

The 1996 and 1997 Paso del Norte Ozone Studies: An Overview of the Field Studies and Data Analyses

99-199

Clinton P. MacDonald, Paul T. Roberts, Hilary H. Main, Timothy S. Dye, and Dana L. Coe

Sonoma Technology, Inc., 1360 Redwood Way, Suite C, Petaluma, CA 94954-1169

James Yarbrough

U.S. EPA, Region 6, 1445 Ross Avenue, Dallas, TX 75202

ABSTRACT

This paper summarizes the measurement campaigns of the 1996 and 1997 Paso del Norte Ozone Studies, the resultant data sets, and the findings and conclusions that arose from subsequent data analyses. The purpose of these data analyses was to develop an understanding of the significant chemical and physical processes that lead to high concentrations of ozone in the Paso del Norte study region which includes El Paso, TX; Sunland Park, NM; and Juarez, Mexico. High ozone concentrations resulted from a combination of conditions, including slow convective boundary layer (CBL) growth, reduced CBL depth, light surface winds, and high concentrations of ozone precursor at ground level in the morning. Synoptic-scale meteorological conditions observed during high ozone episodes included an upstream aloft high-pressure system, and aloft warming. Aloft carryover of ozone and ozone precursors did not significantly contribute to the surface ozone concentration. Furthermore, hydrocarbon and NO_x data, although spatially limited, showed that the system is more often NO_x-limited rather than VOC-limited.

INTRODUCTION

History

El Paso County fails to meet the National Ambient Air Quality Standards (NAAQS) for carbon monoxide (CO), particulate matter (PM-10), and ozone (O₃); it may also exceed the new 8-hr ozone NAAQS and the new fine PM NAAQS. Adjoining Sunland Park exceeds the NAAQS for O₃ and PM-10. Juarez air quality exceeds Mexican ambient standards (which are similar to those of the U.S.) for O₃ and CO. Very high concentrations of PM-10 are also sampled in Juarez, and the Mexican ambient standard for total suspended particulates (TSP) is likely violated there as well. U.S. controls since the 1970s have significantly reduced volatile organic compound (VOC) emissions in El Paso, but this has not resulted in attainment of the ozone NAAQS in El Paso.

In 1989, the U.S. and Mexico signed Annex V to the 1983 La Paz Agreement, a joint agreement to monitor, gather emissions information, and model the Paso del Norte airshed and determine which control strategies would most efficiently improve air quality. Beginning in 1989, a U.S.-Mexico Binational Air Workgroup (formed in 1984) sponsored several major field studies as well as the deployment of the first quality-assured air monitoring network in a Mexican border city. These ongoing bilateral data collection efforts continue to improve our general knowledge regarding the physical causes of air pollution in the region.

In 1991, the U.S. Environmental Protection Agency (EPA) and the Texas Natural Resource

Conservation Commission (TNRCC) agreed to target 1999 for the completion of all data collection and air modeling activities necessary to fulfill the Annex V requirements. Much of the data collected prior to 1996 focused on PM-10 and CO pollution, which tends to be problematic during the wintertime. Thus, a major field study was conducted during the summer of 1996 to provide sufficient data to support photochemical ozone air quality modeling. An abbreviated follow-up study occurred during the summer of 1997.

Purpose

The objective of the 1996 and 1997 field studies and subsequent data analyses was to develop an understanding of the significant chemical and physical processes which lead to high concentrations of ozone in the Paso del Norte study region (see Figure 1) and to support 3-dimensional air quality modeling. The results provided an understanding of the phenomena that the models must reproduce, a basis for model evaluation, a means to select appropriate boundary and initial modeling conditions, and a means of evaluating the field data quality.

This paper presents an overview of the 1996 and 1997 field studies and resultant datasets, followed by a discussion of the phenomena that influence surface ozone concentrations. These phenomena include the impacts of aloft ozone and ozone precursors on daytime ozone concentrations at the surface, the growth and vertical mixing of the convective boundary layer (CBL), the horizontal dilution of ozone and ozone precursors by surface winds, and the relative enrichment or depletion in the surface layer of ozone precursors with respect to ozone formation potential. Many of these phenomena are governed by synoptic-scale meteorology, which controls the growth of the CBL and the strength of surface winds. An understanding of these phenomena composes the basis of a conceptual model of ozone formation in the El Paso-Cuidad Juarez-Sunland Park area. (Roberts¹ contains a fuller discussion of study details and findings.)

SCOPE OF THE 1996 AND 1997 FIELD STUDIES

Operations

The field study domain covered the western corner of Texas and adjoining areas of Chihuahua, Mexico and New Mexico (see Figure 1). The pre-existing air quality and meteorological monitoring network included 15 air quality monitoring sites (14 surface met stations, 1 upper-air met station with Doppler acoustic sounders (SODAR), 14 O₃ monitors, 5 NO/NO_x monitors, 8 CO monitors, 2 hydrocarbon canister samplers operated every 6th day, and 1 continuous hydrocarbon monitor).

The 1996 field study ran from July 21-September 21, 1996. During this period, the existing network of air quality and meteorological monitoring sites was enhanced with the addition of the following equipment (3-letter codes indicate site locations; see Table 1 and Figure 2):

- Four temporary air quality monitoring stations with ozone and NO/NO_x monitors (FKM, TRF, DYR, WIN)
- Supplemental NO/NO_x monitoring equipment at two existing stations (MJA, M23)
- Three temporary upper-air met stations with radar profilers and radio acoustic sounding systems, or “RASS” (ELW, ELD, ELE)

Intensive operation periods (IOPs) were called on a forecast basis. During IOPs, special

activities included hydrocarbon sampling at 4 surface sites (TRF, WIN, M23, TED), carbonyl sampling at 3 surface sites (TRF, WIN, M23) and aloft measurements aboard a Piper Aztec small aircraft (position, altitude, temperature, dew point, ozone, NO/NO_y, hydrocarbons, carbonyls, and CO). (Typically, the aircraft flew vertical spirals over designated sites, reporting vertical profiles of pollutant concentrations from just above the surface to about 1500 m agl; see Figure 2b.) Intermittent special studies included supplemental hydrocarbon sampling, aloft air quality measurements aboard a hot air balloon, gasoline/diesel fuel composition analyses, and aloft air quality measurements collected with tethered sonde equipment.

The aircraft, balloon, and tethered sonde monitoring flights were designed to provide information about boundary pollutant concentrations, aloft vertical and horizontal pollutant gradients, mixed layer depth, the existence of layered strata with elevated pollutant concentrations, and pollutant carryover potential. The flights were also used to provide information regarding local and regional transport of aloft ozone and ozone precursors. Aloft data were compared to observations at proximate surface monitoring sites in order to assess data validity and pollutant gradients between the surface and aloft air parcels.

The 1997 field study was a small-scale follow-up to the 1996 study. From July 24-September 20, 1997 the existing air quality and meteorological monitoring network was enhanced with an ozone monitor (IVH), an NO/NO_x monitor (M23), a continuous hydrocarbon monitor (M23), and an upper-air meteorological station with RASS (ECH).

Data Availability

The 1996-1997 air quality and meteorological data were obtained from the Aerometric Information Retrieval System (AIRS), TNRCC, Los Alamos National Laboratory (LANL), New Mexico Environment Department, Western Regional Climate Center, El Paso City-County Health and Environmental Department, AeroVironment (AV), and Sonoma Technology, Inc. (STI). Surface data included O₃, NO_x, NO, CO, speciated hydrocarbons and carbonyls, temperature, wind speed and direction, relative humidity, solar radiation, pressure, and precipitation data. Upper-air meteorological data include continuous measurements of aloft winds and virtual temperature. Aloft air quality data included the results of the following:

- 21 aircraft sampling flights conducted on August 11-13, 1996 and 13 days in September 1996 (measured parameters: position, altitude, temperature, dew point, O₃, NO/NO_y, hydrocarbons, carbonyls, and CO)
- 3 hot air balloon flights conducted on September 9, 13, and 17, 1996 (measured parameters: altitude, position, O₃, NO, NO_x, temperature, hydrocarbons and carbonyls)
- Tethered sonde measurements collected on August 12-14, 1996 and September 9, 13, 17, 18, and 21, 1996 (O₃, NO_x, NO, and meteorological data)

IMPORTANT PHENOMENA

A combination of physical and chemical phenomena governs surface ozone concentrations in the Paso del Norte airshed. To aid in a discussion of these topics, it is useful first to define the major components of the Planetary Boundary Layer (PBL), which are the nocturnal boundary layer (NBL), convective boundary layer (CBL), and the residual layer (RL), as shown in Figure 3². The NBL forms at night when air near the surface cools. In response to this cooling, stable conditions reduce vertical mixing in the NBL, thus confining surface-based pollutants to the

lowest several hundred meters. Starting shortly after sunrise, the CBL grows as thermals vertically mix heat, moisture, momentum, and pollutants. At sunset, these thermals decay and the stable conditions of the NBL return. Aloft at this time, a RL remains and initially has the characteristics of the recently decayed CBL.³ As discussed by Brown et al.⁴, high wind speeds aloft may significantly affect daytime development of the CBL.

Analyses of surface and aloft air quality and meteorological data during two ozone episodes (August 12 to 14, 1996 and September 3 to 7, 1996) show that the diurnal growth rate of the CBL (or mixing depth) and the surface winds are the primary physical phenomena that influenced ozone concentrations in the Paso del Norte area. Analysis also shows that carryover of ozone from the prior day did not play a significant role in peak ozone concentrations. To understand how these phenomena influenced ozone concentrations, days were compared that had similar weather conditions. For example, in order to examine the influence of mixing heights and mixing depth growth rates (MGRs) on peak ozone concentration, days with similar wind patterns but different MGRs were compared. Likewise, to examine the effect of surface winds on peak ozone concentrations, days with similar MGRs and mixing heights but different surface wind patterns were compared. In particular, on August 12 and 13, morning surface winds were light, but the MGRs were different. However, on August 13 and 14, the MGR and mixing heights were similar, but the morning surface wind speeds were different. On August 12, 13, and 14, peak surface ozone concentrations reached 77, 137, and 87 ppb, respectively.

Carryover

Past ozone studies have shown that ozone and ozone precursors from previous days can contribute significantly to following days' maximum ozone concentration⁵. However, examination of early morning aloft air quality data in the Paso del Norte area shows that carryover of ozone and ozone precursors was not a major contributing factor to high ozone concentrations measured at the surface during the examined episodes.

Comparisons of data collected during early morning aircraft spirals show similar aloft ozone and ozone precursor concentrations on all days examined. This includes days when peak ozone concentrations were no greater than 70 ppb, a day when ozone reached 137 ppb, and several days when peak ozone concentrations were between 70 and 137 ppb. Predawn morning aircraft flights on both high and low ozone days show aloft ozone concentrations ranging from 45 to 65 ppb (only 5 to 25 ppb above natural background concentrations). Also, NO_y and NO concentrations above the residual layer were typically around 2.0 ppb and 0.2 ppb, respectively. NO and NO_y concentrations within the residual layer and in the NBL were higher, with maximum concentrations near the surface where emissions sources are located.

Figure 4 shows data collected during an early morning aircraft spiral near Ciudad Juarez Airport (CJS) on the episode day of August 13. CJS is located about 10 km south of Downtown El Paso. This plot shows the vertical profile of ozone, NO_y, NO, temperature, and dew point as observed by the aircraft at around 0445 MST. This vertical pollutant profile is typical of early morning vertical pollutant profiles, regardless of a given day's peak ozone concentration. Above the NBL at 1250 m msl, ozone concentrations range from 50 to 65 ppb. From the top of the NBL to the surface, ozone concentrations decrease rapidly due to apparent titration by fresh NO emissions emitted in and confined to the NBL. The NO_y and NO concentrations in the NBL range from 8.0 ppb and 1.0 ppb near the surface to about 2.0 ppb and 0.2 ppb at the top of the NBL (1250 m msl), respectively. The decreases in NO_y and NO concentrations with altitude through

the NBL indicate slow mixing of NO_y and NO from surface-level emission sources.

Based on the similarities in aloft ozone and NO_y concentrations between days with high and low peak surface ozone concentrations, and because of the relatively low aloft ozone and NO_y concentrations, it appears that aloft carryover was not a major contributing factor to high ozone concentrations measured at the surface. Although it is likely that aloft carryover of pollutants does not play a major role in peak ozone concentration, the observed aloft NO , NO_y , and ozone concentrations should be used to set appropriate initial and boundary conditions for models. Above the NBL up to about 3000 m msl, ozone concentrations are about 45 to 65 ppb; NO_y concentrations are about 1.0-2.0 ppb; and NO concentrations are about 0.1-0.2 ppb.

Mixing Depth Growth Rate

The growth rate and depth of the mixed layer critically influences day-to-day ozone concentrations. Previous work⁶ showed that violations of the ozone NAAQS, or “exceedance days”, typically exhibit slower daytime MGRs than non-exceedance days. The following discussion explores this effect in the El Paso-Cuidad Juarez-Sunland Park area.

Radar wind profiler (RWP) reflectivity data can be used to infer mixing depths. To estimate mixing depths from RWP data, the returned signal strengths are used to estimate the refractive index structure parameter (C_n^2). C_n^2 indicates the fluctuations of the index of refraction, which are primarily due to fluctuations in the water content of air. Fluctuations in water content are strongest near boundaries, such as at the top of the CBL. Both theoretical and empirical studies have shown that C_n^2 peaks at the inversion located at the top of the CBL due to warm, dry, aloft air entraining into cooler, moister air below the inversion⁷. Generally, C_n^2 estimated from radar profilers will not resolve low-level inversions below 200 to 300 m agl. Under these conditions, T_v data collected by RASS were used instead, coupled with surface T_v measurements, to generate estimates of the maximum NBL depth.

To investigate the role that the evolution of the CBL has on surface ozone concentrations, hourly mixing depths at the El Paso Downtown (ELD) profiler site were estimated for the August 12-14 and September 3-7 periods. These hourly mixing depths were produced using a combination of radar profiler, RASS, and aircraft data. Comparisons of the mixing depths estimated at ELD with two other sites in the area showed similar CBL evolution. From these hourly mixing depths, MGRs from 0600 to 1200 MST were calculated for each day and compared to peak ozone concentrations in the downtown area. The 1200 MST cutoff time was the most frequent time at which the peak hourly ozone concentration occurred. Because horizontal transport by surface winds can negate or accentuate the effect of the MGR on ozone concentrations, mornings with significant surface winds (including August 14, September 3, and September 5) were considered separately from days with light winds. In summary, on days with similar wind patterns, the mixed layer grew much slower on high ozone days compared to low ozone days.

Figure 5 shows time-series plots of mixing depth at the ELD profiler site for August 12-14. Table 2 shows the daily morning MGRs from 0600 to 1200 MST and the peak ozone concentrations in the downtown area for August 12-14 and September 4-7. As shown in Table 2 and Figure 5, the MGRs on August 13 (high ozone day) were significantly slower compared to August 12 (low ozone day). At the downtown site (ELD), the MGR was 150 m/hr on August 13 compared to 380 m/hr on August 12. The slow MGR on August 13 likely contributed to higher ozone concentrations on that day by restricting pollutant dispersion. This conclusion is confirmed by the relatively high CO , NO_x , and NO concentrations observed near downtown

from 0600 to 1000 MST. For example, the average CO concentrations near downtown were 1229 ppb between 0600-1000 MST on August 12 compared to 2358 ppb on August 13. The slower growth rates combined with higher precursor concentrations contribute to the high ozone (137 ppb) observed at Chamizal (ECH) on August 13, whereas the quick increase in the mixing depth and lower precursor concentrations contributed to the modest ozone peak (77 ppb) on August 12.

In conclusion, slow MGR combined with shallow mixing depths played an important role in the high ozone concentrations observed in the El Paso area. When the MGR is slow and the mixing depth is shallow, ozone precursors are confined to a smaller volume than with faster MGRs and a deeper mixed layer. The reduced mixing volume tends to concentrate precursor emissions, which in turn, tends to result in higher ozone concentrations. Additionally, the limited vertical dilution of surface air with cleaner aloft air results in higher surface ozone concentrations.

Dispersion by Surface Winds

Although slow MGRs played a significant role in producing high ozone concentrations, high ozone concentrations did not occur under conditions of moderate-to-strong morning surface winds. When surface wind strengths were moderate to strong, ozone precursor emissions were dispersed horizontally and peak ozone concentrations were lower with broader horizontal extent. (Here, *dispersion* is the scattering of pollutants due to advection by surface winds.)

As mentioned above, August 14, September 3, and September 5 all had relatively strong morning winds. Of these three days, August 14 and September 5 had slow MGRs. The mixing growth rate at ELD on August 14 was only 120 m/hr, or 30 m/hr slower than on August 13. However, the peak downtown ozone concentration on August 14 was only 79 ppb compared to 137 ppb on August 13. Likewise, the mixing growth rate at ELD on September 5 was only 150 m/hr, the same as on August 13. The peak downtown ozone concentration on September 5 was only 60 ppb. Given the slow MGR on both August 14 and September 5, it becomes evident that dispersion of pollutants by wind played a significant role in the low peak ozone concentrations on August 14 and September 5.

Dispersion of ozone precursor emissions by moderate morning winds on August 14 and September 5 is evident from the relatively low NO_x and NO concentrations observed near downtown source areas with high concentrations in downwind areas. On the windy day of August 14, morning NO_x concentrations of about 80 ppb were observed near downtown source areas. However, on the light-wind day of August 13, morning NO_x concentrations were around 200 ppb near downtown source areas. Also, on the morning of August 14, downwind NO_x concentrations were about 40 ppb, but on the morning of August 13, downwind NO_x concentrations were only about 20 ppb. On the windy morning of September 5, the spatial characteristics in NO_x concentrations were similar to those on August 14. CO concentration patterns similarly evidenced the effects of surface wind advection on pollutant concentrations.

In summary, on light-wind mornings, a “cloud” of ozone precursors with high NO_x, NO, and CO concentrations forms and is confined near the emissions source region (as observed on August 13). On these days, the highest ozone concentrations are confined near or slightly downwind from the downtown area (Figure 6). On days with moderate wind, the wind disperses the cloud, and maximum precursor concentrations are lower but are more evenly and widely distributed (as observed on August 14). On such days, relatively low ozone maxima occur, but ozone

concentrations are modestly elevated in downwind areas and are more evenly distributed over the entire region (Figure 7).

Aloft Stability

During ozone episodes in the Paso del Norte region, rawinsonde and RASS virtual temperature data revealed warming in the aloft air mass. Aloft warming contributes to atmospheric stability. A comparison of the RASS virtual temperature data on a day with fast MGR (August 12) to days with slow MGR (August 13 and 14) showed differences in aloft temperature and early morning aloft stability. Figure 8 shows virtual potential temperature profiles at 0600 MST on 12, 13, and August 14 at El Paso West (ELW). As shown in Figure 8, the aloft virtual temperatures on August 12 were cooler than on August 13 and 14. On August 12, the peak aloft temperature was 297.6 K, warming to 298.9 K on August 13, and to 300.9 K on August 14. This warming aloft from August 12 through 14 was also observed at the 850-mb altitude. On August 12 at 0600 MST, the 850-mb observed temperature was approximately 298.2 K, warming to 303.2 K on August 13 and 14. More importantly, the strength of the morning inversion increased during this period (from 6.69 K on August 12, to 7.6 K on August 13, and to 8.4 K on August 14), which was a result of the aloft warming rather than the surface cooling.

The MGR is also controlled and driven by the surface heat flux, or the amount of energy available for heating the air in the mixed layer. On August 12 through 14 the surface heat fluxes were nearly identical. As discussed above, the temperature sounding was more stable on August 13 than on August 12, and was most stable on August 14. Therefore, the same heat flux would result in slower MGRs on August 14 relative to August 13, and on August 13 relative to August 12. The data suggest that the aloft warming and the resulting stability were the major factors controlling growth rates on these days.

Analysis of synoptic weather maps showed that the aloft warming was caused by an upper-level ridge of high pressure drifting and strengthening over the region. On August 12, the aloft high pressure was located northwest of El Paso over eastern Utah. On August 13 and 14, the high pressure broadened and intensified slightly. The broadening and intensification of the high pressure resulted in sinking motion over El Paso (as determined using the NGM numerical forecasting model⁸). As the air sank, it adiabatically warmed. Estimates of warm air temperature advection were negligible in Paso del Norte during the episode.

ASSESSMENT OF NO_x AND VOC LIMITATIONS

Though data were spatially limited, morning ratios of nonmethane hydrocarbons (NMHC) to NO_x were calculated to assess NO_x- versus VOC-limitations on ozone formation potential. The ratio of NMHC to NO_x in the morning characterizes the efficiency of ozone formation in NMHC-NO_x-air mixtures. In general, environmental chamber experiments and photochemical model calculations show that when early morning NMHC/NO_x ratios are low (less than 5 ppbC/ppb), ozone formation is slow, inefficient, and VOC-limited. At high NMHC/NO_x ratios (above 10), ozone formation is limited by the availability of NO_x rather than NMHC. Under this condition, reductions in NMHC emissions do not significantly influence ozone formation. A knowledge of NMHC/NO_x ratios is critically important for the development of effective emissions control strategies.⁹ Note that the NO_x measured at the surface in this field study is the sum of NO, NO₂, and a poorly defined fraction of other NO_y species.

The distribution of morning (0600-0800 MDT) NMHC/NO_x ratios observed during the 1996

field study at canister sampling sites is shown in Figure 9. All collected data were included in the plots, rather than data from IOP days only, in order to compile a more robust data set. Most observations indicated NO_x-limited conditions with the exception of the Campbell site, which exhibited hydrocarbon limitation. The data show that three-quarters of the observed morning ratios were above 10 in the NO_x-limited regime, with most falling between 10 and 30. Figure 9 also shows the distribution of ratios for all sampling periods. Again, three-quarters of the ratios were greater than 10. Therefore, ozone formation is most likely to be NO_x-limited, and NO_x (rather than VOC) emissions control would be the more effective ozone reduction strategy.

It is important to note, however, that large spatial and temporal differences in NMHC/NO_x ratios were observed during the study. Figure 10 illustrates the NO_x versus NMHC concentrations by site for the early morning sampling period. Regression lines are shown for Campbell ($R^2=0.77$), 20/30 Club ($R^2=0.87$), Advanced Transformer ($R^2=0.44$), and Winn Road ($R^2=0.65$) with inverse slopes (NMHC/NO_x) of about 9, 16, 37, and 11, respectively. The Campbell site (TED) is located in downtown El Paso, an area dominated by motor vehicle emissions. The 20/30 Club site (M23) is located in downtown Juarez and is also dominated by motor vehicle emissions. The Advanced Transformer (MJA) site is located in an industrial section of Juarez. The Winn Road site (WIN) is a suburban site in El Paso located near a highway. Table 3 lists the median concentrations and ratios for the 0600-0800 MDT sampling period for each site. The plots and median values show that the hydrocarbon concentrations at Advanced Transformer and 20/30 Club were higher than at other sites while NO_x concentrations were higher at Campbell. Figure 11 shows the median ratios at 0600, 0800, 1000, 1200, and 1600 MDT at each location. Ratios were relatively unchanged with time of day at 20/30 Club and Campbell, while large increases with time of day were observed at the Advanced Transformer, Turf Road (TRF; a suburban/rural site in El Paso), and Winn Road sites.

CONCEPTUAL MODEL AND CONCLUSIONS

Based on the analyses and observations discussed in this report, a simple conceptual model of high ozone episodes in the Paso del Norte area was developed. A *conceptual model* is a description of the important phenomena and characteristics that produce high ozone concentration episodes in a given region. The purposes of developing a conceptual model are to summarize the current state of knowledge regarding ozone episodes, to provide a basis for testing and evaluating specific hypotheses, and to provide a basis for evaluating meteorological and photochemical models and model results. The conceptual model can also be used to help design additional field measurements and to improve episode forecasting. The conceptual model for the Paso del Norte area, summarized below, covers synoptic meteorological conditions, plus air quality and meteorological characteristics associated with high ozone episodes.

Meteorological Conditions

- 500 mb ridge over or just west of the El Paso area
- Weak surface gradients
- Stagnant or weak surface winds during early morning hours
- Maximum surface temperature of at least 90°F
- Diurnal temperature variation of at least 25°F

- Slow mixing layer growth rates (MGRs) and light surface winds
- Aloft warming and increased atmospheric stability
- Calm-to-weak surface winds allow ozone precursors and ozone to accumulate near emissions source areas, contributing to higher ozone peaks

Air Quality Conditions

- On days with high ozone concentrations, elevated morning concentrations of CO, NO, and NO_x are observed near the emissions source regions of El Paso and Juarez. A cloud of ozone precursors forms in the morning and remains confined to the source region due to a slow MGR. On days with lower ozone concentrations, greater wind speeds disperse the source cloud and maximum precursor concentrations are lower, but more widely distributed.
- On days with high ozone concentrations, the midday ozone cloud with the highest concentrations is confined to the source region, or slightly downwind. On days with lower ozone concentrations, maximum ozone concentrations are lower, but more widely distributed.
- Aloft ozone and ozone precursor concentrations during nights that precede exceedence days (and during the early mornings of exceedence days) were significantly lower than the maximum ozone concentrations, with aloft ozone of about 45-65 ppb, NO_y of around 1-2 ppb, NO at approximately 0.1-0.2 ppb, and NMHC at about 25-55 ppbC. Thus, carryover of ozone and precursors did not significantly influence ozone exceedences, but may have contributed as much as 20 ppb to surface ozone concentrations.
- At most of the hydrocarbon sampling sites, ratios of NMHC/NO_x indicated conditions of NO_x-limited ozone formation, with the exception of Campbell, which showed hydrocarbon limitation.

ACKNOWLEDGMENTS

This work was funded by the U.S. Environmental Protection Agency (EPA). The EPA Work Assignment Manager, James Yarbrough of EPA Region 6, provided extensive guidance during this project. Also, the authors wish to thank the many field and data processing personnel whose hard work made this study possible, including those from the EPA, Instituto Mexicano del Petroleo, Los Alamos National Laboratory (LANL), STI, AeroVironment, Desert Research Institute, University of Texas at El Paso, University of Utah, New Mexico State University, Texas Natural Resource Conservation Commission (TNRCC), El Paso City-County Health and Environmental District, Direccion Municipal de Ecologia - Ayuntamiento de Juarez, and the New Mexico Environment Department (NMED). The members of the Technical Review Group (TRG) also provided valuable and much-appreciated comments. The TRG consisted of the following individuals: Jim Price, TNRCC; Ed Michel, TNRCC; Pete Breitenbach, TNRCC; Chris Kennedy, TNRCC; Cecilia Williams, NMED; Victor Paramo, SEMARNAP-INE; Jose Trevino, Chihuahua; Oscar Ibanez, Ciudad Juarez; Jesus Reynoso, El Paso City-County Health and Environmental District; Rich Scheffe, EPA-OAQPS; Quang Nguyen, EPA-Dallas; J.T. Lee, LANL; Clay Heskett, LANL; Steve Ziman, Chevron Corporation. STI MF#1863.

REFERENCES

1. Roberts, P.T.; MacDonald, C.P.; Main, H.H.; Dye, T.S.; Coe, D.L.; Haste, T.L. Analysis of meteorological and air quality data for the 1996 Paso Del Norte ozone study. Final Report prepared for the USEPA, Region 6 Dallas, TX, by Sonoma Technology, Inc. Santa Rosa, CA under subcontract to Science Applications International Corporation Mclean, VA, STI-997330-1754-FR, September 1997.
2. Stull, R.B. *An Introduction to Boundary Layer Meteorology*. Kluwer Academic Publishers: Norwell, MA., 1988.
3. Dye, T.S.; Lindsey, C.G.; Anderson, J.A. Estimates of mixing depths from "boundary layer" profilers. In *Preprints of the 9th Symposium on Meteorological Observations and Instrumentation, Charlotte, NC, March 27-31, 1995* STI-94212-1451.
4. Brown, M.J.; Costigan, K.; Muller, C.; Wang, G. Meteorological simulations of ozone episode case days during the 1996 Paso del Norte Ozone Study, 92nd Annual AWMA Meeting, St. Louis, June 1999.
5. Blumenthal, D.L.; Lurmann, F.W.; Roberts, P.T.; Main, H.H.; MacDonald, C.P.; Knuth, W.R.; Niccum, E.M. Three-dimensional distribution and transport analyses for SJVAQS/AUSPEX. Final report prepared for San Joaquin Valley Air Pollution Study Agency, Sacramento, CA by Sonoma Technology, Inc., Santa Rosa, CA, Technical & Business Systems, Santa Rosa, CA, and California Air Resources Board, Sacramento, CA, STI-91060-1705-FR, February 1997.
6. Dye, T.S.; Roberts, P.T.; MacDonald, C.P. Mixing depth structure and evolution as diagnosed from upper-air meteorological data collected during the NARSTO-Northeast study. Paper No. 5A.6 presented at the 10th Joint Conference on the Applications of Air Pollution Meteorology, Phoenix, AZ, January 11-16, 1998 (STI 1749).
7. Wyngaard, J.C.; LeMone, M.A. Behavior of the refractive index structure parameter in the entraining convective boundary layer. *J. Atmos. Sci.* **1980**, *37*, 1573-1585.
8. National Oceanic and Atmospheric Administration. "Real-Time Environmental Applications and Display System." Retrieved from <www.arl.noaa.gov/ready/arlplota.html>, 1996.
9. National Research Council. *Rethinking the Ozone Problem in Urban and Regional Air Pollution*. National Academy Press: Washington, D.C., 1991.

Table 1. Surface air quality and meteorological research stations operated during the 1996 Paso del Norte Ozone Study.

Site	ID	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m msl)	O ₃	NO	NO _x	CO	PM	Hydrocarbons	Cnyl	Surf Met
La Union, NM	NLU	31.9306	-106.6306	1204	X							X
University Avenue, Las Cruces, NM	NLC	32.2814	-106.7672	1188	X			X				X
Sunland Park City Yard, NM	NSP	31.7958	-106.5575	1200	X				X	Aug 6, 8-10 ^{a,c}		X
Las Cruces Holman, NM	NHM	32.4247	-106.6742	1189	X	X	X		X			X
Chaparral Elem., Chaparral, NM	NCH	32.0408	-106.4092	1249	X	X	X		X			X
Desert View Elem., Sunland Park, NM	NDV	31.7961	-106.5839	1209	X	X	X		X			X
Santa Teresa Intl. Border Crossing, NM	NST	31.7878	-106.6828	1256	X			X	X			X
El Paso Downtown CAMS 6 (Campbell)	TED	31.7625	-106.4869	1140	X	X	X	X		IOPs ^{a,b}		
El Paso East CAMS 30 (Ascarate Park)	TEE	31.7536	-106.4042	1126	X			X		Aug 6-10 ^{a,c} & ¹ / ₆		X
El Paso UTEP CAMS 12	TUT	31.7683	-106.5006	1143	X	X	X	X		¹ / ₆		X
Chamizal Park	ECH	31.7681	-106.4542	1128	X			X	X	Hourly		X
Tecno (Chihuahua State Technical Inst.)	MJT	31.7156	-106.3942	1123	X			X	X			X
Advance Transformer	MJA	31.6900	-106.4597	1167	X	X ^a	X ^a	X	X			X
20/30 Club	M23	31.74	-106.47	1150	X	X ^a	X ^a			IOPs ^{a,b}	IOPs ^{a,b}	X
Zenco	ZEN	31.6381	-106.4431	1183					X	Aug 15-16 ^{a,c}		
Franklin Mountain	FKM	31.79	-106.48	1428	X	X	X			Aug 6-10 ^c		X
Turf Road	TRF	31.81	-106.25	1221	X	X	X			IOPs ^b	IOPs ^b	X
Dyer Street	DYR	31.92	-106.39	1195	X	X	X			Aug 6-10 ^c		X
Winn Road, El Paso	WIN	31.66	-106.31	1117	X	X	X			IOPs ^b	IOPs ^b	X
Lindbergh Elementary School	LIN	31.8606	-106.5864									X
El Paso Tillman, TX	TIL	31.7569	-106.4828									X
Ivanhoe Fire Station	IVH	31.7881	-106.3217									X

O₃ - Ozone, NO - Nitric oxide, NO_x - The sum of nitric oxide and nitrogen dioxide, CO - Carbon monoxide, PM - Particulate matter, Cnyl - Carbonyls, Surf Met - Surface meteorological variables, Hourly - Continuous hourly sampling (auto-GC), ¹/₆ - Eight 3-hour samples collected every 6 days, IOP - Five 2-hour samples collected on IOP days.

^a Temporary equipment installed at existing sites; all other equipment is permanent.

^c Two 2-hour samples per day.

^b Samples collected during intensive operating period (IOPs); five 2-hour samples per day.

Table 2. Mixing depth growth rates (MGRs) and qualitative surface winds for the period 0600-1200 MST at ELW, ELE, and ELD on August 12 through August 14 and September 4 through September 7. High ozone concentrations are related to slow MGRs and light wind conditions.

Site	Aug. 12	Aug. 13	Aug. 14	Sept. 4	Sept. 5	Sept. 6	Sept. 7
Mixing Depth Growth Rates (m/hr)							
ELW	320	80	220	120	130	130	120
ELE	370	50	50	60	80	100	80
ELD	380	150	120	100	150	130	120
Average of all sites	357	93	130	93	120	120	107
Morning Surface Wind Strength (in general, for the entire study area)							
	Light	Light	Moderate	Light	Moderate	Light	Light
Peak Observed Ozone Concentration (ppb)							
	77	137	79	118	60	82	97

Table 3. Median NMHC/NO_x ratios and median concentrations measured during the 0600-0800 MDT sampling period at the hydrocarbon canister sampling sites.

Site	NMHC (ppbC)	NO _x (ppb)	NMHC/NO _x
20/30 Club	762	60.1	12.9
Advanced Transformer	1680	44.3	34.7
Campbell	469	92.0	5.6
Franklin Mtn	209	9.1	26.7
Sunland Park	266	13.0	18.4
Turf Road	180	8.8	21.5
Winn Road	683	50.7	14.0

Figure 1. The Paso del Norte Ozone Study area.

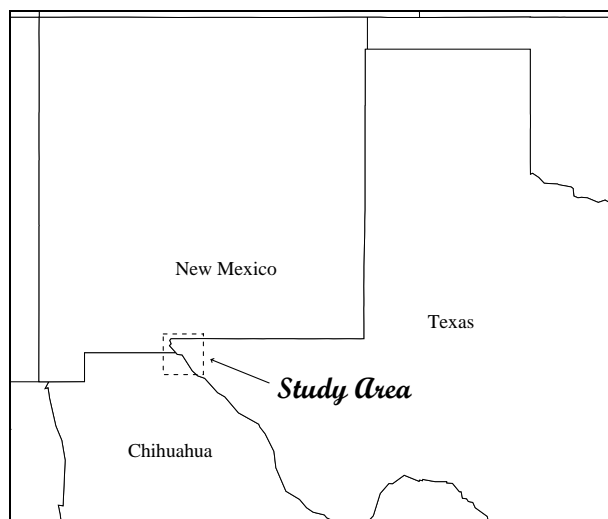
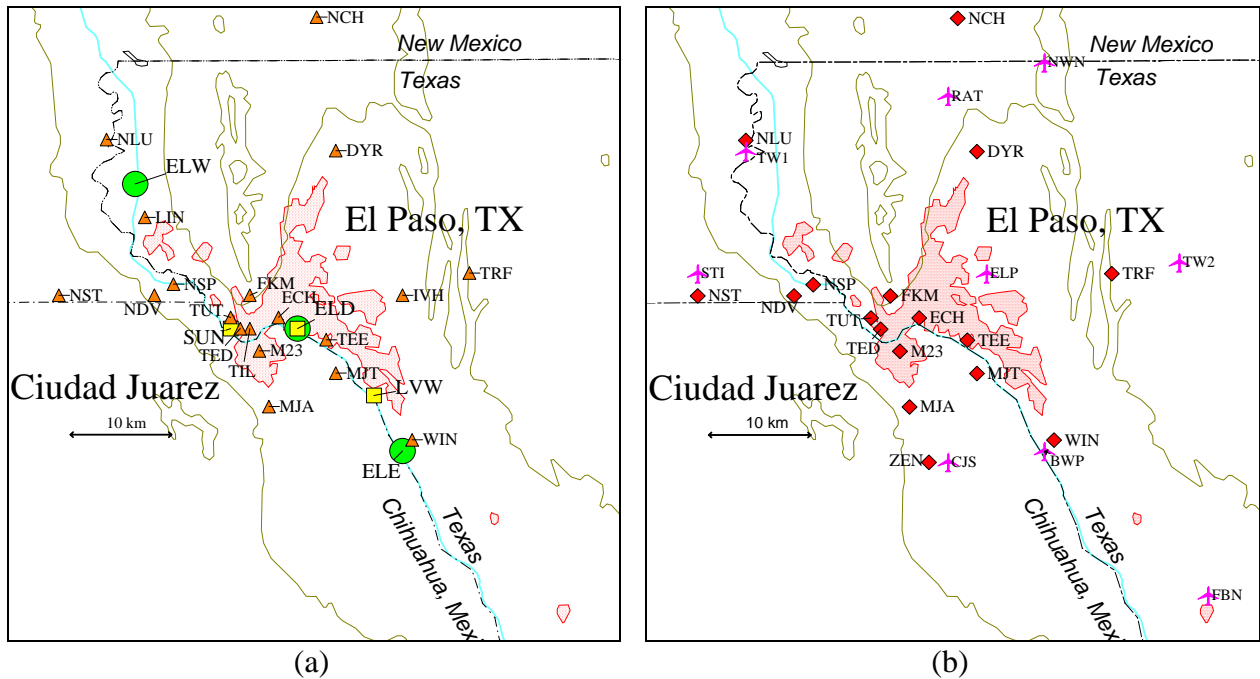


Figure 2. Locations of surface and aloft meteorological and air quality measurements collected during the 1996 Paso del Norte Ozone Study. (a) Radar profilers with RASS and surface met (circles), surface met only (triangles), and sodars (squares). (b) Surface air quality stations (diamonds) and aircraft spiral positions (airplanes).



Map features include topographical contours, political boundaries, rivers, and urbanized areas.

Figure 3. Schematic of the Planetary Boundary Layer (PBL) which shows the Nocturnal Boundary Layer (NBL), the Residual Layer (RL), and the Convective Boundary Layer (CBL). Vertical arrows show the height to which surface air is mixed².

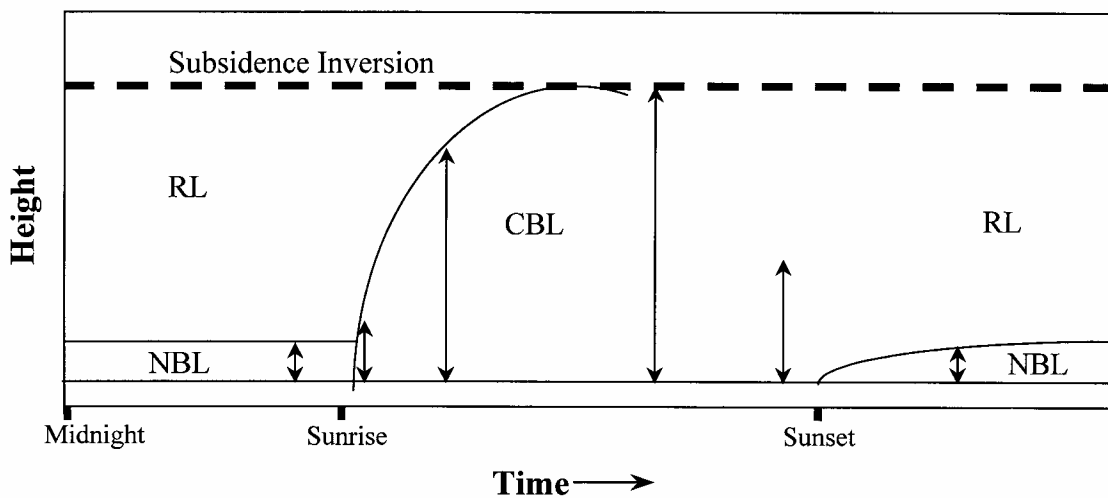


Figure 4. Data collected during an aircraft spiral at Juarez Airport (ELP) from 0446 to

0458 MST on August 13, 1996.

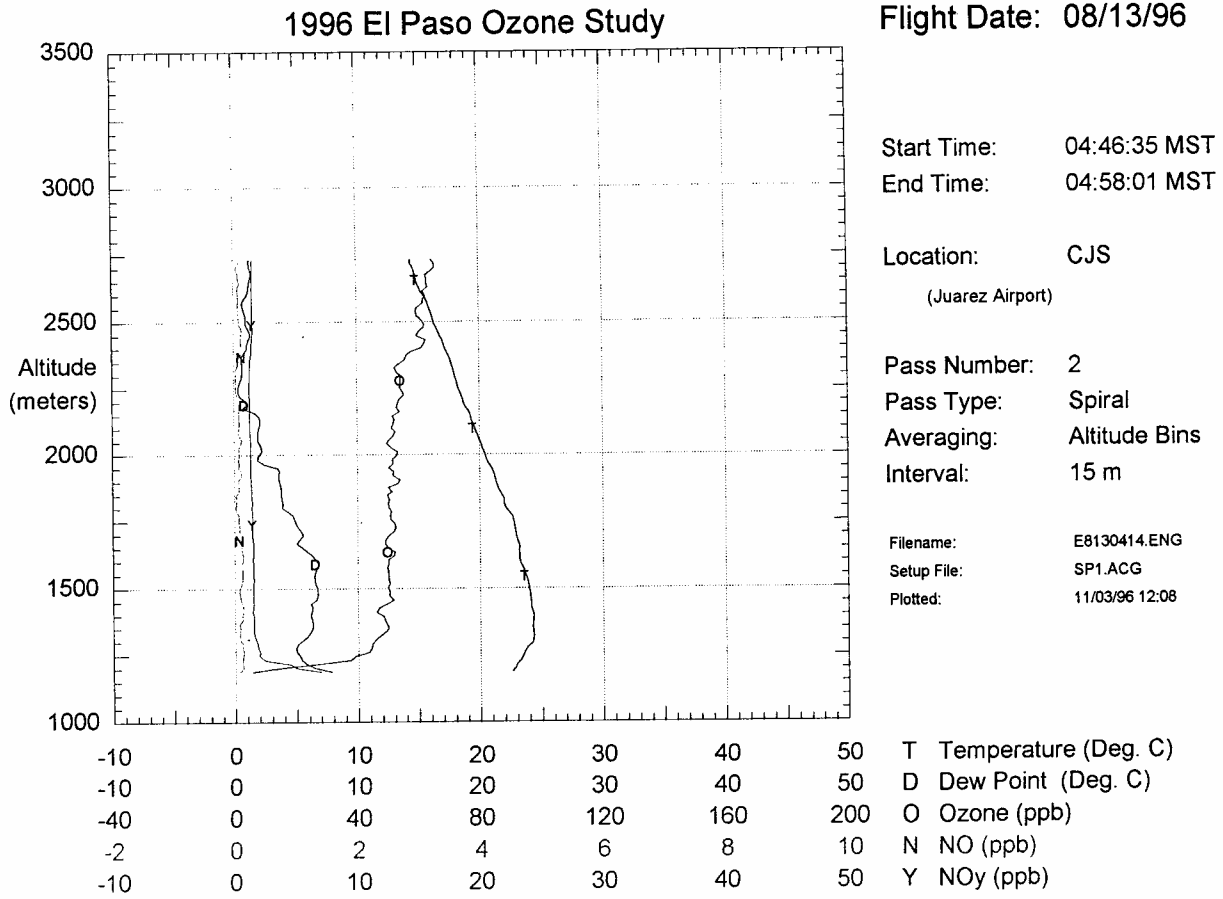


Figure 5. Surface-based mixing heights at ELD on August 12-14, 1996.

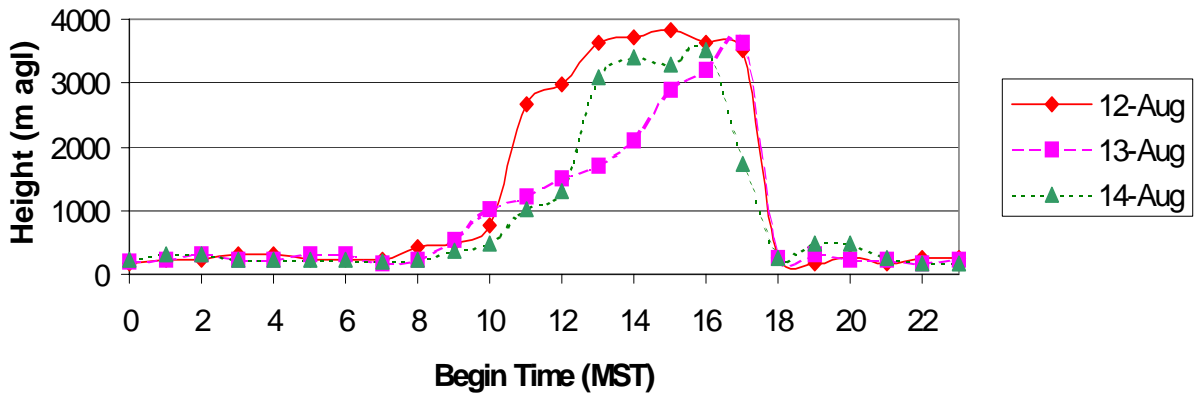


Figure 6. Ozone concentration isopleths (ppb) estimated for August 13 at 1100 MST.

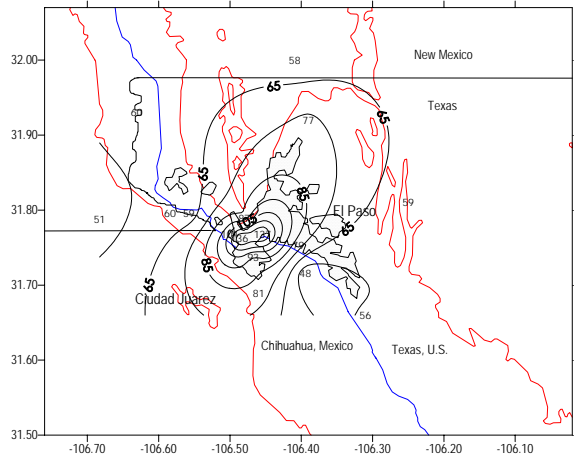


Figure 7. Ozone concentration isopleths (ppb) estimated for August 14 at 1200 MST.

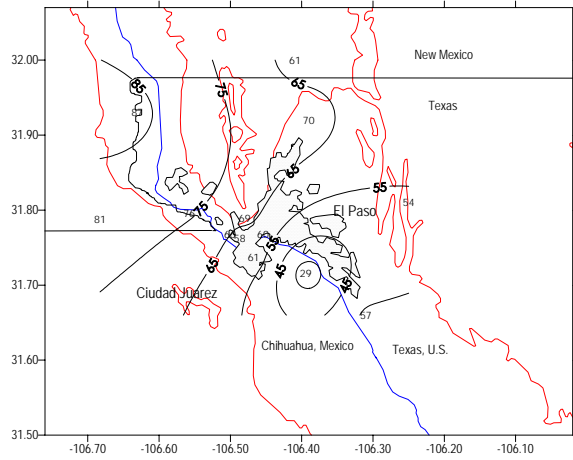


Figure 8. Virtual potential temperature profiles computed from RASS measurements at El Paso West (ELW) from August 12 to 14, 1996 at 0600 MST. Positive slope = stable conditions, negative slope = mixing conditions, vertical slope = neutral conditions.

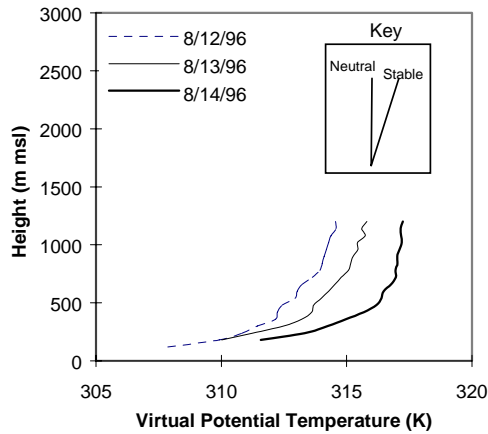


Figure 9. Distribution of NMHC/NO_x ratios for hydrocarbon canister sampling sites for the 0600-0800 MDT time period (left) and all data (right).

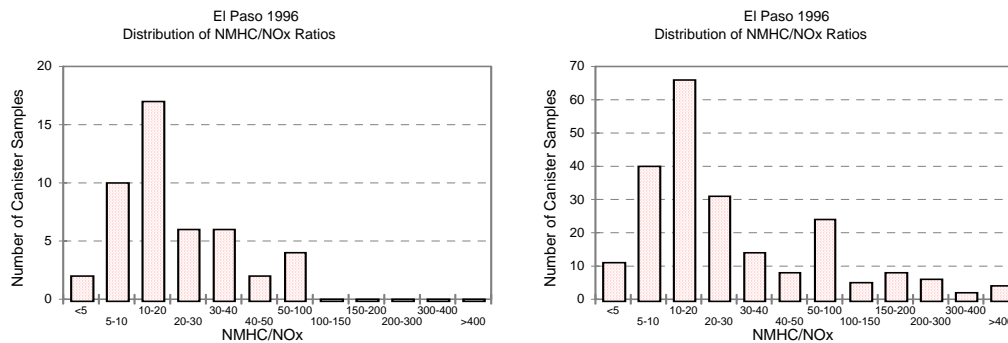


Figure 10. NMHC and NO_x concentrations for the 0600-0800 MDT sampling period at hydrocarbon canister sampling sites. Regression lines, data points, and correlation coefficients are provided for Campbell (C), 20/30 Club (2), Winn Road (W), and Advanced Transformer (A). Individual data points are also shown for Turf Road (T) and Sunland Park (SP).

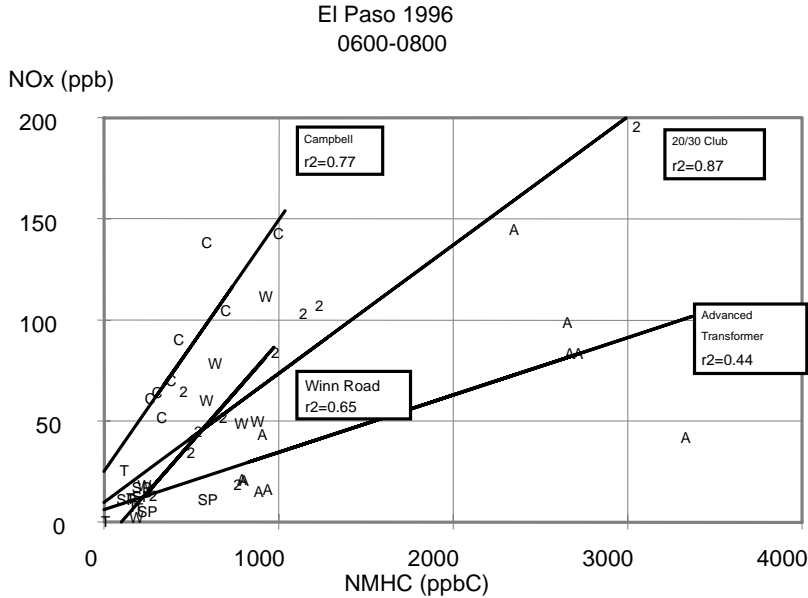


Figure 11. Distribution of median NMHC/NO_x ratios at hydrocarbon canister sampling sites by time of day (MDT).

