Relationship between tropospheric ozone with temperature variability and implications to food security

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Abstract

Summertime ozone (O_3) has been a crucial issue for public health as well as vegetation health concerns. Owing to the enhanced chemical transformation or O_3 precursor gases in the presence of sunlight, the key growing season and ozone production season coincide which can possibly lead to detrimental effects on food security. We analyze the nature of this relationship between growing degree days, O_3 concentrations and soybean yield to assess the impacts that O_3 has on crops. In higher latitude region of Dane county, Wisconsin, the relationship between maximum growing season O_3 and crop yields reveals a decreasing trend while more cumulative growing degree days from temperature increase is correlated with an increasing trend in soybean yields. This relationship does not hold true in lower latitudes (here, Bolivar County, Mississippi) which are more prone to heat stress or exceedance of a threshold temperature defined for a vegetation where the development is adversely affected. Additionally, to characterize the relationship of cumulative growing degree days (CGDD) and growing season O_3, we find that fine scale temporal analysis is necessary in delineating the impact of higher temperature on daily

O_3 production. Yearly CGDDs lack any conclusive effects at both high and low latitude regions. Using the accumulated O_3 threshold over 40 ppb (hereafter AOT40), we show that O_3 production has a statistically significant relationship with daily growing degrees accumulated.

Keywords

Ozone, growing degree days, crop yield, climate change, food security

1. Introduction

Increasing temperatures across the world pose a concern over the evolution of O_3 formation in the future. O_3 is a critical air pollutant not just from climate change and public health point of view but there is increasing evidence that it is posing danger to food security (Chuwah et al., 2015; Da et al., 2022). While the U.S. Clean Air Act of 1970 has bought historical O_3 levels down significantly, because of the complex atmospheric chemistry responsible for the production of this secondary air pollutant, it is still a matter of concern (Cooper et al., 2012). In an agroecosystem, the emission of natural hydrocarbon can also contribute to the production of O_3 (Trainer et al., 1987). This brings up additional concerns about characterizing the influx of O_3 into vegetation and its impact on crop yields.

Ozone (O_3) exposure has been linked to negative impacts on crop yields and hence, is a threat to global food security (Chuwah et al., 2015). These reductions in crop yields are estimated to be about 79-121 million metric tons for the year 2000 and increasing up to

$17-35 billion in 2030 (Avnery et al., 2011a, 2011b). These numbers are consequential specially for developing countries with higher population living below poverty lines. Threat to food security in these areas can lead to widespread disparity in the number of people who can be nourished (Ghude et al., 2014). Additionally, this problem will likely be parallel to the increased requirement for pest management due to rising temperatures (Diffenbaugh et al., 2008).

There is extensive evidence of the detrimental effect of O_3on crop yield from modeling studies looking decades into the future as well as chamber studies. Other studies in the scientific literature also include effects of rise in ambient temperature to the increase in O_3 concentrations. This resulted in a 3.2 ppbv rise in ambient O_3 with every °C of temperature increase (Bloomer et al., 2009). These studies however do not isolate the temperature-ozone relationship particularly in the growing season. The connection of growing degree days and O_3, both of which depend on the ambient temperature has yet to be explored. We attempt to quantify the nature of this relationship on a granular level by using ground monitored O_3 and county scale crop yields for each year.

The proper management of O_3 production in these areas show opportunity to improve yields independent of additional fertilizer application. Owing to the large potential and implications, this question is worth exploring on a local scale.

2. Data and Methodology

2.1 Data

The daily and hourly O_3 data was included from the Environmental Protection Agency (EPA)'s outdoor ground monitoring network through the Air Quality system (EPA AQS). This data was retrieved in two formats; daily maximum 8-hour ozone concentrations (hereafter referred to as MDA8 ozone) as well as hourly monitored ozone for 2021 for each county that was being studied. The crop yield data for soybean was included from the USDA's (U.S. Department of Agriculture) for all available years from 1980 - 2023 through the Quick Stats tool (NASS USDA, QuickStats query tool, 2014). This data was analyzed in its original format i.e yields are in bu/acre.

The daily weather data for maximum and minimum temperature was used from the National Oceanic and Atmospheric Administration - National Centers for Environmental Information (NOAA NCEI)'s Global Historical Climatology Network (GHCN version 3) database (Matthew et al., 2012). This database integrates weather data from several data sources and has data for variables like temperature, precipitation, snow depth etc from land-based stations across the globe. The weather station at each study site was chosen to represent the conditions of the county of interest. This data was analyzed in relation to the corresponding O_3 data available for the time frame between 1980-2023.

2.2 Methodology

The hourly O_3 data was employed to calculate the AOT40 metric for the year 2021(Da et al., 2022). AOT40 metric is used to assess the daily evolution of O_3 concentration throughout the daytime. The metric was calculated by using hourly values of O_3 in ppm and subtracting 40 ppb from all the hours. The time for this AOT40 analysis is consistent at 6:00 to 18:00 (in local time) for each day of the year. Exceeded O_3 values from the AOT40 defined threshold of 40 ppb were summed for each day of the year. This results in a daily time step dataset for O_3.

$$\text{AOT40 (ppm} \cdot \text{hour)} = \sum_h^n OZ_h, \text{ where } OZ_h = \left\{ \begin{array}{l} ozone_h - 0.04, \ ozone_h > 0.04 \\ 0, \ ozone_h \leq 0.04 \end{array} \right\}$$

Equation for AOT40 is taken from (Da et al., 2022). The daily extreme temperature data from GHCN was used to calculate the daily growing degree days metric (GDD) from (McMaster & Wilhelm, 1997)

$$GDD = [(T_{max} + T_{min})/2] - T_{base} \qquad (1)$$

Where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature and Tbase is the base temperature (set as 10°C). An upper temperature threshold for soybean development was considered to be 30°C (Hoffman et al., 2020). The growing season assessed in this study pertains to months ranging from April to September. All the correlation metrics are reported in Spearman correlation. Based on the scientific literature, we assess soybean yields as it has been found to be susceptible to changes in surface ozone. Yield reductions form some of the relevant studies have been summarized in **Table 1**.

Crop	Study Domain	Year	Yield Reduction	Citation
Soybean	Global	2000	8.5–14%	(Avnery et al.,
Maize			2.2–5.5%	2011a)
Wheat			3.9–15%	
Soybean	Global	2030[1]	15–19%	(Avnery et al.,
Maize			4.4–8.7%	2011b)
Wheat			5.4 to 26%	
Soybean	India	2005	0.8% - 4.6%	(Ghude et al.,
Maize		-	-	2014)
Wheat			3.8% - 6.2%	

Table 1 Summary of studies from the literature assessing percent yields reductions from ozone exposure

This analysis and result reporting is set up in two sections. For section one, two counties in the U.S. are analyzed. These counties represent a gradient in latitude and thereby, difference in climatic conditions as well as a measurable area planted with soybean crop. The study areas are Dane county in Wisconsin and Bolivar County in Mississippi as indicated in **Figure 1**. For section 2 of the analysis, Dane county is analyzed for finer temporal trends in ozone and growing degree days for 2021.

[1] Scenario IPCC SRES A2

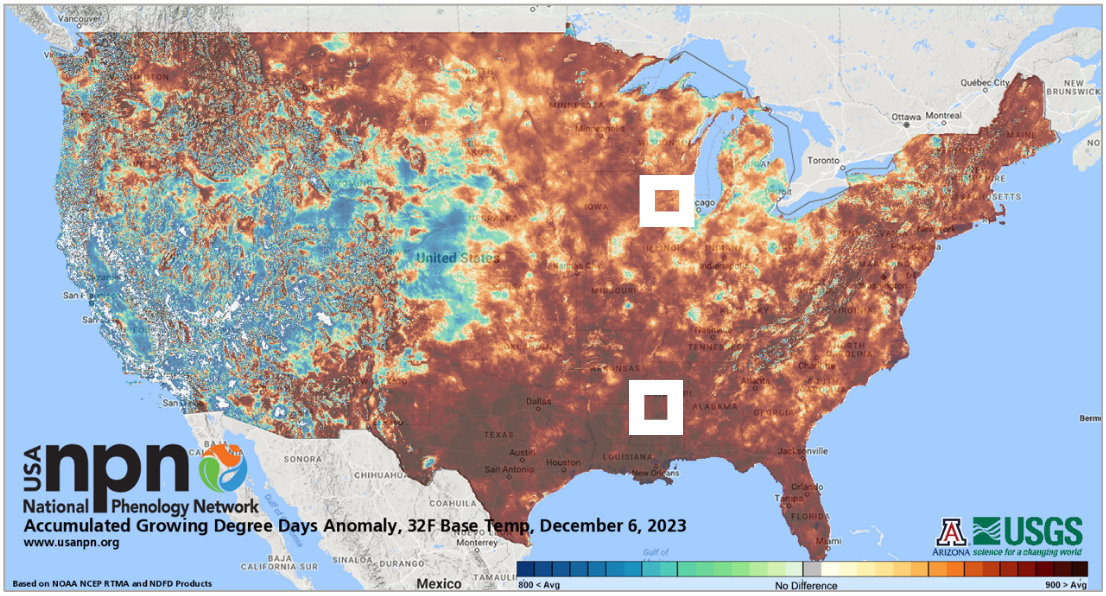

Figure 1 Accumulated growing degree days in 2023 [Map adapted from The National Phenology Network by United States Geological Survey]. The highlighted area in the northern part represents Dane County, WI and the area in southern portion represents Bolivar County, MS.

3. Results and Discussion

3.1 Relationship of growing degree days and ozone with changes in location

We assess the selected variables with correlation analysis. In the higher latitude case study of Dane County, Cumulative GDD and MDA8 O_3 exhibits a correlation of -0.1711, while the correlation of soybean yields per year from (1980-2022) with MDA8 ozone and CGDD is -0.598 and 0.570 respectively. Both correlations are statistically significant with p values <0.05. The CGDD trend with increasing ozone was interesting in Dane County as it is negatively correlated, hence, with increasing O_3, CGDD are decreasing. However, this relationship is not statistically significant as shown in **Figure 2 (a)**. The inconclusive results between CGDD and soybean yields, especially in lower latitude might be indicative of lowered yields caused by increased heat stress. Soybean yields are significantly affected at temperatures above 85° F or 30°C (Hoffman et al., 2020). Temperature mitigating effects from irrigation activities can also be responsible for inconclusive trends of growing degree days with yields.

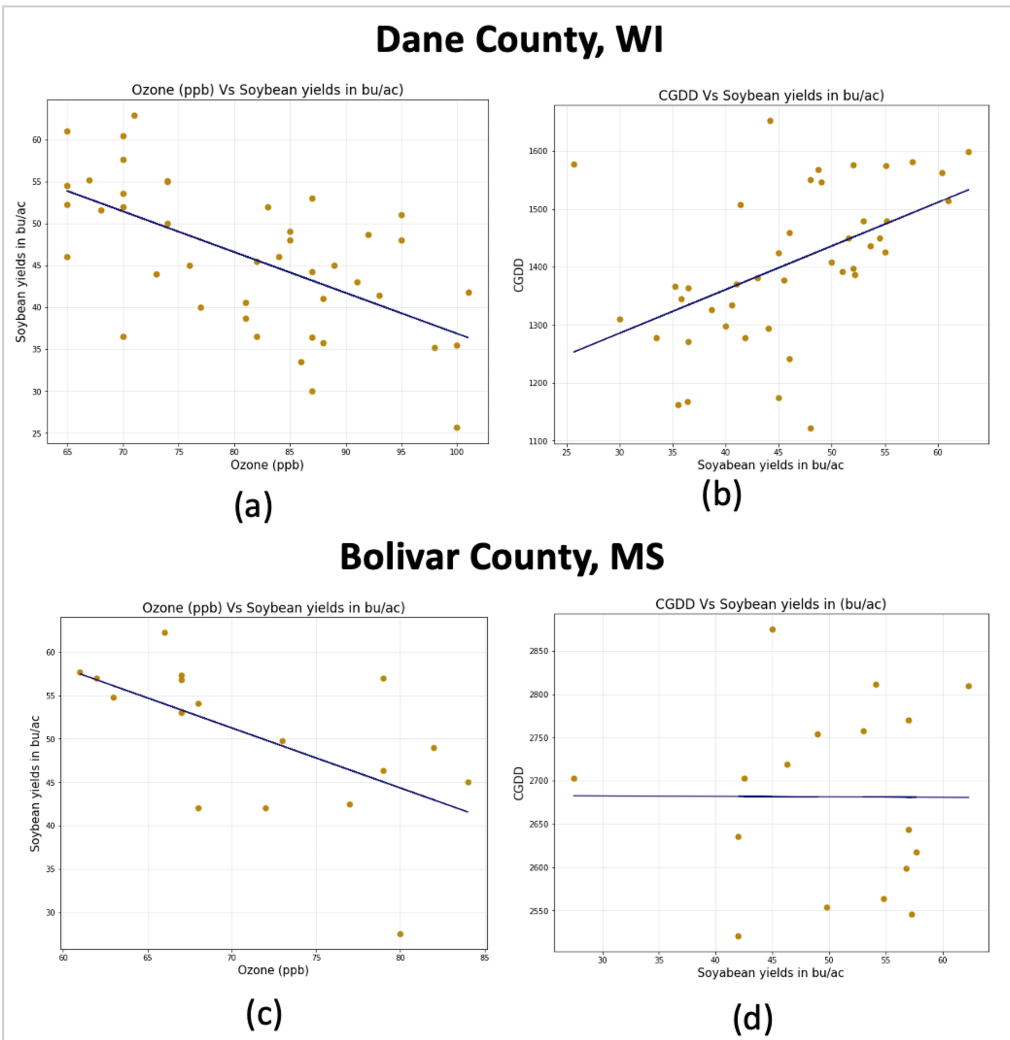

Figure 2 Correlation analysis for both study locations (separated by upper and lower panels) for O_3, CGDDs and Soybean yields (bu/ac)

In the lower latitude scenario of Bolivar County, Mississippi, Soybeans yields are well correlated with O_3.

3.2 Relationship between Ozone (O_3) and Cumulative Growing Degree Days (CGDD)

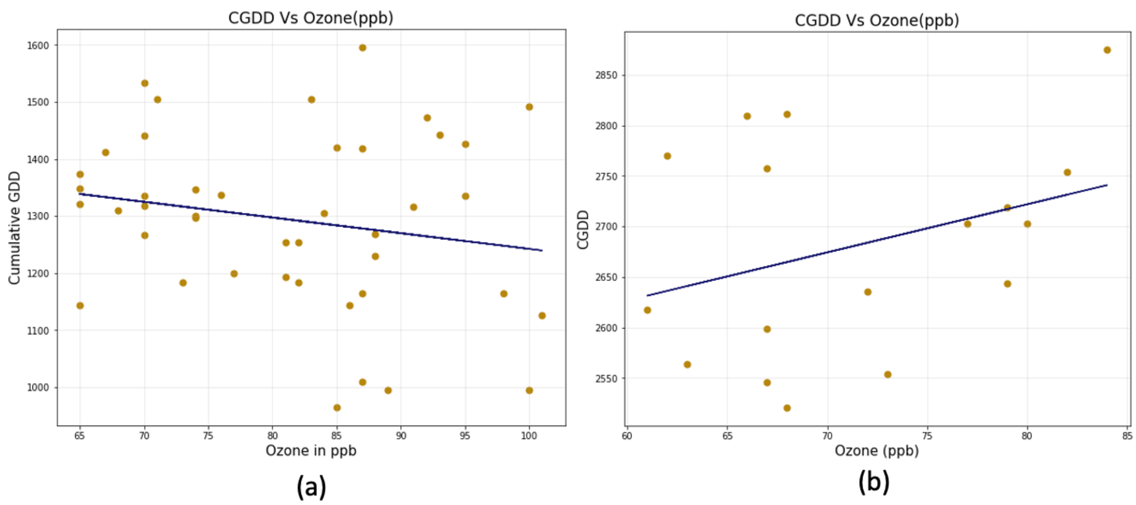

Figure 3 represents the relationship of Ozone with CGDDs for (a) Dane county, WI and (b) Bolivar County, MS

A direct relationship of heat accumulation with ambient ozone concentrations is yet to be explored. The relationship of O_3 with CGDD was also statistically significant with a weak correlation which is opposite to the Dane county case as demonstrated in **Figure 3 (b).** This relationship in Bolivar County shown in Figure 2 (b) along with the Figure 2(d) conclusions about CGDD and soybean yields can be attributed to increased irrigation. Irrigated fields have positive effect on yields in presence of ambient air O_3 as compared to rainfed fields (Liu & Desai, 2021). In places with lower precipitation, irrigation can compensate for the losses in crop yields due to this pollutant. In order to appropriately characterize the drivers of change in irrigated vs rainfed fields in the growing degree days context, on site meteorological data is a crucial requirement. A county scale meteorological measurement site might not be representative of what is happening on the field.

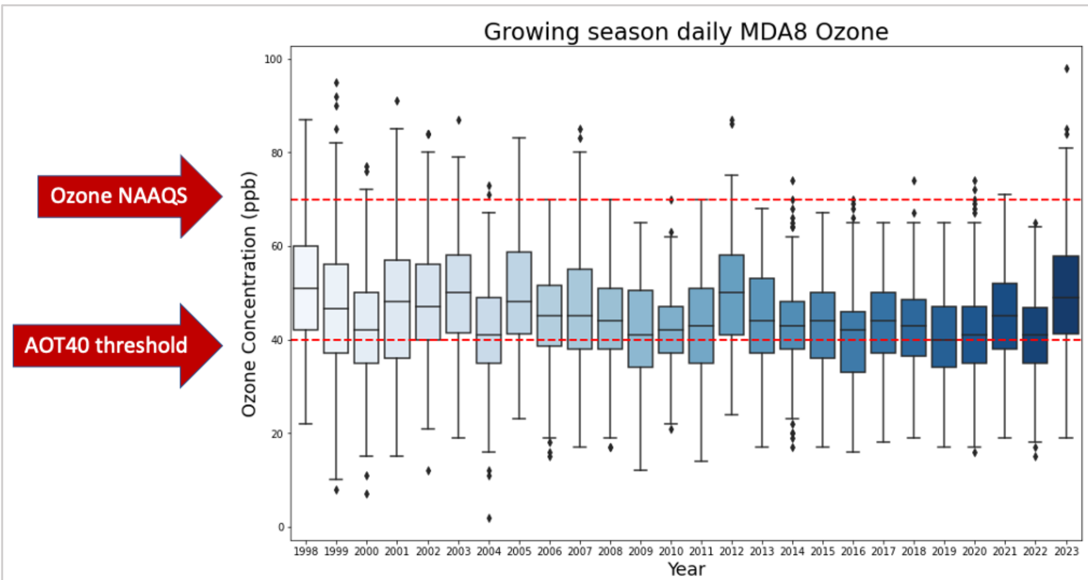

Figure 4 represents the distribution of daily growing season O_3 concentration for Dane county from 1998 - 2023

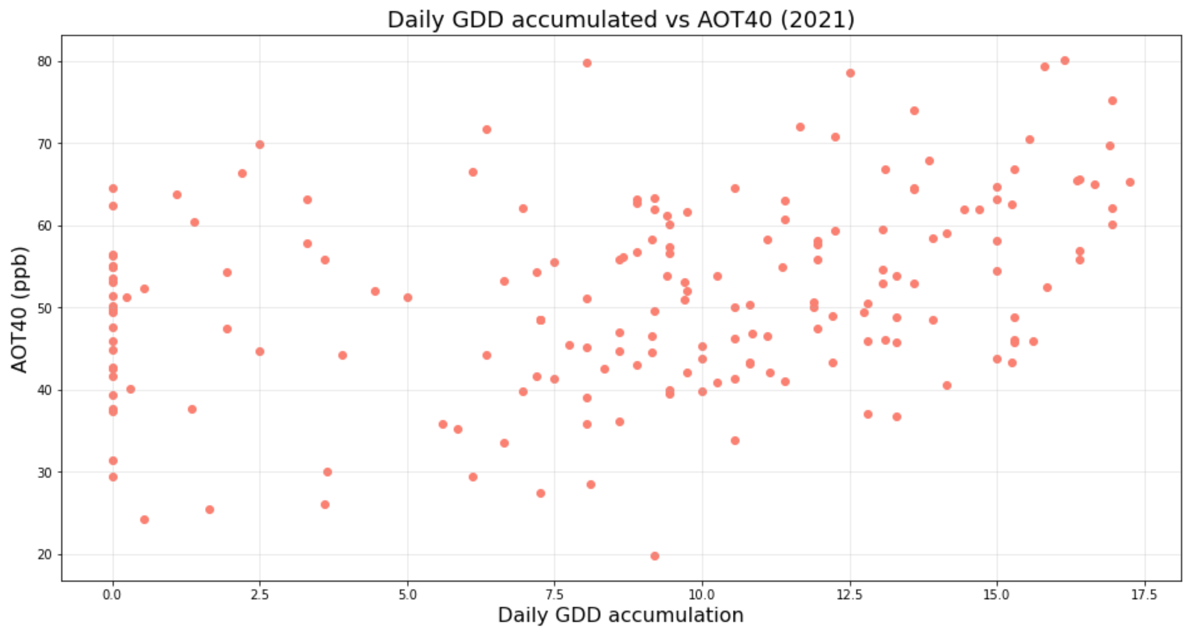

Figure 5 represents the relationship between AOT40 for Dane County and Daily growing degrees accumulated during the year 2021

To further explore the relationship of heat accumulation with ambient O_3 concentrations with higher temporal resolution, **Figure 5** shows AOT40 and daily accumulation GDD from equation (1). AOT40 as described included hourly O_3 concentrations exceeding the threshold of 40 ppb over the course of daytime, here assumed to be from 6:00 to 18:00. This relationship showed a positive trend with a correlation coefficient of 0.335 and p value <0.05. For higher latitude region that is represented in **Figure 5** daily accumulated O_3 concentrations increases as the growing degrees increase. As the findings from **Figure 2** indicate, yields exhibit a declining trend with O_3 concentrations. Additionally, with **figure 5**, the benefits seen with higher growing degrees might be offset by detrimental effects from O_3.

Discussion and Conclusion

Using regression analysis for ground-based O_3 monitored data, county level reported soybean yields and temperature data we estimated the impacts of high temperature and related enhancement in ozone production and its impact to crop yields. With a focus to represent the nature of these relationships in different climatic conditions we focus on two regions at different latitudes.

This analysis indicates difference in the growing season temperature extremes and accumulated O_3 in locations at different latitudes. This relationship provides a basis to further assess such relationships in key areas of concern such as those governed by increasing populations, socioeconomic disadvantages as well as geographical vulnerabilities.

The AOT 40 metric assess the accumulation of O_3 above the 40-ppb threshold. It was primarily developed in Europe as a metric of exposure assessment to sensitive vegetation. However, the existence of higher ozone levels is part of the problem. The assessment of effects of O_3 on plants can be done with flux-based approach that quantifies the actual uptake of O_3 by the plant. This methodology has confounding factors to it such as CO_2 concentration, water availability etc., that drive changes in stomatal conductance. The clean air act has brought positive changes in the ambient air concentrations of criteria pollutant in the U.S. However, the regulations require ozone to be modeled in limited to be under 70 ppb limit which is higher than the 40-ppb threshold

(Figure 4) that vegetation is sensitive to. With improvements of our understand on rural ozone concentrations and utilization of sustainable practices to curb those emissions, the co-benefits to public health, climate system, and food security can be significantly higher.

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