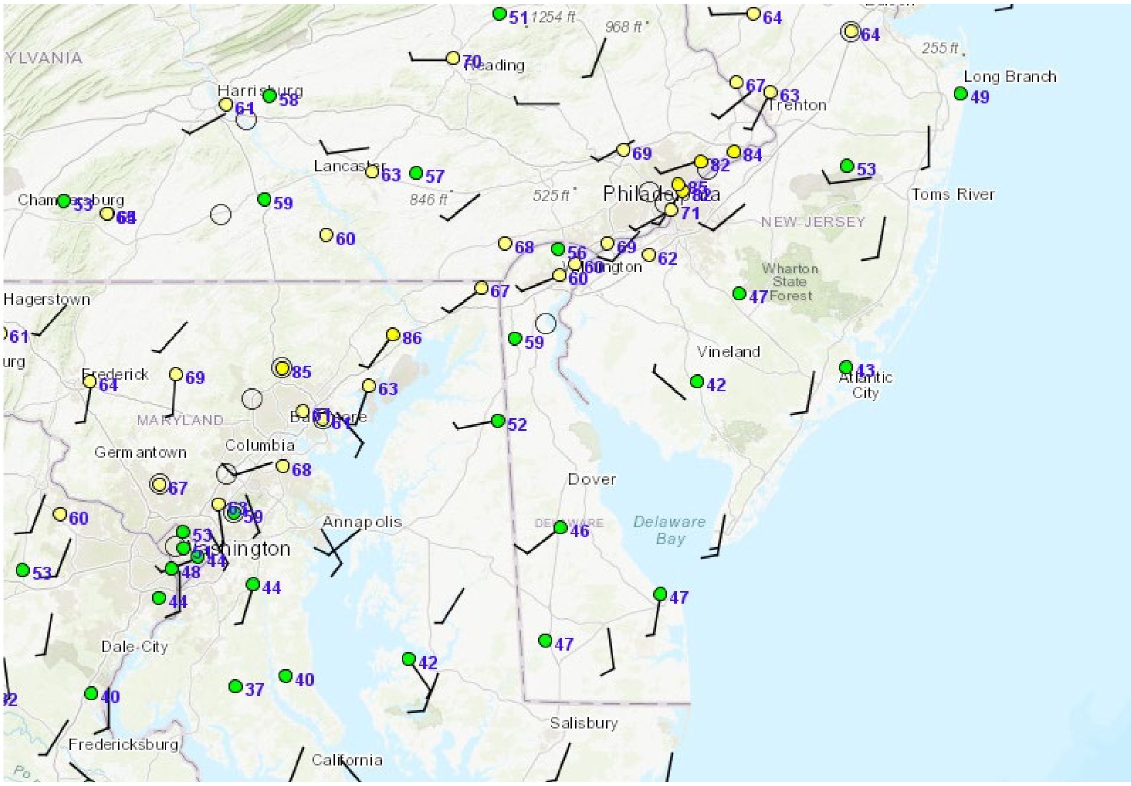

Figure 12. Ozone concentrations (green/yellow dots) and wind barbs at 3:00 p.m. on July 31. West-southwesterly winds transported high ozone concentrations near the Interstate 95 corridor in northeastern Maryland into New Castle County. Courtesy: AirNow-Tech.

2.3 Air Quality Comparison Between Summer 2020 and Previous Years

Ozone levels in Delaware have improved since 2012, driven largely by a reduction in nitrous oxide NO_x emissions across the Mid-Atlantic region. To accurately compare year-to-year trends in ozone levels, STI meteorologists examined summer 2020 ozone levels in comparison to the previous seven summers, dating back to 2013.

Figure 13 provides the yearly distribution of daily maximum ozone AQI levels for Delaware between 2013 and 2020. In general, the recent trend in improved air quality continued through 2020. The number of Good AQI days in summer 2020 was greater than in any summer since 2013. During the 153-day period between May 1 and September 30, Good AQI levels were observed on 81% of days in summer 2020. By comparison, Good AQI levels were observed on 73% of days in summer 2017, which was the highest percentage of Good AQI days prior to summer 2020.

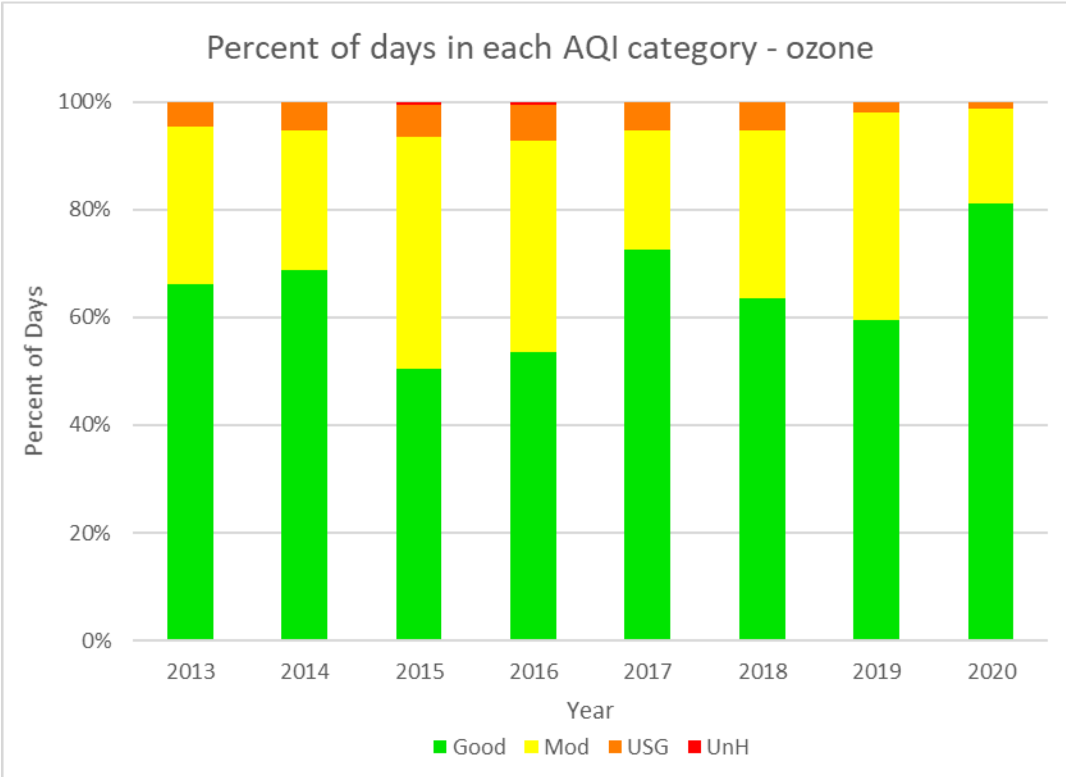

Figure 13. Distribution of daily maximum ozone AQI values between May 1–September 30.

Dating back to 2013, Delaware recorded the fewest Moderate or higher AQI days and fewest ozone exceedances (daily maximum ozone AQI values over 100) in summer 2020. Moderate AQI days were observed 24 times, and USG AQI days were observed on only two days.

Ozone exceedances have become less frequent in Delaware. Figure 14 highlights the occurrence of ozone exceedances for each of Delaware's three counties going back to 2000.

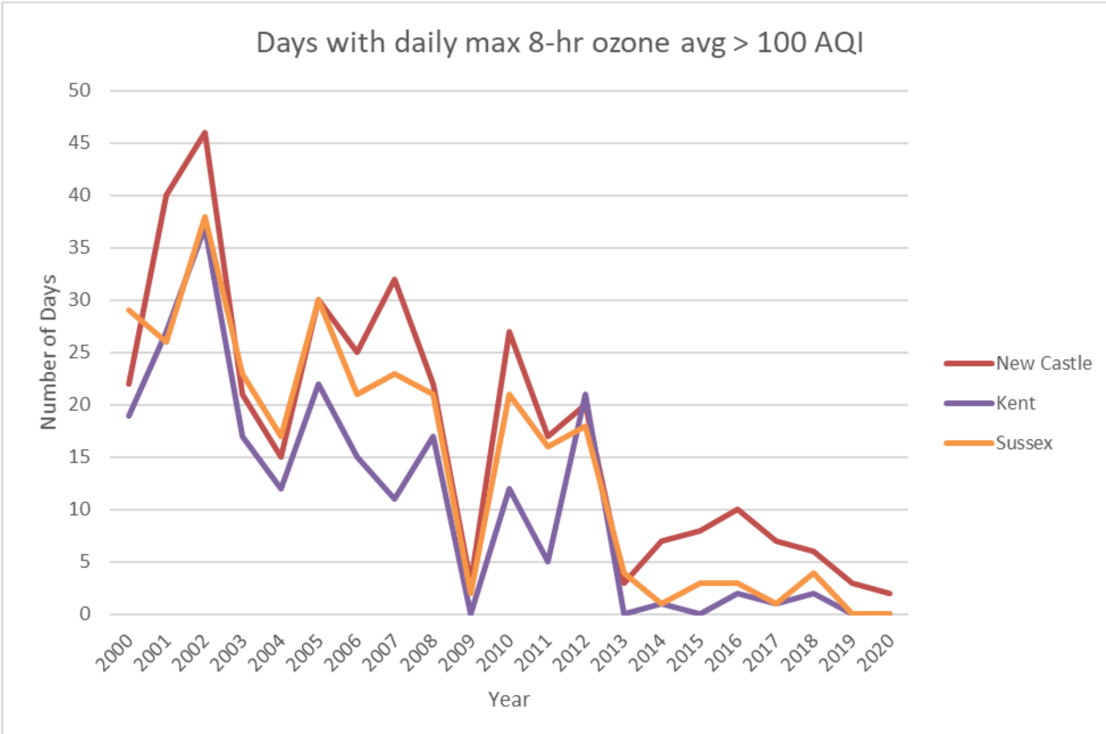

Figure 14. Frequency of ozone exceedances between May-September by county. Source: U.S. EPA Air Data (https://www.epa.gov/outdoor-air-quality-data).

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 decrease. Comparing ozone exceedance data by county since 2000, summer 2020 experienced the fewest ozone exceedances. Additionally, summer 2020 marks the second consecutive year without an ozone exceedance in Kent or Sussex Counties.

2.4 Summer 2020 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, resulting in a reduction in ozone development.

For the summer ozone forecasting season, temperatures at the two Delaware NOAA climate sites were above average between May and September. The Georgetown climate site recorded an average temperature of 73.5°F during this period (Table 3), which is 2.2°F above normal. For the Wilmington climate site, the average May-September temperature was slightly above average.

Table 3. May-September 2020 meteorological summary for Delaware climate locations.

Variable	Wilmington (KILG)	Georgetown (KGED)
Average Temperature (°F)	71.6	73.5
Average Temperature Departure from Normal (°F)	+0.6	+2.2
Total Precipitation (inches)	23.43	19.03
Precipitation Departure from Normal (inches)	+3.46	-0.98
Number of Clear Days	85	82
Average Wind Speed (mph)	7.3	6.5
Average Wind Speed Departure from Normal (mph)	-0.9	0.0

Wind speeds for the Wilmington and Georgetown climate sites were near or slightly weaker than normal during the May-September period. Wilmington's average wind speed was 7.3 mph during the summer, which is nearly 1 mph below normal. To compare, Georgetown's average wind speed was slightly less, averaging 6.5 mph. However, the May-September average wind speed for Georgetown was near normal.

Observed precipitation during the May-September period varied for the two climate sites. While Wilmington's precipitation was above average, Georgetown's measured precipitation was slightly below average.

Table 4 shows a monthly review of weather at the Wilmington climate site, and Table 5 contains a monthly review of weather at the Georgetown climate site. The warmest month of the 2020 summer ozone season for both climate sites was July, which coincided with the most Moderate or higher AQI days of any month this summer. As temperatures gradually cooled in August and September, ozone production decreased, and Moderate AQI days became less frequent.

The monthly ozone trends that occurred in summer 2020 follow the 2015-2019 climatology for ozone in Figure 2, where Moderate or higher AQI days were most frequent in July, followed by a reduction in Moderate or higher AQI days in August and September.

Table 4. 2020 monthly meteorological summary for Wilmington-New Castle Airport (KILG).

Wilmington, (KILG)	May	June	July	August	September
Average Temperature (°F)	60.3	73.1	80.0	76.7	67.7
Average Temperature Departure from Normal (°F)	-2.5	+0.9	+3.2	+1.5	-0.1
Total Precipitation (inches)	2.45	3.31	4.90	9.36	3.41
Precipitation Departure from Normal (inches)	-1.50	-0.57	+0.33	+6.11	-0.91
Number of Clear Days	9	22	21	18	15
Average Wind Speed (mph)	9.4	7.7	6.7	6.4	6.5
Average Wind Speed Departure from Normal (mph)	+0.6	-0.5	-0.9	-0.8	-1.2

Table 5. 2020 monthly meteorological summary for Georgetown (KGED).

Georgetown (KGED)	May	June	July	August	September
Average Temperature (°F)	61.4	74.9	82.0	78.7	70.2
Average Temperature Departure from Normal (°F)	-1.7	+2.4	+5.1	+3.1	+1.7
Total Precipitation (inches)	2.92	2.07	6.62	3.56	3.86
Precipitation Departure from Normal (inches)	-0.63	-2.54	+2.43	+0.03	-0.27
Number of Clear Days	12	21	19	16	14
Average Wind Speed (mph)	8.7	6.9	5.5	5.5	5.8
Average Wind Speed Departure from Normal (mph)	+1.1	+0.4	-0.7	+0.2	-0.3

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

To analyze this pattern, STI 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 associated with upper-level low pressure.

During the May-September 2020 period, the 500-mb height anomalies (Figure 15) indicated persistent upper-level high pressure along the United States west coast. Across the eastern United States, height anomalies were near-normal in the southeast and slightly above-normal in the Mid-Atlantic region. The weak height anomalies in the Mid-Atlantic region suggest a near-normal upper-level weather pattern during summer 2020.

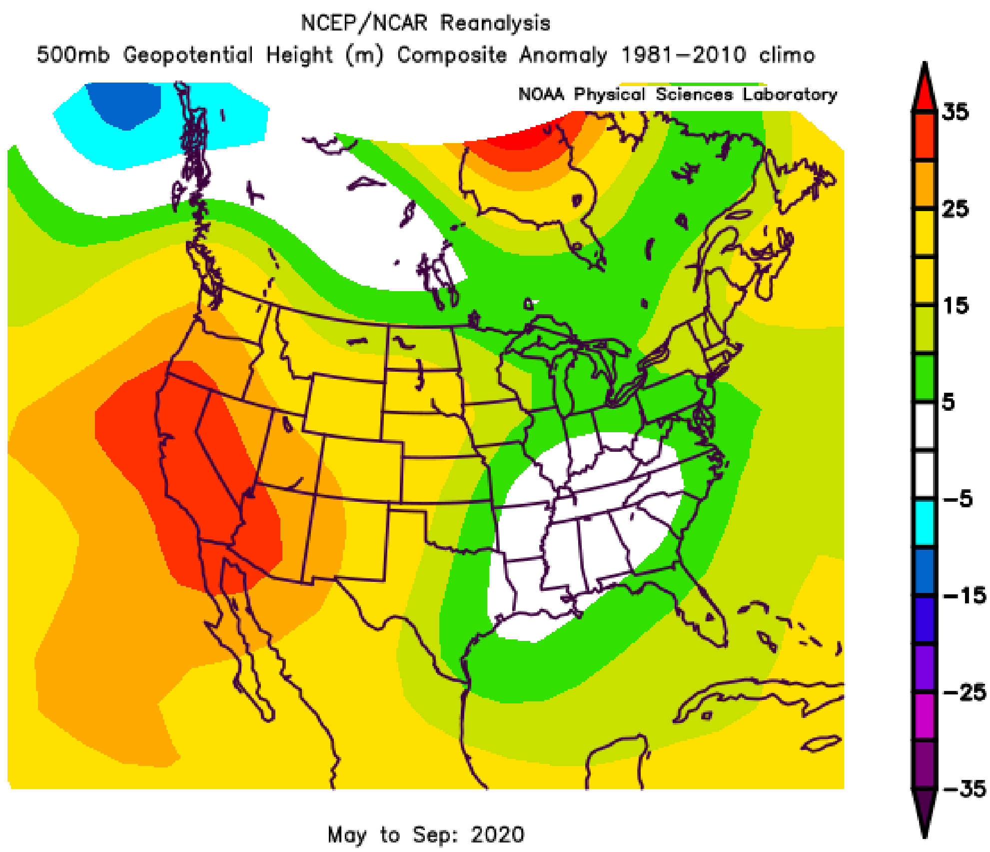

Figure 15. 500-mb height anomalies for May-September 2020. Courtesy: NOAA

Through the summer ozone forecast season, the upper-level weather pattern varied monthly. For instance, 500-mb height anomalies in July (Figure 16) were slightly above-average, suggesting the persistence of upper-level high pressure. As a result, reduced vertical mixing and warmer-than-normal surface temperatures resulted in enhanced ozone formation.

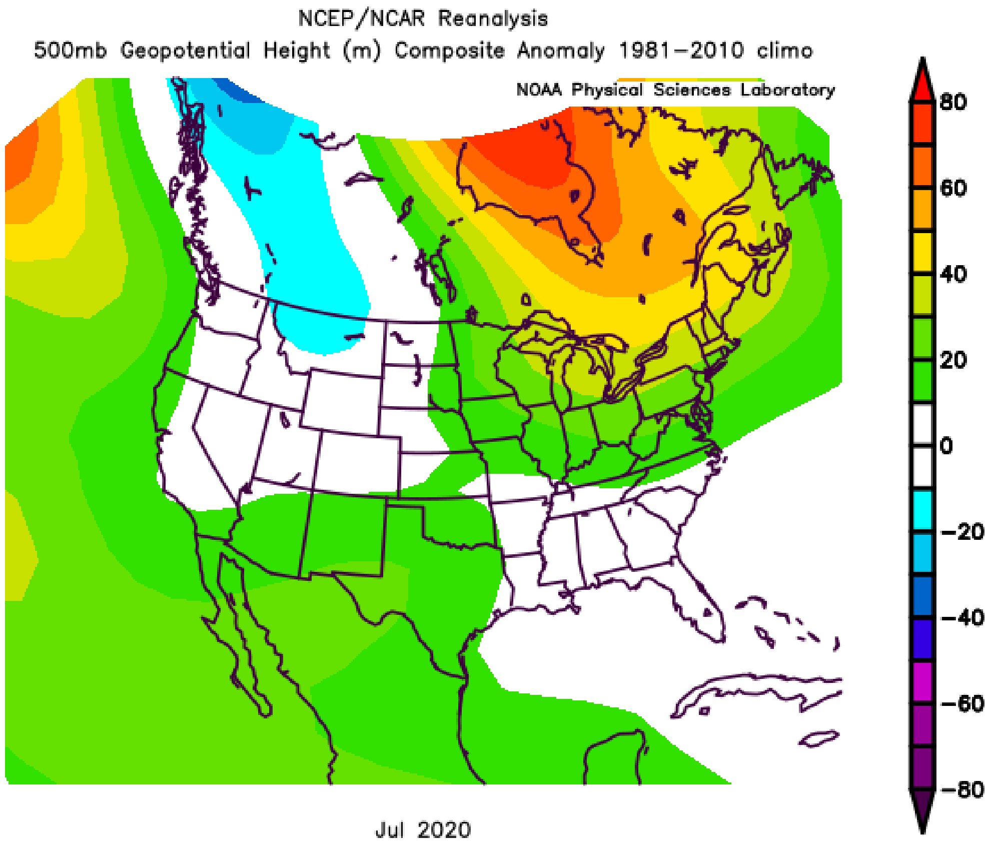

Figure 16. 500-mb height anomalies for July 2020. Courtesy: NOAA

Weaker-than-normal surface wind speeds additionally aided ozone formation in July (Figure 17). Driven in part by these weather conditions, July featured the most Moderate or higher AQI days of all months during summer 2020.

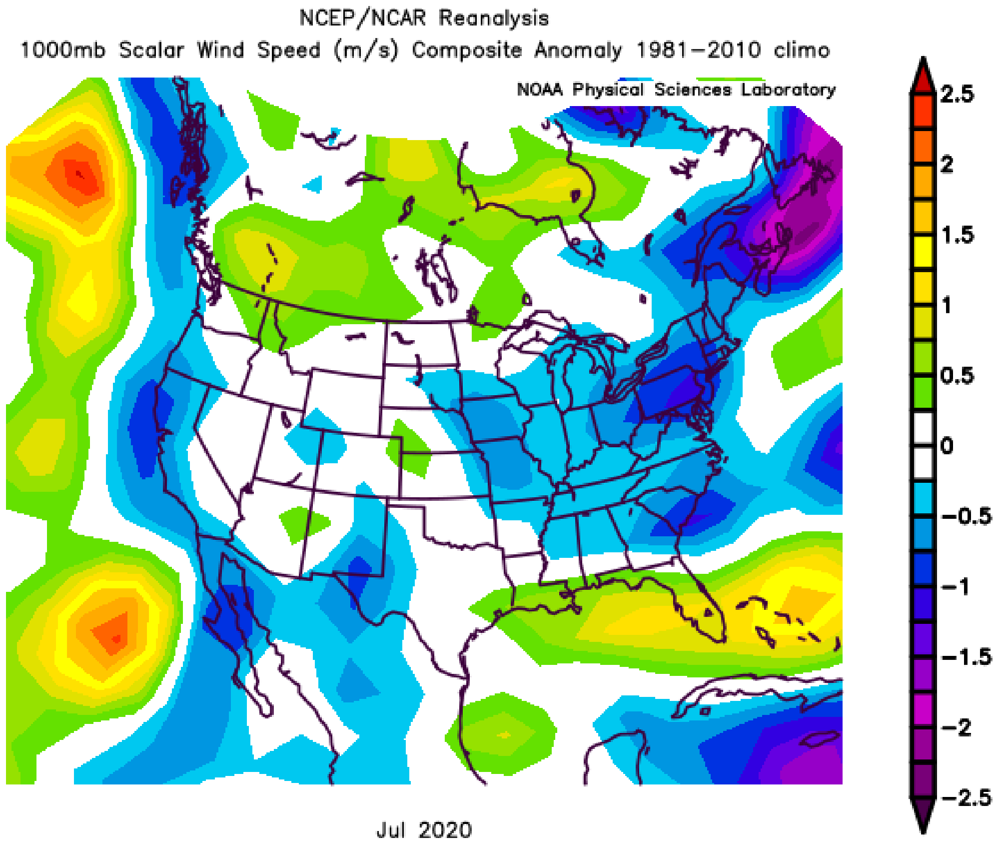

Figure 17. Surface wind speed anomalies for July 2020. Blue shading indicates areas with weaker-than-normal winds. Courtesy: NOAA

In August 2020, 500-mb height anomalies were below average west of Delaware, indicating persistent upper-level low pressure. This pattern likely increased atmospheric mixing and low-level pollutant dispersion, limiting ozone formation. Thus, only five Moderate AQI days for ozone were recorded during August 2020. While the 5-year ozone climatology shows 39% of August days with Moderate or higher ozone AQI levels, only 16% of observed August 2020 days had Moderate AQI levels.

Above-average 500-mb height anomalies (Figure 18) and below-average surface wind speeds were also noted in September 2020. However, ozone formation was limited during the month due to the seasonal decline in surface temperatures, along with reduced daylight. These conditions resulted in only one Moderate AQI day for ozone during September 2020. By comparison, 25% of September days between 2015-2019 featured Moderate or higher ozone AQI levels.

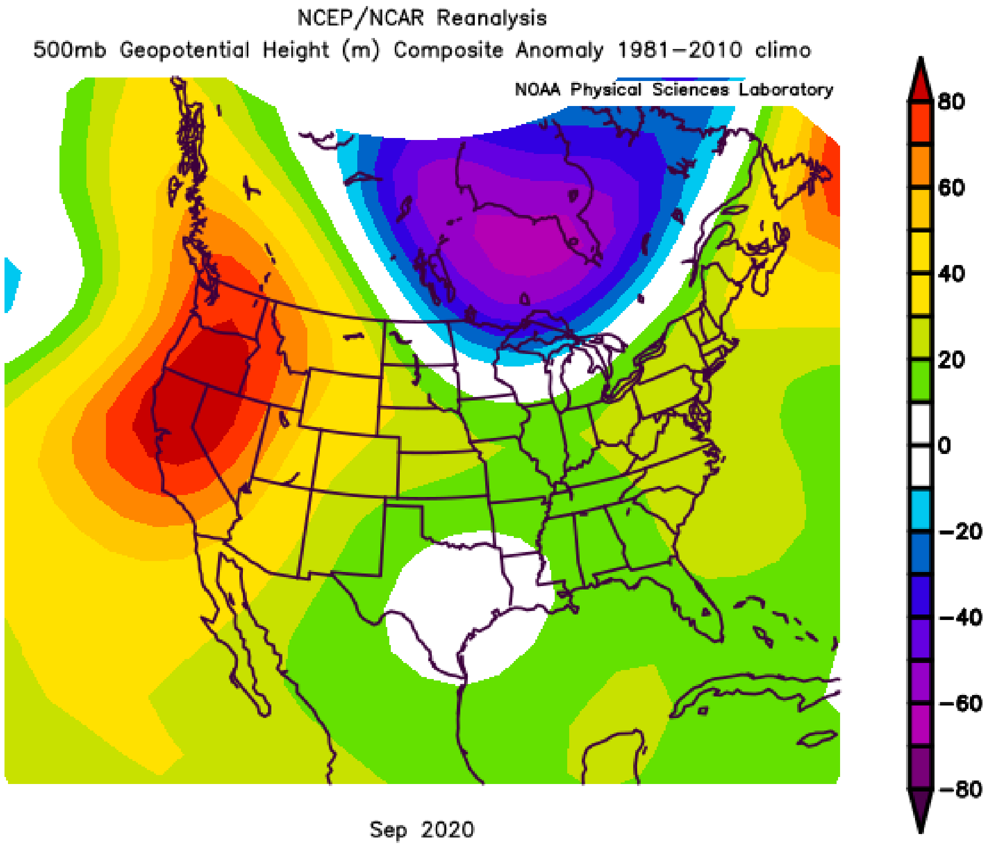

Figure 18. 500-mb height anomalies for September 2020. Courtesy: NOAA

July and September both featured above-normal 500-mb height anomalies and near- to above-normal surface temperatures, which would typically contribute to an increase in Moderate or higher ozone days compared to other years. However, Good ozone days in summer 2020 were more frequent than other years. Because ozone development is not solely dependent on prevailing weather conditions, these patterns suggest that additional factors which further reduced emissions may have played a central role in improved air quality during summer 2020. To explore this possibility, STI meteorologists examined whether emissions reductions possibly linked to the COVID-19 pandemic may have influenced summer 2020 air quality.

3. COVID-Related Impacts on Ozone in 2020

3.1 Introduction

In response to the global COVID-19 pandemic, a Stay-at-Home order was issued for Delaware on March 24, 2020, lasting through May 31, 2020 (https://coronavirus.delaware.gov/). Although this order was lifted at the end of May, many industries were still not permitted to re-open at that time. Reduced travel and industrial activities due to COVID-related restrictions might have had a significant impact on pollutant emissions and, subsequently, air quality throughout summer 2020. STI forecasters analyzed air quality and meteorological trends in Delaware during the summer of 2020 to gain insight into whether reduced emissions–possibly related to COVID-related reductions in activity–might have also contributed to the better-than-normal air quality.

3.2 Methods and Results

Using statewide ozone data from 2011 through 2020, we compared monthly observed ozone levels in 2020 to previous years to determine if the differences in monthly mean concentrations from May through September were statistically significant compared to past years. Ozone observations were grouped by county. Because air quality has been generally improving over the past three decades, the ozone data were detrended using linear regressions of annual means for the 2011-2019 period. An example regression is shown in **Figure 19**. In this example, ozone concentrations declined at an average rate of roughly 0.8 ppb per year.

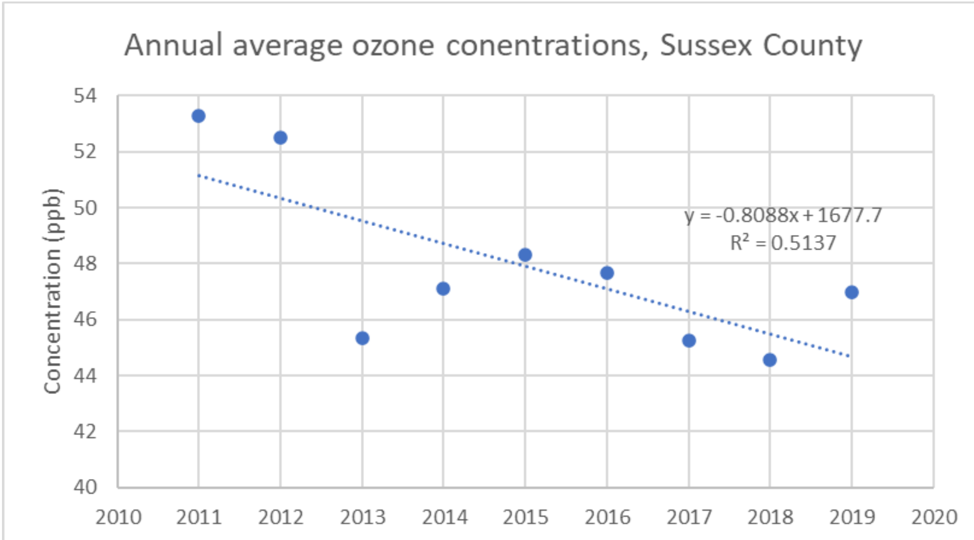

Figure 19. Linear regression of annual ozone data in Sussex County, used to detrend data.

The results of the first phase of the analysis are shown in Figures 20-22. In each figure, the detrended 2011-2019 monthly mean ozone concentrations are compared to 2020 monthly means. Error bars for each month indicate 95% confidence intervals. For months when the means differ by a magnitude that exceeds the confidence intervals (error bars *do not* overlap), the differences are said to be statistically significant.

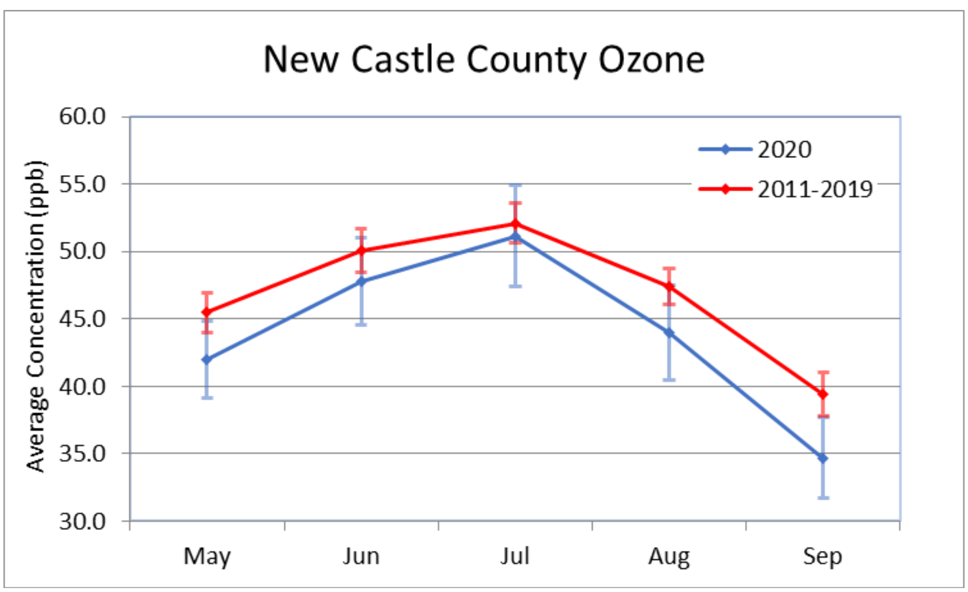

Figure 20. Monthly mean ozone concentrations in New Castle County, 2020 vs. 2011-2019.

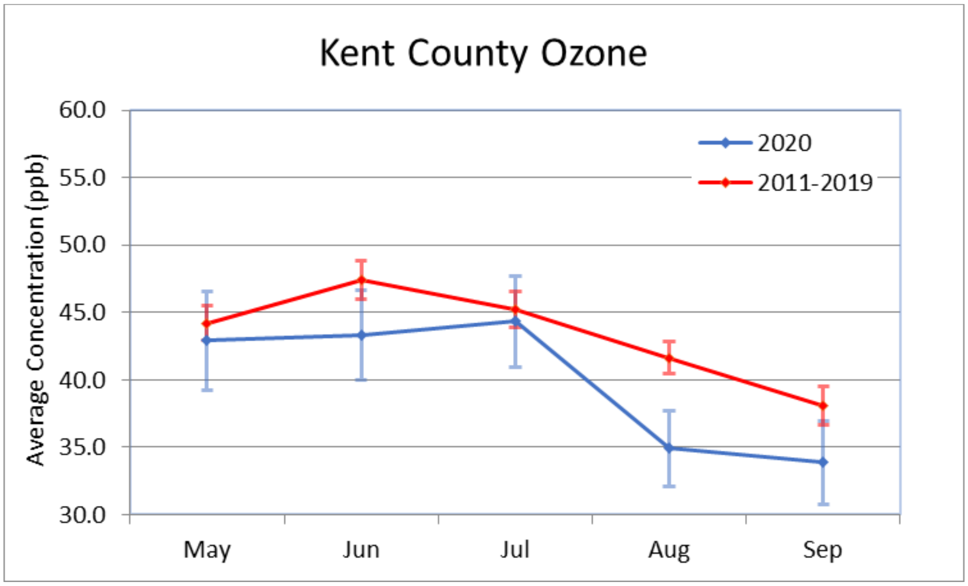

Figure 21. Monthly mean ozone concentrations in Kent County, 2020 vs. 2011-2019.

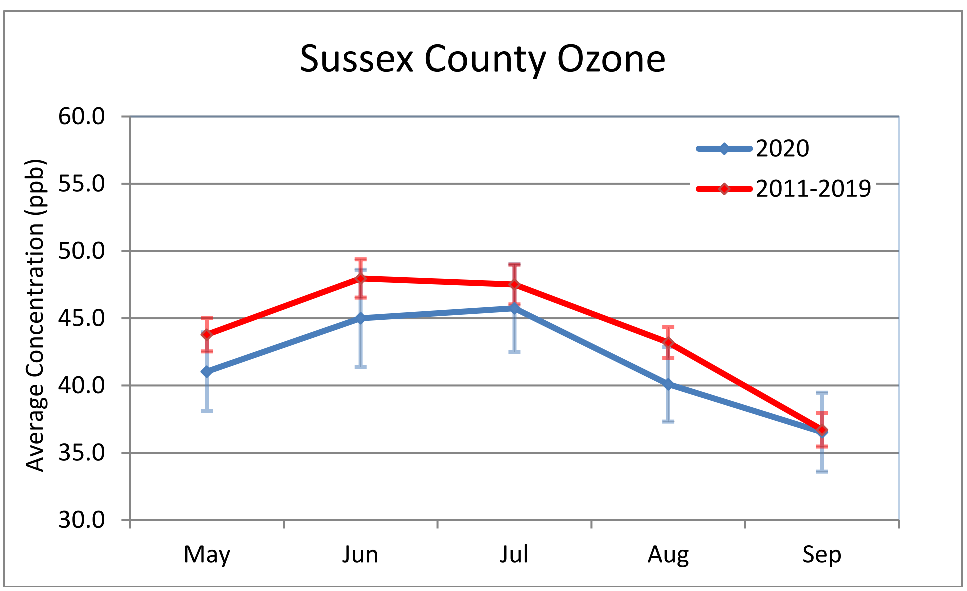

Figure 22. Monthly mean ozone concentrations in Sussex County, 2020 vs. 2011-2019.

Because the differences in monthly means in 2020 compared to previous years might have been driven by both changes in emissions *and* changes in meteorological patterns from year to year, STI meteorologists performed a "meteorological filtering" of the data. Specifically, five observed meteorological parameters were used to determine which summer months (May to September) in 2011-2019 were "meteorologically similar" to summer months in 2020:

- Temperature, wind speed, sea level pressure, and precipitation data obtained for county-specific stations, from Automated Surface Observing System (ASOS). Sources: Iowa Environmental Mesonet xmACIS2 (rcc-acis.org)

- 500-mb heights based on model grid data (not county-specific), from https://psl.noaa.gov/cgi-bin/data/timeseries/timeseries1.pl

If the 2020 monthly means for at least four out of five meteorological parameters fell within one standard deviation of the 2011-2019 means, the month was considered a meteorological match. We then filtered the matching months in 2011-2019 and compared observed pollutant concentrations in matching years *only* to those observed in 2020. Similar to the first phase of the analysis, all data were detrended based on linear regression from 2011-2019. An example table showing the number of meteorological parameter matches is shown in Table 6.

Table 6. Counts of meteorological parameters that matched 2020 conditions for Sussex County.

	May	Jun	Jul	Aug	Sep
2011	2.00	3.00	4.00	2.00	4.00
2012	2.00	1.00	4.00	4.00	3.00
2013	3.00	3.00	3.00	2.00	2.00
2014	3.00	3.00	2.00	2.00	4.00
2015	2.00	3.00	2.00	4.00	4.00
2016	3.00	3.00	4.00	3.00	4.00
2017	4.00	3.00	4.00	2.00	4.00
2018	1.00	3.00	2.00	3.00	2.00
2019	0.00	4.00	4.00	5.00	5.00

For example, for the month of August, weather conditions in 2020 most closely matched those observed in 2012, 2015, and 2019. At least four of five meteorological parameter means in August 2020 fell within one standard deviation of the August means during those years.

For months when none of the previous years matched at least four meteorological parameters, the data for 2011-2019 were left out of the comparisons. The resulting meteorologically filtered comparisons of monthly mean ozone concentrations are shown in Figures 23-25.

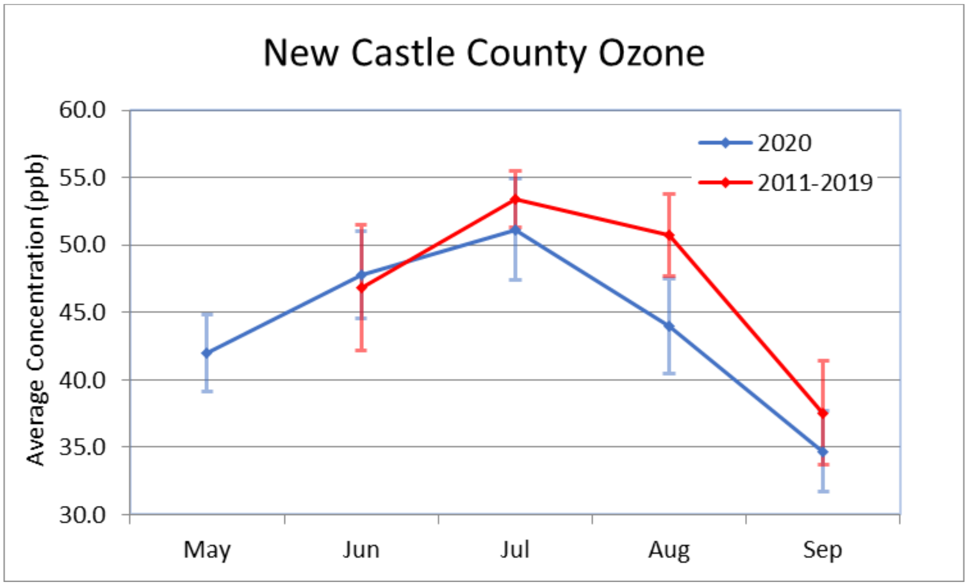

Figure 23. Monthly mean ozone concentrations in New Castle County with meteorological filtering, 2020 vs. 2011-2019.

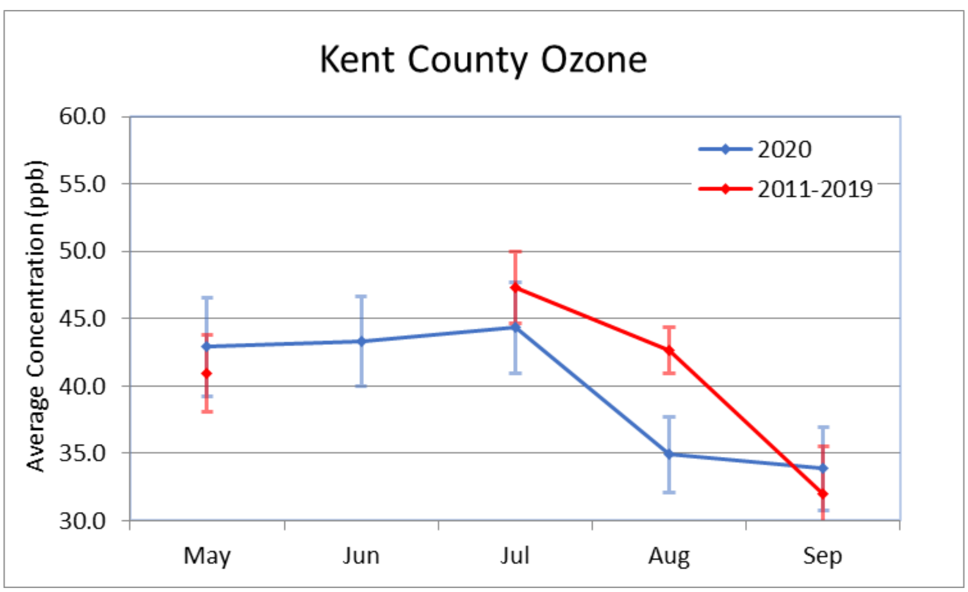

Figure 24. Monthly mean ozone concentrations in Kent County with meteorological filtering, 2020 vs. 2011-2019.

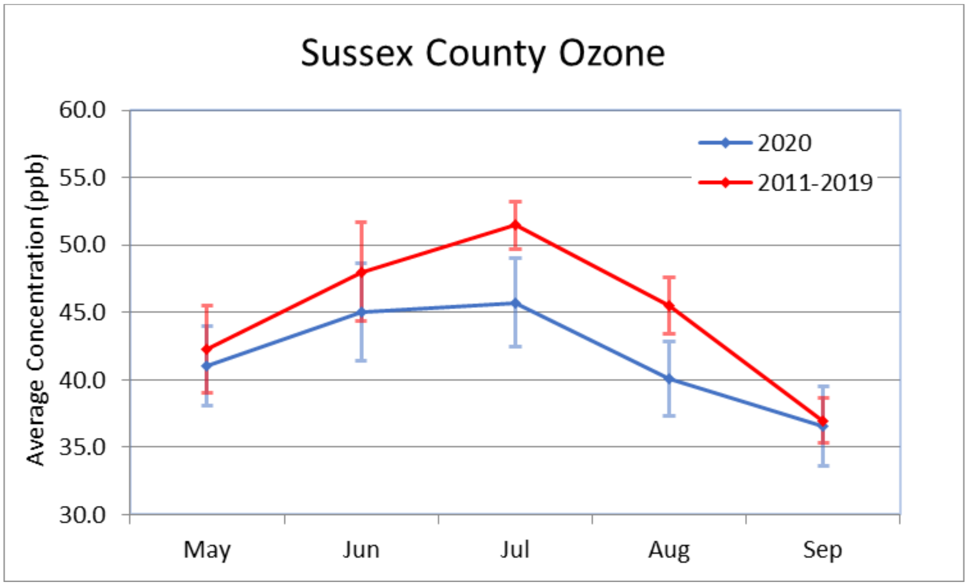

Figure 25. Monthly mean ozone concentrations in Sussex County with meteorological filtering, 2020 vs. 2011-2019.

Tables 7 and 8 summarize these results, showing the differences in monthly mean ozone concentrations by county in 2020 compared to 2011-2019 means, without meteorological filtering (Table 7) and with meteorological filtering (Table 8). Negative values indicate lower concentrations in 2020 compared to previous years. Differences that were statistically significant at the 95% confidence level are highlighted in green.

Table 7. Summary of differences in monthly mean ozone concentrations in 2020 compared to 2011-2019 means, without meteorological filtering.

		Without met filter				
		May	Jun	Jul	Aug	Sep
Ozone	New Castle	-3.5	-2.3	-0.9	-3.4	-4.7
	Kent	-1.3	-4.1	-0.9	-6.7	-4.2
	Sussex	-2.8	-3.0	-1.8	-3.1	-0.2

Table 8. Summary of differences in monthly mean ozone concentrations in 2020 compared to 2011-2019 means, with meteorological filtering.

		With met filter				
		May	Jun	Jul	Aug	Sep
Ozone	New Castle		0.9	-2.2	-6.8	-2.8
	Kent	2.0		-3.0	-7.7	1.9
	Sussex	-1.3	-3.0	-5.7	-5.4	-0.4

3.3 Discussion

Monthly mean ozone concentrations observed in all three Delaware counties were lower for most months compared to 2011-2019 means, even after applying meteorological filters. However, many of the differences in the means were not statistically significant. Without meteorological filtering, only the ozone concentrations in Kent County in August and New Castle County in September were significantly lower in 2020 compared to past years.

When meteorological filtering was applied to correct year-to-year variations in weather, we observed statistically significant reductions in ozone concentrations in 2020 for Sussex County in July and all three Delaware counties in August.

Although the meteorological filters were fairly rudimentary, these preliminary results suggest a significant improvement in air quality, especially in August, coinciding with statewide reductions in industry and transportation emissions possibly related to COVID restrictions.

4. Skill of Ozone Forecasts in 2020

4.1 Introduction to STI Forecasts

During the summer 2020 ozone season in Delaware, STI meteorologists issued three-day forecasts during the weekdays. On occasion, forecasts were issued on the weekends, when ozone concentrations were approaching Code Orange or higher 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 2020 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 "STI Forecasts" in the following sections.

4.2 2020 Ozone Forecast Statistics

STI Forecasts captured the general trend of observed ozone levels in Delaware during summer 2020 (**Figure 26**). All STI Forecasts during summer 2020 were in the Good-to-Moderate AQI categories, with no Code Orange or higher forecasts issued. Using this Good-to-Moderate threshold, STI Forecasts were correct 74% of the time.

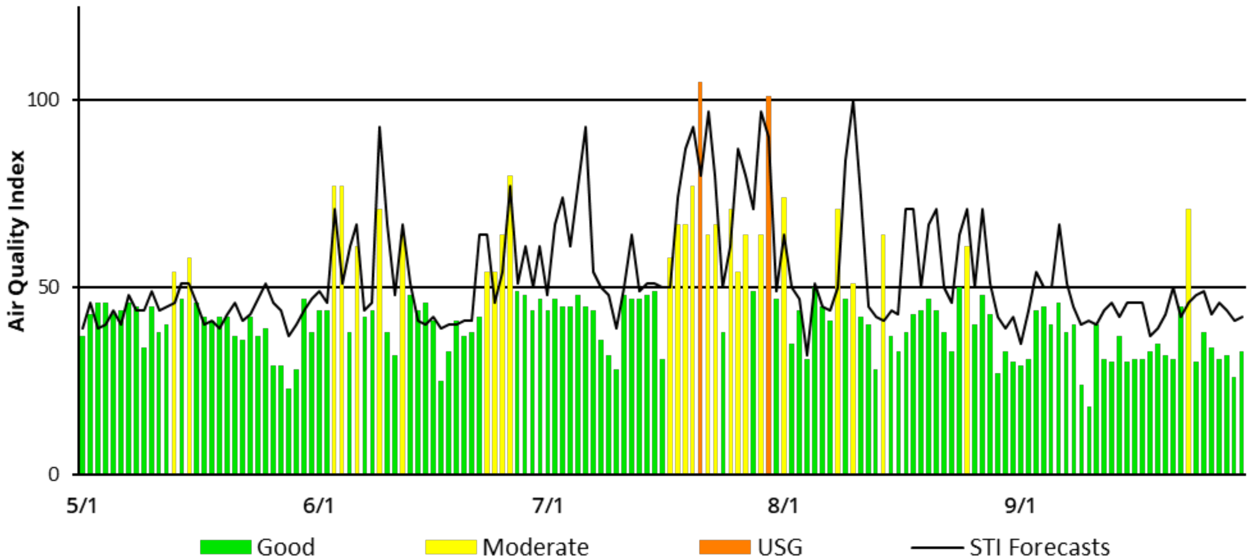

Figure 26. Daily observed ozone levels in Delaware versus STI Forecasts.

Out of 153 forecast days in summer 2020, Moderate or higher ozone levels were observed on 29 days. STI forecasters issued a Moderate AQI forecast on 21 of the 29 observed Moderate AQI days. This resulted in a POD of 72% for STI Forecasts.

Forecast false alarms occur when forecast ozone AQI category is higher than observed ozone AQI category. Of the 55 days during summer 2020 when Moderate ozone levels were forecast, there were 32 instances when observed ozone AQI levels were lower than the forecast (i.e., in the Good AQI category). As a result, the FAR for Moderate forecasts during summer 2020 was 58%.

Forecast skill can also be assessed by calculating forecast bias and mean absolute error within forecasts. 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.

Mean absolute error (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 mean absolute error for all STI Forecasts during summer 2020 based on daily maximum 8-hr average ozone concentrations. For the May-September period, STI Forecasts exhibited a bias of +6.2 ppb over observed ozone values, with a MAE of 8.0 ppb. STI Forecasts in May and June exhibited a lower positive bias, with forecasts averaging a bias of +3.4 ppb during this period. STI Forecast biases and MAE increased monthly from July to September, with the maximum monthly bias and MAE recorded in September.

Table 9. 2020 monthly meteorological summary for Wilmington-New Castle Airport (KILG).

Month	Bias (ppb)	Mean Absolute Error (ppb)
May	+3.3	6.0
June	+3.4	5.7
July	+6.4	7.7
August	+7.7	9.5
September	+10.3	11.4
May - September	+6.2	8.0

While forecasts were biased high throughout the summer, it is worth noting that observed ozone concentrations in 2020 were lower than observed values during the 2011-2019 period (**Figure 27**). The mean ozone concentration for summer 2020 was 45.6 ppb, which was 6.4 ppb lower than the 2011-2019 May-September mean. The mean ozone concentration was lower in every month in 2020 versus the 2011-2019 monthly mean.

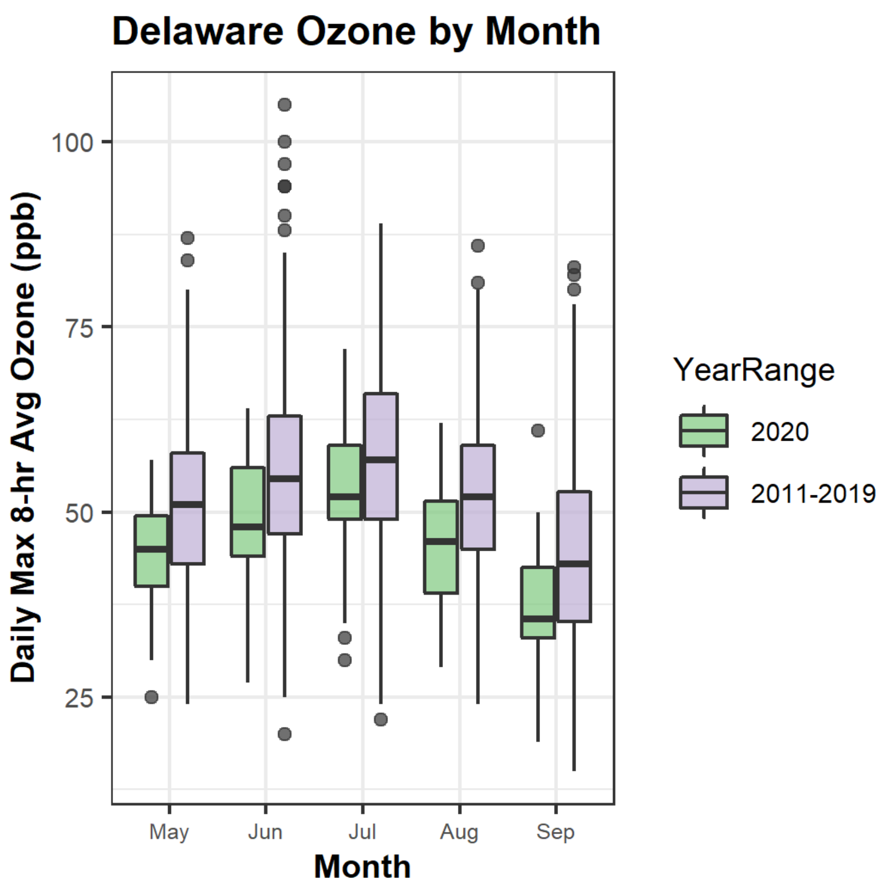

Figure 27. Box & whisker plot of 2020 ozone concentrations in Delaware versus the 2011-2019 values.

The greatest difference in ozone concentrations occurred in September, when the 2020 median ozone concentration was 7.5 ppb lower than the 2011-2019 median. Additionally, the September 2020 median ozone concentration matched the lower quartile of September 2011-2019 ozone concentrations, while the upper quartile of September 2020 ozone concentrations was near the September 2011-2019 median.

In addition to factoring in meteorological variables, STI meteorologists also consider past observed ozone levels when issuing air quality forecasts for Delaware. In Figure 28, a comparison is shown between the monthly mean ozone concentrations between 2011-2019, the monthly mean ozone concentrations in summer 2020, and the monthly mean ozone STI forecasts in summer 2020.

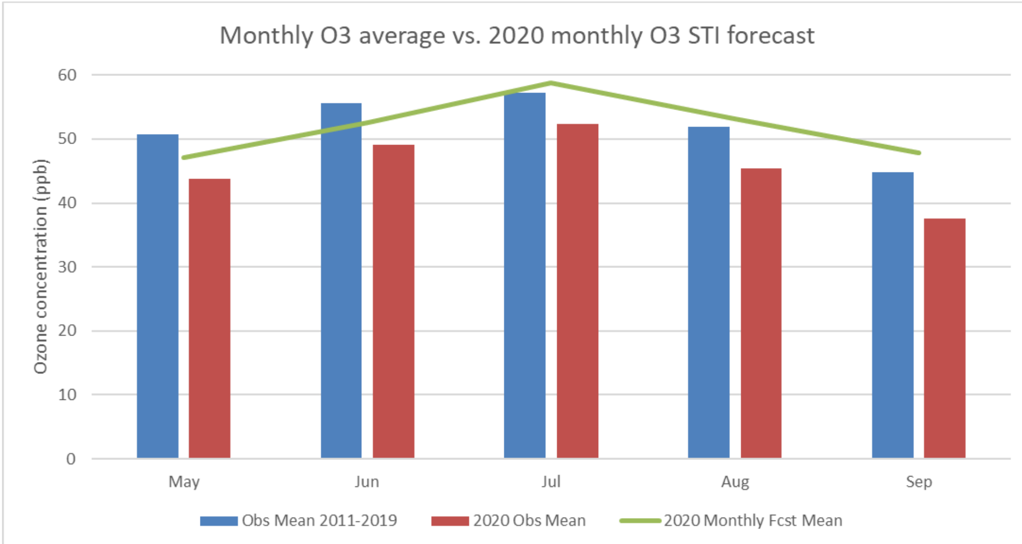

Figure 28. Monthly average ozone levels for 2011-2019, monthly average ozone for 2020, and average monthly STI forecasts in 2020.

In general, STI Forecasts were more aligned with past observed ozone levels. While summer 2020 forecasts exhibited a season-average high bias of 6.2 ppb when compared to observed 2020 ozone levels (Table 9), 2020 forecasts had an extremely low bias of 0.16 ppb when compared to 2011-2019 monthly average ozone levels. This partially suggests that observed ozone concentrations in 2020 were much lower than what is typically expected during the summer in the First State. Aside from erring on the side of caution, the high bias in STI forecasts in 2020 was likely also a reflection of the reduced emissions in 2020 during the COVID pandemic.

5. Skill of Ozone Model Forecasts in 2020

5.1 Introduction to Ozone Model Forecasts

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

To aid in forecast decision-making, STI 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 (https://www.emc.ncep.noaa.gov/mmb/aq/cmaqbc/web/html/max.html)
- BlueSky-Gateway (BSG) ozone model, run once daily

The following sections analyze the skill of each model's next-day forecast output and compare model performance to STI Forecasts during summer 2020.

5.2 2020 Ozone Model Forecast Statistics

Table 10 provides each model run's next-day forecast bias and MAE for the 2020 summer ozone forecast season. Data for each model run is specific to Wilmington, Delaware.

Table 10. May-September 2020 next-day forecast model statistics for Wilmington, Delaware.

Model	Bias (ppb)	Mean Absolute Error (ppb)
NOAA 06Z	+4.4	6.9
NOAA 12Z	+5.0	6.9
BSG Bias-Corrected 00Z	-1.6	5.6
BSG Raw 00Z	-0.6	5.8
NCEP CMAQ Bias-Corrected 06Z	-1.4	5.8
NCEP CMAQ Bias-Corrected 12Z	-0.8	5.6

For the 2020 ozone forecast season, next-day forecast bias and MAE were highest for the NOAA model, regardless of the model initialization time (both 06Z and 12Z). In comparison, all initializations of the BSG and NCEP CMAQ Bias-Corrected models exhibited lower bias and MAE than the NOAA model. The BSG Raw 00Z model run had the best next-day forecast bias at -0.6 ppb. Additionally, the BSG Bias-Corrected 00Z and NCEP CMAQ Bias-Corrected 12Z models each recorded a MAE of 5.6 ppb, which was better than other models.

A month-by-month breakdown of next-day forecast bias and MAE is provided in **Figures 29 and 30**. Throughout summer 2020, both initializations of the NOAA ozone model were biased high in comparison to other model output. Furthermore, all models were biased high in September 2020, when observed ozone concentrations were lower than normal. Both initializations of the NCEP CMAQ Bias-Corrected model were more skillful than other models in September, recording lower bias and MAE compared to other models.

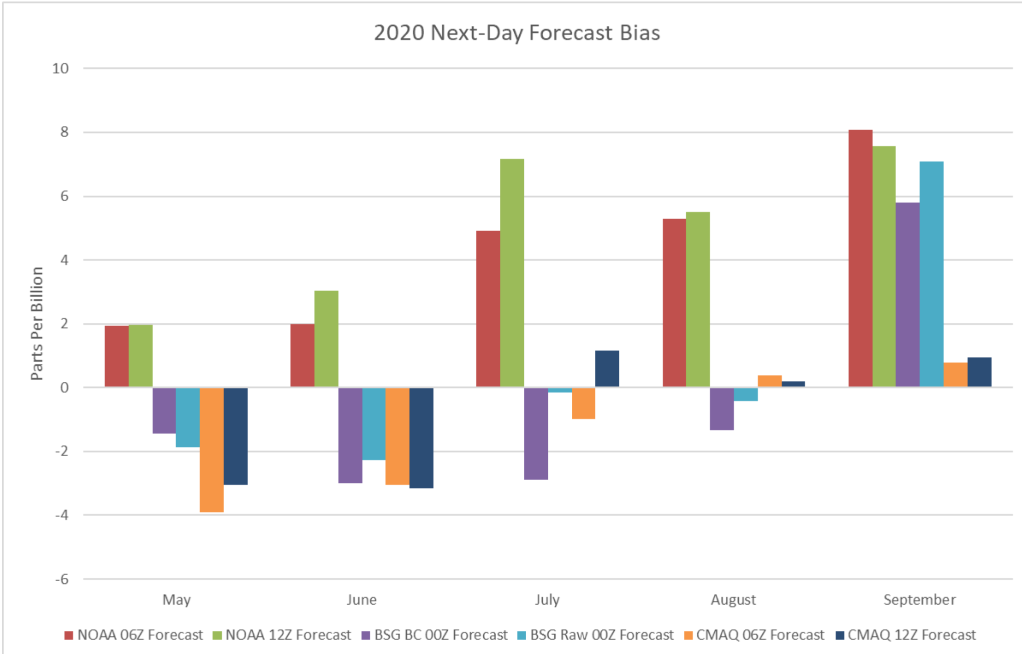

Figure 29. Monthly next-day forecast bias during summer 2020 in Wilmington, Delaware.

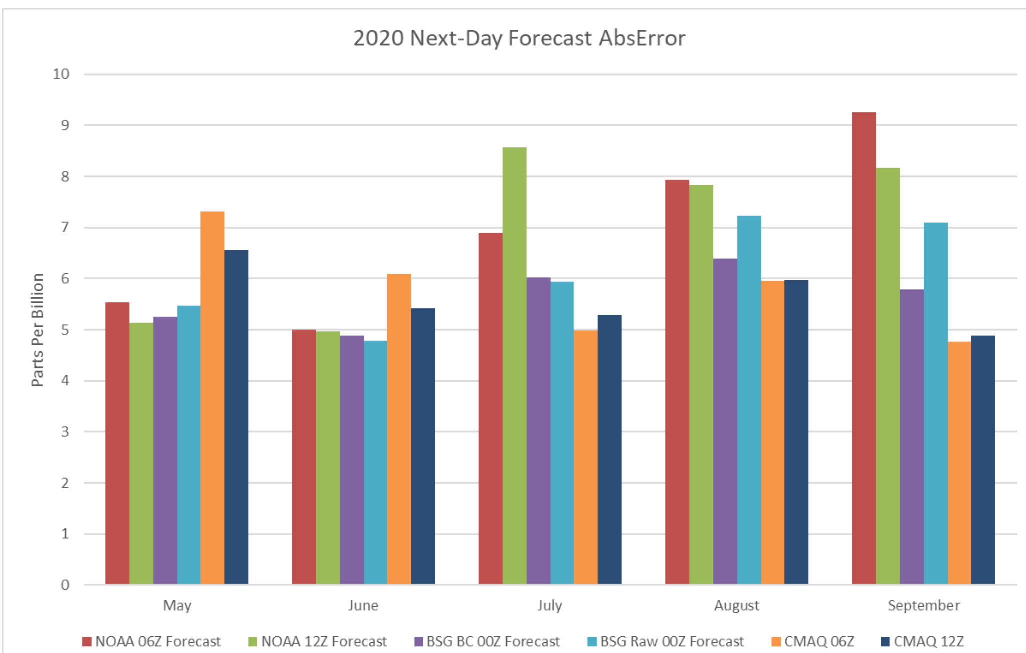

Figure 30. Monthly next-day MAE during summer 2020 in Wilmington, Delaware.

5.3 Comparison of STI Forecasts to 2020 Ozone Model Forecasts

Similar to Figures 30 and 31, Figures 31 and 32 provide next-day forecast bias and MAE. However, these figures include both ozone model predictions *and* STI Forecasts issued in summer 2020. Additionally, the average bias and MAE for the entire May-September period is shown at the far right of each figure.

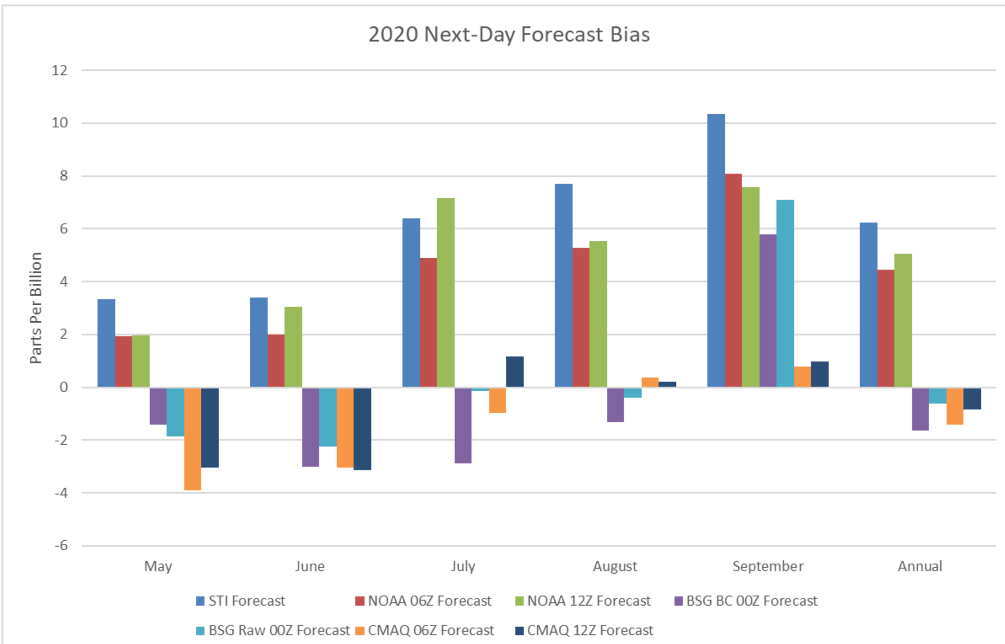

Figure 31. Monthly next-day forecast bias for both models and STI forecasts during summer 2020 in Wilmington, Delaware. Annual averages shown at far right.

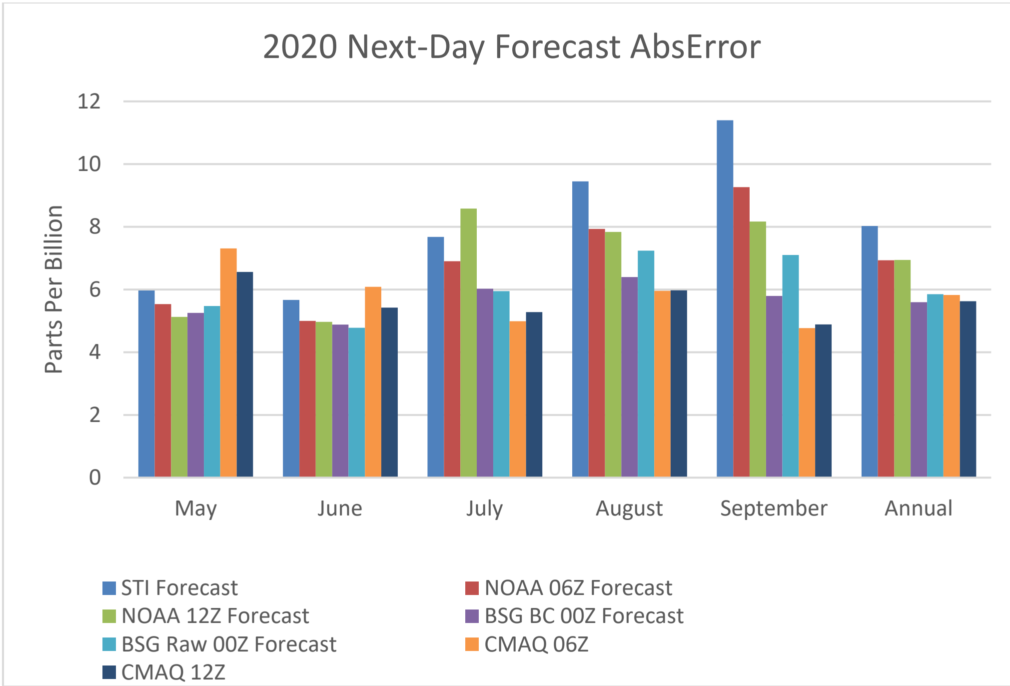

Figure 32. Monthly next-day forecast bias for both models and STI forecasts during summer 2020 in Wilmington, Delaware. Annual averages shown at far right.

In general, STI Forecasts were high-biased in every month versus ozone models. Additionally, MAE for STI Forecasts was higher than each model between July and September.

STI Forecasts tend to be biased high to err on the side of caution. This allows forecasters to alert vulnerable populations whose health may be negatively impacted by poor air quality and to aid agencies with decision-making support for any air quality programs implemented on high AQI days. In addition, STI Forecasts in summer 2020 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 STI Forecast statistics further increased forecast bias and MAE.

COVID-related emissions reductions in summer 2020 might have further contributed to the increased high-bias in STI Forecasts. More Good AQI days were observed in summer 2020 in comparison to previous years. Furthermore, ozone levels in August were significantly lower than previous years when meteorological conditions were similar. This suggests emission reductions related to the COVID-19 pandemic likely lowered ozone concentrations and increased bias and MAE of both the ozone models and STI Forecasts.

Although STI air quality forecasters do err on the side of caution, we also strive to maintain forecast accuracy. We will consider our high bias during the summer 2020 forecast season as we prepare to forecast in 2021. Additionally, the superior performance of the NCEP CMAQ Bias-Corrected model relative to other models gives us good reason to weight its predictions more heavily when considering our suite of forecasting tools and guidance.

6. Outlook for 2021

6.1 Summer Meteorological Outlook

To gauge the potential for ozone development during the upcoming 2021 summer season, STI's meteorologists reviewed seasonal forecasts by NOAA's Climate Prediction Center (CPC) as well as analog composites of temperature and precipitation anomalies, along with model output from the European Centre for Medium-Range Weather Forecasts (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 2021, as these months represent the peak of ozone season in Delaware.

CPC's forecast for temperature and precipitation anomalies for the summer of 2021 are shown below (Figures 33 and 34).

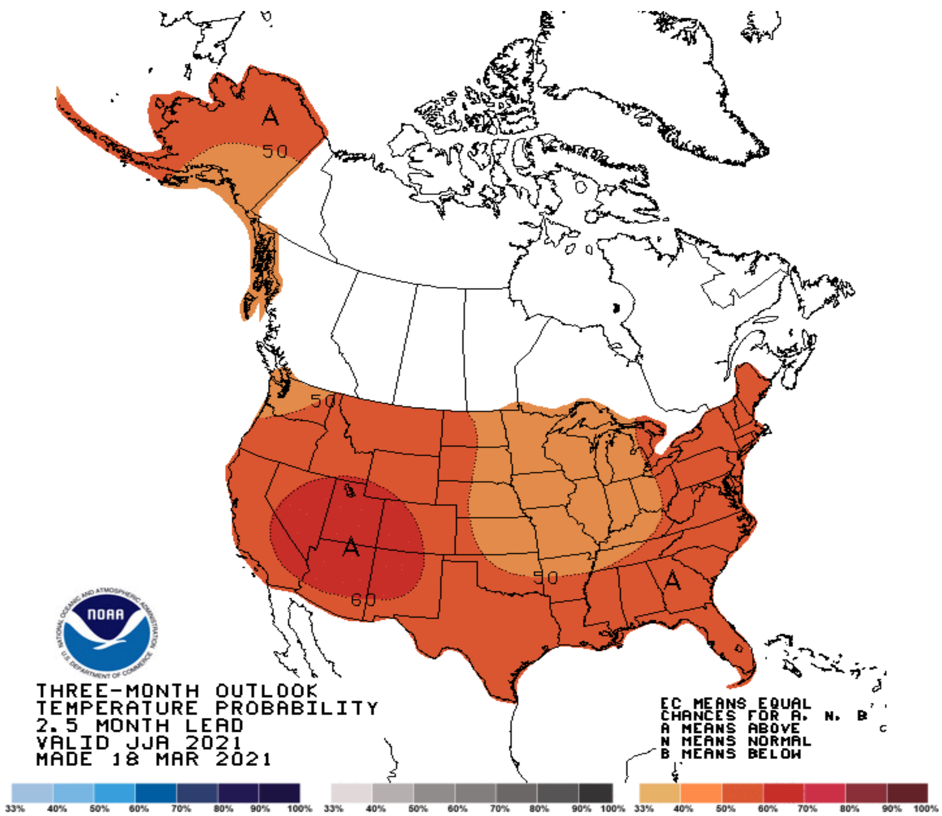

Figure 33. CPC forecast probability of surface temperature anomalies for June, July, and August 2021.

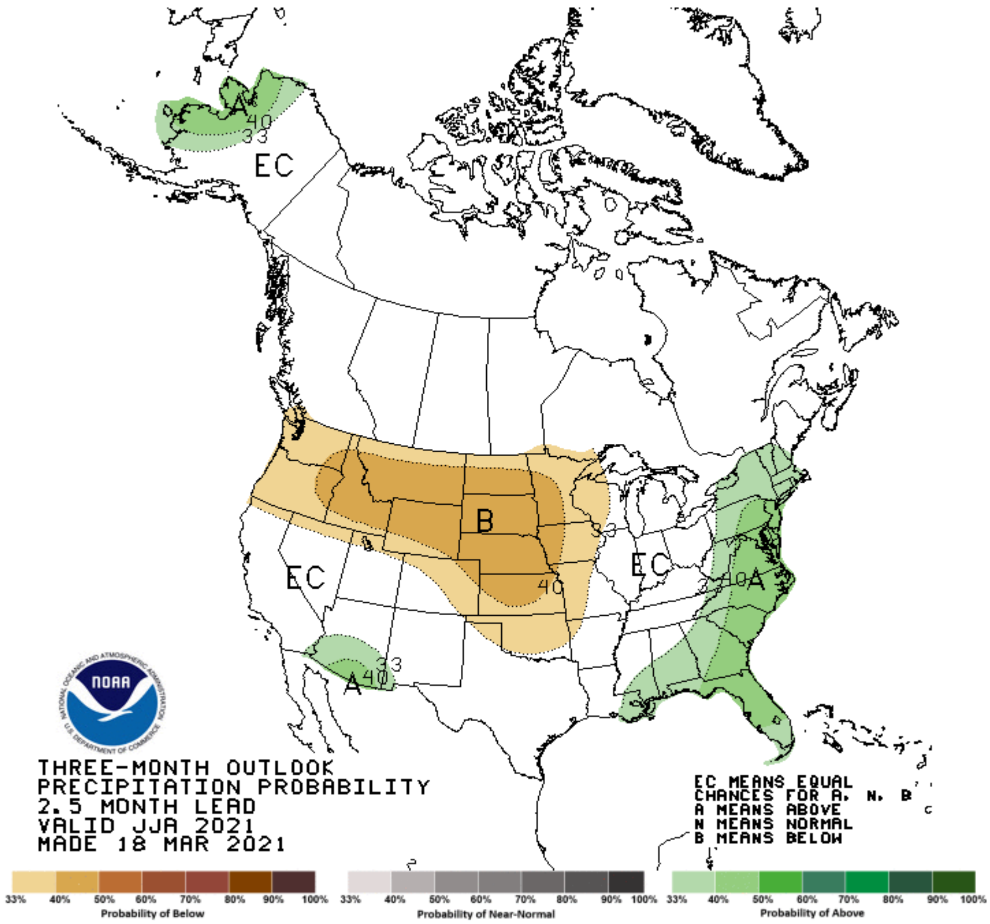

Figure 34. CPC forecast probability of precipitation anomalies for June, July, and August 2021.

Figures 33 and 34 indicate that the CPC is predicting a greater than 50 percent chance of above normal temperatures over the Mid-Atlantic this summer and a greater than 40 percent 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 this summer.

6.2 El Niño Southern Oscillation (ENSO)

While La Niña conditions are currently present over the west-central to eastern equatorial Pacific region, the CPC's ENSO outlook calls for a transition from La Niña to ENSO-Neutral conditions during Northern Hemisphere spring 2021. ENSO-Neutral conditions are then expected to continue through summer 2021. 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. STI 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, and most recently 2018. Figures 35 and 36 are composites of the temperature and precipitation anomalies that occurred on those years.

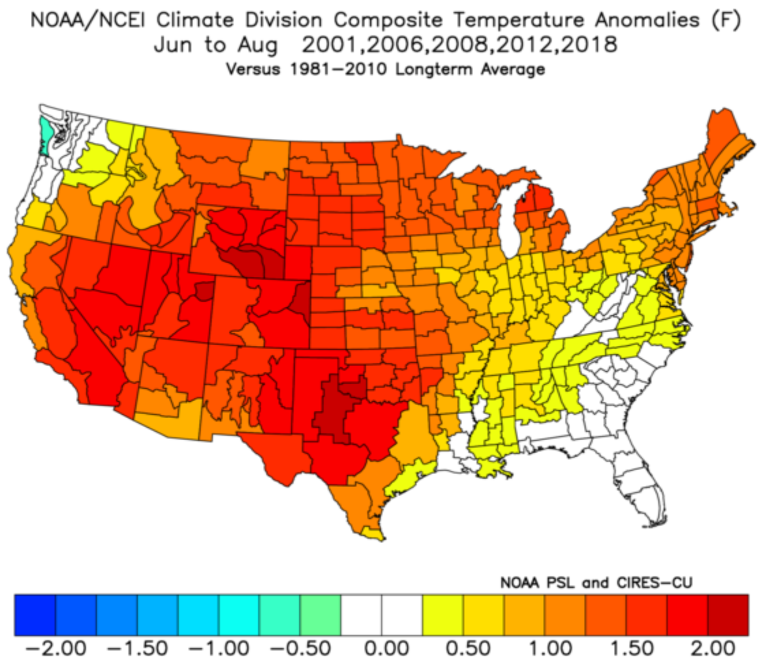

Figure 35. Temperature anomalies (F) for ENSO-Neutral summers after La Niña subsided.

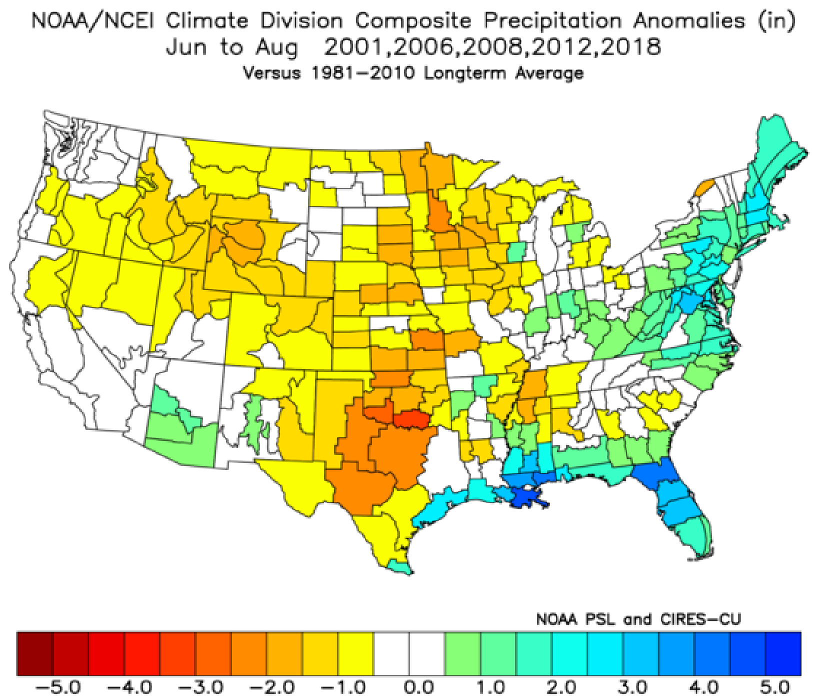

Figure 36. Precipitation anomalies (in.) for ENSO-Neutral summers after La Niña subsided.

While there are differences between CPC's forecast and the analog ENSO years across the Southeast and Midwest, Figure 35 reveals a picture that is largely similar to the CPCs forecast temperature anomalies, in that much of the country experienced above average temperatures during these ENSO-Neutral summers. In addition, temperatures in Delaware averaged above normal for these years with similar ENSO conditions. Precipitation anomalies in Figure 36 also correspond well to the CPC's forecast, with drier than normal conditions over the central and western U.S., and wetter than normal conditions from the Southeast into New England. Overall, analog conditions from years with transitions from La Niña to ENSO-Neutral support the CPC's forecast of above-average temperatures and precipitation in Delaware this summer.

While ENSO conditions and forecasts are 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.

6.3 Model Forecasts

The seasonal temperature and precipitation forecasts from the ECMWF are shown in Figures 37 and 38. The forecast temperature and precipitation anomalies are nearly identical to the patterns shown in the maps for the analog ENSO years (Figures 35, 36). The temperature anomalies for Delaware are similar in magnitude, (0.5° C on the ECMWF vs. 1° F on the analog maps), and the overall pattern is also similar. The ECMWF is also forecasting above-normal precipitation across much of the eastern U.S. (Figure 38).

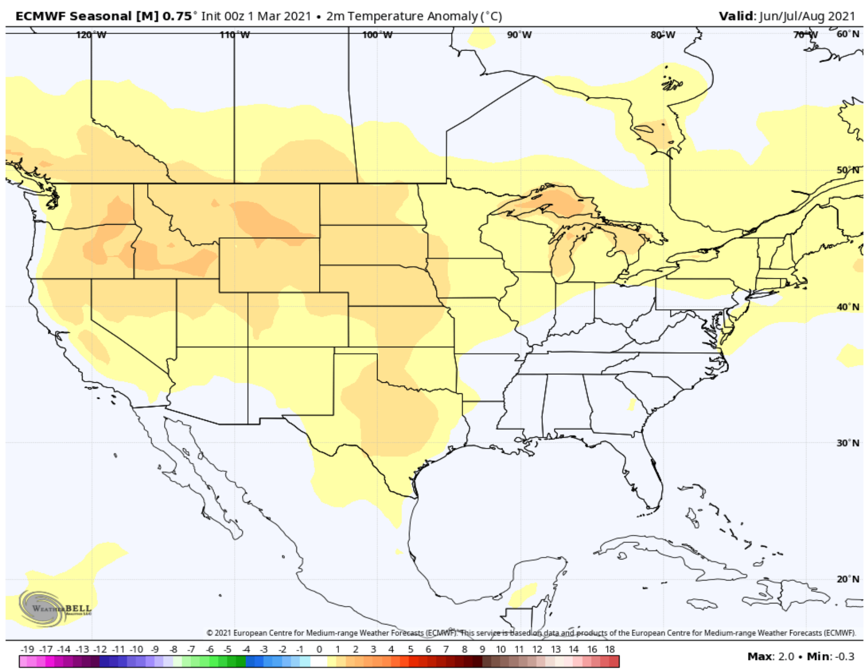

Figure 37. ECMWF forecast temperature anomalies for June-August 2021.

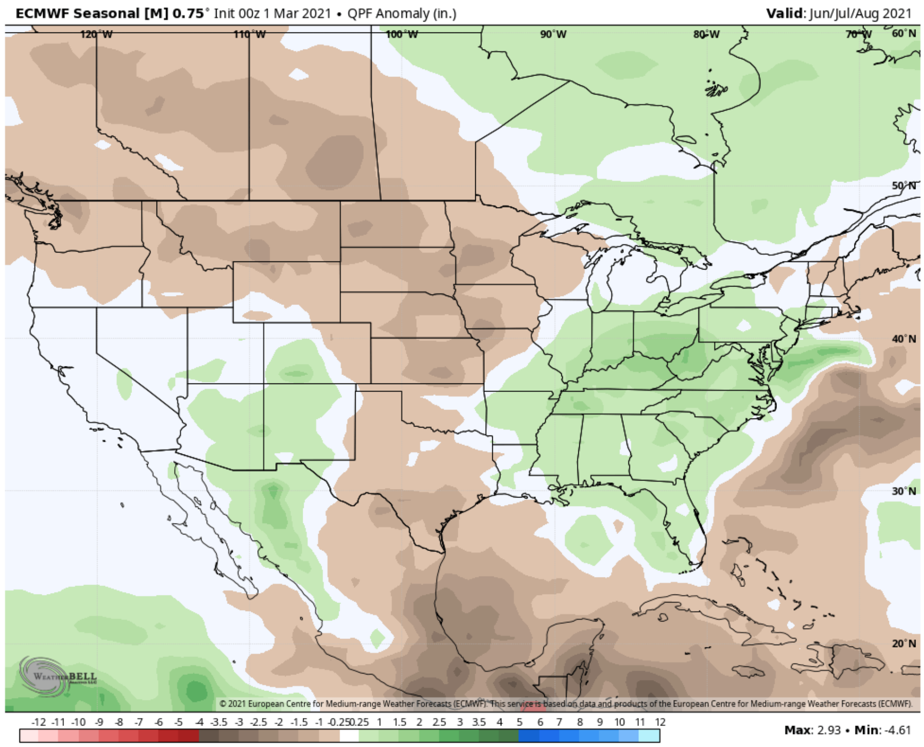

Figure 38. ECMWF forecast precipitation anomalies for June-August 2021.

The CanSIPS model forecast also predicts above-normal temperatures across much of the U.S. this summer (**Figure 39**). Even though the magnitude of warming over much of the U.S. is greater than the ECMWF for most locations, the forecast for Delaware is very similar with slightly above-average temperatures forecast for June through August.

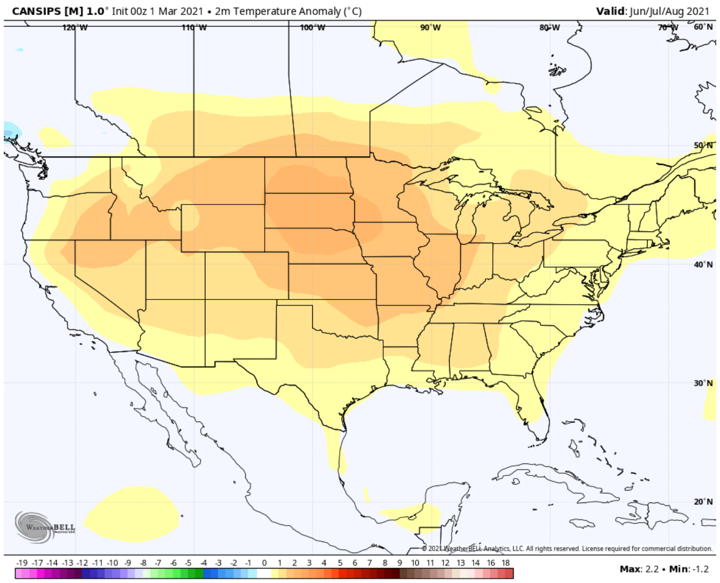

Figure 39. CanSIPS forecast temperature anomalies for June-August 2021.

The largest disagreement between these models comes with the precipitation forecast (**Figure 40**). While the ECMWF had above normal precipitation for much of the eastern U.S., the CanSIPS model predicts below-normal precipitation across almost the entire country.

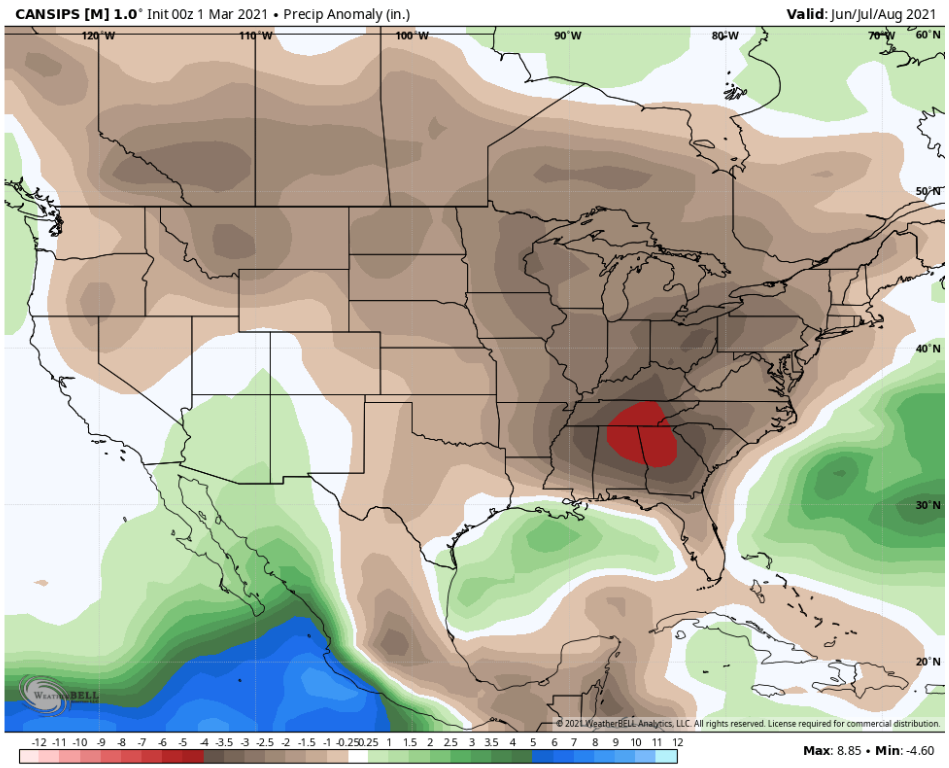

Figure 40. CanSIPS forecast precipitation anomalies for June-August 2021.

6.4 Trends in Summer Temperatures and Precipitation

Another factor to consider in seasonal weather predictions are 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 ten years, and the temperature climatology between 1981-2010. Precipitation trends reflect the difference between the average precipitation during a selected three-month period over the last fifteen years, and the precipitation climatology between 1981-2010. The trends maps are shown in Figure 41.

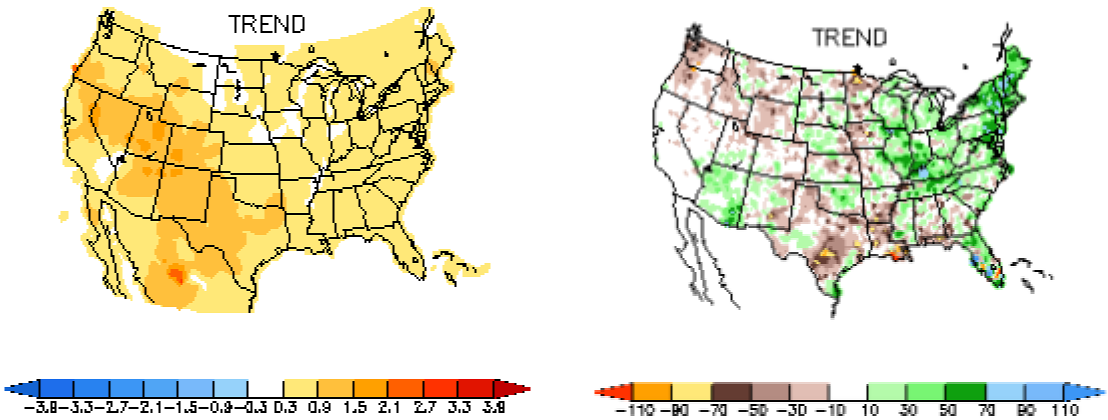

Figure 41. Recent trends in temperature in degrees Celsius (left) and precipitation in millimeters (right) for June, July, and August. The recent trend is estimated by the Optimal Climate Normal (OCN) of Huang et al. (1996)[2].

Trends in summertime temperatures and precipitation further support CPC's summer forecast as well as the ENSO related analogs and the model forecast produced by the ECMWF, with Delaware trending warmer and wetter on average.

6.5 Implications for Summer Ozone Season in Delaware

With official forecasts, model output, and trends largely showing a similar picture for this coming summer, there is a good chance that temperatures in Delaware will be slightly above average, with 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 average daily ozone levels and the frequency of high-AQI events compared to 2020.

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. As with any meteorological forecast, specifics for Delaware will become clearer as summer approaches, and the large-scale patterns begin to develop. STI meteorologists will track the latest developments and use the best tools available to stay on top of the upcoming ozone season.

[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.

6.6 COVID-19 Impacts on Summer 2021 Ozone Development

Summer 2020 ozone concentrations were lower than previous years, possibly related to emissions reductions due to the COVID-19 pandemic. However, as pandemic-related restrictions continue to loosen, the business and industrial sectors will likely return to pre-pandemic operations in summer 2021. Therefore, STI forecasters anticipate that emissions from traffic and industrial activities will increase to near-normal levels in summer 2021.

While ozone development is also dependent on weather, the anticipated increase in traffic and industrial emissions may influence ozone production in summer 2021, resulting in ozone levels that more closely follow trends observed between 2013 and 2019. As a result, STI meteorologists anticipate that Good AQI ozone days will not be as frequent as in summer 2020. Additionally, Code Orange days may be more frequent in 2021 than in 2020.