# Analysis of Mesoscale and Synoptic Scale Meteorological Influences on Ozone

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# **Executive Summary**

This is a comprehensive study of how meteorological variables, particularly the Synoptic and Mesoscale conditions, influence the Ozone Concentrations in the Paso del Norte (PdN) Region.

The central purpose of this work is to create a better understanding of the role that mesoscale and synoptic-scale weather phenomena play in local El Paso del Norte (Ciudad Juárez, El Paso, Doña Ana County, NM) air quality, including a thorough characterization of mesoscale and synoptic-scale winds during the ozone season and high ozone days; identification of critical relationships between synoptic and mesoscale winds and local meteorology; also the differences between high ozone days dominated by local effects and those dominated by regional transport of background ozone.

We begin by reviewing the general meteorological conditions that affect ozone production; we then concentrate our analysis specifically to the PdN region, analyzing all physical and meteorological variables that impact ozone production. Subsequently, we perform statistical analysis on TCEQ monitoring stations, and using regression models. Further, we perform meteorological simulations using models, e., g., WRF, to aid our analysis. Stratospheric Intrusions are analyzed, and also the impact of the residual ozone layer.

Finally, we perform a modeling study of surface ozone source-receptor relationships for the PDN Region using the CAMx and OSAT techniques.

The significant findings are:

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• Meteorological Factors Associated with High Ozone Days:

The large majority of high ozone days occurred when El Paso was located within an anticyclonic circulation aloft associated with a middle and upper tropospheric high-pressure area centered within 500 miles of the city. Usually the high-pressure center was located to the west or north of El Paso. This suggests large scale subsidence or sinking motion was frequently present over the area, which tends to trap pollutants.

In the lower troposphere, including the surface, the pressure gradient was weak, and thus winds were generally light at less than 10 mph. Temperatures were usually near or above normal to El Paso and most often above 90 F, consistent with most high ozone events occurring during June, July, and August, which are the warmest months of the year.

The soundings revealed an air mass that, at best, was weakly unstable with a convective available potential energy usually less than 500 J/kg. The air mass was usually dry below 700 mb with the 700 mb to surface layer relative humidity most often less than 40 percent. The rain was reported at El Paso Airport on 11 of the 34 event days, which may be associated with the monsoon season. In most cases, the rainfall was light, with precipitation amounts below 0.05 inches per day.

In one case study, four consecutive high ozone episodes from June 4-7, 2017 were analyzed. The aerosol layer height, which is also the proxy of the Planetary Boundary Layer (PBL), was lower in height when compared to some of the low ozone days when the PBL was very high. Analysis of the CAPE values for all the high ozone days under study indicated higher atmospheric stability, with an exception on only one day. Under such a stable environment, the vertical mixing of the aerosols is restricted, and leads to the accumulation of the pollutants. Weak winds blowing within the limited volume of atmosphere available within the boundary

layer result in poor ventilation conditions, causing accumulation of precursors in the region, leading to high ozone episodes.

 Analysis of wind roses during the high ozone events indicated calm winds from the southeast and east of downtown El Paso. This part of the city is at a lower elevation compared to its surrounding region.

Valleys are subject to diurnal variations in winds such as upslope (transporting pollutants out of the valley to the region) during the morning hours and downslope (transporting pollutants from the region into the valley). Synoptic conditions that produce clearer skies with higher daytime temperatures and lower nighttime temperatures may increase these effects.

- The air monitoring stations closest to CAMS 12, which are located in the state of New Mexico, did not record the high ozone days recorded by CAMS 12. This led us to suspect that the New Mexico CAMS Stations, which are closer to a port of entry and a Highway, are exhibiting ozone titration because of higher NO values.
- A leading cause of ozone formation in the El Paso region is its production by photochemical reactions. Emissions of NOx and VOCs are precursors that react by photochemistry caused by solar radiation to produce ozone. The daily pattern in the regional ozone concentrations usually displays a well-defined diurnal pattern.
- Furthermore, synoptic conditions producing stagnant high-pressure systems lead to cloud free, clear skies due to adiabatic warming aloft. These clear skies during the daytime produce high temperatures and intense solar radiation at the surface that are conducive to the photochemical production of ozone. These conditions occur over the PdN during the summer season so that it experiences high temperatures at that time. Photochemical production in El Paso/Juarez is exacerbated by cross-border transportation of ozone precursors which increase when temperatures increase due to evaporative emissions of gasoline and other volatile organic compounds.

- The statistical studies showed that temperature and solar radiation are the most positively correlated with the high ozone events. However, PM<sub>2.5</sub>, relative humidity, wind speed etc. have a negative correlation (ranging from 0.1 to 0.6). Relative humidity has the strongest negative correlation with ozone, which illustrates that the value of humidity will be relatively low during high ozone days with higher temperatures compared with the low ozone days. There are numerous factors that affect PM2.5 concentrations including direct emission, photochemical formation of PM2.5 precursors and the condensation of the precursors to produce PM2.5. Although the same meteorological conditions that are conducive to ozone formation between these meteorological conditions and the lower temperatures needed to form PM2.5 particles through the condensation of their precursors. Note that the El Paso/Juarez ozone season is during summer, while its aerosol season is during late fall and early winter.
- The presence of a high-pressure ridge at synoptic scales and at the 500 mb level was frequently observed throughout all high ozone episodes studied and concurrently calm winds or stagnant air were observed at the surface.
- Another source of ozone in the PdN is the Stratosphere. Isolated cases of stratospheric intrusion of ozone may have contributed to NAAQS exceedances of the 70 ppb ozone on a small number of days.
- The correlations of elevated ozone, carbon monoxide and weekdays suggest that local emission sources are also important. Within linear regression of MDA8 on afternoon CO and day type at CAMS 12, on weekdays afternoon CO was significant at p<0.0001, but was not significant on weekends, and was not significant at CAMS 37 and 41. Analysis of a 2-day back trajectories suggests that on a meso-scale, West Texas's oil and gas regions are likely contributors to El Paso and Dona Ana county ozone, which may be one of the most significant results of this analysis. This

was confirmed both using a residence time graphic of air parcel endpoints density on 57 MDA8 exceedance days qualitatively compared to a similar graphic of 57 random non-exceedance days, in which a higher percentage of endpoints lay in West Texas on exceedance days and using a potential source contribution function on a larger scale for 177 days with MDA8 at 65 ppb and above, which showed higher contributions from oil & gas regions around the American Southwest including Texas.

We also conducted a comprehensive ozone study applying OSAT technology in a Eulerian photochemical dispersion model, CAMx, over the region of El Paso, TX/Ciudad Juárez, Mexico. The model reasonably reproduced diurnal variation for ground ozone concentration. The modeling results showed that initial condition and local emissions play a significant role in the formation of ozone concentration, but boundary conditions did not make evident contributions. States from Mexico, especially states with a border with El Paso, TX, made contributions to ozone formation. But their contributions are less than 5% for the cases studied. This is probably due to the correlation of high ozone days with synoptic conditions than produce stagnant high-pressure systems. Stagnant high-pressure systems are associated with low wind speeds so the transport of ozone and its precursors from Mexican states to the pollution budget would be expected on more windy days. However, more case studies are needed to obtain a general conclusion about their contributions.

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# 1. Statement of the Problem

#### 1.1 Introduction

Systematic weather analysis and forecasting demand an in-depth understanding of various processes and phenomena are acting on various spatial and temporal scales. Weather observations taken synoptically at several weather stations worldwide can be drawn on a weather map where the information can be interpreted. Surface weather maps help in summarizing weather conditions and patterns that affect our daily life. We receive vital information, such as the precipitation, the snow, cyclones, hot and humid, or windy and dry places from these charts. In addition, they provide us raw weather reports, surface weather charts also help us analyze critical features such as air masses, the center of low and high pressure, and frontal passages [R. Stull].

Global weather observation standards are set by one branch of the United Nations, known as the World Meteorological Organization (WMO). The American Meteorological Society (AMS) is the premier scientific and professional organization promoting and broadcasting information about the atmospheric, oceanic, and hydrologic sciences in the US. A procedure known as Scale Analysis is used to determine the primary scales of the weather phenomena. A wide range of horizontal scales of motion is superimposed in the atmosphere: from large global-scale circulations through extra-tropical cyclones, thunderstorms, and swirls of turbulence. The troposphere is roughly 10 km thick, and this constrains the vertical scale of most weather phenomena. Thus, a large horizontal scale will have a constrained vertical scale, causing them to be similar to a pancake. In Figure 1, a generalized horizontal scale of motion in the troposphere is specified. For this study, we have used a scale defined by the AMS since it focuses on a particular US region.

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**Figure 1:** Generalized horizontal scale of motion in the troposphere defined by the World Meteorological Organization (WMO) and the American Meteorological Society (AMS). Source: Practical Meteorology, R. Stull, page no. 315.

Synoptic meteorology traditionally involves studying weather systems, such as extratropical high- and low-pressure systems, jest streams and associated waves, and fronts. The study of weather phenomena on somewhat smaller spatial and temporal scales, mesoscale meteorology, includes convective storms, land-sea breezes, gap winds, and mountain waves.

Exposure (both acute and chronic) to ground-level ozone adversely affects human health and some delicate plants and vegetation [Stewart et.al, 2017]. High concentrations of ground-level ozone are a significant concern for significant metropolitan cities in the US, and the border cities of El Paso, Texas, and Juárez, Mexico, are one such good example. The climate of this region is arid and is characteristic of the urban southwestern US climate. Its air quality problem is partially due to contributions from industrial activities in the region and high emissions from automobiles (Zora et al.; Gent et al.; Gold and Wright). Besides, the geopolitical region of El Paso-Juárez exhibits exceptional meteorological conditions (MacDonald et al.; Karle et al.), such as higher planetary boundary layer heights (PBLHs), than any other Texas city, influenced by the local terrain.

From April to September, El Paso experiences high ozone episodes [Karle et al., 2020]. High ozone episodes are defined as days with an 8 h ozone concentration above 70 parts per billion volume (ppb) as per the Air Quality Index (AQI) set by the National Ambient Air Quality Standards (NAAQS). The total number of annual high ozone episodes recorded by different Continuous Ambient Monitoring Stations (CAMS) installed by the Texas Commission on Environmental Quality (TCEQ) from the year 2000 is given in Figure 2a. The study's data also indicates June to August being the summer months with most of the high ozone episodes commonly recorded in this region (Figure 2b). As expected, since all the favorable conditions for high production of ozone were available during these months, such as high temperatures (month of June and July, which are the peak summer months with an average temperature of approximately 40 °C or above) with calms winds (averaged approximately 4–5 m/s), low relative humidity and high solar radiation (averaged approximately 1.5 Langley/min) [Karle et al., 2020].



Note: Based on ALL sites Source: U.S. EPA AirData <https://www.epa.gov/air-data>

#### Figure 2a: Total number of days with 8-hr daily ozone exceedance (above 70

ppbv) from 2013-2019 in El Paso, Texas



# Figure 2b: Ozone daily Air Quality Index (AQI) values from 2013-2019 for all the CAMS stations in El Paso, Texas

Previous air quality studies conducted in this region were mainly focused on chemical composition analysis, the sources, the physical characteristics of the ozone episodes. Karle et al., 2020, studied the planetary boundary layer (PBL) on the regional ozone episodes. In the same work, authors also briefly pointed out the role synoptic and mesoscale meteorology played during the consecutive low ozone episodes by flushing out the region's pollutants with the help of intense winds. The passage of the dryline also explained the reason for the sudden drop in the regional atmospheric humidity.

Several meteorological variables that influence a given midlatitude region's air quality are strongly influenced by the synoptic-scale circulations such as the passage of fronts, cyclonic systems, and anticyclones. Hence it is significant to investigate the synoptic-scale meteorology associated with regional bad air quality episodes. In particular, this study focuses on the synoptic and mesoscale meteorological conditions that were observed during all the 57 high ozone events that occurred from 2013-2019. Along with the midlatitude synoptic and mesoscale study, a detailed micro-scale study is also conducted to understand the source of the ozone formation and related transport.

#### 1.2 Objectives

The purpose of this work is to create a better understanding of the role that mesoscale and synoptic scale weather phenomena play in local El Paso del Norte (Ciudad Juárez, El Paso, Doña Ana County, NM, as shown in Figure 3) air quality including: a good characterization of mesoscale and synoptic-scale winds during the ozone season and high ozone days; identification of important relationships between and sequences of synoptic and mesoscale winds and local meteorology; and the differences between high ozone days dominated by local effects and those dominated by regional transport of background ozone.

To achieve this objective, the Performing Party-analyzed available ground-based and upper air meteorological data including (as appropriate), but not limited to:

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- air parcel trajectories;
- ceilometers operated by (or in cooperation with) Performing Party;
- National Weather Service radiosonde launches at Santa Teresa, New Mexico;
- TCEQ radar profiler data (if available);
- National Weather Service observations made at local airports;
- quality assured meteorological data from additional local data sources (e.g. University of Juárez);
- meteorology data from local air quality monitoring sites (Texas, New Mexico, Ciudad Juárez); or
- meteorological model output.
- The data for this study should come from the years 2013-2019, if available. This analysis will focus on addressing the following series of questions:
- What are the primary mesoscale and synoptic scale features affecting the El Paso del Norte area's weather from April through September and what local meteorological features/conditions are associated with these features? Is there evidence that El Paso's meteorology is influenced by Stratospheric intrusions (tropopause folding)? When are these conditions most likely to occur?
- Of these mesoscale and synoptic features, which are associated with days in which the daily maximum 8-hour ozone average (MDA8) is over 70 parts per billion (ppb) and what are the relationships/patterns seen in local meteorology with these larger scale influences? Which are the most/least likely to occur on days when the MDA8 is greater than 70 ppb?

 What are the relative contributions to total ozone from locally generated ozone and background ozone transported into the El Paso area by the different mesoscale and synoptic scale influences?



Figure 3. Paso del Norte map

# 2. Meteorological Conditions that Influence Air Quality

This section presents the types of weather conditions that have a strong influence on PM<sub>2.5</sub> or ozone concentrations forecasts [ EPA document: "Guidelines for Developing an Air Quality (Ozone and PM<sub>2.5</sub>) Forecasting Program, EPA-456/R-03-002].

Since daily weather variations best explain the day-to-day changes in air quality concentrations, understanding how weather influences air quality in a region is critical for producing accurate air quality forecasts.

Different scales of weather phenomena are essential to air quality. The weather phenomena range from large storm systems that can encompass thousands of kilometers to small turbulent eddies that are a few meters in size. In general, large-scale weather phenomena are easier to characterize compared to small ones. In addition, weather forecast models typically do a better job of predicting large weather phenomena than small-scale, short-lived phenomena. Therefore, to understand and predict air quality, it is usually best to use a large-scale to small-scale approach by first understanding the relationship between large-scale weather features and local air quality and then understanding the relationship between local weather and air quality.

Meteorological conditions that strongly influence air quality include transport by winds, recirculation of air by local wind patterns, and horizontal dispersion of pollution by the wind; variations in sunlight due to clouds and season; vertical mixing and dilution of pollution within the atmospheric boundary layer; temperature; and moisture. The variability of these processes, which affects pollution variability, is primarily governed by the movement of large-scale high- and low-pressure systems, the diurnal heating, and cooling cycle, and local and regional topography.

Figures 4 (a) and (b) show the general relationships among meteorological phenomena and air quality. Table 1 describes how specific meteorological conditions directly influence PM<sub>2.5</sub> and ozone concentrations. The remainder of this section discusses the key meteorological phenomena in these figures and tables. Educational resources on basic meteorology are available on the Internet (Cooperative Program for Operational Meteorology, 2002; University of Illinois Urbana-Champaign, 2002).



	Emissions	Chemistry	Accumulation/Dispersion/Removal
Aloft Pressure Pattern	No direct impact.	No direct impact.	Ridges tend to produce conditions conducive for accumulation of PM <sub>2.5</sub> and ozone. Troughs tend to produce conditions conducive for dispersion and removal of PM and ozone. In mountain-valley regions, strong wintertime inversions and high PM <sub>2.5</sub> levels may not be altered by weak troughs. In addition, high PM <sub>2.5</sub> and ozone concentrations often occur during the approach of a trough from the west.
Winds and Transport	No direct impact.	In general, stronger winds disperse pollutants, resulting in a less ideal mixture of pollutants for chemical reactions that produce ozone and PM <sub>2.5</sub> .	Strong surface winds tend to disperse PM <sub>2.5</sub> and ozone regardless of season. However, strong winds can create dust which can increase PM <sub>2.5</sub> concentrations. In the East and Midwest, winds from a southerly direction are often associated with high PM <sub>2.5</sub> and ozone, due to transport from one region to another.
Temperature Inversions	No direct impact.	Inversions reduce vertical mixing and therefore increase chemical concentrations of precursors. Higher concentrations of precursors can produce faster, more efficient chemical reactions that produce ozone and PM <sub>2.5</sub> .	A strong inversion acts to limit vertical mixing allowing for the accumulation of PM <sub>2.5</sub> or ozone.
Rain	No direct impact.	Rain can remove precursors of ozone and PM2.5.	Rain can remove PM <sub>2.5</sub> , but it has little influence on existing ozone.
Moisture	No direct impact.	Moisture acts to increase the production of secondary PM <sub>2.5</sub> including sulfates and nitrates.	No direct impact.

Temperature	Warm	Photochemical	Although warm surface temperatures are
-	temperatures	frequencies for	generally associated with poor air quality
	are associated	ozone increase	conditions, very warm temperatures can
	with increased	slightly with	increase vertical mixing and dispersion of
	evaporative,	temperature.	pollutants.
	biogenic, and		
	power plant		
	emissions, which		
	act to increase		
	both PM <sub>2.5</sub> and		
	ozone. Cold		
	temperatures		
	can also		
	indirectly		
	influence PM <sub>2.5</sub>		
	concentrations		
	(i.e., home		
	heating on		
	winter nights).		
Clouds/Fog	No direct	Water droplets can	Convective clouds are an indication of strong
	impact.	enhance the	vertical mixing, which disperses pollutants.
		formation of	
		secondary PM <sub>2.5</sub> .	
		Clouds can limit	
		photochemistry,	
		which limits ozone	
		production.	
Season	Forest fires,	The sun angle	No direct impact.
	wood burning,	changes with	
	agriculture	season, which	
	burning, field	changes the	
	tilling,	amount of solar	
	windblown dust,	radiation available	
	road dust, and	for	
	construction	photochemistry.	
	vary by season.		

Table 1

## 2.1 Aloft Pressure Patterns

Aloft large-scale (1000 km or more) atmospheric circulations strongly influence regional and local weather conditions. Meteorologists generally focus on the so-called

"500-mb level" to evaluate the aloft large-scale pressure systems. They particularly focus on the location, size, intensity, and movement of 500-mb high-pressure ridges and lowpressure troughs (mountains of warm air and cold air, respectively). In general, poor air quality conditions are associated with high-pressure ridges and good air quality conditions associated with low-pressure troughs. However, high PM<sub>2.5</sub> levels can occur without the existence of aloft ridges, from a very strong PM<sub>2.5</sub> emission source, such as a forest fire. Figure 4 (c and d) shows an example of a 500-mb ridge over the eastern United States on July 17, 1999, a day with high PM<sub>2.5</sub> concentrations throughout the region, and on September 21, 1999, a day with low PM<sub>2.5</sub> concentrations throughout the region. The existence of ridges and troughs can be diagnosed by reviewing weather charts, which are widely available as observations and forecasts on the Internet.

#### 2.2 Temperature Inversions and Vertical Mixing

A temperature inversion is a layer of warm air above a layer of relatively cooler air. An inversion acts to limit the vertical mixing of pollutants, which allows concentrations to build. Several temperature inversions can exist at different altitudes in the lower part of the atmosphere. Typically, a temperature inversion can form from 25 to 300 m agl when the ground (and air near the ground) cools at night, while air above remains warmer. This type of inversion is called a nocturnal inversion. Nocturnal inversions are strongest when skies are clear at night and in the winter when nights are long. In the presence of clouds or strong winds, nocturnal inversion is often weak or do not form at all. Nocturnal inversions trap emissions released during the overnight hours, close to the ground. As the ground warms during the day, the air near the surface warms, which erodes the nocturnal inversion. Typically, a nocturnal inversion disappears by mid-morning, allowing the trapped pollutants to mix vertically. If a nocturnal inversion is strong or if solar heating is weak, the inversion may not break until late in the day or at all. Under these circumstances, pollutants do not mix vertically, and high pollutant concentrations are typical. When there is an aloft ridge of high pressure over an area, there is often another inversion above the nocturnal inversion, called a subsidence inversion. A subsidence inversion is caused by sinking air in the mid- to low levels of the atmosphere associated with the aloft ridge. As the air sinks, it warms due to compression. The warmest temperatures associated with the sinking air are typically found from 500 to 2000 m agl. When there is a strong subsidence inversion as indicated by aloft temperatures, the daytime heating at the surface may not be strong enough to break this inversion. Under such circumstances, vertical mixing of pollutants is weak, and pollutants remain trapped near the surface for the entire day. An aloft inversion can also form when winds transport warm air at a greater rate aloft compared to the surface. This differential warming typically occurs on the west side of an upper-level ridge, ahead of an upper-level trough.





Figure 4 c, d . 500-mb heights (c) on the morning of July 17, 1999 (1200 UTC) and (d) on the morning of September 21, 1999 (1200 UTC).

Subsidence inversions do not form when there is an aloft trough over the region. This is because aloft troughs cause rising motion in the mid- to low levels of the atmosphere. As the air rises, it cools due to expansion resulting in cooler air above warmer air. When there is cooler air above warmer air, the atmosphere is unstable. This instability causes vertical mixing, which dilutes pollutants whose source is near the surface.

Figure 5 shows the diurnal cycle of mixing, vertical temperature profiles, and boundary layer height on a day with a weak temperature inversion and on a day with a strong temperature inversion. On the day with the weak inversion, the convective boundary layer grows rapidly as the sun warms the ground during the day. The rapid growth of the convective boundary layer is associated with strong vertical mixing and the vertical dispersion of pollutants.

On the day with the strong inversion, the convective boundary layer growth is inhibited. The limited growth of the convective boundary layer is associated with weak vertical mixing and limited vertical dispersion of pollutants (Karle, et.al, 2020).



**Figure 5.** Schematic showing diurnal cycle of mixing, vertical temperature profiles, and boundary layer height (a) on a day with a weak temperature inversion and (b) on a day with a strong temperature inversion. In (a) the pollutants mix into a large volume resulting in low pollution levels and in (b) pollutants mix into a smaller volume resulting in high pollution levels.

#### 2.3 Winds and Transport

Winds can be described as large-, regional-, and local-scale. The large-scale winds are driven by the pressure gradients between surface high- and low-pressure systems. Light, regional, surface winds often occur near the center of the surface-high, below the ridge of high pressure, where pressure gradients are weak. Light winds are not effective at dispersing pollutants and, therefore, often occur during high pollutant concentrations. Moderate to strong winds occur between surface high- and low-pressure systems or near the center of low-pressure systems, provided that moderate to strong pressure gradients exist. Moderate to strong surface winds act to disperse pollution and thus are typically associated with low pollutant concentrations. However, high pollutant concentrations can occur during moderate to strong wind conditions, if the winds transport pollution from one region to another.

In general, surface lows occur under the leading half of aloft troughs (typically on the eastern side), whereas, surface highs occur under the leading half of aloft ridges. Figures 6 and 7, respectively, show a 500-mb ridge and an associated surface high and a 500-mb trough and an associated surface low. The ridge and surface high on January 7, 2002, created conditions conducive to high PM<sub>2.5</sub> concentrations in Salt Lake City, Utah, including light surface winds and reduced vertical mixing. The trough and surface low on January 22, 2002, created conditions conducive to low PM<sub>2.5</sub> concentrations including strong surface winds, clouds, and vertical mixing.

Local winds are driven by the interaction between the large-scale pressure patterns and lower-scale meteorological factors. The local meteorological factors include the diurnal temperature cycle, topography, soil moisture, land-use etc.

Local winds tend to dominate over the large- and regional-scale winds when the largescale pressure patterns are weak (i.e., at the center of a surface high pressure). The local winds may include land breezes, sea breezes, morning downslope flows, afternoon upslope flows, and terrain channeled flows, which can combine in various ways to recirculate air and cause stagnation.

#### 2.4 Clouds, Fog, and Precipitation

Clouds, rain, and fog all influence pollutant concentrations through a variety of mechanisms as detailed in Table 1. Clouds form when air is cooled, and water vapor condenses. This cooling can be caused by rising motion or contact with a cool surface such as a body of water or cool land during the night. Rising motion is generated by aloft low-pressure systems, frontal boundaries, air flowing over mountains, and convective

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instability (warm air below cooler air). Clouds are important because they typically reduce the amount of sunlight available for photochemical reactions that participate in the production of ozone and PM<sub>2.5</sub>. Fog is a type of cloud that is in contact with or near the ground. Fog and clouds can dramatically increase the conversion of sulfur dioxide to sulfate (a secondary type of PM<sub>2.5</sub>). Precipitation is a removal mechanism for fine particles.



**Figure 6.** 500-mb heights (left) and surface pressure (right) on the afternoon of January 7, 2002 (0000 UTC on January 8).



**Figure 7.** 500-mb heights (left) and surface pressure (right) on the afternoon of January 22, 2002 (0000 UTC on January 23).

### 2.5 Weather Pattern Cycles

Typically, a region will cycle between a ridge and trough pattern every 2 to 7 days, but more stationary patterns can develop. Studying and understanding these cycles and their impact on local weather and air quality will help improve forecasting capabilities. Figure 8 shows the typical life cycle of large-scale weather patterns. The following meteorological descriptions are generic and may vary from one region to another and between pollutants, Table 2:

Ridge—high pressure pattern	(Figure 8a and b) is typically associated with poor air quality.
	This pattern occurs about one to two days after a cold front
	and trough have passed through an area. As surface high
	pressure develops in an area, winds become weak allowing for
	the accumulation of pollutants. Warming temperatures
	increase the biogenic and evaporative VOCs and lower
	humidity results in clearer skies, which are favorable for
	photochemistry. Sinking air (subsidence) warms and stabilizes
	the lower atmosphere, which suppresses cloud development
	and mixing. In addition, an aloft temperature inversion may

	form that inhibits vertical mixing and reduces dilution of
	pollutants. The aloft high pressure ridge typically occurs west
	of the surface high and can be diagnosed using 500-mb height
	fields.
Ridge—back side of high	(Figure 8c and d) occurs as the surface high pressure moves
pattern	east of the region and the accumulated pollutants are
	transported to downwind locations. In some regions, warm air
	is advected into the region and winds may increase from a
	southerly to a westerly direction depending on the orientation
	of the high. This pattern typically produces warm temperatures
	and relatively clear skies, even with a low-pressure system
	approaching from the west. Pollutant levels can remain high
	on these types of days, and the potential for longer-range
	transport is greater.
Trough— cold front pattern	(Figure 8e and f) is characterized by a low-pressure system at
	the surface and associated cold and warm fronts. Aloft at 500
	mb, a trough of low pressure exists just upstream (west) of the
	surface low. This weather pattern produces clouds and
	precipitation that reduce photochemistry. Stronger winds and
	mixing also reduce pollutant concentrations.

#### Table 2

Although aloft ridges and their associated regional and local weather conditions are generally associated with poor air quality, slight variations in the meteorological processes described above can have a dramatic effect on the spatial and temporal characteristics of air quality. It is these variations in meteorological processes that need to be analyzed and understood for different pollutants, seasons, and regions of interest to better understand the processes that produce air quality episodes.



Figure 8. Life cycle of synoptic weather events at the surface and aloft at 500 mb for (a) and (b) Ridge—high pressure, (c) and (d) Ridge—back side of high, and (e) and (f)
Trough—cold front patterns. Surface maps show isobars and frontal positions. The 500-mb maps show contours of equal height.

# 3. Results

#### 3.1 Analysis of Physical Variables

#### 3.1.1 Average Temperature, and UV Index

El Paso is popularly known as Sun city as it receives, on average, 302 days of sun every year. Figure 9 (a) below gives us the average monthly temperature of the city. The warmest months are June and July, with an average temperature of 95.5- and 94.7-degree Fahrenheit (°F). June has an average 14.2 hour of daylight, making it the month that has longest days of the year in PdN region. June and July are also the two months when the region is exposed to maximum ultraviolet (UV) radiation. As seen in the Figure 10 below, the highest UV index is observed in June and July with an index of 12. Hence as rightly observed by (Karle et al., 2020), these are also the two months with the maximum number of high ozone cases, because local conditions are favorable for the production of ground level ozone.



Figure 9(a): Average monthly temperature of the city of El Paso. Source: Weather-us.com



Average Hourly Temperature

Figure 9(b): The average hourly temperature, color coded into bands for the Paso Del Norte region. Source: Weatherspark.com

As seen in Figure 9 (b), starting from April, the afternoon temperature in this region is warm but the nighttime is relatively cool. However, starting from May, we can observe that from early morning 8 am to midnight or later, the hourly average temperature in this region is warm with peak observed around 4 pm in the afternoon. This could also result in lower inversions heights during the nighttime resulting in lower nocturnal boundary layer heights.



Figure 10: Average monthly UV index recorded in the city of El Paso. Source: Weather-

us.com

#### 3.1.2 Analysis of the Geopotential Height

The Geopotential height approximates the actual height of a pressure surface above mean sea-level. Therefore, a geopotential height observation represents the height of the pressure surface on which the observation was taken. We analyzed the 500 mb geopotential heights contour maps during and a day before the high ozone episodes. The geopotential height at 500 mb is a dominant parameter in controlling weather and climatic conditions (Hafez, Y.Y. and Almazroui, M., 2014). They play an important role in synoptic meteorology by assisting to identify weather systems such as cyclones, anticyclones, troughs and ridges. A common observation during this entire study period is the presence of the high-pressure ridge observed in the geopotential heights in the Paso del Norte (PdN) region.

The pressure gradient force is proportional to the geopotential height gradient. Since the hydrostatic balance considers the equation of state, we can relate geopotential height to temperature and pressure, as they are in a direct proportionality relationship. This confirms the presence of the warm air masses along the region. Geopotential heights are lower in cold air masses and higher in warm air masses.

Throughout the study period of the high ozone episodes from 2013-19, we found that geopotential height anomalies are similar for the summertime (May-August) during these years, where high geopotential height dominates over PdN areas. Geopotential height anomalies are defined as deviations in the geopotential height field from longterm ((e.g., 30 years) average values.

The Figure 11 (a) and (b), depicts the geopotential height at 500 mb on June 6th, 2017, at 12 Z. The solid white line depicts the temperature, and the colored regions depict geopotential heights. Geopotential heights increase from dark violet to dark blue. A trough is observed over the eastern United States and is indicated by the dip in the geopotential height field. Usually, strong troughs are typically preceded by stormy

weather and colder air at the surface. A ridge is observed from the eastern Pacific ocean into the western tip of Texas, southern parts of Arizona and New Mexico into the central United States and is indicated by the bulge in the geopotential height field. It is also an extension of a high-pressure surface center associated with warm temperatures caused by the northward transport of warmer air in the lower troposphere. Usually, strong ridges such as the one seen below, are accompanied by warm and dry weather conditions at the surface, ideal for producing ground-level ozone and other photochemistry processes.

This is further discussed on the Synoptic Meteorology Analysis.



Figure 11a : Geopotential height at 500 mb observed at the synoptic scale on June 6, 2017 12 Z.



Figure 11b : Fronts analysis at the synoptic scale on June 6, 2017 12 Z.



Figure 11c : Geopotential height at 500 mb observed at the synoptic scale on June 12, 2017 12 Z, which was a low ozone event.



Figure 11d : Geopotential height at 500 mb observed at the synoptic scale on May 21, 2015 12 Z, which was a low ozone event.



**Figure 11e :** Geopotential height at 500 mb observed at the synoptic scale on June 11, 2017 12 Z, which was a low ozone event.

As seen in Figure 11(c-e) the geopotential heights above the Paso Del Norte region are lower as compared to values from Mexico and southern region. These are three randomly picked low ozone events which are used here as an example. This happened in many days where a low ozone event was observed in this region.



Figure 11f: Fronts analysis at the synoptic scale post passage of the dryline on June 12, 2017 12 Z, which was a low ozone event.



**Figure 12:** Overall distribution of geopotential height values for all the high ozone days from 2013-19.



**Figure 13:** Daily averaged surface temperature in degree Celsius at the synoptic scale averaged over April 2018 to September 2018. We can clearly see that PdN region has high temperatures throughout this period.
# 3.1.3 Effect of Surface Wind Speed and Direction

HYSPLIT back trajectories (Section 3.4) were used to explain the air masses' movement, understanding the regional flow of the winds became of utmost importance. All of this was necessary in order to get a good explanation of the local pollutant transport. This investigation utilized two different criteria: first, locate the CAMS station in the region that has recorded most of the 57 high ozone episodes in this region and analyze the wind direction and speed recorded by that station. UTEP, CAMS 12, is one of the fully functional CAMS in the El Paso region. It is located very close to the UTEP campus and has also reported most of the high ozone episodes that are part of this study. For this study period, all the high ozone events recorded by CAMS 12 were summarized in the form of wind roses representing the respective year they were recorded. Wind roses are the data maps that show the general wind direction and speed for each sampling period. The wind's circular format shows the direction the winds blew from, and the length of each spoke around the circle shows how often the wind blew from that particular direction (www.epa.gov). During the ozone events, the wind directions were also a strong indicator of the direction of the incoming ozone and its precursors as recorded by the CAMS 12.

As seen below for CAMS 12, each Figure 14 (a-g) represents wind roses for the respective year. Data were examined in the light of the daily hourly average wind speed and direction measured at CAMS 12. In general, surface winds were calm during high ozone days with minimal exceptions. This was expected because calm winds do facilitate the accumulation of precursors and their ozone-producing reactions. As seen in the figure, wind direction during the high ozone episodes tended to be East, East-southeast, and Southeast.

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(a) Wind rose representing all the high ozone events that occurred in the year 2013 as recorded by CAMS 12



(b) Wind rose representing all the high ozone events that occurred in the year 2014 as recorded by CAMS 12



(c) Wind rose representing all the high ozone events that occurred in the year 2015 as recorded by CAMS 12



(d) Wind rose representing all the high ozone events that occurred in the year 2016 as recorded by CAMS 12



(e) Wind rose representing all the high ozone events that occurred in the year 2017 as recorded by CAMS 12



(f) Wind rose representing all the high ozone events that occurred in the year 2018 as recorded by CAMS 12



## (g) Wind rose representing all the high ozone events that occurred in the year 2019 as recorded by CAMS 12

Figure 14: Wind roses for 2013-2019 (a-g) as recorded by CAMS 12, UTEP

The lowest average wind speed was observed on September 12, 2017, which was 3.5 mph, whereas the highest wind speed was observed on June 15, 2014, which was 13 mph. As observed, low wind speed on certain events shows that the pollution source in those individual cases was mainly local and not long-range transport, given the wind intensity.

## 3.1.4 Analysis of Atmospheric Stability Conditions

Atmospheric stability determines the amount of mixing between the boundary layer and the remainder of the troposphere aloft. A stable boundary layer traps air pollutants in the lowest level. If the boundary layer is thermally unstable then there will be significant amount of vertical mixing. Atmospheric stability is determined by temperature changes that occur with altitude, which are affected by synoptic conditions, as discussed in section 2.2.

Convective available potential energy (CAPE) is the amount of energy available to an air parcel as it freely rises between the level of free convection (LFC) and the equilibrium level (EL). CAPE is a standard variable used to characterize atmospheric convection. The CAPE is non-zero only if LFC exists. It is expressed as Joule/kg. CAPE of the value of 0 indicates the stable atmosphere, while CAPE of less than 1000 shows marginally unstable conditions. CAPE of 1000-2500 refers to moderately unstable conditions, CAPE of 2500-3500 indicates precarious conditions. CAPE of larger than 3500 is volatile conditions.

As seen in the figure below, Figure 15, for the majority of the ozone events, CAPE values from the radiosonde dataset obtained from the nearest NSW suggests atmospheric stability. This also supports the ground-based wind speed measurements, which were found to be on the lower side (calm winds). There were a few events when the atmosphere had marginally unstable conditions. Except for one occurrence on July 11, 2013, at 12Z, Figure 16 and 17, when the CAPE value was 1093 Joule/kg, indicating moderately unstable atmospheric conditions. This moderate nonlocal conditional instability must have occurred when a temperature inversion capped warm, humid atmospheric boundary layer air.



**Figure 15** CAPE values from the Santa Teresa, NWS daily soundings. Majority of the days had CAPE values in between 0-150 indicating highly stable atmospheric conditions.



**Figure 16** A vertical profile from July 11, 2013 at 12 Z. The CAPE value was the highest observed during this entire study period.



Figure 17 Surface Analysis chart of July 11, 2013 at 12 Z.

# 3.1.5 Effect of Local Topography

PdN region is surrounded by complex topography, and its influence can be clearly seen on the ozone concentrations measured across various air monitoring stations. The wind flow was upslope with respect to the river valley during most high ozone events. The ozone concentrations were observed to decrease down the valley when moving away from El Paso downtown towards Socorro Region.

Table 3 gives the high ozone days from the year 2013 and the highest ozone concentration (hourly averaged) measured on that particular day. It can be clearly seen that CAMS 12 at UTEP registered 6 high ozone episodes, whereas three different stations, located within less than 20 km radius from CAMS 12 did not record any ozone concentrations exceedances except Santa Teresa which recorded 75 ppb on July 3, 2013. Similar observations were made for several other high ozone episodes which were recorded by the CAMS 12 at UTEP but CAMS 49 at Socorro did not observe similar high ozone concentrations as seen in Figure 18, the locations of different air monitoring

stations in New Mexico which are close to El Paso. Since CAMS 12 during those high ozone episodes observed winds coming from east, south-east directions, it was evident that ozone could have traveled further, and similar higher concentrations could have been recorded by monitoring stations in the New Mexico side, but was not observed. This indicates that ozone was formed more at the local level within El Paso. Further in-depth analysis can help in a better understanding of these observations.

Year 2013	UTEP (CAMS 12) Highest Ozone concentration (ppbV)	Desert View, Highest Ozone concentration (ppbV)	Santa Teresa, Highest Ozone concentration (ppbV)	La Union, Highest Ozone concentration (ppbV)
April 28	73	55	61	38
May 24	75	32	56	41
June 11	75	53	59	40
July 3	82	67	75	49
August 17	73	48	63	43
August 19	73	43	60	45

Table 3 Ozone peak value observed by CAMS 12 UTEP and three closest air monitoring stations in the state of New Mexico.



Figure 18: Location of the closest three air quality monitoring stations in New Mexico (yellow) from TCEQ CAMS 12 at UTEP (red)

## 3.1.6 Cloud Cover

The average percentage of the cloud cover over Paso Del Norte region signifies mild seasonal variations over the course of the year. As seen from the Figure 19, this region experiences clearer skies around mid-March and lasts for around 4 months. The cloudier part of the year begins and continues till September and from November till March.

NASA's worldview was used to analyze the cloud cover over the El Paso and neighboring regions during high ozone episodes, Figure 20. In particular, NASA's Terra satellite images were used for this visual study. Terra orbits 705 km above the earth's surface with 16 orbits per day. The Terra satellite passes over PdN at 10:45 am  $\pm$  5 mins and 10:15 pm  $\pm$  5 mins in a near polar, sun-synchronous orbit. Images obtained represented the average upper air visuals for the day. Total days were categorized into cloudy days, partially cloudy days, and clear days, as seen in the figures below, respectively. We observed that 46% of the total ozone episodes occurred on a clear day, whereas 37% of events occurred on partially cloudy days as seen in Figure 21.



**Figure 19**. The percentage of time spent in each cloud cover band, categorized by the percentage of the sky covered by clouds. Source: WeatherSpark.com. Graph is based on a statistical analysis of historical hourly weather reports and model reconstructions from January 1, 1980 to December 31, 2016.



20 (i). Clear day, July 15, 2019





20 (ii). Clear day, July 15, 2019 at 12 pm. Source: http://www.caps.ou.edu/



20 (iii). Partial cloudy day, June 23, 2016









**20 (v). Cloudy day, July 10, 2017** CONUS20 (280×180×50, d×=20 km) Analysis for 16Z Mon 10 Jul 2017



20 (vi). Cloudy day, July 10, 2017 at 10 am

Figure 20 (i-vi) Satellite Pictures of the PdN region during some of the high ozone events.



Figure 21: Percentage distribution of clear, partial and cloud days throughout the study period.

# Analysis and Conclusions

The ozone season for El Paso is from April to September, and ozone episodes are observed due to intense solar radiation characterizing especially the central and eastern United States and the advection of warm and dry air. High frequencies of clear skies or low clouds coverage for summer months over PdN ensures that maximum solar radiation is available on the surface. Due to the relatively week pressure gradient, the winds were quite calm on the surface. As seen in the case study conducted by (Karle et al., 2020), planetary boundary layer heights were relatively lower during the consecutive high ozone days in 2017. Weak winds blowing within the limited volume of atmosphere available within the boundary layer result in poor ventilation conditions and accumulating precursors in the region, leading to high ozone episodes. One of the leading ozone formation mechanisms in El Paso region is photochemical reactions and cross-border transport.

PdN experiences high temperatures during the summer season. The ozone does get strongly influenced by the intensity of the solar radiation, emissions of NOx and VOCs,

the daily pattern in the regional ozone concentrations usually display well defined diurnal pattern (Karle et al. 2020).

# 3.2 Statistical Analysis3.2.1 Analysis per station

For the analysis of high ozone days that occurred from 2013-2019, we collected the number of high ozone days and high ozone occurrences in the Paso del Norte region which consist of El Paso, Juárez and some counties of New Mexico. Figure 22 gives the cumulative number of days of high ozone events recorded in the El Paso region.



**Figure 22.** Cumulative number of days when 8-hr ozone concentration was above 70 ppb for El Paso region between 2013-2019.

For the analysis part, we use two different approaches: Statistical and Simulation. We retrieve the data from 6 different location of Paso del Norte region (Figure 23). Total number of high ozone occurrences in the time period of 2013-2019 are as follows:



Figure 23. Number of High ozone event occurrences from 2013-2019 in PdN region

We analyzed all the meteorological variables from the CAMS station for those high ozone days.

Year	UTEP	Skyline	Chamizal	Ivanhoe	Socorro	Ascarate	Total High
	(CAMS	(CAMS 72)	(CAMS	(CAMS	(CAMS 49)	Park	Ozone
	12)		41)	414)		(CAMS	event
						37)	occurrences
2013	6	1	3	0	0	0	10
2014	3	2	2	0	1	0	8
2015	4	2	2	1	1	0	10
2016	4	1	2			3	10
2017	10	4	6	1	0	1	22
2018	7	12	5	5	3	4	38
2019	7	6	7	3	1	1	25

Table 4

# Statistical Approach

We create a database of all high ozone incidences in our study area and applied different statistical tests to find out significant contributors of high ozone events in El

Paso. Pearson Correlation Coefficient is one of the statistical methods where we can find the correlation of those meteorological variables with Ozone.

## Correlation

Correlation is a bivariate analysis that measures the strength of association between two variables and the direction of the relationship. In terms of the strength of relationship, the value of the correlation coefficient varies between +1 and -1. A value of  $\pm$  1 indicates a perfect degree of association between the two variables. As the correlation coefficient value goes towards 0, the relationship between the two variables will be weaker. The direction of the relationship is indicated by the sign of the coefficient; a + sign indicates a positive relationship and a – sign indicates a negative relationship.

In our study we use Pearson Correlation method. We use the following formula to calculate the correlation between those multi variables.

$$r_{xy} = rac{n\sum x_iy_i - \sum x_i\sum y_i}{\sqrt{n\sum x_i^2 - (\sum x_i)^2}} rac{\sqrt{n\sum y_i^2 - (\sum y_i)^2}}{\sqrt{n\sum y_i^2 - (\sum y_i)^2}}$$

 $r_{xy}$  = Pearson r correlation coefficient between x and y

n = number of observations

x<sub>i</sub> = value of x (for ith observation)

y<sub>i</sub> = value of y (for ith observation)

## **Correlation Matrix**

A correlation matrix is a table showing correlation coefficients between variables. Each cell in the table shows the correlation between two variables. A correlation matrix is used to summarize data, as an input into a more advanced analysis, and as a diagnostic for advanced analyses.

#### **Boxplots**

A boxplot is a standardized way of displaying the distribution of data based on a five number summary ("minimum", first quartile (Q1), median, third quartile (Q3), and "maximum"). Boxplots from all different CAMS are plotted to show the statistical characteristics of those variables. We also provided outliers to show the whole picture.

As different CAMS stations have different meteorological variables tracking capabilities and not all the variables are important for high ozone event, we have selected the following variables for the calculation: Outdoor temp (Fahrenheit), PM (ug/cu meter), solar radiation (langleys per minute), Wind speed (mph) and Dew point temp (Fahrenheit) Relative humidity (Percentage).

#### UTEP (CAMS 12)

In this correlation matrix plot, we are trying to establish correlation plots to determine the relationship of Ozone with all the meteorological variables available. As demonstrated, the solar radiation and Temperature have a positive correlation more than 0.5 while the Wind speed, Relative humidity and PM2.5 shows a negative correlation with Ozone. In addition, in the box plot, we can see that maximum value of Ozone is over 100 while the median value is around 60 ppb. The temperature has an average value of 80 degrees Fahrenheit and Dew point temperature is around 40 degrees.



Figure 24. Correlation Matrix of the variables at UTEP (CAMS12)

	WS	Temp	Dew	RH	SR	PM2.5	Ozone
			Temp				
WS		-0.24	0.02	0.09	-0.09	0.28	-0.14
Temp	-0.24		-0.20	-0.65	0.41	0.01	0.58
DewTemp	-0.02	-0.20		0.78	-0.15	-0.08	-0.21
RH	0.09	-0.65	0.78		-0.38	-0.12	-0.51
SR	-0.09	0.41	-0.15	-0.38		-0.15	0.61
PM2.5	0.28	0.01	-0.08	-012	-0.15		-0.11
OZONE	-0.14	0.58	-0.21	-0.51	0.61	-0.11	



Figure 25. Box plots of the variables at UTEP (CAMS 12)

# Chamizal

Chamizal has a unique geographical location in El Paso. It shows the same trend of Ozone correlation plot where Temperature and Solar radiation show the positive correlation of 0.56 and 0.69 respectively. On the other hand, the remaining variables show the negative correlation ranging the values closer to 0. In the box plots, the mean value of Ozone is higher than 70 with no outliers and maximum values over 100 ppb. Temperature also has maximum value over 100, which is very usual for a summer day in our study area.



Figure 26. Correlation Matrix of the variables at Chamizal (CAMS 41)

	WS	Temp	Dew	RH	SR	PM2.5	Ozone
			Temp				
WS		-0.26	0.39	0.39	-0.17	-0.16	-0.06
Temp	-0.26		-0.67	-0.93	0.42	0.12	0.56
DewTemp	0.39	-0.67		0.80	-0.32	-0.03	-0.41
RH	0.39	-0.93	0.80		-0.47	-0.16	-0.54
SR	-0.17	0.42	-0.32	-0.47		-0.04	0.69
PM2.5	-0.16	0.12	-0.03	-0.16	-0.04		-0.12
OZONE	-0.06	0.56	-0.41	-0.54	0.69	-0.12	



Figure 27. Box plots of the variables at Chamizal (CAMS 41)

## Ascarate Park

Ascarate Park is one of the high ozone occurrence station at El Paso area. The positive correlation trend still continues for this station, however, the correlation coefficient between ozone and solar radiation decreased by a significant number. The mean value of ozone is more than 60 ppb while the maximum value is closer to 120 ppb.



Figure 28. Correlation Matrix of the variables at Ascarate Park (CAMS 37)

	WS	Temp	Dew	RH	SR	PM2.5	Ozone
			Temp				
WS		-0.33	0.24	0.06	0.65	0.01	-0.12
Temp	-0.33		-0.53	-0.75	-0.22	0.01	0.54
Dew Temp	0.24	-0.53		0.81	0.14	-0.06	-0.32
RH	0.06	-0.75	0.81		-0.05	-0.08	-0.45
SR	0.65	-0.22	0.14	-0.05		0.01	0.19
PM2.5	0.01	0.01	-0.06	-0.08	0.01		-0.22
OZONE	-0.12	0.54	-0.32	-0.45	0.19	-0.22	



Figure 29. Box plots of the variables at Ascarate Park (CAMS 37)

## **Skyline Park**

Skyline Park, which resides at the east side of El Paso area, has limited meteorological sensors compared to other stations. For the sake of normalization, we only choose temperature and wind speed and they exhibit the same trend like the other stations with a value of more than 0.7. Temperature mean value is slightly higher (more than 80 deg F) and Ozone is around 60 ppb.



Figure 30. Correlation Matrix of the variables at Skyline Park (CAMS 72)

	WS	Temp	Ozone
WS		-0.04	0.07
Temp	-0.04		0.71
Ozone	-0.07	0.71	



Figure 31. Box plots of the variables at Skyline Park (CAMS 72)

# Socorro

Socorro site is at the Far East part of El Paso with more vegetation index and rural background. Like the Skyline, Socorro station has limited capability of tracking meteorological variables, which resulted to use only PM, Temperature and Wind speed. Like any other station, it follows the same trend, positive correlation with Temperature, while negative with other variables.



Figure 32. Correlation Matrix of the variables at Socorro (CAMS 49)

	WS	Temp	PM2.5	Ozone
WS		0.11	-0.14	0.25
Temp	0.11		-0.05	0.81
PM2.5	-0.14	-0.05		-0.26
Ozone	0.25	0.81	-0.26	



Figure 33. Box plots of the variables at Socorro (CAMS 49)

#### Analysis and Conclusion for this section

We have plotted the correlation matrix for all the available data from all the CAMS in high ozone days. Parameters like Temperature, Wind Speed, Relative humidity, PM2.5, Solar radiation, Dew Point Temperature, etc. Box plots of all meteorological variables were also calculated and plotted based on the CAMS. The goal of this statistical analysis is to determine which parameters contribute the most or have a good correlation with high ozone event. As all of the meteorological variables are in local scale (i.e. area within 100 miles), our calculations actually represent the local level meteorology.

Our Interpretations are as follows: Temperature and Solar Radiation are the most positively correlated with the High ozone events. However, PM2.5, Relative Humidity, Wind Speed etc. have a negative correlation (ranging from 0.1 to 0.6). In addition, from the box plot we can observe that the average value of high ozone is around 60 ppb with a maximum value of more than or near to 100 ppb. The hourly data we collected during the months of July to September resulted on an average temperature of more than 80 degree Fahrenheit. Linear regression analysis was applied between ozone and temperature values. It shows the following results:



Figure 34. Linear regression between Temperature and Ozone (2013-2019)

Number of observations: 2006

Root Mean Squared Error: 7.81

R-squared: 0.332, Adjusted R-Squared 0.332

P-value = 7.09e-178

Correlation Coefficient = 0.573

Above, P value is less than 0.05 which strongly suggest that we can reject the null hypothesis and it is statistically significant.

At the other part of the spectrum, the relative humidity has the strongest negative correlation with ozone, which depicts that in a high ozone days, the value of humidity will be relatively low compared to any given day. Linear regression analysis between Relative Humidity and Ozone was conducted and the following results were attained:



Figure 35. Linear regression between Relative Humidity and Ozone (2013-2019)

Number of observations: 2006

Root Mean Squared Error: 14.3

R-squared: 0.242, Adjusted R-Squared 0.241

F-statistic vs. constant model: 638,

P-value = 1.79e-122

Correlation Coefficient = -0.495

The p-value is also less than 0.05 which actually demonstrate the relation between Ozone

and Relative humidity is statistically significant.

## 3.2.2 Analysis Using Statistical Models

## Data Collected

To date, the following data have been gathered or extracted:

- All hourly ozone (O<sub>3</sub>), carbon monoxide (CO), wind speed & direction, outdoor temperature, dew point temperature, relative humidity, barometric pressure, solar radiation, and precipitation data collected at TCEQ monitoring stations in El Paso from April through September of 2013 through 2019 have been compiled. For ozone all daily MDA8 values have been calculated.
- All O<sub>3</sub> 8-hour ozone averages by hour 2013 2019 in the U.S.A., downloaded from the Environmental Protection Agency (EPA) Air Quality System (AQS).
- A list of the 57 dates with at least one station's MDA8 values at or above 70 ppb from 2013 to 2019 in El Paso, extracted from Texas Commission on Environmental Quality (TCEQ) data.
- A list of 161 dates with at least one station's MDA8 values at or above 70 ppb from 2013 to 2019 in El Paso and Dona Ana NM counties, extracted from AQS data.
- An incomplete set of daily Radar Wind Profiler Data from the TCEQ's Socorro Hueco station from 2015 – 2019.
- GlobalData Assimilation System (GDAS) data files for running HYSPLIT from April through September of 2013 through 2019, gathered from NOAA. (<u>https://www.ready.noaa.gov/gdas1.php</u>)

## **Data Analyses**

Most of the focus in this report is on El Paso County in Texas, but data from Dona Ana County in New Mexico is also an important resource. No data were available for Ciudad Juárez, Chihuahua, Mexico. The populations of the three regions are heavily weighted to the south, with the Ciudad Juárez Municipality holding a 2010 population of 1.3 million, El Paso County with a 2010 population of 800,647, and Dona Ana County with a 2010 population of 209,233. By focusing on El Paso in the middle of this region, area-wide conclusion may be drawn.

**Error! Reference source not found.** shows the monitoring network in El Paso, TX with a "CXX" CAMS (continuous ambient monitoring station) number for the six ozone monitors sites in the community. **Error! Reference source not found.** shows only the six ozone monitoring stations on a Google Earth map, along with an additional point that represents the geographic centroid of the six stations, which has been used as the starting location for HYSPLIT two-day (mesoscale) and five-day (synoptic scale) upper air back-trajectories.

The distribution of O<sub>3</sub> exceedances has been uneven with the Dona Ana and El Paso counties. Table 5 lists the count of dates from 2013 – 2019 on which each of the five Dona Ana and six El Paso monitoring stations recorded an MDA8 equal to or higher than 70 ppb. Two Dona Ana stations have the highest counts. **Error! Reference source not found.** Table 6 indicates the areal extent of exceedance days by counting the number of stations at which an MDA8 equal to or higher than 70 ppb on a given day, 2013 – 2019. So, of 161 days on which an exceedance was measured, on 116 days (72 percent) it was only one or two stations, while on six dates (3.7 percent), eight or more stations all had exceedances.

County	Station	Number days MDA8 ≥ 70ppb
Dona Ana, NM	60 La Union	22
Dona Ana, NM	6ZK Chaparral	29
Dona Ana, NM	6ZM Desert	67
	View	07
Dona Ana, NM	6ZN Santa	101
	Teresa	
Dona Ana, NM	6ZQ Solano	17

El Paso, TX	Ivanhoe C414	12
El Paso, TX	UTEP C12	45
El Paso, TX	Chamizal C41	35
El Paso, TX	Ascarate Park	10
	C37	10
El Paso, TX	Socorro Hueco	10
	C49	10
El Paso, TX	Skyline Park C72	35

Table 5. Number days a station measured an O3 MDA8 ≥ 70ppb, 2013 - 2019

Number of stations	Frequency
1	77
2	39
3	12
4	10
5	10
6	4
7	3
8	2
9	1
10	1
11	2

**Table 6.** Frequency with which multiple stations measured MDA8  $\geq$  70ppb, 2013 – 2019



Figure 36. TCEQ Monitoring Stations in El Paso (UT operates El Paso Delta 481411011)



Figure 37. Six ozone monitoring stations in El Paso and their geographic centriod

Local effects on ozone concentrations

Time series graphs were made of all days on which UTEP CAMS 12, Ascarate Park CAMS 37, or Chamizal CAMS 41 had an MDA8 at 70 ppb or greater. These three stations have been focused on because of the instrumentation at these stations and the fact that UTEP and Chamizal have the highest number of MDA8 days at or above 70 ppb over this period in El Paso County. The rationale for the time series graphs is that they provide a means to select dates for more detailed examination of the possibility of, say, stratospheric intrusion, in which case one would see a drop in relative humidity and carbon monoxide, as clean, dry air mixes down as O<sub>3</sub> goes up. The graphs can also provide information by looking at differences in the time of peak concentration of O<sub>3</sub>, which could be created by a gradient in concentrations caused by the passage of a plume from a specific upwind local source.

Linear regressions have been run with the TCEQ O<sub>3</sub> and meteorological data, and with other pollutants. The idea behind fitting the data to regression models in which MDA8 O<sub>3</sub> is a function of various meteorological variables is that if a model explains much of the variation in O<sub>3</sub> MDA8s then high concentrations can be explained, at least in part, by local meteorology. Use of carbon monoxide and hydrocarbon concentrations may help to implicate primary pollutant sources that are precursors to O<sub>3</sub> formation. Among the available meteorological data are wind speed, wind direction, relative humidity, temperature, and solar radiation. Wind direction, measured in compass degrees from 0 to 360, is not useful in a model in this form, because 1 degree and 359 degrees are only 2 degrees apart, but a regression model would think they are 358 degrees apart. Wind direction can be included in a model by converting the angle measurements to Cartesian X, Y components. In this application, the wind speed and direction data have been combined into u (east/west) and v (north/south) by the formulas

$$v = wsr * cos(wdr / 57.3)$$

where

wsr = hourly wind speed resultant and

wdr = hourly wind direction resultant.

The constant 57.3 converts degrees to radians for the sine and cosine functions. Taking this approach a step further, the u components were added together from noon MST back in time 4 or 8 hours as were the v components, to estimate the distance in X (east-west) and Y (north-south) directions to the general location of an air parcel in the early morning. A serious weakness of this approach is that it only uses the data from the one station in back-tracking the air parcels.

Another use of the regression results is that by examining dates which are outliers with regard to the regression fit, we may find candidates for examining the possibility that local emissions of highly reactive volatile organic compounds (HRVOCs) contributed to elevated O<sub>3</sub> concentrations, or that meso-scale or synoptic scale distance transport contributed to elevated O<sub>3</sub> concentrations. Local meteorological variables include the surface wind speed, wind direction, solar radiation, and relative humidity. Barometric pressure, measured at Ascarate Park CAMS 37 may be more regional but was also used.

Models developed for this project only using meteorological variables only explained 33 to 38 percent of the variance (R<sup>2</sup>) in MDA8, and 51- 57 percent of the variance in using meteorological and pollutant variables. Morning and afternoon toluene and ethane from the Chamizal auto-GC and morning and afternoon carbon monoxide from each station were the pollutant variables used in modeling. CO data at UTEP C12 were missing for 2015 – 2017, CO data at Ascarate C37 were missing for part of 2015 and all of 2018 and 2019, and CO data were missing at Chamizal C41 for much of 2016, 2018 and 2019, and all of 2017. The two types of models are shown separately, because the availability of CO led to many more incomplete records. Motor vehicles would be the most common source for these pollutants, though ethane, which has very low chemical reactivity, could be transported over long distances and associated with natural gas extraction, and toluene could also be an industrial factor. **Error! Reference source not found.**7 shows the linear regression results with meteorological variables only for UTEP

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CAMS 12, with 34% of the variation in MDA8 associated with the model ("C12" notation removed):

MDA8 = 47.14 - 1.142\* WSR\_pm + 12.1 \* SIr\_Rad - 0.31 \* RH\_pm + 0.035 \* whereX

Where

- WSR\_pm = resultant wind speed miles / hour mean over four hours: 12 noon to 15
  MST
- Slr\_Rad = the one hour maximum solar radiation, langley / hour
- RH\_pm = relative humidity in percent mean over four hours: 12 noon to 15 MST
- whereX = the east (positive) / west (negative) location component in miles of an air parcel advected back in time 8 hours from 12 MST using only winds measured at CAMS 12.

Table 8 and Table 9 show the coefficients for the model equations for Ascarate CAMS 37 and Chamizal CAMS 41.

Root MSE	8.27	Obs. Used	1,175
Dependent Mean	52.32	Missing Values	106
R-Square	34.0%		
Adj R-Sq	33.6%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	47.140	2.587	18.22	<.0001
C12_wsr_pm	-1.142	0.116	-9.85	<.0001
C12_Slr_Rad	12.119	1.632	7.42	<.0001
C12_RH_pm	-0.311	0.048	-6.43	<.0001
whereX12	0.035	0.008	4.6	<.0001
C12_RH_am	0.039	0.034	1.14	0.254
C12_wsr_am	0.128	0.133	0.97	0.335
whereY12 -0.007	0.019	-0.34	0.731	
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 Table 7. Linear regression results of MDA8 on meteorological variables at UTEP CAMS 12

Root MSE	7.89	Obs. Used	1,242
Dependent Mean	46.91	Missing Values	29
R-Square	32.8%		
Adj R-Sq	32.5%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	38.423	2.792	13.76	<.0001
C37_wsr_pm	-0.890	0.072	-12.28	<.0001
C37_Slr_Rad	13.618	1.780	7.65	<.0001
C37_RH_pm	-0.249	0.044	-5.63	<.0001
whereX37	0.006	0.006	1.02	0.309
C37_RH_am	0.036	0.030	1.19	0.233
C37_wsr_am	0.134	0.096	1.4	0.162
whereY37	0.015	0.012	1.19	0.236

**Table 8**. Linear regression results of MDA8 on meteorological variables at Ascarate CAMS37

Root MSE	8.04	Obs. Used	1,156
Dependent Mean	51.01	Missing Values	125
R-Square	38.4%		
Adj R-Sq	38.0%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	50.440	2.582	19.54	<.0001
C41_wsr_pm	-0.760	0.078	-9.7	<.0001
C41_Slr_Rad	9.840	1.628	6.05	<.0001

C41_RH_pm	-0.355	0.046	-7.79	<.0001
whereX41	-0.034	0.006	-5.41	<.0001
C41_RH_am	0.014	0.033	0.42	0.678
C41_wsr_am	-0.074	0.103	-0.71	0.476
whereY41	0.011	0.016	0.72	0.469

<b>Table 9</b> . Linear r	egression resu	lts of MDA8	on meteorol	logical va	ariables at C	hamizal (	CAMS
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For all three models, the afternoon wind speed, afternoon relative humidity, and daily maximum solar radiation are important variables, as represented by the relatively large t values and small p-values. A p-value represents the probability that the absolute value of a t-value would be as large as it is if it really did not have a significant effect on the dependent variable MDA8, so when a p-value is small, we know the associated variable <u>is</u> statistically significant. At UTEP CAMS 12, the "whereX12" is statistically significant and the coefficient is positive, suggesting higher O<sub>3</sub> concentrations when the wind direction has persisted from the east. At Chamizal CAMS 41, the "whereX41" is statistically significant and the coefficient is negative, suggesting higher O<sub>3</sub> concentrations when the wind direction has persisted from the west. At Ascarate CAMS 37, the "whereX37" is smaller and not statistically significant. At none of the sites do the morning relative humidity or wind speed or north/south wind direction component (the "whereY" variable) seem to have any significant effect.

Three models of linear regression were employed in adding morning and afternoon mean concentrations of CO, ethane, and toluene. In the first, these species were simply added, with CO concentrations measured at each station and the ethane and toluene from the Chamizal auto-gas-chromatograph (AGC). In addition to the "where" variables, a one-hour wind direction value at 14 CST was added with u, v components to reflect the immediate upwind direction in Cartesian components. These steps had the effect of improving the model performance with adjusted R<sup>2</sup> values of 44 percent, 46

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percent, and 50 percent for UTEP C12, Ascarate C37, and Chamizal C41, respectively. As is noted below, MDA8 exceedances are slightly more likely on weekdays versus weekends in El Paso County, so a "day type" binary variable was added to the model. This had negligible effect on UTEP and Ascarate, but raised the adjusted R<sup>2</sup> to 52 percent at Chamizal. An examination of the statistical distributions of the variables led to the third model, in which logarithmic transformations were made of variables with skewed distributions. It is the nature of many variables we found to have lognormal statistical distributions, and a log transform preserves ordering but reduces the effect of high values in the original skewed distribution. The new model produced significantly better results, with adjusted R<sup>2</sup> values of 50 percent, 51 percent, and 58 percent for UTEP C12, Ascarate C37, and Chamizal C41, respectively Table 11 shows linear regression results of MDA8 on day type and log-transformed meteorological and pollution variables at Ascarate CAMS 37.Error! Reference source not found. The regression results with log-transforms, day type, and pollution variables are somewhat enlightening. At all three stations, the day type shows a statistically significant effect, with the negative parameter values indicating weekdays have higher MDA8 values than weekend. All three stations show positive associations with afternoon ethane concentrations, and Ascarate and Chamizal are affected by afternoon toluene concentrations, and UTEP and Chamizal are sensitive to afternoon CO concentrations. The one u, v wind direction components seem to have little effect.

Root MSE	7.52	Obs. Used	629
Dependent Mean	52.40	Missing Values	652
R-Square	50.6%		
Adj R-Sq	49.7%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	62.274	2.64082	23.58	<.0001

Day type	-1.617	0.71999	-2.25	0.0250
u12	0.106	0.12092	0.88	0.3802
v12	0.292	0.14480	2.02	0.0439
C12_wsr_pm	-8.098	0.68432	-11.83	<.0001
C12_SIr_Rad	-9.427	1.07639	-8.76	<.0001
C12_RH_pm	-4.697	0.62952	-7.46	<.0001
whereX12	-0.060	0.01824	-3.30	0.0010
whereY12	-0.060	0.02858	-2.12	0.0346
C12_co_pm	-0.015	0.00317	-4.79	<.0001
C41_toluene_pm	0.274	0.69959	0.39	0.6947
C41_ethane_pm	8.334	0.58783	14.18	<.0001

Table 10. Linear regression results of MDA8 on day type and log-transformedmeteorological and pollution variables at UTEP CAMS 12

Root MSE	6.64	Obs. Used	757
Dependent Mean	45.7	Missing Values	524
R-Square	51.5%		
Adj R-Sq	50.7%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	50.940	2.933	17.36	<.0001
Day type	-1.500	0.571	-2.62	0.0089
u37	0.201	0.095	2.12	0.0345
v37	0.269	0.101	2.65	0.0081
C37_wsr_pm	-7.519	0.463	-16.22	<.0001
C37_Slr_Rad	-13.555	1.197	-11.32	<.0001
C37_RH_pm	-3.150	0.612	-5.14	<.0001
whereX37	-0.064	0.013	-4.75	<.0001
whereY37	-0.058	0.016	-3.56	0.0004
C37_co_pm	0.002	0.004	0.56	0.5786
C41_toluene_pm	-1.702	0.599	-2.84	0.0046
C41_ethane_pm	5.722	0.529	10.80	<.0001

Table 11. Linear regression results of MDA8 on day type and log-transformedmeteorological and pollution variables at Ascarate CAMS 37

Root MSE	6.53	Obs. Used	779
Dependent Mean	50.0	Missing Values	502
R-Square	58,5%		
Adj R-Sq	57.9%		

Variable	Parameter estimate	Standard error	t Value	Pr >  t
Intercept	63.468	2.483	25.55	<.0001
Day type	-2.396	0.554	-4.32	<.0001
u41	-0.145	0.090	-1.61	0.1085
v41	0.126	0.111	1.14	0.2561
C41_wsr_pm	-7.768	0.469	-16.56	<.0001
C41_SIr_Rad	-8.220	0.881	-9.32	<.0001
C41_RH_pm	-5.723	0.540	-10.58	<.0001
whereX41	-0.073	0.012	-5.81	<.0001
whereY41	-0.044	0.018	-2.38	0.0174
C41_co_pm	0.017	0.006	2.67	0.0077
C41_toluene_pm	-1.850	0.604	-3.06	0.0023
C41_ethane_pm	6.215	0.498	12.48	<.0001

 Table 12. Linear regression results of MDA8 on day type and log-transformed

 meteorological and pollution variables at Chamizal CAMS 41

As was noted above, assessment of the frequency with which MDA8 exceedances occur on Monday through Friday (weekdays) as opposed to Saturday and Sunday (weekends) may be an indication of the strength of local sources on O<sub>3</sub> concentration. Because the weekday motor vehicle use pattern is such that more vehicles are on the road in the early morning rush hour,more vehicle emissions may be present in the period in which concentration accumulate under the night/early morning temperature inversions. This means higher concentrations of O<sub>3</sub> precursors may be available on weekdays for photochemical reactions leading to local O<sub>3</sub> formation. On weekends, vehicle trips are generally concentrated more heavier midday when the mixing height of the lower atmosphere has risen and pollutant concentration are lower owing to greater dilution. **Error! Reference source not found.**Figure 38 shows the frequency with which MDA8 O<sub>3</sub> exceedances occur on weekdays, which are 71 percent of all days, for nine of the ten TCEQ

regions with ozone monitoring. (The Laredo Region has only one exceedance day and thus not useful in this comparison.) The graph suggests that El Paso (74 percent) is in the bottom one third among the regions, with a relatively weak day of the week effect, despite the regression results. This could be an indication that regional and transport factors are relatively more important regrading El Paso than in other large Texas urban areas.



**Figure 38.** The frequency with which MDA8 exceedances occur on Monday through Friday, which are 71% of all days, 9 TCEQ regions

### 3.3 Simulations

WRF or Weather Research Forecast Model is a community numerical weather prediction model developed by a collaborative partnership of different scientific institutes like National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), and National Center for Environmental Protection (NCEP), etc. This model is a next generation mesoscale NWP system which is designed for both atmospheric research and operational forecasting applications. It contains two computational or dynamical cores known as Advanced Research WRF or ARW and Nonhydrostatic .





Figure 39. Domain Configuration

Parameter	Description	
Period	2013-2019	
Initial Condition Meteorology	GFS-ANL 0.5 degree	
Vertical Levels/Eta Levels	35	
Horizontal Grids	172*172	
Time Steps	180s,180s,180s	
Microphysics	WSM or WRF single moment	
Planetary Boundary Layer	YSU (Yonsei University)	
Cumulus Parametrization	Kain-Fritsch scheme	
Shortwave and Longwave	RRTM Longwave Scheme	
Land Surface	Noah Land surface Scheme	
Surface Layer Option	Monin Obukhov Similarity Scheme	
Projection	Lambert	
Boundary Condition Meteorology	GFS-ANL 0.5 degree	

 Table 13. WRF model Description

We used three model domains with two-way nesting condition (Fig 39). The outermost domain, D01, covers the Whole United States with the adjacent countries, including the North Pacific Ocean on the West side and the Gulf of Mexico and Caribbean Sea on south. The intermediate domain, D02, is focused on the mesoscale simulation, which covers neighboring states of Texas and also Mexico in the southern part. The smallest domain, which is denoted by D03, is focused on our research area of interest which is The Paso Del Norte region, comprised of El Paso city, some of the counties from New Mexico State and Juárez city in Mexico. We executed the simulations for the 96-hour interval run, where first 72 hours were the spin-up or warm-up run, and the next 24 hours were our simulation day.

WRF version 3.9.1 was used for the simulation with ARW (Advance Research WRF) core. Grid nudging was switched on for every domain and the simulation was restarted every 1440 minutes, which is 24 hours.

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**Plots:** 

We plot 3 different domains for our desired scale analysis. Domain 1 represent the Synoptic scale meteorological analysis, Domain 2 covers the mesoscale analysis and Domain 3 covers the Local scale meteorology. We plotted the Contour map on the domain using Sea level pressure (hPa), Surface temperature (Fahrenheit) and Winds (Knots). We choose representative high ozone day from each year 2013-2017.

#### Format:

do1 = Domain Number, 2013-08-17 = Date of Simulation, 06\_00\_00 = Starting time (UTC) August 17, 2013



### wrfout\_d01\_2013-08-17\_06\_00\_00.nc

From the domain 1 contour plot, as we can see, the Pacific Ocean (East side), Gulf of Mexico (North side) has low pressure area compare to the land area of United States. Also,

we can see a north western originated wind flow coming to the south bound way. In terms of temperature, the land area of US has higher values compared to the other part of this synoptic map.



wrfout\_d02\_2013-08-17\_06\_00\_00.nc



wrfout\_d03\_2013-08-17\_06\_00\_00.nc

July 15, 2014:



### wrfout\_d01\_2014-07-15\_06\_00\_00.nc

This domain depicts the same information regarding the synoptic plots. However, in domain 2 and 3, we can visualize the wind flow as it is northerly winds. In domain 2, the northern part of the map has higher magnitude in terms of surface temperature and also sea level pressure. Moreover, the south west part of Texas has low pressure area with higher in temperature as it is demonstrated in domain 3.



wrfout\_d02\_2014-07-15\_06\_00\_00.nc

Figure 44. Domain 2

wrfout\_d03\_2014-07-15\_06\_00\_00.nc

Surface Temperature (degF) Sea Level Pressure (hPa) Wind (kts) H1023 90 34°N 85 80 75 70 33°N 65 60 55 50 45 32°N 40 35 30 25 20 31°N 15 10 5 0 -5 30°N -10 -15 -20 106°W 109°W 107°W 105°W 108°W 104°W

Figure 45. Domain 3



## wrfout\_d01\_2015-08-10\_06\_00\_00.nc

All of those dates correspond to the summer season, which resulted in the average temperature of more than 80 degrees Fahrenheit. We can see the wind direction is flowing counter-clockwise in a low-pressure area while it is in a clockwise direction in a High-pressure area. In the local scale domain, the north east part of Texas exhibits high pressure area with higher temperature. Wind directions are westerly as they are originated from the west and flowing towards the east.



wrfout\_d02\_2015-08-10\_06\_00\_00.nc

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# wrfout\_d01\_2016-08-08\_06\_00\_00.nc

Northerly winds with medium magnitude flowing towards United States. At the mesoscale level, winds are flowing in the direction originated from the north eastern direction. High pressure areas are depicted in southern part of Texas and also in Mexico.



## wrfout\_d02\_2016-08-08\_06\_00\_00.nc

wrfout\_d03\_2016-08-08\_06\_00\_00.nc



Figure 51. Domain 3



In the Paso del Norte region, winds are flowing towards the south direction with medium magnitude. We can see a low pressure area at the north eastern part of Mexico. The temperature is around 80 degrees for the Paso del Norte region.



Figure 54. Domain 3



2017-06-05\_18:00:00





2017-06-05\_06:00:00





Figure 55. (a-e) Wind barbs for a high ozone day with a 6 hour interval

Detailed knowledge of wind speed and direction is essential if the gas phase and aerosol pollution measurements are to be linked to specific local sources, source regions, or general flow regimes. In most cases, because the local transport is assumed to occur near the surface, the wind speed and direction measured with different methods (radiosonde, NWP models, and wind profiler) are used. (Gilman et al. 2009, Bates et al. 2008). In the above figures, we can clearly see in an arbitrary high ozone day, the winds are flowing from the north east part of USA with the medium magnitude. We plotted the wind direction during the day and it indicates the same wind pattern for 24 hours which resemble with the wind roses of CAMS 12.

#### Analysis and Conclusion for this section:

It has long been known that one of the key meteorological situations to create ozone in urban areas and/or their downwind neighbors are stagnant, low winds (to "trap" secondary pollutants nearby) and clear skies (plenty of solar radiation) that develop higher ozone mixing ratios over a period of two to three days. Certainly, regardless of the sky conditions or the temperature, high winds will prevent significant ozone formation (Banta et al. 2005; Camalier et al. 2007). The large-scale winds during the summer months in the southeastern United States are sometimes dominated by a strong subtropical anticyclone centered at or to the east of the Atlantic coast of the United States (J Nielson, 2002). Accordingly, the large-scale winds along the Texas coastline, which lies under the western branch of this high-pressure system, are southerly, persistent, and stronger than the amplitude of the sea breeze cycle. As a result, the winds in at least the lowest several hundred meters of the atmosphere or the lower troposphere have a southerly component during both the day and night (Sara et al. 2010). Continental air flow brings air masses that typically have higher levels of Ozone than air masses flowing from the Gulf of Mexico.

### Future Work:

- Cluster analysis of hourly averaged surface winds from Paso del Norte region:
- Retrieving the wind amplitude and direction and divide them into different wind patterns while keeping track of maximum ozone in these areas can yield promising results. Various wind patterns like thermally driven flows, stagnant winds, thunderstorm outflow etc.
- Regional Ozone background can be determined by applying extensive statistical approach like Principal Component analysis or Variability reduction:

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- Establish a relationship with the Planetary boundary layer and aerosol concentration especially ozone to determine contributing factors like emission or poor ventilation (Rappenglück et al., 2008; Langford et al., 2009)
- Influence of Nocturnal Low level jets on forming the Ozone.

### 3.4 Meso-Scale Effects on Ozone Concentrations

HYSPLIT back trajectories of 48-hour duration from three starting altitudes over central El Paso have been run for the 57 days with MDA8 at or above 70 ppb in recent years. Trajectories were 48-hour back trajectories from the O<sub>3</sub> station centroid shown in **Error! Reference source not found.** at 50 m, 100 m, and 300 m above ground level (AGL) at 12 noon MST (19 UTC). These altitudes were selected to represent the lower levels in the troposphere through which the air mixes vertically midday, although mixing does occur up to higher altitudes. These have been mapped with the one hour time step "end points" from the trajectories shown in the "spaghetti" plot in **Error! Reference source not found.** Using these end points, a density graph of the number of points per unit area appears in Figure 57 and a contour map of the densities appears in **Error! Reference source not found.**.

As a second step, HYSPLIT back trajectories at the three starting altitudes have been run for a *random* selection of 57 days with MDA8 <u>below</u> 70 ppb. The 57 random dates were selected to have the same month/day values as the exceedance days, but in different years among the 2013 – 2019 period so as to have a similar distribution of number of days within the spring/summer months in the two 57 day data sets. A density graph of points and contour map of the end point dentistry appear in **Error! Reference source not found.** and **Error! Reference source not found.**. The random day end points are more spread out over the bi-national/multi-state region than the high MDA8 end points. This suggests that the upwind meso-scale directionality is important, and the easterly winds, extending into the Permian Basin region in Texas, likely play a role in higher MDA8. This approach is expanded on in the next section



**Figure 56.** HYSPLIT 48 hour back trajectories on 57 O<sub>3</sub> exceedance days, 2013 – 2019, starting from center of monitoring network, noon MST, 3 altitudes (50, 100, 300 m AGL)



**Figure 57.** High ozone back trajectory grid square density points > 50 and < 200 miles from El Paso



**Figure 58.** High ozone day back trajectory contouring points > 50 and < 200 miles from El Paso



Figure 59. Random day back trajectory grid square density points > 50 and < 200 miles from El Paso



Figure 60. Random summer back trajectory contouring points > 50 and < 200 miles from El Paso

In order to probe the possibilities of meso-scale to synoptic-scale transport affecting El Paso, a more rigorous potential source contribution function analysis was performed. The potential source contribution function (PSCF) is a conditional probability function to estimate possible upwind source area using back-trajectories. The PSCF is related to residence time analysis in that it is based on the passage of back trajectories through upwind areas; however, PSCF is based on the *ratio* between the number of back trajectory endpoints in a specific upwind area on high ozone days to the number of back trajectory endpoints in the specific upwind area using all days. In this application, rather than using the 57 MDA8 exceedance days, the threshold for "high O<sub>3</sub>" was lowered to 65 ppbv, for which 177 days were available. Also, in this application, all trajectories were run at a larger scale, running 120 hours (5 days), using May through September, 2013 – 2019, starting every day at noon MST (19 UTC) from three altitudes – 100m, 500m, and 1000m AGL. Trajectory end points were filled in by linearly interpolated in between the one hour time step trajectory end points increasing the number of points. In several applications of PSCF, the researchers use 1 deg. latitude by 1 deg. longitude gridding. A shortcoming of this is that at 30 deg. latitude, a degree of longitude is 59 miles wide and a degree of latitude is 69 miles wide. Several approaches at different scales were applied to use smaller square grids, but the simple 1 deg. longitude × 1 deg. latitude was found to be satisfactory.

The PSCF is defined as PSCF(i,j) = m(i,j) / n(i,j), where n(i,j) is the total number of back-trajectory endpoints in cell (i,j), and m(i,j) is the number of back-trajectory endpoints in cell (i,j), on the days that El Paso MDA8 exceeded the threshold of interest (65 ppbv). In this application, each cell is an area centered on an integer longitude, latitude - e.g., -102 deg., 34 deg., - bounded by the four corners

- -102.5, 33.5
- -101.5, 33.5

- -101.5, 34.5
- -102.5, 34.5

This is achieved simply by rounding each back-trajectory endpoint to the closest integer longitude, latitude.

A serious issue with PSCF is that as one moves farther from the starting point, the density of back trajectory endpoints drops, and care is needed in interpreting results. If there is a small number of total points at an integer longitude, latitude, and a few high MDA8 endpoint points, then the PCSF may be high, but not statistically or practically valid. An approach taken by researchers (cite all references) is to scale the PCSF based on the number of total endpoints at an integer longitude, latitude. Since the approach taken in this study used days May through September, 2013 through 2019, this involves 1,070 days over 7 years, with 3,600 points per day (120 hours, 3 starting altitudes, 10 interpolations steps), there would be 3.9 million total points, but with the 80 mile to 800 mile cutoffs there are 2.7 million, and 540 integer longitude, latitude points, with approximately 5,000 points per integer longitude, latitude on average. Following other published studies, PSCFs were discounted based on the count of endpoints at integer longitude, latitudes integer longitude, latitudes at integer longitude, latitudes at integer longitude, latitudes at integer longitude, latitudes the studies integer longitude, latitudes on average. Following other published studies, PSCFs were discounted based on the count of endpoints at integer longitude, latitudes (n\_pts\_all\_days) being fewer than the average number of endpoints as follow:

If 5,000 >= n\_pts\_all\_days > 500 then PSCF = 0.70 × PSCF; Else if 500 >= n\_pts\_all\_days > 50 then PSCF = 0.40 × PSCF; Else if n\_pts\_all\_days <= 50 then PSCF = 0.10 × PSCF;

Figure 61 is a grid map showing the number back-trajectory endpoints between 80 and 1,200 miles of El Paso. The general pattern reflect the topography of the region, with winds in the lower troposphere generally moving east-west in the summer months. Figure 62 is a grid map restricted to the days with MDA8 greater than or equal to 65 ppbv, using 177 days, showing the number back-trajectory endpoints between 80 and 1,200 miles of El Paso. The gross comparison to the first figure suggests few westerly winds on high MDA8 days. These gridded graphs hide the fact that although there may be relatively fewer endpoints in the lighter colored portions, there may be a relatively higher percentage of high MDA8 endpoints in some of those lighter colored area than expected. This is illustrated by Figure 63 and Figure 64, which show the gridded PSCF in Figure 63, and a kriging contouring map with state and Texas county boundaries shown to provide geographic references in Figure 64. Note that the range of grids in Figure 63 and 64 are restricted to between 80 and 800 miles of El Paso.

Despite the weighting scheme, there are hot spots in New Mexico, Colorado, Arizona, and Oklahoma. Eastern New Mexico does have many natural gas wells. More important, however, are the more frequently upwind areas in West Texas, and the oil and gas regions South Texas to the Gulf Coast.



**Figure 61.** Gridded back trajectory grid density points > 80 and < 1,200 miles from El Paso, all days May - September 2013 – 2019, trajectories run from 12 noon MST (19 UTC) 100 m, 500m, and 1,000 m AGL, averaged to 1 deg. long. × 1 deg. lat.



**Figure 62.** Gridded back trajectory grid density points > 80 and < 1,200 miles from El Paso, 177 days with MDA8 >= 65 ppbv, May - September 2013 – 2019, trajectories run from 12 noon MST (19 UTC) 100 m, 500m, and 1,000 m AGL, averaged to 1 deg. long. × 1 deg. lat.



**Figure 63.** Gridded PSCF values for grids > 80 and < 800 miles from El Paso, 177 days with MDA8 >= 65 ppbv, May - September 2013 – 2019, trajectories run from 12 noon MST (19 UTC) 100 m, 500m, and 1,000 m AGL, averaged to 1 deg. long. × 1 deg. lat.



**Figure 64.** Potential source contribution function for O3 in El Paso, May - September 2013 – 2019, trajectories run from 12 noon MST (19 UTC) 100 m, 500m, and 1,000 m AGL, 1 deg. long. × 1 deg. lat., 80 mile to 800 miles from El Paso

## 3.5 Synoptic-Scale Effects on Ozone Concentrations

The data used to analyzed was obtained from the following Data Centers:

The sounding from the Plymouth State University weather center

(https://vortex.plymouth.edu/myo/upa/raobplt-a.html)

The surface analysis from the NOAA weather prediction center (https://www.wpc.ncep.noaa.gov/archives/web\_pages/sfc/sfc\_archive.php)

The upper air from the NOAA storm prediction center (<u>https://www.spc.noaa.gov/obswx/maps/</u>).

We observed a high-pressure ridge at synoptic scales outside the County of El Paso. In what follows we present three representative high ozone days.

High Ozone Days, from 2013-2019, were examined using the 500 mb synoptic upper air data, we present 3 cases:



Figure 65. Maximum and Minimum avg. Temp of Synoptic Scale



Figure 66. July 03 Synoptic scale map at 7 AM



**500-Millibar Height Contour at 7:00 A.M. E.S.T. Figure 67.** Zoomed version of July 3<sup>rd</sup> Synoptic plot

June 06, 2017



Figure 68. Maximum and Minimum avg. Temp of Synoptic Scale



Figure 69. June 06, 2017 Synoptic scale map



500-Millibar Height Contour at 7:00 A.M. E.S.T. Figure 70. Zoomed version of Figure 65
# July 29, 2018





Figure 72. July 29, 2018 Synoptic scale map



500-Millibar Height Contour at 7:00 A.M. E.S.T. Figure 73. Zoomed version Figure 68.

We have observed that on most of our high ozone days, the synoptic scale conditions show a high pressure aloft.

# 3.6 Stratospheric Intrusion Case Studies

Examples of synoptic scale influences on air quality in Texas and the U.S. are well documented with the long distance transport of North African dust that is advected across the Atlantic Ocean and deposited across the U.S. Southern States most, if not all summers, smoke from agricultural burning in Southern Mexico and Central America that affects the Gulf Coast region with elevated fine particulate matter most, if not all springs, and boreal forest fires in Canada have contributed measurable carbon monoxide concentrations in Midwestern U.S. states. For this project, one form of synoptic scale influence being investigated is intrusion of stratospheric O<sub>3</sub> transported in Paso del Norte. Stratospheric intrusions occur when stratospheric air moves dynamically to the troposphere, reaching

the surfaces and causing high levels of ozone. There is a good illustration of stratospheric folding at

https://gmao.gsfc.nasa.gov/research/composition/modeling/stratospheric\_intrusi ons/ (accessed October 2020).

Stratospheric intrusion is known to affect the U.S. Southwest in the springtime months. Based on this, efforts have been focused on MDA8 exceedances in April, May, and June. Only one El Paso exceedance day over the 2013 – 2019 period has occurred in April, and a handful of exceedance days have occurred in late June after the summer solstice, which are still being included for consideration.

From the https://gmao.gsfc.nasa.gov website cited above, relative to clean tropospheric air, clean stratospheric air has lower carbon monoxide (CO) concentrations, and is dryer than surface air. Three forms of data analyses have been employed to look for indications of stratospheric intrusion. First, changes within a day for large drop in carbon monoxide and relative humidity with increased O<sub>3</sub> could signal downward air movement of a stratospheric intrusion. Such an instance has not been identified. Second, an examination of the residuals from the linear regressions may show cases of large positive differences in observed versus predicted MDA8, which could be a result of transported O<sub>3</sub>. Lastly, in the case of observed MDA8 exceedances, the HYSPLIT back trajectories can be examined for modelled altitudes going to very high heights. So, for example, consider 4. This is a graph of the altitudes for HYSPLIT back-trajectories on the MDA8 exceedance days in April, May, and June from 2013 through 2019, started at 12 noon MST from 100 m, 500 m, and 1,000 m AGL and run for 120 hours (5 days). GDAS 1-3-dimensional wind field data files found degree at (ftp://arlftp.arlhq.noaa.gov/archives/gdas1/) were used to generate the HYSPLIT trajectories. These trajectories are higher in altitude and for a longer period compared to the ones shown earlier for meso-scale study. Error! Reference source not found. shows that on a few occasions, back trajectories rose above 5,000 m, and on three dates rose above 8,000 m AGL: June 10, 2014, and June 4 and 6, 2017. On Tuesday, June 10, 2014,

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eight out of 11 monitoring stations in El Paso and Dona Ana counties recorded MDA8 greater than or equal to 70 ppb, with exceedance values from 70 to 76 ppb. The June 4 and 6, 2017 dates are part of the four MDA8 exceedance days in a row, from Sunday, June 4 – Wednesday June 7, 2017.



**Figure 74.** Altitudes AGL associated with 120 hr back trajectories from El Paso, exceedance days in April, May, June 2013 - 2019

### Tuesday June 10, 2014 Case Study

**Error!** Reference source not found. through 78 show the hourly data for O3, carbon monoxide (CO), and relative humidity for June 10, 2014, at four monitoring stations that measure all three of these parameters. On this day, three El Paso stations – Chamizal, UTEP, and Skyline Park – had MDA8 exceedances of 71, 73, and 71 ppb, respectively, and five Dona Ana stations also had exceedances. On this date, it is the case that relative humidity drops, but as **Error! Reference source not found.** shows, the mean relative humidity also follows a diurnal pattern with higher percentages in the morning and lower percentages in the afternoon, and a comparison of the values on June 10 to the means for June overall show that the change on June 10 over the course of the day is typical and

does not support local drier than usual air present in the afternoon. Error! Reference source not found. shows the surface weather map for the U.S. on June 10, 2014 at 18 UTC (11 MST). It shows high pressure to the east and low pressure to the southwest, which suggests winds would be advected from the southeast to the northwest to Paso del Norte along the Rio Grande/Rio Bravo del Norte. However, as shown in three images of HYSPLIT 120-hr back trajectories from El Paso in Error! Reference source not found., Error! Reference source not found., and Error! Reference source not found., air movement occurred from both the southeast at low altitudes and from the north and west at higher altitudes. Sheering in the lower atmosphere is common. Winds blow from high pressure to low pressure, and these highs and lows can exist at different altitudes. Topographic features such as mountains also can have effects on direction at lower altitudes. This is demonstrated using the "ensemble trajectory" option using 500 m, 1,000 m, and 1,500 m starting points, with more southeasterly flow starting with 500 m and more north and west flow at increasing altitude. The "ensemble" method is described by NOAA as follows:

The trajectory ensemble option will start multiple trajectories from the first selected starting location. Each member of the trajectory ensemble is calculated by offsetting the meteorological data by a fixed grid factor (one grid meteorological grid point in the horizontal and 0.01 sigma units in the vertical). This results in 27 members for all-possible offsets in X, Y, and Z. Note: the starting height should be greater than 250 m for optimal configuration of the ensemble.

(https://www.ready.noaa.gov/hypub-bin/trajtype.pl?runtype=archive accessed July 2020).

In the HYSPLIT figures, the time history in UTC for altitude appears at the bottom of the map. Each shows subsidence in air parcel height on June 9 and on June 8. Error! Reference source not found. shows a graph of the radar wind profiler at Fort Huachuca in

Southern Arizona on June 9 - 10. The Ft Huachuca upper air measurements indicate downward air movement hours 3, 4 and 6 UTC on June 10 in the center of Fig. 84, where the wind barbs are vertical, indicating downward air flow. These data support a hypothesis that stratospheric air intruded in the troposphere to the west and was transport east to Paso del Norte to affect surface O3 on June 10. Admittedly, the regressions are much weaker than similar modeling in East Texas. Nevertheless, the regressions are statistically significant and of practical value.

Finally, as was noted earlier about comparing regression predictions to observed MDA8 values provides additional evidence.

- For UTEP CAMS 12, with 1,175 observations ranked based on magnitude of residuals, June 10, 2014 ranks 40th with a predicted value of 57 ppb and a measured MDA8 of 73 ppb.
- For Chamizal CAMS 41, with 1,157 observations ranked based on magnitude of residuals, June 10, 2014 ranks 36th with a predicted value of 55 ppb and a measured MDA8 of 71 ppb.
- For Ascarate CAMS 37, with 1,252 observations ranked based on magnitude of residuals, June 10, 2014 ranks 89th with a predicted value of 54 ppb and a measured MDA8 of 65 ppb.



Figure 75. UTEP CAMS 12 hourly data for O<sub>3</sub>, CO, and relative humidity, June 10, 2014



Figure 76. Ascarate CAMS 37 hourly data for O<sub>3</sub>, CO, and relative humidity, June 10, 2014



Figure 77. Chamizal CAMS 41 hourly data for O<sub>3</sub>, CO, and relative humidity, June 10, 2014



Figure 78. Ivanhoe CAMS 414 hourly data for O<sub>3</sub>, CO, and relative humidity, June 10, 2014



Figure 79. Mean relative humidity at three stations month, morning & afternoon



Figure 80. National weather map June 10, 2014, 18 UTC



Figure 81. Ensemble 120 hr back trajectories El Paso, 500 m AGL, June 10, 2014, 12n MST start



Figure 82. Ensemble 120 hr back trajectories El Paso, 1,000 m AGL, June 10, 2014, 12n MST start



Figure 83. Ensemble 120 hr back trajectories El Paso, 1,500 m AGL, June 10, 2014, 12n MST start



Figure 84. Radar Wind Profiler data from Ft. Huachuca, AZ, 230 miles west of El Paso, TX

#### June 4 – 7, 2017 Case Study

**Error! Reference source not found.** shows a time series of 5-minute time resolution O<sub>3</sub> data from the six El Paso O<sub>3</sub> stations for June 1 through June 11, 2017. This period featured MDA8 O<sub>3</sub> exceedances from Sunday June 4 through Wednesday June 7, and exceedances in both El Paso and Dona Ana counties.

through **Error! Reference source not found.** show the five-minute time scale data for O<sub>3</sub> at El Paso stations for each of the four days. It is interesting to note the elevated O<sub>3</sub> overnight between June 5 and June 6, 2017, which may have been caused by recirculation of the June 5 O<sub>3</sub> back into the area overnight. This was determined by examining the surface wind data from TCEQ LEADS for the two dates. **Error! Reference source not found.**, **Error! Reference source not found.**, and **Error! Reference source not found.** show O<sub>3</sub>, and relative humidity for June 4, 2017 at UTEP, Ascarate, and Chamizal, with carbon monoxide include at Ascarate. As was the situation in the earlier case study the change in relative humidity on June 4, 2017 over the course of the day is typical and does not support local drier than usual air present in the afternoon.

**Error! Reference source not found.** through **Error! Reference source not found.** show the weather maps for the U.S. for June 4 through June 7, 2017. The period begins with high pressure to the north and low pressure to the southwest in California, which suggests winds would be advected from the southeast to the northwest to Paso del Norte along the Rio Grande/Rio Bravo del Norte. Later, high pressure persists over much of the area, which is generally associated with stagnation. On the afternoon of June 5, wind speeds in El Paso were low, ranging between 0 to 6 miles per hour. **Error! Reference source not** 

**found.** and **Error! Reference source not found.** show HYSPLIT 120-hr back trajectories from El Paso on Sunday June 4, 2017. **Error! Reference source not found.** shows three altitude starts and **Error! Reference source not found.** is an ensemble map described earlier. Following these two figures there are images in **Error! Reference source not found.** to **Error! Reference source not found.** of the two types of plots – three discrete starting altitudes plot and an ensemble starting plot – for June 5, 6, and 7. The combination of plots suggest that O<sub>3</sub> may have been transported into the area with high altitude O<sub>3</sub> having been contributed over the U.S.A. western states or the Pacific Ocean. Subsequently, stagnant air in the region allowed the formation and accumulation of O<sub>3</sub> with recirculation within the region. On June 6, again it is possible that a contribution of stratospheric O<sub>3</sub> could have been introduced to the incoming air over the Pacific Ocean. As noted earlier, there are some indications of stratospheric ozone accompanied by low H<sub>2</sub>O and CO in El Paso, but data from outside Texas and New Mexico were not accessed to examine far upwind surface.



Figure 85. Time series of 5-minute time resolution  $O_3$  data from the El Paso stations June 1 – 11, 2017





Figure 90. UTEP CAMS 12 hourly data for O3 and relative humidity, June 4, 2017



Figure 91. Ascarate CAMS 37 hourly data for O<sub>3</sub>, CO, and relative humidity, June 4, 2017



Figure 92. Chamizal CAMS 41 hourly data for O<sub>3</sub> and relative humidity, June 4, 2017



Figure 93. National weather map June 4, 2017, 18 UTC



Figure 94. National weather map June 5, 2017, 18 UTC



Figure 95. National weather map June 6, 2017, 18 UTC



Figure 96. National weather map June 7, 2017, 18 UTC



Figure 97. Three 120 hr back trajectories El Paso, 1,000 m AGL, June 4, 2017, 12n MST start



Figure 98. Ensemble 120 hr back trajectories El Paso, 1,000 m AGL, June 4, 2017, 12n MST start



Figure 99. Three 120 hr back trajectories El Paso, 100m, 500m, 1,000m AGL, June 5, 2017, 12n MST start



Figure 100. Ensemble 120 hr back trajectories El Paso, 1,000 m AGL, June 5, 2017, 12n MST start



Figure 101. Three 120 hr back trajectories El Paso, 100m, 500m, 1,000m AGL, June 6, 2017, 12n MST start



Figure 102. Ensemble 120 hr back trajectories El Paso, 1,000 m AGL, June 6, 2017, 12n MST start



Figure 103. Three 120 hr back trajectories El Paso, 100m, 500m, 1,000m AGL, June 7, 2017, 12n MST start



Figure 104. Ensemble 120 hr back trajectories El Paso, 1,000 m AGL, June 7, 2017, 12n MST start

## Analysis and Conclusions

Isolated cases of stratospheric intrusion of ozone may have contributed to exceedances of the 70 ppb ozone NAAQS on a small number of exceedance days. The correlation of elevated ozone and carbon monoxide and weekdays suggests local emission sources are also important. Analysis of 48-hour back trajectories suggest that on a meso-scale, the oil and gas regions in West Texas are likely contributors to El Paso and Dona Ana county ozone, and this may be the most significant result of this analysis. Overall, a combination of factors at local, regional, and synoptic scales contribute to the ozone concentrations measured in Paso del Norte.

Additional work to consider includes looking more for more detailed information with the Dona Ana data. It would be valuable to examine the "random day" meso-scale

back trajectories to see if on higher MDA8 days, whether trajectories were more likely to match the exceedance day trajectories. Also, more trajectories could be run on the Dona Ana County exceedance days which were not El Paso exceedance days. It is also the case that trajectory results could be used in the regression analysis. In previous work, UT showed that the "closest point of approach" of a multi-day back-trajectory from Dallas with Houston was statistically significant for predicting higher peak O<sub>3</sub> in Dallas.

# 3.7 Modeling study of surface ozone source-receptor relationships for the PDN Region

The main goal of this research was to perform a comprehensive ozone study by applying an Eulerian photochemical dispersion model, Comprehensive Air Quality Model with Extensions (CAMx), to simulate high ozone episodes occurring in June, 2017 over the region of El Paso, TX/Ciudad Juárez, Mexico and to evaluate the impact of various anthropogenic/biogenic emissions and boundary/initial conditions on ozone concentrations. The cases chosen were based on the data availability.

The tropospheric formation of ozone is formed through photochemical reactions of the nitrogen oxides (NOx = NO + NO2) and volatile organic compounds (VOCs). O3 plays an important role in controlling the chemical composition and climate of the troposphere and harms vegetation and human health, especially in industrialized regions (Kleinman et al., 2002). El Paso is located in the far west corner of Texas, separated only by the Rio Grande River from the Mexican city of Juárez, which is one of the most populous cities in the Mexican state of Chihuahua and is surrounded by the Chihuahua desert. These two cities share the same airshed, the El Paso–Juárez airshed, and in the past, both have violated their air quality standards for ground-level ozone (Karle et al., 2020). Ozone episodes in El Paso-Juárez airshed are known to be partially due to contributions from industrial activities in the region, and to high emissions from automobiles due to prolonged traffic congestion across the international bridges between the two countries. The concentration of ozone is influenced by long range transport of ozone and its precursors. On the other hand, the role of VOC and NOx from various source emissions (i.e., anthropogenic and biogenic emissions) in the formation of ozone is complex and it becomes a big challenge to set up effective local/regional emission reduction strategies to mitigate the regional-scale ozone problem (Wang et a., 2008). Developing effective ozone control strategies must consider the complexity of ozone format processes which can only be simulated by sophisticated three-dimensional Eulerian models (Farooqui et al., 2013). Currently, the development of an ozone attainment strategy involves many simulations with the photochemical grid model to determine which source regions, source categories, and emission types (i.e., VOC and NOx) must be controlled to reduce ozone most effectively. Quantitative source-receptor relationships are important information when considering effective strategies. There are two major indicators representing source-receptor relationships (Clappier et al., 2017). One is source sensitivity, which corresponds to a change in ambient pollutant concentrations caused by a certain perturbation in precursor emissions. The second is source apportionment, which corresponds to the contribution of precursor emissions to ambient pollutant concentrations (Chatani et al., 2020). There are some techniques developed for regional transport models to evaluate source sensitivities and apportionments (Dunker et al., 2002; Cohan and Napelenok, 2011). A simple technique for evaluating source sensitivities is the brute force method (BFM). Differences in the simulated pollutant concentrations between two simulation cases with and without perturbations in the input precursor emissions is considered as the sensitivity of a given emission source based on the BFM. This technique can require significant computational demand when evaluating the sensitivities of many emission sources (Chatani et al., 2020). Another approach, called the "on-line tracer-tagged" method, calculated the contribution of chemically created ozone inside specified regions to the modeling domain. This

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approach facilitated assessment of contributions from different regions to ozone concentration. The ozone source apportionment technology (OSAT) (Dunker et al., 2002) is a technique that evaluates the source apportionments of ozone concentrations by tagging contributions of precursor emissions to simulated concentrations. In this study, we applied an Eulerian photochemical dispersion model, Comprehensive Air Quality Model with Extensions (CAMx), to simulate high ozone episodes occurring in June 2017 over the region of El Paso, TX/Ciudad Juárez, Mexico in order to evaluate the impact of various anthropogenic/biogenic emissions and boundary/initial conditions on ozone concentrations. The CAMx is a state-of-the-science model system, publicly available model for urban and regional simulations of ozone formation in the lower troposphere.

#### Methodology

In this study, the version of CAMx V7.0 was used (ENVIRON 2020). The CAMx model requires a meteorological model to produce meteorological fields and an emissions processing system (Stockwell et al., 2013). The emissions are processed with the Sparse Matrix Operator Kernel Emissions (SMOKE, version 4.7; Houyoux et al. 2001). The SMOKE model is used to convert the source-level emissions (county total emissions) reported on a yearly basis to model-ready emissions that spatially resolved, hourly and aggregated into model species. The meteorological model used is the Weather Research and Forecast model (WRF, version 3.9; Skamarock et al. 2001).

In this project, the map projection is the Lambert Conformal, centered at the city of El Paso, TX. The WRF model meteorological results output at hourly intervals. The data incorporated into the WRF model as initialization and lateral boundary conditions are obtained from NCEP Final Analysis (FNL) dataset with a 6-h interval. This is the global dataset in the format of the grid with the resolution of 1×1°. Initialization for three domains were obtained through interpolation from NCEP Final Analysis (FNL) dataset (FNL) dataset for NCEP Final Analysis (FNL) dataset in the format of the grid with the resolution of 1×1°.

outer domain was produced from FNL while lateral boundary conditions for two inner domains were obtained from real-time results of outer domain. The fourdimensional data assimilation (FDDA) technique was applied to the WRF simulations. The emission inventory used in this study is the U.S. Environmental Protection Agency's (EPA) National Emission Inventory released originally in 2014 (NEI14) (US EPA, 2014), available from https://www.epa.gov/air-emissionsinventories/2014-national-emissions-inventory-nei-data. Since the modeling domain includes both USA and Mexico, the latest released Mexico emission dataset (Mexico NEI, https://drive.google.com/drive/u/0/folders/1lhlfOYn6Az-UZ37w\_kwYQH0-GUJ0F7V5) obtained from Community Modeling and Analysis System (CMAS) Data Warehouse, as the supplementation for NEI14.

The CAMx model is run over a three-nested domain configuration with 36-, 12- and 4-km resolutions for coarse, middle and fine domains respectively (Fig. 105). The coarse grid number is 82x94 (2950 x 3380 km) and covers most of continental US. The second nested grid is 128 x 122 (1530 x 1460 km) and the fine grid is made of 182 x 164 cells (728 x 656 km). All domains are centered at the city of El Paso, TX area (31.70 N, 106.40 W). The WRF model simulations are made using a total of 35 sigma vertical layers with 15 of these layers representing the planetary boundary layer (PBL). The lowest sigma level is at a height of 12 m and the top of the PLB is less than 1,500 m for this episode. WRF output is converted to a format readable by CAMx and collapsed into 24 layers to alleviate computational costs. However, the 15 layers within the PBL are unchanged to maintain high resolution at elevations where emission and chemical reactions of pollutants occur. All three CAMx domains possessed identical vertical layer structures spanning the entire troposphere and lower stratosphere up to a pressure altitude of 100 mb. The model is run from 0000 UTC June 2. 2017, 2014 through 0000 UTC June 14, 2017. The first four simulated days are treated as a spin-up period. As we did in our previous research (Stockwell et al., 2013), for the cold starting run (e.g., the first day of simulation), chemical initial and boundary conditions for the 36 km grid are obtained by down-scaling threedimensional output from the global chemistry model, MOZART (Emmons et al., 2010). We used a converter from CAMx model, MOZART2CAMx, which generates CAMx initial, lateral boundary, and (optionally) top boundary condition input files from the NCAR suite of global chemistry models output such as MOZART (http://www.acom.ucar.edu/wrf-chem/mozart.shtml). This processor interpolates 3D concentration fields horizontally and vertically to the CAMx initial and boundary grid definition. It then maps the predefined gas species in profile to the compounds required by CAMx. Initial and boundary conditions for each 12- and 4-km simulations are subsequently extracted from the CAMx 36 km simulation results on an hourly basis. For the warm starting run (e.g., cycle running), the simulation for 36km domain still use MOZART model output while the other two domains use coarse domain results to produce boundary conditions. The hourly observation of ozone concentrations came from the sites of the Texas Commission on Environmental Quality (TCEQ, 2017), which were used to perform model-observation validation (Fig. 106).

The advection solver used into the CAMx model is the Piecewise Parabolic Method (Colella and Woodward 1984). This scheme possesses high-order accuracy, little numerical diffusion, and is sufficiently quick for applications on very large grids. For the chemistry solver, the Euler-Backward Iterative (EBI) model has been applied. EBI provides improved accuracy with similar speed compared to other chemistry mechanism (ENVIRON, 2020). For vertical diffusion (mixing) option, we used the version 2 of the Asymmetric Convective Model (ACM2; Pleim, 2007), which includes mixing between adjacent layers using Ktheory and includes mixing between non-adjacent layers only for transfer from the surface to layers aloft during convective conditions. The updated Zhang scheme (Zhang et al., 2001; 2003) is applied for dry deposition in this project. This method incorporates vegetation density effects via leaf area index (LAI), possesses an updated representation of non-stomatal deposition pathways including a better snow cover treatment, and has been tested extensively through its use in daily air quality forecasting. The TUV radiative transfer and photolysis model (Madronich, 2002), developed at the National Center of Atmospheric Research (NCAR), is used as a preprocessor to provide the air quality model with a multi- dimensional lookup table of clear-sky photolysis rates by surface albedo, total ozone column, haze turbidity, altitude, and zenith angle. This approach uses a fast in-line version of TUV (Emery et al., 2010) to calculate photolysis adjustment profiles through each cloudy grid column. The Carbon Bond v6, Revision 4 (CB6r4) (Emery et al., 2015; Emery et al., 2016; Emery et al., 2019) scheme was used in this project as chemical mechanism.

The OSAT is a technique for attributing the ozone predicted by a model to emission sources and initial and boundary concentrations. This technique employs a set of tracers for NOx, total VOCs, and ozone and an indicator that ascribes instantaneous ozone production to NOx or VOCs. There are separate tracers for different geographic regions and different emission categories (e.g., area sources, biogenic sources, and point sources). Hence, OSAT apportions the ozone concentration at a receptor location into a detailed set of source contributions. The tool of OSAT needs an input file called Source Map file that allows the user to indicate the sources and regions contributing towards the ozone concentration of a location of interest (receptor).

The 36-km modeling domain was divided in to 8 source regions as shown in Fig. 107. The receptor is El Paso, TX. Through this method, we will investigate which region plays significant role in the ozone formation of El Paso, TX. The emissions in each source region were classified into four (3) emissions categories: biogenic, anthropogenic and point emissions. The boundary conditions (BC) and initial conditions (IC) were also tracked separately for quantifying their contribution towards the ozone concentrations.

#### Simulations

During the period from June 6, 2017 through June 13, 2017, there were some high ozone events (e.g., June 6, June 9) and low ozone occurrences (e.g., June 11-13). Below

are results from the OSAT analysis. Fig. 108 shows hourly ozone concentrations simulated by CAMx and observed at the El Paso UTEP monitoring station. It shows that there is a reasonably good agreement between ozone levels predicted by the model and observed data. The model clearly reproduced diurnal variation of ozone concentration for high and low concentration events. It is also noticed that the model tend to underestimate ozone concentration for high (a and b) and low (c) ozone events. Fig. 109 shows that the percentage contribution to El Paso peak ozone concentration from various sources including initial condition (IC), boundary condition (BC), emissions from Texas, New Mexico, Arizona, Chihuahua, Sonora, Coahuila, all other Mexico and other locations within the domain. For one high ozone day (June 6), the contribution mainly came from IC (46%) and Texas emission (49%). Other places made a contribution of less than 5%. BC only had a marginal contribution. Chihuahua had a contribution of nearly 4% while Sonora had 0.5% and New Mexico 0.4% (Fig. 109a). For another high ozone day, June 9, 2017, IC and Texas made contributions of 58% and 37% respectively whereas other place emissions made contribution about 5%. It was noticed that Sonora and Chihuahua made contributed nearly the same ozone concentration, 2% (Fig. 109b). Source emission contribution to ozone formation is case dependence. On a low ozone day, June 13, 2017, the ozone concentration mainly results from IC, BC and Texas emission (Fig. 109c), especially Texas emission. About 68% came from Texas emission, while BC made a contribution of 18%. IC only had 12% for this case. No other source emission made a noticeable contribution for local ozone concentration



**Figure 105.**The nested domain configuration used for the CAMx simulations. The coarse, middle and fine domains have spatial resolutions of 36-, 12- and 4-km respectively.



**Figure 106.** TCEQ sites over El Paso-Juárez area. Available from TCEQ website: <u>http://www.tceq.texas.gov/cgi-bin/compliance/monops/select\_summary.pl</u>? region06.gif



(b)

(a)

**Figure 107.** OSAT Source map with grids (a). The domain was assigned into 8 source regions (b) including Arizona, New Mexico, Texas, Chihuahua, Sorona, Coahuila, Other Mexico regions, and Other US regions. The black area in (c) denotes the region of El Paso, TX (receptor region )



**Figure 108.** Time series of ozone concentrations between observations and model simulated for high ozone events (a and b) and low ozone event (c).





(b)

(a)



**Figure 109.** The contributions (percentage) to peak ozone concentration over El Paso, TX at 4:00pm om (a) June 6, 2017, (b) June 9, 2017 and (c) June 13, 2017 from initial condition (IC), boundary condition (BC), emissions from Texas, New Mexico, Arizona, Chihuahua, Sonora, Coahuila, all other Mexico and other places with domain.

# Analysis and Conclusion

(C)

Through modeling studying of a few ozone cases occurring in the summer of 2017, we conducted a comprehensive ozone study by applying OSAT technology in an Eulerian photochemical dispersion model, CAMx, over the region of El Paso, TX/Ciudad Juárez, Mexico. Our study aimed to evaluate the impact of various anthropogenic/biogenic emissions and boundary/initial conditions on ozone concentrations. The model reasonably reproduced diurnal variation for ground ozone concentration. The modeling results showed that initial condition and local emissions play significant role in the formation of ozone concentration. But boundary conditions did not make evident contributions. Mexico states, especially those states that has border with El Paso, TX, made contributions to ozone formation. But their contributions are less than 5% for the cases studied. Obviously, more case studies are needed to in order to get a general conclusion about their contributions.
## 3.8 Determining the Residual Layer Contribution Using Paired Dawn and Afternoon Ozonesondes from El Paso in 2019

Aloft residual layers of ozone and other pollutants are expected to be connected to synoptic weather conditions. The formation of residual layers is due to the diurnal cycle of heating and cooling of the atmospheric boundary layer. In the mixed boundary layer during the day ozone is formed from its precursor emissions. Following sunset the nocturnal boundary layer forms at the surface below much of the mixed boundary, the region above is a residual layer that contains much of the daytime pollution. The next day when the nocturnal boundary layer breaks the previous day's pollution may enter into the new mixed layer lowering air quality. Synoptic meteorological conditions such as stagnant high-pressure conditions which lead to stable atmospheric conditions will promote the formation aloft of residual layers while meteorology that lead to unstable atmospheres and/or high winds will not.

Of the 27 ozonesondes flown from El Paso from July 31 – September 6, 2019, 24 of them were flown in pairs (i.e., 12 paired flight days): one flight at dawn to capture the residual layer and another flight coinciding with the peak afternoon ozone. The image on the left in Figure 110 shows the tropospheric profiles for paired flights on August 1, 2019. Following Morris et al. (2010), we can determine the amount of variability to the afternoon ozone concentration that is accounted for by the ozone that is entrained overnight in the residual layer. The image on the right in Figure 110 shows a plot of the peak ozone concentration in the afternoon boundary layer versus the highest ozone in the dawn residual layer. The sample is biased in that we launched primarily on days when the ozone concentration was expected to be relatively high. On those days, 56% of the variability in the afternoon ozone concentration was accounted for by contributions from the dawn residual layer that mixed into what became the afternoon boundary layer. ["Ozonesonde Launches in San Antonio and El Paso," (the 2019 ozonesonde campaign; James Flynn (PI))



Figure 110. Left: Tropospheric profiles where the flights were flown in pairs (one at dawn and the other in the early afternoon) from the UTEP campus in El Paso. The black line shows the afternoon boundary layer height. Right: The peak ozone concentration in the boundary layer measured in the afternoon flight is plotted against the peak ozone concentration in the morning residual layer for all 12 days with twice-daily paired flights from El Paso in from July 31 – September 6, 2019. An upward sloping regression line (shown in red) is superimposed on the plot with a slope of 0.84 ± 0.24 and a coefficient of determination (R squared) of 0.56. The dashed black line shows a 1-to-1 line, courtesy of Dr Paul Walter.

## 4. Overall Conclusions

Meteorological Factors Associated with High Ozone Days:

- The large majority of high ozone days occurred when El Paso was located within an anticyclonic circulation aloft associated with a middle and upper tropospheric high-pressure area centered within 500 miles of the city. Usually the high-pressure center was located to the west or north of El Paso. This suggests large scale subsidence or sinking motion was frequently present over the area, which tends to trap pollutants.
- In the lower troposphere, including the surface, the pressure gradient was weak, and thus winds were generally light at less than 10 mph. Temperatures were usually near or above normal to El Paso and most often above 90 F, which is consistent with most high ozone events occurring during the months of June, July and August, which are the warmest months of the year.
- The soundings revealed an air mass that at best was weakly unstable with a convective available potential energy usually less than 500 J/kg. The air mass was usually dry below 700 mb with the 700 mb to surface layer relative humidity most often less than 40 percent. Rain was reported at El Paso Airport on 11 of the 34 event days, which may be associated with the monsoon season. In most cases the rainfall was light, with precipitation amounts below 0.05 inches per day.
- In one case study four consecutive high ozone episodes from June 4-7, 2017 were analyzed. The aerosol layer height, which is also the proxy of the Planetary Boundary Layer (PBL), was lower in height when compared to some of the low ozone days when the PBL was very high. Analysis of the CAPE values for all the high ozone days under study indicated higher atmospheric stability, with an exemption on only one day. Under such stable environment, the vertical mixing of the aerosols is restricted, and leads to accumulation of the pollutants. Weak winds

blowing within the limited volume of atmosphere available within the boundary layer result in poor ventilation conditions, causing accumulation of precursors in the region, leading to high ozone episodes.

- Analysis of the wind roses during the high ozone events indicated calm winds coming mostly from southeast and east direction of downtown El Paso. This part of the city is at a lower elevation compared to its surrounding region.
- The air monitoring stations closest to CAMS 12, which are located in the state of New Mexico, did not record the high ozone days recorded by CAMS 12. This led us to suspect that the New Mexico CAMS Stations, which are closer to a port of entry and a Highway, are exhibiting ozone titration because of higher NO values.
- A leading cause of ozone formation in the El Paso region is its production by photochemical reactions. Emissions of NOx and VOCs are precursors that react by photochemistry caused by solar radiation to produce ozone. The daily pattern in the regional ozone concentrations usually displays a well defined diurnal pattern.
- Furthermore, high temperatures and strong solar radiation are known to be conducive to the photochemical production of ozone. The PdN experiences high temperatures during the summer season. Photochemical production is exacerbated by cross-border transportation.
- The presence of a high-pressure ridge at synoptic scales and at the 500 mb was frequently observed throughout all high ozone episodes studied and concurrently calm winds or stagnant air were observed at the surface.
- Another source of ozone in the PdN is the Stratosphere. Isolated cases of stratospheric intrusion of ozone may have contributed to NAAQS exceedances of the 70 ppb ozone on a small number of days.
- The correlations of elevated ozone, carbon monoxide and weekdays suggest that local emission sources are also important. Analysis of a 2-day back trajectories suggest that on a meso-scale, the oil and gas regions in West Texas are likely

contributors to El Paso and Dona Ana county ozone, and this may be one of the most significant results of this analysis.

 We also conducted a comprehensive ozone study applying OSAT technology in an Eulerian photochemical dispersion model, CAMx, over the region of El Paso, TX/Ciudad Juárez, Mexico. The model reasonably reproduced diurnal variation for ground ozone concentration. The modeling results showed that initial condition and local emissions play a significant role in the formation of ozone concentration, but boundary conditions did not make evident contributions. Mexico states, especially those states that have a border with El Paso, TX, made contributions to ozone formation. But their contributions are less than 5% for the cases studied. However, more case studies are needed to obtain a general conclusion about their contributions.

Additional work to consider includes looking for more detailed information with the Dona Ana data. It would be valuable to examine the "random day" meso-scale back trajectories to see if on higher MDA8 days, whether trajectories were more likely to match the exceedance day trajectories. In addition, more trajectories could be run on the Dona Ana County exceedance days which were not El Paso exceedance days. It is also the case that trajectory results could be used in the regression analysis. In previous work, UT showed that the "closest point of approach" of a multi-day back-trajectory from Dallas with Houston was statistically significant in Dallas high.

 We have plotted the correlation matrix for all the available data from all the CAMS in high ozone days. Parameters like Temperature, Wind Speed, Relative humidity, PM2.5, Solar radiation, Dew Point Temperature etc. Box plots of all meteorological variables also calculated and plotted based on the CAMS. The goal of these statistical analysis is to determine which parameters contribute the most or havea good correlation with high ozone events. All of the meteorological variables are at the local scale (i.e. area within 100 miles), representing a local level meteorology.

• We interpret from our analysis

Temperature and Solar Radiation are the most positively correlated with the High ozone events. However, PM2.5, Relative Humidity, Wind Speed etc. have a negative correlation (ranging from 0.1 to 0.6).

At the other part of the spectrum, the relative humidity has the strongest negative correlation with ozone which illustrate that in high ozone days, values of the humidity will be relatively low compared to any given day.

In regions without significant topography, it has long been known that one of key meteorological situations that creates ozone in urban areas and/or their downwind neighbors are stagnant high pressure systems with warm temperatures, low winds (to "trap" secondary pollutants nearby) and clear skies (plenty of solar radiation) that develop higher ozone mixing ratios over a period of two to three days. Certainly, regardless of the sky conditions or the temperature, high winds will prevent significant ozone formation (Banta et al. 2005; Camalier et al. 2007). The large-scale winds during the summer months in the southeastern United States are sometimes dominated by a strong subtropical anticyclone centered at or to the east of the Atlantic coast of the United States (J Nielson, 2002). Accordingly, the large-scale winds along the Texas coastline, which lies under the western branch of this high-pressure system, are southerly, persistent, and stronger than the amplitude of the sea breeze cycle. As a result, the winds in at least the lowest several hundred meters of the atmosphere or the lower troposphere have a southerly component during both the day and night (Sara et al. 2010). Continental

air flow brings air masses that typically have higher levels of ozone than air masses from the side of Gulf of Mexico.

## Future Work:

Cluster analysis of hourly averaged surface winds from Paso del Norte region.

Retrieving the wind amplitude and direction at different heights and divide them into different wind patterns while keeping track of maximum ozone in these areas can yield promising results. Various wind patterns like thermally driven flows, stagnant winds, thunderstorm outflow etc.

Regional ozone background can be determined by applying extensive statistical approach like Principal Component analysis or Variability reduction.

Establish a relationship with the Planetary boundary layer and aerosol concentration especially ozone to determine contributing factors like emission or poor ventilation (Rappenglück et al., 2008; Langford et al., 2009)

Influence of Nocturnal Low level jets on forming the ozone.

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