WOE Chapter 1

The Relationship between Urban Tree Cover and Ground Level Ozone

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Abstract

Tree cover in urban areas plays an important role in the complex system of ground level ozone production. Numerical modeling studies predict a decrease in surface temperatures (on the order of 1-2 deg C) will occur when more (estimates range from 10-40 % over urban area) trees are planted in an urban environment. Corresponding changes in wind speed will occur in modified areas as well. These changes are the result of the lessening of the urban “heat island” effect. Heat islands form as cities replace natural land cover with pavement, buildings, and other infrastructure. The heat in a heat island is the result of the different radiative properties (i.e. the ability of objects to absorb and/or reflect the sun’s energy) between urban and rural areas. Urban areas are more efficient at absorbing sunlight than rural areas. The excess energy absorbed by urban areas is eventually reradiated back to the atmosphere in the form of heat (aka infrared radiation). Weakening of the heat island effect results in a transfer of energy from the urban areas to downwind areas which causes some locations to observe a slight increase in surface temperatures (1-2 °C) and in wind speeds (1-2 ms^{-1}). The modeled temperature changes are accompanied by changes in ground level ozone concentrations. Owing to the complexity of the system, changes in ozone, like temperature, are not confined to locations where trees are planted. Different locations downwind of modified areas observed either increased or decreased ozone levels depending on a variety of factors. The reduction of surface temperature (specifically, cooling in urban areas) obtained from the numerical modeling studies was used as the basis for predicting changes in daily mean peak 8-hour ozone levels derived from a multiple linear regression model for the Baltimore Non-Attainment Area. Results from both methods of study (numerical and multiple linear regression) suggest that decreases in ground level ozone concentrations on the order of 1-3 ppbv could be realized with an increase in urban tree cover ranging from 20 - 40 %. Averaged over the entire modeling domain of the North Eastern and Mid-Atlantic U.S., this change would amount to ~1-2 % increase in tree cover. It is believed that the genera of tree used to reforest is important but what species of tree offers the most benefit is not clear and may differ from locale to locale. Other significant, logistical questions also need to be considered when planning a large-scale tree planting program. The general consensus from the studies mentioned above suggests that increased tree cover has a beneficial effect on local air quality by reducing ozone in and around urban areas. The major decreases in ozone occur near urban areas where the 8-hour ozone NAAQS is not met, while the minor increases in ozone occur in upwind areas where the NAAQS is met. Thus, the net impact is favorable for reaching the standards across entire

Baltimore Non-Attainment Areas. It should be noted that any plan involving tree planting to improve air quality should be viewed as a long term plan (e.g. 10-20 years) given the growth rate of many of the trees considered.

Introduction

The Roman poet Caecilius Statius more than 2000 years ago wrote “we plant trees not for ourselves, but for future generations.” The words are as true today as they were then. The role that trees play in the air quality of an urban environment for several years has been a subject of keen interest to air quality planners both from a policy and scientific perspective. The interest has been motivated by the principle desire to improve air quality. Trees have an important function in the urban environment which are easily observed: Trees provide shade, create habitats for flora and fauna, limit soil erosion and are often esthetically appealing. However, trees may also have a subtle, more complex connection to air quality that is challenging for scientists to observe and understand. For instance, through a series of complex relationships, trees have a connection to ground level ozone and PM2.5. The degree to which trees add to pollutant levels is dependent on the amount and type of biogenic volatile organic compounds (BVOC) emitted by the trees (Lee et. al., 2006, Geron, et. al., 2001, Moukhtar et. al., 2005). Trees may affect air quality by changing meteorological parameters such as surface temperatures, boundary layer winds, and vertical mixing heights. These changes occur because energy transfer between the Earth’s surface and the atmosphere is altered though factors such as surface roughness, albedo and soil moisture (1988, Taha et. al., 1996, Rossa et al., 2005). Trees can also impact air quality indirectly through changes to dry deposition rates (Chameides et. al.). Dry deposition is a removal process for atmospheric species that denotes direct transfer of species to the Earth’s surface. Wet deposition is a similar process but involves precipitation. Understanding the connection between trees and air quality in an urban area, as well as considering some of the challenges associated with a large-scale tree-planting program are important issues that need to be addressed prior to any planning and implementation of such a plan.

Background

Several studies have been undertaken both nationally and internationally to study how trees influence air quality. Perhaps the most relevant investigation was a recent joint research effort undertaken by the New York Department of Environmental Conservation, the USDA and the Davey Resource Group (Bond, 2006). The work addressed important considerations of large-scale tree planting for a state implementation plan. The overall goal of Bond’s work was to examine the feasibility of a large scale tree planting program. Others studies have focused on particular aspects of the problem of wide scale tree planting in urban areas such as:

What genera of trees emit the most BVOC’s?

What is the effect on meteorology from large scale tree planting?

What is the diurnal and seasonal variation of BVOC’s emissions from trees?

(Nowak et. al, 2000, Civerolo et. al., 2000, et. al, Geron, 2001, Donovan, 2005). The tools used to answer these questions were state-of-the-art meteorological (i.e., MM5, WRF) and photochemical (i.e., CMAQ and CAMx) 3-dimensional gridded air-shed models. The changes associated with large scale tree planting were assayed by performing meteorological and photochemical simulations using existing land use inventories and comparing those results to model runs with increased tree cover in urban areas. The simulations were typically performed on historical time periods (i.e. the ozone seasons of 1988, 1995, and 2003) when high ozone occurred (Cardelino and Chamedies, 1990, Civerolo et al, 2000, Taha, 2005).

Results from a study of a high ozone period in Atlanta, GA. on June 4th, 1984 suggested that a reduction in tree cover by 20% would increase maximum peak 1-hour ozone concentrations by ~14% (Cardelino and Chamedies, 1990). Increase in temperature was the principle cause of the increased ozone. Investigations of other cities such as New York City and Los Angeles conclude that in order to achieve a reduction in peak 8-hour ozone on the order of 2-3 ppbv, eight-to-ten million trees would need to be planted in the large urban areas (Luley and Bond 2002, Taha, 2005). More recent work investigated the diurnal and seasonal variation of isoprene concentrations and its effect on peak 1-hour ozone levels in Taiwan (Lee and Wang, 2006). It was determined that the timing of isoprene flux from trees, which is different from season to season, is important in shaping daily ozone profiles and may in some cases be more significant than the reactivity of isoprene. Another study of air quality in Taiwan used remote sensing and numerical modeling to assess the impact of biogenic emissions on ground level ozone concentrations (Jeng and Chang, 2004). The conclusion was that the majority of biogenic emissions occurred in farmland and mountain areas downwind from the major urban areas in South Taiwan. Therefore, compared to anthropogenic emissions biogenic emissions have a lower impact on air quality than anthropogenic sources. The work by Jeng and Chang highlights the important point that regions with different geographic patterns (i.e. land use and topography) will not have the same relative contributions from biogenic and anthropogenic emissions and therefore will likely require different tree planting strategies. Recent simulations of a high ozone period in Birmingham, England produced results of reductions in urban ozone comparable to the work by Luley, Bond, and Taha when 10% of the available planting space was filled with low-VOC emitting trees (Donovan et. al, 2005). The Donovan study stressed the importance of planting trees that are low-VOC emitters. In that work trees were ranked based on observations and simulations for their potential to impact air quality. The least favorable trees were the genera poplar, willow and oak while the most beneficial were maples, hawthorns and pines. It should be noted that there is some disagreement within the scientific community regarding what genera of trees are most suitable for planting. For instance, the Donovan study ranked oak trees as some of the worst trees to select for planting because of their comparably high levels of isoprene emission. The Davey group on the other hand, favored the inclusion of oak trees, sighting the high variation in isoprene emissions among oak tree species as well as other considerations such as the drought tolerant nature of oaks and the endemic nature of oaks in many parts of the country. The divergence between the two investigations underscores the complexity and evolving nature of this research. Efforts to better understand this system continue with both the Donovan and Davey groups.

One of the most important ways that trees can alter air quality is believed to be surface modifications, which lessen the “heat island” effect, which in turn reduces surface temperatures. Other secondary effects include changes in wind fields and planetary boundary layer heights. The modeling study by Nowak et. al (2000) demonstrated that increased tree cover lowered surface temperatures in areas where tree cover was increased and in some cases also in locations downwind. The sensitivity of MM5 to changes in tree cover was determined by comparing simulations using an existing land use data base and simulations using a ~ 40% increased tree cover of deciduous trees in grid cells containing the urban areas of New York, NY., Philadelphia, PA., and Baltimore, MD. In extreme cases modeled temperature differences were as much as 6 °C with more typical differences on the order of ~1-2 °C (Nowak et. al, 2000, Civerolo et. al., 2000). Considering the complex nature of ground-level ozone production, it is perhaps not surprising that the work by Nowak et. al (2000) presented results that showed a slight increase in ozone over the entire model domain including the northeastern US urban corridor and extending from northern Virginia to Massachusetts. A 0.26 ppbv increase over the entire domain was less than the average 1 ppbv decrease in ozone observed over urban areas. The peak decrease over urban areas was 2.4 ppbv. Part of the net increase was the result of higher nighttime ozone levels (~ 1 ppbv), caused by weaker wind speeds and the increased loss of NOx (a scavenging agent of ozone) through higher NOx deposition rates. The general consensus from the studies mentioned above suggests that increased tree cover has a beneficial effect on local air quality by reducing ozone in and around urban areas. The major decreases in ozone occur near urban areas where the 8-hour ozone NAAQS is not met, while the minor increases in ozone occur in upwind areas where the NAAQS is met. The net impact is favorable in terms of entire regions meeting the NAAQS.

It is worth noting that there are other questions relevant to the planning aspects of large-scale tree planting which are more logistical in nature but nonetheless are an important consideration. Some of these issues include:

- Where will all of the trees come from?
- How long will it take to grow a stand of trees?
- What work force will be used to plant the trees?
- How will the work force to plant the trees be trained?
- Is there a plan to deal with problems such as disease or extreme drought that could lead to failure of the tree planting program?
- How much of the existing tree population will be lost to land development?

Methodology and Results

Another method to assay potential improvements in ozone from increased tree planting is to review historical correlations between ozone and temperature. Multiple linear regression models have been used for several decades to forecast daily maximum ozone (Wolff and Lioy, 1978; Ryan, et al. 2000). In order to to develop a new statistical correlation between ozone and temperature, an estimate of changes in peak 8-hour ozone levels can be made by applying adjusted temperature data which reflect cooler temperatures resulting from increased tree cover. While temperature is the strongest predictor of ozone it is not the only parameter important to ozone formation. Wind speed and cloud cover boundary layer heights are among a number of other important factors. However for this study only temperature adjustments are considered. All other parameters used in the linear regression model (i.e. minimum temperature, wind speed, relative humidity) are held constant. The next portion of this section attempts to correlate, using statistical techniques, changes in ozone over a region associated with temperature changes that might be expected from a large-scale tree planting program. Figure 1, a plot of daily peak 8-hour ozone for the Baltimore Non Attainment Area versus maximum temperatures for Baltimore Washington International Airport, illustrates the general correlation between temperature and ozone. In light of the modeling work discussed above, an analysis was performed by the University of Maryland using a multiple linear regression model to calculate peak 8-hour ozone levels. Adjusted temperature data used in the model was derived by Nowak et al (2000). Using ozone and meteorological data from the Baltimore Non-Attainment area covering the time period 1994-2005, a multiple linear regression model was developed to predict daily mean peak 8-hour ozone values for the Baltimore Non-Attainment Area. The model was created with the aid of the analytical software program SPSS®. Using a forward, stepwise regression technique the correlation coefficients in Equation 1 in Appendix A for the meteorological variables were determined. From this regression model a sensitivity of ozone to reductions in temperature was calculated (see Equation 1 in Appendix A). It was determined that a decrease in maximum temperature of 1 °F corresponded to ~ 2 ppbv reduction in the mean peak ozone levels (see Table 1 and Figure 2). When considering a subset of high ozone days when the daily 8-hour peak ozone ≥ 85 ppbv, the slope increased so that a cooling of 1 °F resulted in a ~ 3ppbv decrease in the daily peak 8-hour ozone levels (Table 1). The change in slope, which is a result of the inherent non-linearity of ozone-meteorology relationship, implies that at higher temperatures ozone production is more sensitive to changes than at lower temperature. Some of the causes of the nonlinearity are rates of chemical reactions, precursor emissions and planetary boundary layer processes. Explain the difference – why is the change of 1°F have a greater impact on the subset? The work by Nowak et. al, (2000) estimated a temperature decrease of 1-2 °C (2-4 °F) as a direct result of a 40% increase in tree cover. From Figure 2 this implies a change in the mean peak 8-hour ozone of from 4 - 8 ppbv. Given that only temperature was considered here, it is reasonable to assume that the range of 4-8 ppbv is perhaps the upper limit as many of the other meteorological predictors (e.g. minimum temperature) are negatively correlated with ozone. Civerolo et. al (2000), reported a slight lowering of both minimum temperatures and maximum temperatures from increased tree cover. Thus, it is reasonable to conclude that a change in maximum temperature will be associated with other subtle changes in weather that may slightly offset maximum temperature changes. For instance, inspection of Equation 1 in Appendix A suggests that the slight lowering of minimum temperatures would counter some of the benefit of cooler maximum temperatures. Considering all of the ancillary weather changes associated with an increase in tree cover, perhaps a more conservative estimate of changes in daily peak 8-hour ozone as reflected by a multiple linear regression model would be closer to 2-4 ppbv.

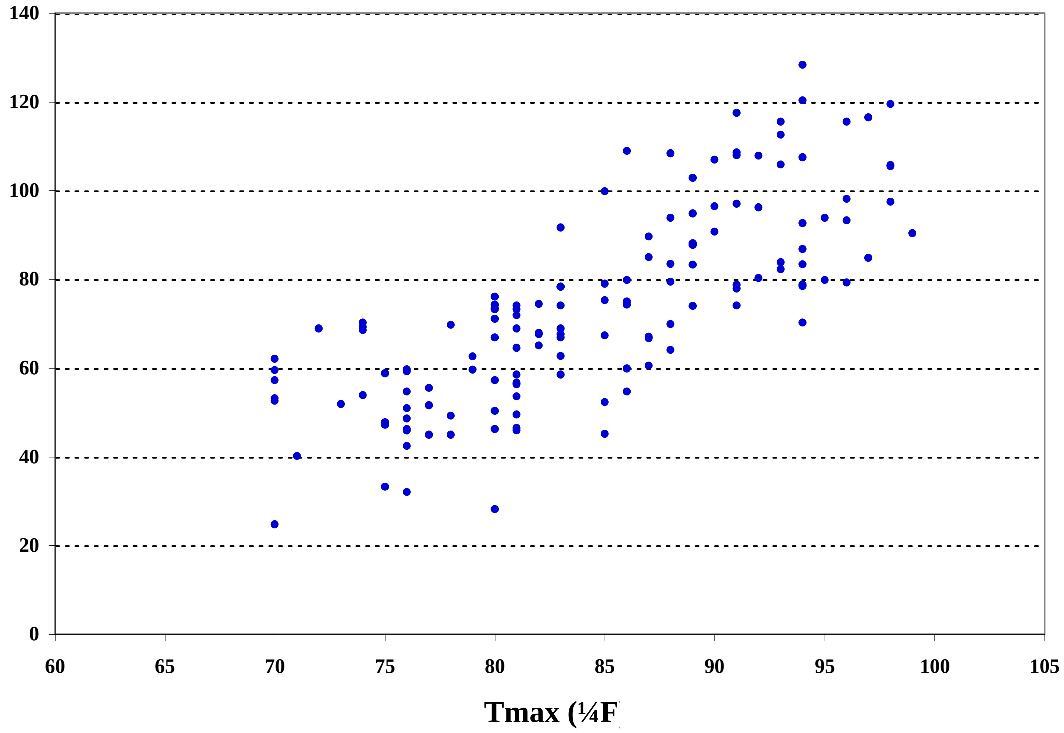

Figure 1. A scatter plot of the daily 8-hour peak ozone over the Baltimore Non Attainment Area versus the daily maximum temperature at BWI Airport for the year 2002 (May-September, N = 138, Tmax ≥ 70 °F).

Table 1. Observed and predicted ozone in parts per billion (ppbv) for the summer of 2002 over the Baltimore Non-Attainment Area.

	Observed	Tmax$_0$	Tmax$_{0\text{-}0.5}$	Tmax$_{0\text{-}1.0}$	Tmax$_{0\text{-}1.5}$	Tmax$_{0\text{-}2.0}$
Average Maximum 8-hour Ozone for153 cases (ppbv)	71	69	68	67	66	65
Average Peak 8-hour Ozone for subset of 39 High Ozone cases (≥ 85 ppbv)	101	92	90	89	88	87

These results come from the regression analysis for adjusted maximum temperature values for the summer of 2002 (May-September). The subset of high ozone cases shown in row two are defined as 8-hour maximum ozone ≥ 85 ppbv.

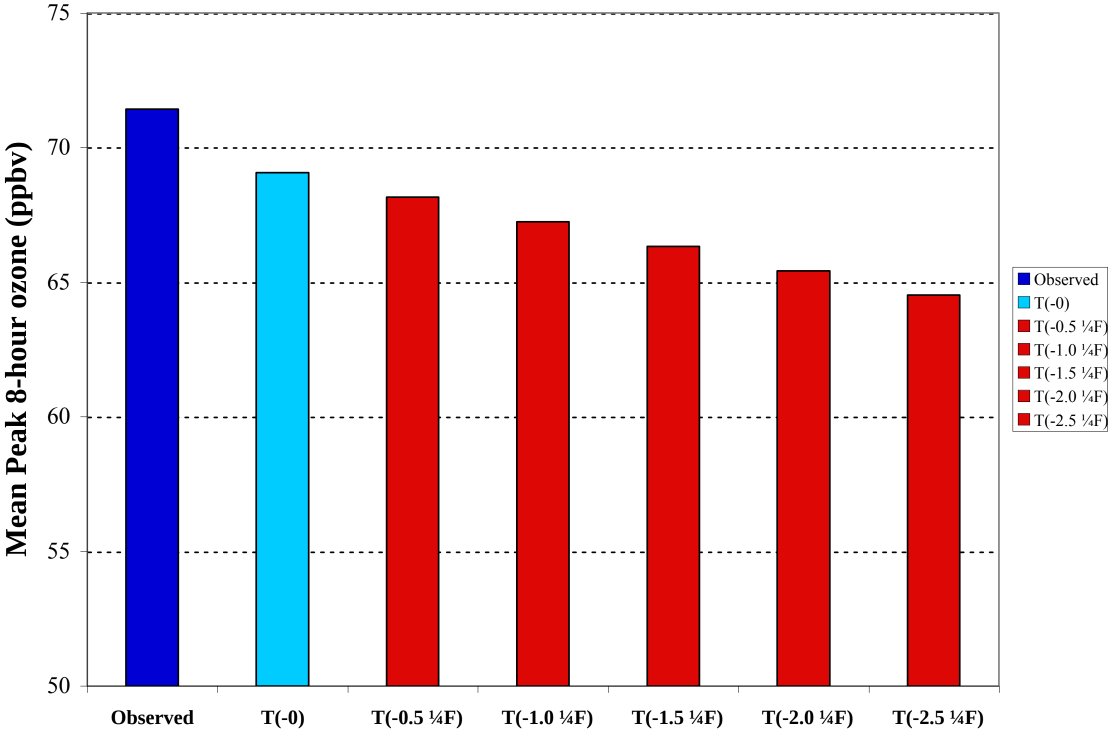

Figure 2. Observed and predicted mean daily maximum 8-hour Ozone over the Baltimore Non-Attainment Area. Predicted data was determined from a regression analysis using meteorological and ozone data from 1994-2005. The maximum temperature was reduced by 0.5 ºF increments and mean daily maximum 8-hour ozone was recalculated using the adjusted temperature data.

Conclusions

This analysis presents results of studies performed by the University of Maryland and other research institutions which support the theory that increased tree cover in urban areas results in a decrease in peak ground level ozone concentrations. A review of current literature suggests that the changes in meteorology (i.e. surface temperatures, and boundary layer winds), dry deposition rates and BVOC levels that are associated with an increased tree cover over urban areas, could lead to a decrease of 1-2 ppbv in daily mean peak 8-hour ozone. Land use modifications to 10-40 % of the urban area land surface, or to 1-2 % of the model domain (e.g. the Baltimore Non-Attainment Area) are needed to create the change in peak 8-hour ozone concentrations. The change in ozone (and meteorological parameters) is typically observed in and downwind of the urban areas. Some studies determined that over the entire modeling domain there is a net increase in ozone when more trees are planted. However, this increase is smaller in magnitude than improvements observed in urban areas. The small increases in ozone over non-urban areas (where daily peak 8-hour ozone levels rarely occur) is perhaps less significant in terms of air quality planning than reductions observed in and just downwind of an urban area. It is the latter locations that historically have the poorest air quality and thus stand to benefit the most.

Using historical ozone and meteorological data from the Baltimore Non-Attainment Area and BWI airport, a statistical correlation determined the sensitivity of ozone to changes in temperature for the Baltimore Non-Attainment Area. From the results of the work by Civerolo et. al (2000), and Nowak et al (2000), an estimate of modeled temperature changes that would result from large scale tree planting was obtained. Derived temperature changes from the photochemical modeling exercises were used as a starting point for what might be a reasonable temperature change associated with tree planting. These modeled temperature changes were then applied to the statistical relationship between ozone and maximum temperature. The relationship was derived from peak 8-hour ozone data for the BNAA and the maximum temperature values from BWI. The correlation was used to form the estimate that a cooling of 1-2 deg F would lead to a 2-4 ppbv decrease in peak 8-hour ozone levels. By combining the modeled temperatures changes with the statistical correlation between ozone and temperature, it was estimated that a cooling of 1-2 deg F would lead to a 2-4 ppbv decrease in peak 8-hour ozone levels , hereby demonstrating evidence that trees reduce ozone indirectly. The numerical models cited in the report focused on the benefits to ozone levels from an increased tree canopy. While ozone is ultimately a significant source of haze in the summer, and some ozone precursors also contribute to summertime PM2.5 formation, it is unclear what effect large scale tree planting in urban areas will have on urban PM2.5 levels.

Future Work

Future work should focus in part on improving existing land use databases; specifically, the inclusion of up to date land use inventories. This is important because land use is constantly changing so that any predicted change to tree cover distribution must consider land use changes which have occurred since the last collection of land use information. Efforts to improve estimates of changes in air quality from large scale tree planting should also focus on improving meteorological modeling to take advantage of better land use estimates. Refined emissions inventories which better describe BVOC emissions from particular tree genera, would provide policy makers with additional information to determine which species of tree are most suitable for planting. Future work at the University of Maryland involves a plan to run NCAR's Coupled WRF/Noah/Urban-Canopy Model in a *nested-grid* (27/9/3/1 km) mode. A nested grid has successively smaller domains (with successively better grid resolutions) nested together. One major advantage of a nested grid model is that the finer-scale models employ data from the larger domains as input (e.g. boundary conditions) which, in theory, creates a more stable modeling environment. This version of the Coupled WRF/Noah/Urban-Canopy Model will be run for the Washington-Baltimore metropolitan region for a period of one week (at the finest grid size of 1km) when ozone concentrations were elevated..

After verifying the model-simulated surface meteorology against observations, three urban tree scenarios will be examined over the region to assay the sensitivity of the model-simulated surface conditions to varying tree canopies: unchanged base tree population, increased tree canopy of 10%, and increased tree canopy of 30%.

Appendix A: A Regression equation used to determine sensitivity of ozone to changes in temperature.

The variables listed below were used to create the multiple linear regression equation used to test the sensitivity of ozone to temperature changes. From the input variables listed below, Equation 1 was created using the analytical software program SPSS®. DEFINE SPSS. SPSS® is a modular, integrated, software program used for analytical process such as data management and preparation, data analysis, reporting, and deployment. The program used a forward, stepwise regression algorithm to select the input variables (from a larger set of meteorological input variables) below. The meteorological data was obtained from the National Climate Data Center (NCDC). The response of ozone to the adjusted temperatures was determined by feeding the new temperatures into Equation 1, along with the other meteorological variables (which were unchanged) for each case in 2002. From those values the average responses for the temperature ranges was obtained.

Input Variables:
Tmax = Maximum Temperature (°F)
Tmin = Minimum Temperature (°F)
$RH_{19\text{-}21UTC}$ = Average Relative Humidity between 19-21 UTC (%)
WS_{18UTC} = Wind Speed at 18 UTC (ms^{-1})
$WS850_{12UTC}$ = 12 UTC Wind Speed at 850 MB (ms^{-1})
SZA = Solar Zenith Angle
LAG_{8hr} = The previous day's peak 8-hour ozone (ppbv)

Output:
$[O3]_{8hr}$ = Daily maximum 8-hour ozone

Equation 1:

$$[O_3]_{8hr} = \begin{pmatrix} 2.774 + 0.113 * T_{\max} - 0.062 * T_{\min} - 0.003 * RH_{19-21UTC} - 0.015 * WS_{18UTC} - \\ 0.026 * WS850_{12UTC} - 030 * SZA + 0.019 * LAG_{8hr} \end{pmatrix}^2$$

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