DOI: 10.32481/djph.2017.10.004

Ozone pollution in Delaware:

How does climate change influence ozone-related health?

Joseph F. Brodie, PhD[1]; Cristina L. Archer, PhD[2]; Sara A. Rauscher, PhD[3]

1. Postdoctoral Researcher, University of Delaware

2. Associate Professor, University of Delaware

3. Assistant Professor, University of Delaware

Corresponding Author:

Cristina L. Archer, University of Delaware, Interdisciplinary Science and Engineering Laboratory, Rm #371, 221 Academy St., Newark, DE 19716; carcher@udel.edu

Abstract

Ozone is the only pollutant that exceeds national and state standards in Delaware. Using observations and two different climate models, the number of high-ozone days (days exceeding 70 ppb based on the 8-hour average in Delaware) is investigated for the late 20th and early to mid-21st centuries using a synoptic typing methodology, which relates surface conditions conducive to high-ozone events to atmospheric circulation. High-ozone days are associated with the absence of precipitation and southwesterly to west-northwesterly flow over Delaware, which tend to bring higher daily mean temperatures (exceeding 25.5°C). Models underestimate the number of observed high-ozone days in the 20th century, because the models do not include the effects of ozone regulation, which has decreased the number of ozone days. Meanwhile, higher concentrations of greenhouse gases and the resulting higher temperatures favor increased ozone days, an effect that is captured by the models. As temperatures continue to rise in the 21st century, climate projections indicate that high-ozone conditions will occur more frequently. By mid-century, the number of high-ozone days is projected to increase by about an extra day every two years, which is faster than it was in the previous 30 years. Thus global warming cancels out a quarter of the progress made in improving air quality in the state of Delaware, meaning that the air quality in mid-century is expected to be the same as it was around 2006. In a warming world, air quality standards will need to stricter to maintain or reduce the number of high-ozone events in Delaware.

Background

Climate change is much more than simply an atmospheric phenomenon; it can have profound impacts on public health. The most recent report of the Intergovernmental Panel on Climate Change (IPCC) describes an average warming of the global climate of about 2°C by the end of the 21st century,[1] while regional studies[2] have indicated a stronger warming along the east coast of the United States, between 2.5°C and 5.5°C the authors examine projections of twenty-first-century climate in the representative concentration pathway 8.5 (RCP8.5). Exacerbating the impact of this temperature increase is the expectation that heat waves will occur with greater frequency, intensity, and duration. If emissions of carbon dioxide (CO2) continue on their current trajectory, by mid-century the mid-Atlantic may experience 50 more days per year of high temperatures exceeding 32°C (90°F),[3] while in Delaware the number of days with maximum temperatures above 35°C (95°F) is expected to vary from less than 5 to 15-30.[4] These temperature increases are likely to impact Delaware's public health, due to the known relationship between high temperatures and increased mortality.[5,6] In particular, this link appears strongest in the eastern United States when compared to elsewhere in the country.[5,7]

This increase in temperature influences public health in ways other than the direct mortality impact. One of these indirect impacts is the temperature influence on tropospheric (surface) ozone (O3) pollution.

Tropospheric ozone, which is regulated by the U.S. Environmental Protection Agency (EPA), is a summer pollutant that forms in the lower atmosphere as a result of photochemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOC). Ozone is currently the only pollutant that exceeds national and state standards in Delaware. Ozone can: cause damage to the respiratory tracts, including shortness of breath and inflammation; exacerbate asthma, emphysema, and chronic bronchitis; and cause chronic obstructive pulmonary disease (COPD). Children are generally at higher risk than adults because their lungs are still developing, they are generally more active outdoors, and they are more susceptible to asthma; however, older individuals are also considered to be a more at-risk population (https://www.epa.gov/ozone-pollution/ health-effects-ozone-pollution). Higher ozone levels have also been shown to increase hospital admissions for asthma and COPD for the elderly and children.[8]

There are three mechanisms by which ozone may reach higher concentrations and/or exceed regulatory standards more frequently in a warming climate.

The first is that higher temperatures enhance the photochemical reactions that produce ozone.[9] Secondly, episodes of high ozone are associated with certain large-scale weather conditions, such as the passage of mid-latitude cyclones or the western expansion of the Bermuda High.[10] The weather conditions over a region of interest on a particular day are known as the "synoptic weather conditions". Due to climate change, the synoptic weather conditions conducive to high-ozone events may occur with greater frequency, leaving the potential for more high-ozone episodes. Finally, synoptic conditions that today are not typically associated with high-ozone events may become more conducive to the formation of ozone as the climate warms. This paper will focus on the second factor: the synoptic weather conditions associated with high ozone and their changes in frequency due to climate change.

The synoptic weather conditions can be grouped into a few "synoptic types", thus each day can be assigned to a synoptic type that represents all days of the year with similar synoptic weather conditions. This is done using a variety of meteorological variables, including temperature, sea-level pressure, humidity, precipitation, cloud cover, and wind speed and direction. Thresholds and/ or spatial distributions of these variables are identified and used to classify each date into one of a limited number of synoptic types. The synoptic typing used in this study was developed by a team at the University of Delaware and includes data spanning back to 1946.[11,12] In the summer, the season most favorable to ozone formation, nine synoptic types were identified, four of which are associated with a high probability of high ozone. The number of days that belong to one of the four favorable synoptic types is evaluated in this study using future climate projections. The resulting trends are indicative of changes in the number of high- ozone days.

The extensive work performed in preparation of the climate assessment reports of the IPCC resulted in a plethora of available climate modeling data, which are publicly available online. Specifically, the Coupled Model Intercomparison Project (CMIP5)[13] database consists of dozens

DOI: 10.32481/djph.2017.10.004

of climate models from agencies worldwide, along with a number of experiments for each model to assess model performance and make projections of climate in the past, present, and future. For this study, two climate modeling suites were selected, which are considered to be among the most accurate and have fine enough resolution to evaluate local Delaware climate.

These are the Hadley Centre Global Environment Model (HadGEM2),[14] run by the Met Office in the United Kingdom, and the Model for Interdisciplinary Research on Climate (MIROC5),[15] run by the University of Tokyo and the National Institute for Environmental Studies in Japan. This research uses historical runs from both models to examine the past and present climate in Delaware from 1986 through 2015. Additionally, future projections are included from the Representative Concentration Pathway 8.5 (RCP 8.5),[16] which represents a "business-as-usual" scenario of future carbon emissions. Specifically, this paper examines the period 10 years into the future (2025– 2034) and in the middle of the century (2045–2054).

What is a "high-ozone" event?

The EPA has established the Air Quality Index (AQI)[17] in order to assess the public health impacts of ozone and other pollutants as high levels of pollution are occurring.

The AQI includes 6 color-coded levels that indicate the severity of the particular pollutant, ranging from "good" on the low end to "hazardous" at the high end (Figure 1).[18] These levels help users see at a glance when they should consider seeking shelter from prolonged ozone exposure. An AQI exceeding 100 indicates an increased level of caution for at-risk groups; for ozone, this means that the 8-hour average exceeds 70 ppb. The maximum AQI index is 500, corresponding to the pollutant reaching the Significant Harm Level (SHL); for ozone, the SHL is 600 ppb using a 2-hour average.

Figure 1. US EPA Air Quality Index (AQI) for ozone, as defined by the 2015 standards.

AQI Category	Index Value	8-hr Ozone (ppb)
Good	0 - 50	0 – 54
Moderate	51 100	55 70
Unhealthy for Sensitive Groups	101 150	71 85
Unhealthy	151 - 200	86 – 105
Very Unhealthy	201 - 300	106 – 200
Hazardous	301 - 500	201 - SHL*

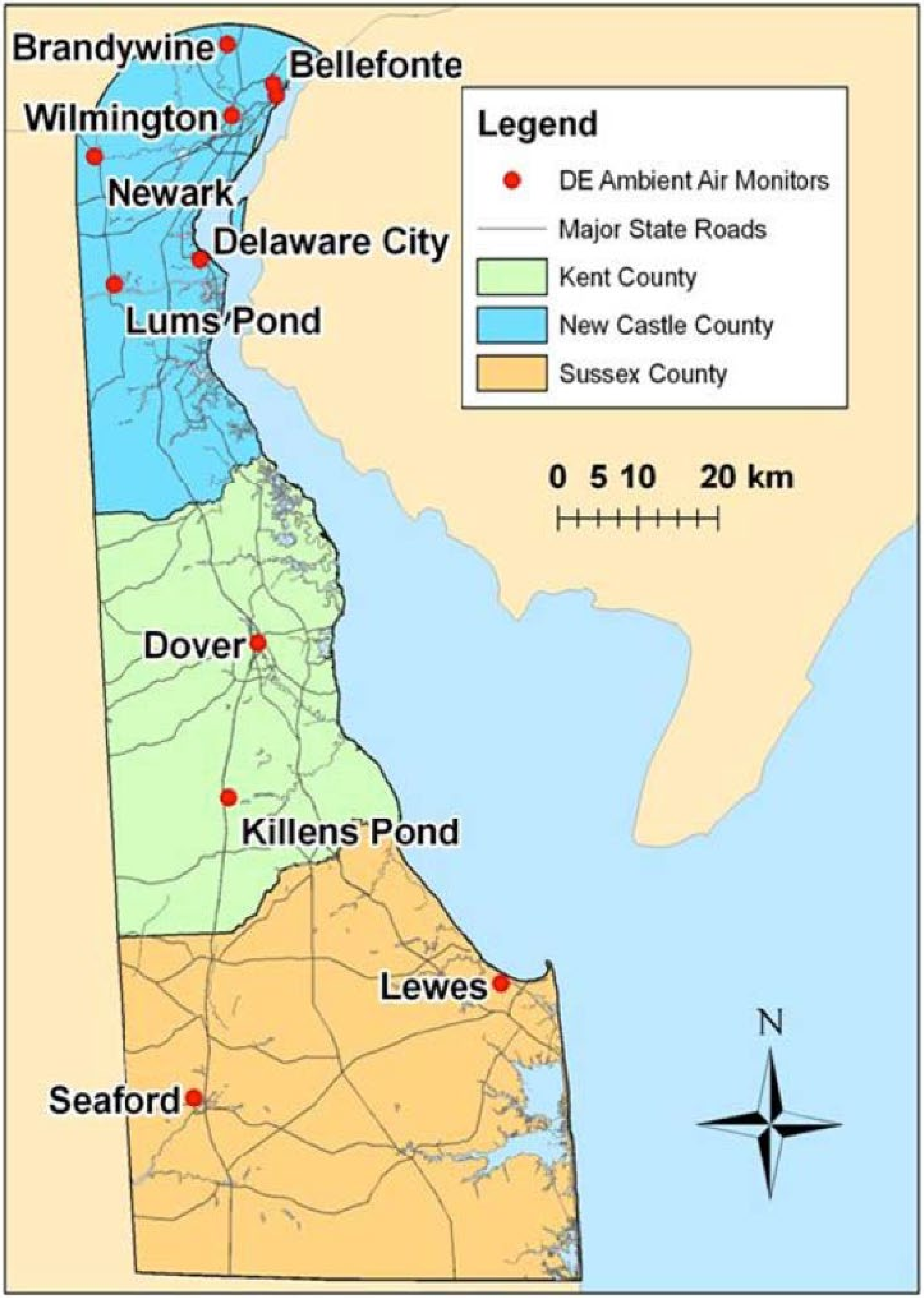
*SHL represents the Significant Harm Level, which is 600 ppb based on a 2-hour average.

The Delaware Department of Natural Resources and Environmental Control (DNREC) Division of Air Quality (DAQ) operates several air quality observing stations throughout the state of Delaware that track several pollution parameters, including ozone. The first of these stations reporting ozone became operational in 1980, and additional stations have been added, removed, or replaced since then. As of 2015, Delaware has 7 air quality stations that measure ozone (Figure 2). Due to Delaware's small size, the 7 stations (2 stations in Sussex County, 1 station in Kent County, and 4 stations in New Castle County) provide a good spatial coverage of ozone levels in the state. The data from these stations are archived by DNREC and are available online via the EPA Air Quality System (AQS) Data Mart at https:// www.epa.gov/outdoor-air-quality-data.

DOI: 10.32481/djph.2017.10.004

Figure 2. Location of the Delaware air quality monitoring stations. Note that the Newark, Delaware City, and Dover stations do not record ozone levels.

DOI: 10.32481/djph.2017.10.004



DOI: 10.32481/djph.2017.10.004

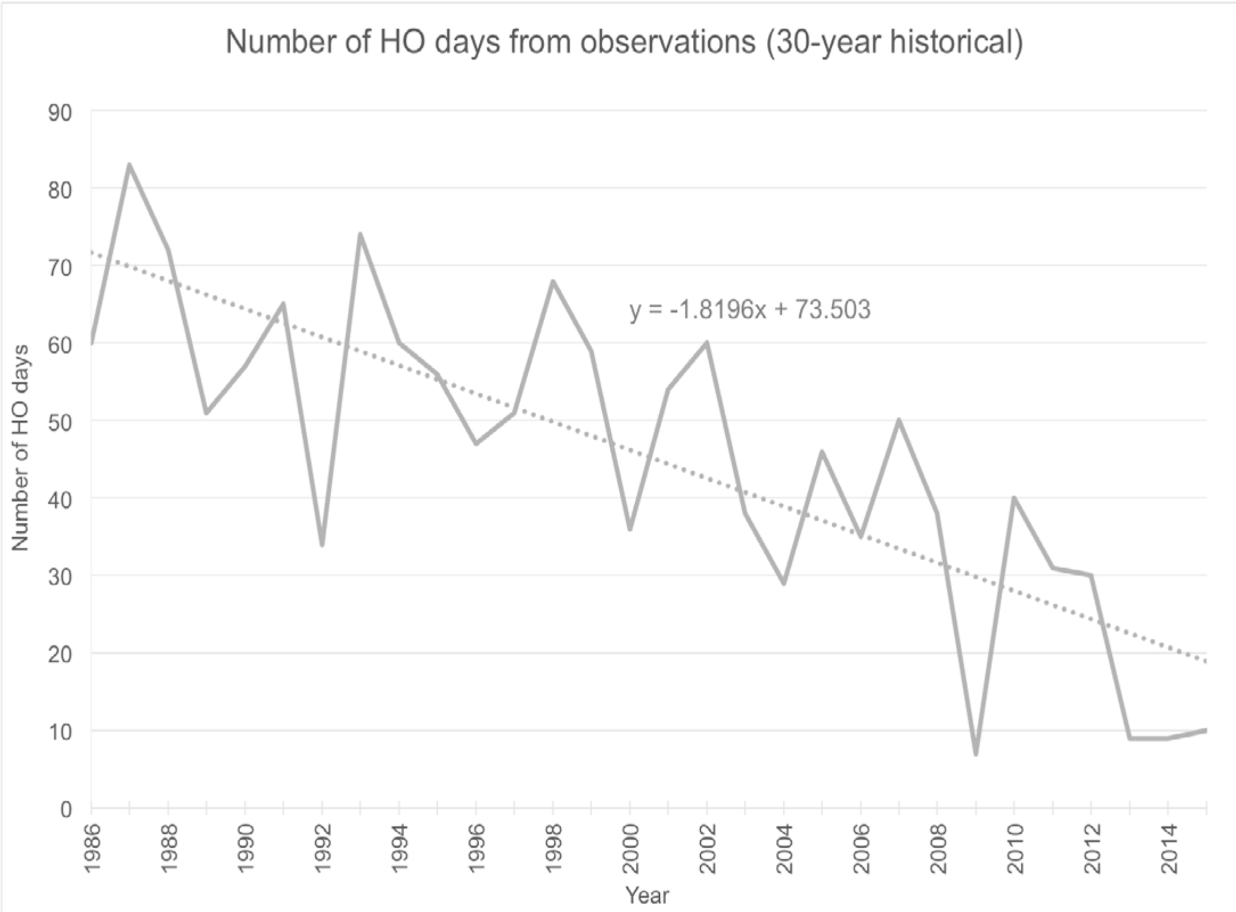
In order to determine what qualifies as a "high-ozone" (HO) day using this observational data, it was necessary to set a threshold value. Since the AQI index value of 100 indicates a pollution level that can be considered harmful to sensitive populations, the corresponding ozone level of 70 ppb based on the 8-hour average was used to classify days that are considered HO events. Since Delaware is a small state, even if only one station's 8-hour average exceeds this level, the day is classified as HO.

Based on these criteria, the observational record of ozone for the historical 30-year period from 1986 through 2015 was analyzed. As can be seen in Figure 3, the number of HO days has been decreasing over the 30-year period. On average, each year during the study period had about 2 fewer days of high ozone per year (as the trend line in Figure 3 has a slope of -1.82 HO days/year), changing from about 70 HO days per year to less than 10 in the past few years. This steady decrease was not a random phenomenon, but rather the result of stricter regulation (such as federal and state air quality standards) and societal reductions in the emissions of ozone-forming pollutants. This improvement in air quality has occurred despite the underlying warming trends from climate change, which would have caused an increase, not a decrease, in the number of HO days.

Since past or future regulation and emission controls are not simulated in climate models, only trends due to global warming will be identified in this study.

Figure 3. Number of high-ozone (HO) days in Delaware from historical observations during the 30-year period 1986-2015.

DOI: 10.32481/djph.2017.10.004



Detecting high-ozone events using climate models

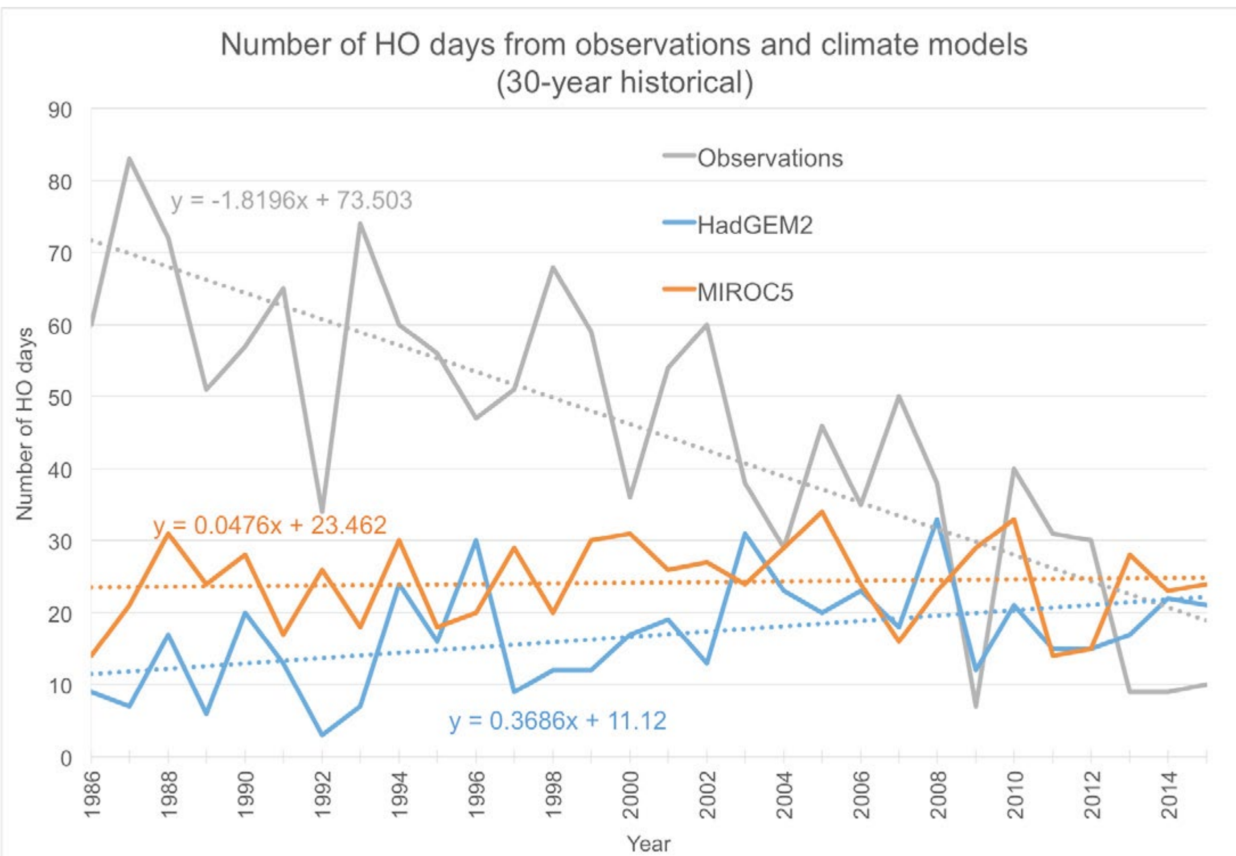
In order to evaluate how ozone levels in Delaware may change due to the changing climate, it is necessary to establish criteria to detect conditions in climate models that would be conducive to high ozone. This was done by evaluating the synoptic weather conditions that were present on days in the most recent decade of the period of interest (2006–2015) which were classified as HO based on the aforementioned criteria (i.e., 8-hour ozone exceeding 70 ppb). The calibration period was the last decade, as opposed to any other decade in the historical period, to ensure that the projected changes in HO days due to climate alone would be inclusive of current, not past, regulation. Several meteorological variables were used to detect synoptic weather conditions favorable for high ozone in climate models. First and foremost, the spatial distribution of sea level pressure (SLP) was used, since it is representative of the flow patterns near the surface.

Only cases with an overall spatial distribution of SLP that would lead to transport of the ozone precursors (NOX and VOC) into the state were included, specifically, southwesterly to west-northwesterly flow. The second condition involves temperature, since higher temperatures make HO events more likely. Days with mean daily temperature in the state exceeding 25.5°C (78°F) had a high likelihood of high levels of ozone. Note that this is a mean daily temperature; the daily highest temperature on these days consistently exceeded 32°C (90°F), but mean temperature was used since that variable is more readily available in climate models.

The third condition leading to a HO event was the absence of precipitation. Rain prevents ozone from forming, due to both a lack of sunlight that drives the photochemical reactions and the washout of the available precursor pollutants. As such, only days when there was no measurable precipitation (defined as less than 1 mm/day) in the climate model were considered to be favorable to high ozone.

These criteria were used to evaluate daily climate model output during the summer months (June through August hereafter) for the same 30-year period as the observations (1986–2015). Any day that met all three criteria was classified as a HO day. These results are shown in Figure 4. Since the criteria were tuned to the most recent decade, the model data match the observations very well in the last 10 years, but underestimate the number of HO days in the earlier decades. This is to be expected due to the aforementioned calibration, because earlier in the historical period the regulation was less strict and therefore ozone concentrations were generally higher. Weather evolves in a climate model the same way as it does in the real word, but not exactly on a day-to-day or year-to-year basis. For example, if temperature was above 35°C on September 1, 2015, it is not expected to be above 35°C on the same day or year in the climate model. Rather, the climate model will have the same frequency of days above 35°C as the real world over the course of a decade.

Figure 4. Number of high-ozone (HO) days in Delaware from the historical observations versus the two climate models (HadGEM2 and MIROC5) for the 30-year period 1986-2015.



With respect to ozone, climate models are not expected to perfectly capture the number of ozone days year by year, but rather the characteristics of the underlying variability and frequency over time scales of a decade or longer. In other words, the model results show how the number of HO days would have changed over the past 30 years if the regulatory and societal factors were held constant at 2015 levels (i.e., a standard of 70 ppb for 8-hour average O3, along with 2015 emission standards and industry pollution controls). This allows the models to estimate how the number of HO days would fluctuate solely due to the climate, and not to societal and regulatory changes.

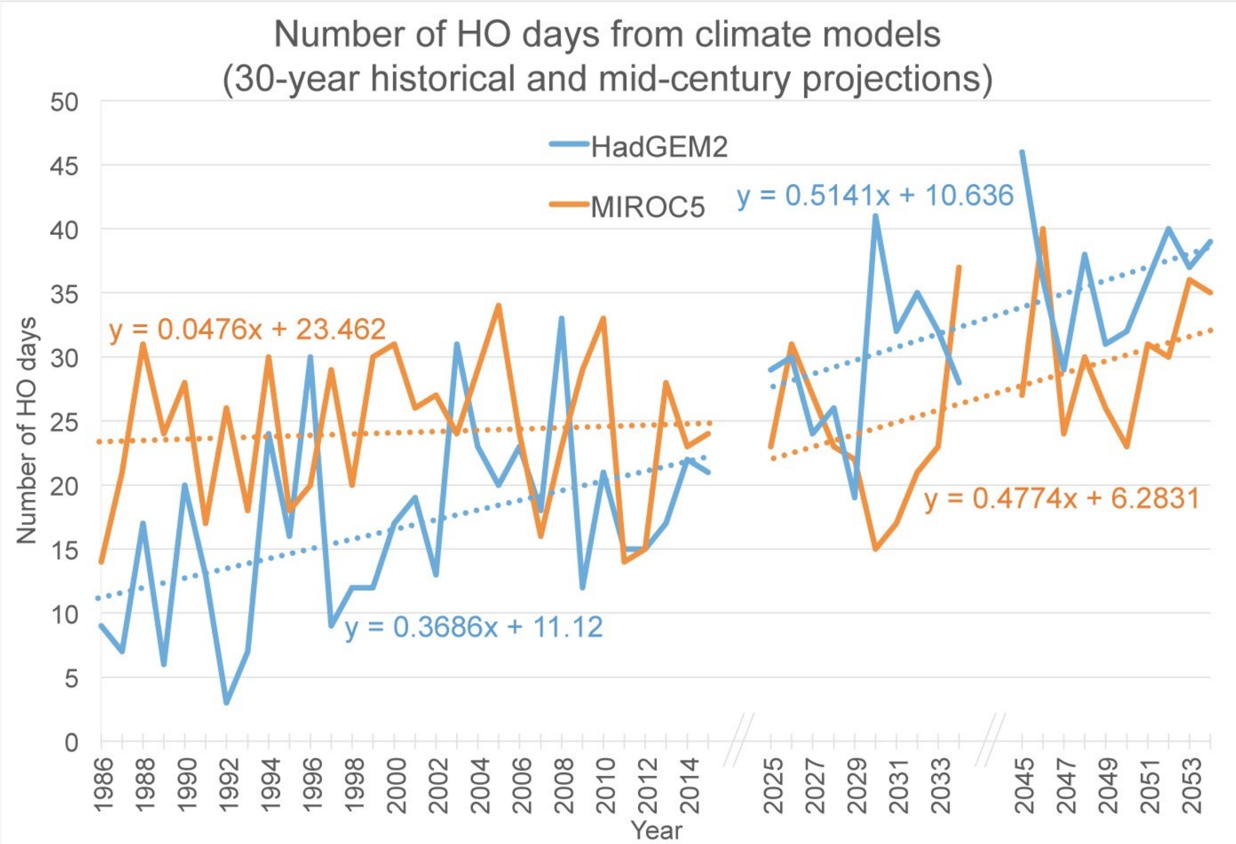
The HadGEM2 model indicates that, under the warming trend of the past 30 years, Delaware could expect about one extra HO day every 3 years, given that the trend line in Figure 4 has a slope of +0.37 HO days/ year. This trend is not as strong in the MIROC5 model, which shows only about 1 extra HO day every 20 years (or +0.05 HO day/year). In terms of variability, both models exhibit a lower standard deviation than observed in the last decade (~6 vs. 16 HO days for models and observations, respectively (not shown).

Projected changes in the number of high-ozone events

The climate models were evaluated for 10 years from now (2025–2034) and mid-century (2045–2054) together. These results are shown next to the 30-year historical results in Figure 5. Once again, the assumption behind these results is that all regulatory and societal factors that impact the production of ozone remain at the 2015 levels and therefore the results indicate how the number of HO days may change solely due to the changing climate in Delaware. By mid-century, there is a clear increase in the number of HO days to between 30 and 40 days, depending on the model, from the current ~20 days per year. Both models also indicate an acceleration in the increase of the number of HO days, as indicated by the steeper slope of the trend lines (from +0.05 to +0.48 HO days/year for the MIROC5 and from +0.37 to +0.51 HO days/year for HadGEM2). Both models converge to the same estimate of one extra HO day every 2 years, as opposed to every 3 years (HadGEM2) or every 20 years (MIROC5).

Figure 5: Number of high-ozone (HO) days in Delaware from the two climate models (HadGEM2 and MIROC5) for the historical 30-year period 1986- 2015 and for two future periods, 2025-2034 and mid-century (2045-2054).

DOI: 10.32481/djph.2017.10.004



Global warming erases about 25% of the progress from regulation in reducing the number of HO days in the past 30 years (Figure 3), as the slopes went from approximately -2 to +0.5 HO days/year.

Conclusions and Future Work

The goal of this study was to investigate the impact of the changing climate in Delaware on the expected number of days with ozone levels high enough to be unhealthy for sensitive populations. A combination of observations and climate model data were used to identify and link synoptic conditions to days with high- ozone concentrations. High-ozone days are associated with: southwesterly to west-northwesterly flow over Delaware, which brings pollutants from upwind states; no precipitation; and high daily-mean temperatures (exceeding 25.5°C). Future climate projections showed that these conditions will occur more frequently in mid-century, thus increasing the number of HO days by about an extra day every two years, which is faster than it was in the previous 30 years. As such, global warming basically undoes a quarter of the progress in air quality in the state of Delaware, meaning that the air quality in mid-century is expected to be the same as it was around 2006. To maintain the current ozone levels, therefore, regulation will need to be stricter than it is today, and even stricter to maintain the past negative trends. Future work includes: the analysis of additional climate models, such as the CCSM4, GFDL, and CNRM-CM5, to better represent the uncertainty around future climate projections; a quantification of the potential increases in ozone concentrations, not only in the frequency of high- ozone days; and an assessment of the health impacts of the expected changes in ozone.

Acknowledgments

This research was funded by the Delaware Natural Resources and Environmental Control (DNREC). The authors would like to thank Daniel Leathers and Zachary Suriano of the University of Delaware for their help with the synoptic types.

References

1. Intergovernmental Panel on Climate Change. (2013). Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (T. F. Stocker, D. Qin, G.-K. Plattner, M. M. B. Tignor, S. K. Allen, J. Boschung, … P. M. Midgley, Eds.). Cambridge, UK and New York, NY USA: Cambridge University Press. Retrieved from http://www.ipcc.ch/report/ar5/wg1/
2. Maloney, E. D., Camargo, S. J., Chang, E., Colle, B., Fu, R., Geil, K. L., . . . Zhao, M. (2014). North American climate in CMIP5 experiments: Part III: Assessment of twenty-first-century projections. *Journal of Climate*, *27*(6), 2230–2270. https://doi.org/10.1175/JCLI-D-13-00273.1
3. Melillo, J. M., Richmond, T. C., & Yohe, G. W. (Eds.). (2014). Climate change impacts in the United States: The third national climate assessment. https://doi.org/10.7930/J0Z31WJ2
4. Hayhoe, K., Stoner, R., & Gelca, A. (2013). Climate change projections and indicators for Delaware. Retrieved from http://www.dnrec.delaware.gov/energy/Documents/Climate Change 2013- 2014/ARC_Final_Climate_Report_Dec2013.pdf
5. Anderson, B. G., & Bell, M. L. (2009, March). Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. *Epidemiology (Cambridge, Mass.)*, *20*(2), 205–213. PubMed https://doi.org/10.1097/EDE.0b013e318190ee08
6. Roldán, E., Gómez, M., Pino, M. R., & Díaz, J. (2015). The impact of extremely high temperatures on mortality and mortality cost. *International Journal of Environmental Health Research*, *25*(3), 277–287. PubMed https://doi.org/10.1080/09603123.2014.938028
7. Curriero, F. C., Heiner, K. S., Samet, J. M., Zeger, S. L., Strug, L., & Patz, J. A. (2002, January 1). Temperature and mortality in 11 cities of the eastern United States. *American Journal of Epidemiology*, *155*(1), 80–87. PubMed https://doi.org/10.1093/aje/155.1.80
8. Halonen, J. I., Lanki, T., Tiittanen, P., Niemi, J. V., Loh, M., & Pekkanen, J. (2010, September). Ozone and cause-specific cardiorespiratory morbidity and mortality. *Journal of Epidemiology and Community Health*, *64*(9), 814–820. PubMed https://doi.org/10.1136/jech.2009.087106
9. Seinfeld, J. H., & Pandis, S. N. (1998). Atmospheric chemistry and physics. John Wiley and Sons.
10. Shen, L., Mickley, L. J., & Tai, A. P. K. (2015). Influence of synoptic patterns on surface ozone variability over the eastern United States from 1980 to 2012. *Atmospheric Chemistry and Physics*, *15*(19), 10925–10938. https://doi.org/10.5194/acp-15-10925-2015

DOI: 10.32481/djph.2017.10.004

11. Siegert, C. M., Leathers, D. J., & Levia, D. F. (2016). Synoptic typing: Interdisciplinary application methods with three practical hydroclimatological examples. *Theoretical and Applied Climatology*, *128*, 1–19. https://doi.org/10.1007/s00704-015-1700-y
12. Suriano, Z. J., & Leathers, D. J. (2017). Synoptic climatology of lake-effect snowfall conditions in the eastern Great Lakes region. *International Journal of Climatology*.
13. Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An Overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*(4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1
14. Collins, W. J., Bellouin, N., Doutriaux-Boucher, M., Gedney, N., Halloran, P., Hinton, T., . . . Woodward, S. (2011). Development and evaluation of an Earth-System model – HadGEM2. *Geoscientific Model Development*, *4*, 1051–1075. https://doi.org/10.5194/gmd-4-1051-2011
15. Watanabe, M., Suzuki, T., O'ishi, R., Komuro, Y., Watanabe, S., Emori, S., . . . Kimoto, M. (2010). Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *Journal of Climate*, *23*(23), 6312–6335. https://doi.org/10.1175/2010JCLI3679.1
16. van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., . . . Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, *109*(1–2), 5–31. https://doi.org/10.1007/s10584-011-0148-z
17. Environmental Protection Agency. (2017). Air Quality Index (AQI) Basics. Retrieved January 1, 2017, from https://www.airnow.gov/index.cfm?action=aqibasics.aqi
18. Environmental Protection Agency. (2015). National ambient air quality standards for ozone, 80 Federal Register §. United States of America. Retrieved from https://www.gpo.gov/fdsys/pkg/FR- 2015-10-26/pdf/2015-26594.pdf