The 1996 Paso del Norte Ozone Study: Analysis of Meteorological and Air Quality Data That Influence Local Ozone Concentrations

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Abstract

The 1996 Paso del Norte Ozone Study and subsequent data analyses were implemented to develop an understanding of the chemical and physical processes which lead to high concentrations of ozone in the Paso del Norte study area which includes El Paso County, Texas, Sunland Park, New Mexico, and Ciudad Juárez, Mexico. Both the data and data analysis results are being used to support photochemical grid modeling. El Paso County and Sunland Park fail to meet the National Ambient Air Quality Standard (NAAQS) for ozone, and neighboring Ciudad Juárez fails to meet the Mexican ambient standard for ozone. This paper summarizes the measurement campaigns of the 1996 Paso del Norte Ozone Study and the findings and conclusions that arose from subsequent data analyses. Data analyses show that high ozone concentrations resulted from a combination of conditions, including high surface temperatures, strong sunlight with few clouds, light surface winds and high concentrations of ozone precursors at ground level in the morning, and slow convective boundary layer (CBL) growth. Synoptic-scale meteorological conditions observed during high ozone episodes included an aloft high pressure system and aloft warming. Aloft carryover of ozone and ozone precursors did not significantly contribute to high concentrations of ozone at the surface.

Key Words

Ozone, ozone formation, ozone episodes, mixing depth, mixing height, El Paso, Texas, Ciudad Juárez, Mexico

1. Introduction

El Paso County, Texas, fails to meet the National Ambient Air Quality Standards (NAAQS) for carbon monoxide (CO), particulate matter (PM_{10}), and ozone (O_3); it may also exceed the proposed 8-hr ozone NAAQS and the proposed fine PM ($PM_{2.5}$) NAAQS. Adjoining Sunland Park, New Mexico, exceeds the NAAQS for O_3 and PM_{10}. Ciudad Juárez air quality exceeds Mexican ambient standards (which are similar to those of the United States) for O_3 and CO. Ciudad Juárez experiences very high PM concentrations and likely violates the Mexican ambient standard for total suspended particulates (TSP) as well. United States controls since the 1970s have significantly reduced volatile organic compound (VOC) emissions in the Paso del Norte study area, but this reduction has not resulted in ozone NAAQS attainment.

In 1989, the United States and Mexico signed Annex V to the 1983 La Paz Agreement (1989), 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 (Annex V, 1989). Beginning in 1989, the United States–Mexico Binational Air Workgroup 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 of the 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 a problem during the wintertime. A major field study, the Paso del Norte Ozone 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.

The objective of the 1996 Paso del Norte Ozone Study and subsequent data analyses was to develop an understanding of the chemical and physical processes which influence high ozone concentrations in the Paso del Norte study area, which includes El Paso County, Texas, Sunland Park, New Mexico, and Ciudad Juárez, Mexico (see Fig. 1), and to support three-dimensional air quality modeling in the study region. Initial data analyses were performed using historical data, but the data was not sufficient to identify the major influences on high ozone concentrations in the study area. The major data gaps included additional surface-level ozone precursor data plus upper-air meteorological and air quality data. Thus, the 1996 field study was planned and executed to provide the data needed to meet the objectives listed above. The objectives of the data analyses were to provide an evaluation of the 1996 field data quality, an understanding of the phenomena that the models must reproduce, a basis for model evaluation, and a means to select appropriate boundary and initial conditions for modeling. The data analysis results have been used as part of the meteorological modeling effort (see Brown et al., 2001) and to support the photochemical modeling effort (see Emery et al., 2000, for current status). In addition to this paper, further data analysis results from this study are provided in Fujita et al. (2001), Funk et al. (2001), and Seila et al. (2001).

This paper presents an overview of the 1996 Paso del Norte Ozone Study field measurements and a discussion of the meteorological and air quality conditions that influence surface ozone concentrations, especially using data from the August 12 to 14, 1996, weekday ozone episode. Roberts et al. (1997) presents a complete discussion of study details and findings. The factors discussed here 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), and the dispersion of ozone and its precursors by surface winds. Synoptic-scale circulations control many of these phenomena, such as the growth of the CBL and the strength of surface winds. An understanding of these processes will provide an understandingof ozone formation in the Paso del Norte study area during the episode studied and episodes under similar conditions.

Ozone is formed when sunlight interacts with nitrogen oxides (NO_x) and various volatile organic compounds (VOC), including many hydrocarbons. NO_x and VOCs are emitted in the Pase del Norte area from man-made sources such as motor vehicles, power plants, an oil refinery, a smelter, industrial manufacturing facilities, and area sources such as dry cleaners and restaurants. Ozone precursors are also emitted into the air by biogenic sources in the Paso del Norte study area; evaluation of the emissions inventory for this area estimated biogenic emissions contributed 27 percent of total VOCs for the entire Paso del Norte study area (see Fig. 1) and a 4 percent contribution of total VOCs in urban regions of this area (Funk et al., 2001). Ozone precursors react and form ozone throughout the day as the atmosphere mixes, disperses, and transports the air in the region.

One of the physical phenomena influencing surface ozone concentrations in the Paso del Norte study area is surface-based mixing height, including its diurnal evolution. The surface-based mixed layer is the portion of the planetary boundary layer (PBL) above the surface, through which vigorous vertical mixing of heat, moisture, momentum, and pollutants occur

(Holtzworth, 1972). The PBL is made up of the CBL during the day, and the nocturnal boundary layer (NBL)and a residual layer at night. The NBL forms in the evening when air near the surface cools. This results in stable conditions that reduce vertical mixing in the NBL and, thus, confines surface-based pollutants to the lowest several hundred meters during the night. During the daytime, the mixing height is defined as the altitude of a stable layer, or an inversion capping a well-mixed CBL; the CBL grows shortly after sunrise 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 residual layer remains and initially has the characteristics of the recently-decayed CBL. At night, identification of the top of the mixed layer is more complicated because, often, several stratified layers exist below the base of a well-defined inversion, and vertical mixing is confined to the lowest tens or hundreds of meters.

2. Study Area

The Paso del Norte study area encompassed the western corner of Texas and adjoining areas of New Mexico and Chihuahua, Mexico (see Fig. 1). This area, mostly desert with agriculture along the Rio Grande River, is about 40 km north to south and about 80 km east to west. In the center of the study area is El Paso, Texas, and Ciudad Juárez, Mexico. The total population of the area is about 1.9 million. The main geographical features in the study area are the Franklin Mountains, which run north to south and end abruptly just north of downtown El Paso; the Juárez Mountains which lie to the west of Ciudad Juárez; and the Rio Grande River valley that divides the Franklin and Juárez Mountains and runs generally northwest-to-southeast through the area.

These geographical features have a strong influence on the local surface-level winds in the summertime when frequent large-scale high pressure systems allow for local forcing to dominate the local winds. The typical summer day begins with drainage flow down the Franklin and Juárez Mountains and the Rio Grande river valley; this flow results in light northwesterly winds in the area. As the morning sun warms the east, and then south, sides of the Franklin and Juárez Mountains, the drainage flow weakens. As more heating occurs throughout the day, the winds reverse direction and become upslope winds from the south and east. At the same time, the strong summertime-daytime heating causes the boundary layer to deepen rapidly throughout the late morning and early afternoon. The deepening of the boundary layer allows for momentum transfer between the surface and aloft air. This transfer of momentum can either impede or enhance the locally driven upslope flows. In the evening, as the ground cools, the surface and aloft layers de-couple and the momentum transfer stops. Since cooling on the mountains is more rapid than in the valley, drainage flow begins and continues until the next morning.

3. Data

The pre-existing air quality and meteorological monitoring network included fifteen air quality monitoring sites: fourteen surface meteorological stations; one upper-air meteorological station with a Doppler acoustic sounder (SODAR); fourteen ozone monitors; five NO/NO_x monitors; eight CO monitors; two hydrocarbon canister samplers operated every sixth day; and one continuous hydrocarbon monitor. These monitoring sites were operated by the TNRCC, El Paso City–County Health and Environmental District, Direccion Municipal de Ecologia–Ayuntamiento de Juárez, and the New Mexico Environment Department (NMED), with support from the EPA.

The 1996 Paso del Norte Ozone Study ran from July 21 to September 21, 1996. During this period, the existing network of air quality and meteorological monitoring sites was supplemented by the addition of four temporary air quality monitoring sites with ozone and oxides of nitrogen (NO/NO_x) monitors, supplemental NO/NO_x monitoring equipment at two existing stations, and three temporary upper-air meteorological stations with radar wind profilers and radio acoustic sounding systems (RWP/RASS). See Table 1 and Fig. 2 for site details.

Intensive operation periods (IOPs) were established on a short-term forecast basis when ozone concentrations were expected to be high. Special activities during the IOPs included hydrocarbon sampling at four surface sites, carbonyl sampling at three surface sites, and aloft measurements from a Piper Aztec small aircraft which collected continuous (every second) data for position, altitude, temperature, dew point, ozone, NO/NO_y (NO_y are oxides of nitrogen with a short inlet that does not remove reactive species such as nitric acid), and CO, plus grab samples for hydrocarbons and carbonyls. See Table 1 and Fig. 2 for surface-site details. Data from the routine monitoring networks were combined with the data from the enhanced network in a single database for use in data analysis and modeling. Additional details of the measurements and database are available in Roberts, et al., 1996.

4. Methods

Gaining an understanding of the physical and chemical processes which lead to high ozone concentrations in the Paso del Norte study area involved several tasks. In summary, analyses were performed to determine whether the 1996 ozone episodes are representative of typical ozone episodes in the Paso del Norte study area. If the episodes re representative, it is appropriate to apply conclusions drawn from the analysis to other historic ozone episodes and to use the episodes for urban airshed modeling. Next, analysis of the synoptic meteorology and local dispersion and transport of ozone and its precursors was completed. Dispersion and transport were assessed by reviewing the evolution of the PBL and winds during episode and non-episode days, in conjunction with analysis of surface and aloft air quality data. Details of this effort follow.

Ozone episode days during the 1996 Paso del Norte Ozone Study were defined as days on which 1-hr surface ozone concentrations exceeded 95 ppb at any site. This threshold value of 95 ppb was selected to increase the statistics computed to assess yearly distributions of ozone concentration during exceedances. During the 1996 study, there were ten episode days. Of these days, August 13 was the only day with an exceedance of the 1-hr NAAQS of 0.12 ppm. Therefore, much of the analysis focused on the August 13 episode and surrounding days. On September 4 to 6, ozone concentrations ranged from about 80 ppb (0.08 ppm) to 118 ppb (0.12 ppm); these days were also included in some of the analyses.

To determine if the August 13 ozone episode was representative of typical ozone episodes, synoptic and local meteorological conditions associated with past ozone episodes were reviewed and compared to the synoptic and local meteorological conditions associated with the August 13 episode. Maximum ozone concentrations in the Paso del Norte study area from 1985 through 1996 were reviewed, and all ozone episodes (exceedance of the 1-hr NAAQS of 0.12 ppm) were extracted. The ozone sites used to determine episode days included the three sites with data for all years, 1985 through 1996: El Paso UTEP, El Paso Campbell, and La Union (Fig. 2). There were 76 ozone episode days from 1985 through 1995. Weather charts were readily available for only 32 of these 76 days. For each of the 32 ozone episodes, the 0700 Mountain Standard Time (MST) 500-millibar (mb) height and wind field, the 0700 MST surface wind and surface pressure field, and the daily maximum surface temperature in the Paso del Norte study area were analyzed.

To determine how meteorology influences the transport and dispersion of ozone and its precursors in the Paso del Norte study area, a detailed analysis of the synoptic and local meteorology during the 1996 ozone episode days and surrounding days was completed. In particular, the 0700 MST 500-mb height and wind field and daily rawinsonde temperature soundings were used to characterize the evolution of the large-scale meteorology during the episodes. These results were combined with results from analyses of the evolution of the local meteorology and air quality during ozone episodes and surrounding days.

The surface air quality data were analyzed using spatial contour plots of the hourly surface CO, NO, NO_x, and ozone that were created using kriging interpolation. Note that, although there were a limited number of monitoring sites, the contours are still useful for visualizing concentration gradients and the general air quality patterns. The contours are not meant to fill in data where there were no nearby monitoring sites.

In addition to the surface air quality data, vertical profiles of available early morning air quality data collected by the aircraft on several flight days were analyzed. The purpose of this analysis was to determine whether aloft ozone and ozone precursor concentrations located in the residual layer are different on non-episode days (August 12 and September 5) compared to an episode day (August 13). The residual layer is the region above the NBL, which may contain ozone and ozone precursors from the previous day’s emissions. Past studies have shown that aloft ozone and its precursors (carryover) can contribute significantly to the daytime peak ozone concentrations when the growth of the daytime CBL mixes aloft air with the surface air (Blumenthal et al., 1997).

The local meteorological variables analyzed included hourly surface and aloft winds, hourly temperature soundings, hourly mixing heights, and morning mixing height growth rates. Surface winds were measured at fourteen sites; the aloft winds were measured at the three RWP sites; the temperature soundings were measured by RASS at three sites; and the hourly mixing heights were produced using radar reflectivity data from the three RWP sites.

RWP reflectivity data can be used to infer mixing heights (Dye et al., 1995 and White, 1993). To estimate mixing heights 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; the fluctuations are primarily due to gradients in the water content of air. Gradients 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 inversion (Wyngaard and LeMone, 1980). Generally, C_n^2 estimated from RWPs will not resolve low-level inversions below 200 to 300 m above ground level (agl). Under these conditions, virtual temperature (T_v) data collected by RASS coupled with surface T_v measurements were used to generate estimates of the height of the inversion base at night.

To investigate the role that the evolution of the CBL played on surface ozone concentrations, hourly mixing heights at the El Paso Downtown RWP monitoring site were estimated for August 12 to 14 and September 4 to 7. Comparisons of the mixing heights estimated at the El Paso Downtown site with two other sites in the area showed similar CBL evolution. From these hourly mixing heights, mixing-height growth rates (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 moderate surface winds (August 14 and September 5) were considered separately from days with light winds. To assess morning wind strength, the 0600 through 1000 MST vector average winds for the El Paso East, El Paso Downtown, El Paso UTEP, and 20/30 Club sites were calculated and then averaged together. If this four-site average of the morning vector winds were less than 1.5 ms^{-1}, then the morning winds were considered light; otherwise, the winds were considered moderate. The El Paso East, El Paso Downtown, El Paso UTEP, and 20/30 Club sites were selected because they capture the winds in El Paso and Ciudad Juárez.

5. Results

5.1. Meteorological Representativeness of the August 13, 1996, Ozone Episode

Seventeen of the 32 historical ozone episodes were characterized by a ridge just west of, or over, the Paso del Norte study area; an example episode is shown in Fig. 3. During nine of the 32 ozone episodes, a broad high with no well-defined ridge existed over the southwestern United States. A flat synoptic height field existed during four ozone episodes. Even though the ridge and broad high events are classified separately, local surface conditions affecting ozone concentrations are similar in both scenarios. The surface features associated with these synoptic-scale meteorological conditions and with ozone episodes typically include daily maximum surface temperatures above 32°C, light southeasterly (1.5 ms^{-1} or less) or calm winds at 0700 MST, weak 0700 MST surface pressure gradients, and a surface trough near the Paso del Norte study area extending to the north or northeast.

The synoptic and local meteorology associated with the August 13 ozone episode is representative of the synoptic and local meteorology associated with historic ozone episodes: the 500-mb height field at 1700 MST shows a ridge just west of the Paso del Norte study area, typical of the most common event; the 0700 MST surface flow was light southeasterly with a surface trough extending to the north; and the daytime maximum surface temperature was 36°C.

5.2. Synoptic Meteorology From August 12 through 14, 1996

This section summarizes the development of the large-scale synoptic meteorology from August 12 through August 14 encompassing the August 13 ozone episode. The August 13 ozone episode occurred at a time characterized by a brief period of limited mixing, warm surface and aloft temperatures, and light-to-stagnant surface winds. The predominant synoptic feature in the days prior to, during, and after the ozone episode was the expansion, intensification, and slow progression eastward of an upper-level ridge of high pressure. This synoptic event can best be illustrated by reviewing the characteristics of the 500-mb constant pressure pattern over the western United States and other associated sub-synoptic patterns.

On August 12, an upper-level high intensified and centered over western Utah with the ridge axis oriented north-south to the west of the Paso del Norte study area. As the upper-level high intensified, upper-level temperatures increased slightly over the Paso del Norte study area as indicated by the increase in height between the 1000-mb and 500-mb pressure levels. The associated surface high also moved farther south and broadened out eastward. Thus, morning surface winds in the Paso del Norte study area diminished from the day before and turned light southeasterly. Peak ozone concentrations reached 80 ppb.

On August 13, the 500-mb ridge continued to build and extend farther south with the ridge axis still west of the Paso del Norte study area. The 500-mb height over Utah reached its peak of the ozone episode on the afternoon of August 13 (Fig. 3). As a result of the intensification of the 500-mb ridge, the 850-mb temperatures over the Paso del Norte study area increased from 25°C on August 12 to 30°C on August 13. This aloft warming strengthened the morning inversion from 6.5°C on August 12 to 8.7°C on August 13. The morning inversion strength was estimated by taking the difference between the maximum temperature within the inversion and the surface temperature at 0600 MST. The surface high became much broader and less defined, resulting in near stagnant morning surface winds. On this day, the highest ozone concentration during 1996 of 137 ppb was observed at 1100 MST at the Chamizal monitoring site.

On August 14, the 500-mb ridge dissipated slightly from the day before and surface pressure began to fall west of the Paso del Norte study area, while slightly rising to the east of the study area. This resulted in strong southeasterly and easterly winds in the Paso del Norte study area for the entire day of August 14. Aloft temperatures continued to warm slightly, further strengthening the inversion to 9.7°C. Ozone on this day reached 87 ppb.

5.3. Evolution of Regional Mesoscale Meteorology

The evolution of the mesoscale meteorology can be used to assess the transport and dispersion characteristics of ozone and ozone precursors during the August 13 ozone exceedance and the surrounding days. The major mesoscale features discussed are the surface and aloft winds, the mixing heights, and mixing growth rates.

On the morning of August 12, surface winds were light (about 1 ms^{-1}) from the east and northeast. By early afternoon the surface winds increased to around 5 ms^{-1} from the east-southeast with maximum wind velocities occurring between 1500 MST and 1700 MST; the winds were probably forced by the combination of local upslope flow and synoptic southeasterly flow. Aloft winds within the PBL showed characteristics similar to the surface flow with light southeasterly winds in the morning peaking in the early afternoon and decreasing slowly throughout the night.

On August 12, the base of the inversion at all three sites was approximately 300 m in the predawn hours. By midmorning, surface heating and thermals resulted in a rapid rise in mixing heights. At 1100 MST, the mixing heights at all sites were above 2000 m, peaking at approximately 3700 m in the mid-afternoon hours. Ozone in the downtown area peaked at 77 ppb at 1000 MST, one hour prior to the rapid mixing-height rise.

By the morning of August 13, calm and light (less than 1.5 ms^{-1}) and variable winds were observed in the river plain encompassing the metropolitan area, with light drainage flow occurring in the river valley to the northwest. As the day progressed, light and variable conditions continued at the surface and in the mixed layer. By late afternoon, a light upslope southerly flow returned to the area.

On August 13, the early morning inversion base was lower than on August 12, and the mixing-height rise through the morning hours was significantly slower. The potential cause of the slower mixing growth rate is related to aloft warming caused by sinking air as observed in the Nested Grid Model forecast model (National Oceanic and Atmospheric Administration, 1996). At 1100 MST the mixing height at the El Paso Downtown profiler site was 1200 m, while the mixing height at the El Paso East and El Paso West RWP sites was 600 m. Peak ozone concentration reached 137 ppb at the Chamizal monitoring site.

As on August 13, a slow morning mixing-height rise and associated low midmorning mixing heights were observed on August 14. At 1100 MST the mixing height at the El Paso Downtown site was only 1000 m. Unlike the conditions on August 13, there were moderate easterly to southerly winds (greater than 2 ms^{-1}), and air was channeled up the river valley to the northwest of El Paso along the west side of the Franklin Mountains. Southeasterly flow aloft was also observed for the entire day of August 14. Peak ozone concentration of 80 ppb on this day occurred downwind of El Paso at the La Union, NM monitoring site. Meteorological simulations for August 12 to 14 to assess conditions that influence ozone concentrations in the Paso del Norte air shed are discussed in Brown et al., 2000.

5.4. Primary Physical Factors Controlling Ozone Concentrations

The physical phenomena that are typically associated with high ozone concentrations include high surface temperatures, strong sunlight with few clouds, and light early morning winds. In the Paso del Norte study area, the basic conditions that produce high ozone concentrations are present during most of the period from mid-July through mid-September, with abundant sunshine, maximum surface temperatures above 32°C, and only brief periods of thunderstorm clouds and bursts of rain. With these basic conditions met during the ozone episodes of August 12 to 14 and September 3 to 7, 1996, we focused our efforts on the diurnal growth rate of the CBL, on the maximum height of the CBL (i.e. the mixing height), and on the surface winds. Analysis 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 with similar weather conditions were compared. For example, to examine the influence of mixing heights and MGRs on peak ozone concentrations, 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 MGRs 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.

5.4.1. Carryover

Past ozone studies have shown that ozone and ozone precursors from previous days can contribute significantly to the following days' maximum ozone concentrations (Blumenthal et al., 1997). However, examination of early morning aloft air quality data collected during the Paso del Norte Ozone Study 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 during the summer of 1996. These comparisons include 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 118 ppb. Fig. 4 shows a vertical pollutant profile that is typical of early morning vertical pollutant profiles, regardless of a given day's peak ozone concentration. 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. These concentrations are lower than morning and mid-day concentrations of ozone and NO_y and NO by a factor of 2 (for ozone) and 2 to 4 (for NO_y and NO). 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.

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. Ozone concentrations above the NBL up to about 3000 m mean sea level (msl) were about 45 to 65 ppb; NO_y concentrations were about 1.0 to 2.0 ppb; and NO concentrations were about 0.1 to 0.2 ppb.

5.4.2. Mixing-Height Growth Rate

The growth rate and height of the mixed layer critically influences day-to-day ozone concentrations. Dye et al. (1998) 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 Paso del Norte study area.

To investigate the role that the evolution of the CBL has on surface ozone concentrations, hourly mixing heights at the three RWP monitoring sites were estimated, and MGRs from 0600 to 1200 MST were calculated for each day and compared to peak ozone concentrations in the downtown area. In summary, on days with similar wind patterns, the mixed layer grew much slower on high ozone days compared to low ozone days.

Fig. 5 shows time series plots of mixing heights at the El Paso Downtown RWP monitoring site for August 12 to 14 (see Brown et al. [2001] for time series plots of mixing heights at this and other locations from August 12 to 13). Table 2 shows the daily morning MGRs from 0600 to 1200 MST and the peak ozone concentrations in the downtown area for August 12 to 14 and September 4 to 7. As shown in Table 2 and Fig. 5, the MGRs on the high ozone episode day of August 13 were more than a factor of 2 slower, compared to the low ozone day of August 12. At the El Paso Downtown site, the MGR was 150 mhr^{-1} on August 13 compared to 380 mhr^{-1} on August 12. Analysis of the temperature sounding data indicated that the slower mixing growth rates on August 13 compared to August 12 were probably due to increasing aloft stability and the strengthening of the inversion from August 12 to August 13. In addition, meteorological modeling results indicated that the MGR was more rapid on August 12 due to aloft winds being lower in elevation; which would increase mechanical mixing(Brown et al., 2001). The slow MGR on August 13 likely contributed to higher ozone concentrations on that day by restricting pollutant dispersion in the vertical direction. 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 1.2 ppm between 0600 and 1000 MST on August 12 compared to 2.4 ppm on August 13, about a factor of 2 different. The slower growth rates combined with higher precursor concentrations contribute to the high ozone (137 ppb) observed at the Chamizal site on August 13, whereas the quick increase in the mixing height and lower precursor concentrations contributed to the modest ozone peak

(77 ppb) on August 12. Meteorological simulations of the MGR for the August episode using boundary-layer meteorological modeling are discussed by Brown et al. (2001).

Note that if there were high concentrations of ozone located aloft from the previous day (carryover), then a fast MGR could increase ozone concentrations. However, aloft carryover concentrations on all days were lower than mid-morning concentrations by a factor of 2 or more; thus, this mechanism did not contribute to ozone concentrations.

In conclusion, slow MGR combined with low mixing heights played an important role in the high ozone concentrations observed in the Paso del Norte study area. When the MGR is slow and the mixing height 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 keep precursor emissions concentrated; this condition is associated with higher ozone concentrations later in the day. Additionally, the limited vertical dilution of surface air with cleaner aloft air results in higher surface ozone concentrations.

Historically, maximum daytime mixing heights have often been considered to represent the volume of air for pollutants. However, as shown in Fig. 5, all three days, August 12 to 14, had similar maximum mixing heights but very different ozone concentrations. Also, as shown in Table 2, the maximum mixing heights on August 12 to 14 and September 4 to 7 do not relate to peak ozone concentrations.

5.5. Dispersion and Transport by Surface Winds

Although slow MGRs could play a role in producing high ozone concentrations, high ozone concentrations did not occur under conditions of moderate-to-strong morning surface winds (wind speeds greater than about 1.5 ms^{-1}). When surface wind strengths were moderate to strong, ozone precursor emissions were dispersed horizontally and peak ozone concentrations were lower with broader horizontal extent even if the MGR was slow. In this context, *dispersion* is the scattering of pollutants due to advection by surface winds.

As mentioned above, on August 14 and September 5, relatively strong morning winds occurred. Slow MGRs occurred on August 14 and September 5. The mixing growth rate at the El Paso Downtown site on August 14 was only 120 mhr^{-1}, or 30 mhr^{-1} 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 the El Paso Downtown site on September 5 was only 150 mhr^{-1}, the same as on August 13. The downtown peak ozone concentration on September 5 was only 60 ppb. Given the slow MGRs on both August 14 and September 5, it is 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 (vector wind speeds greater than 1.5 ms^{-1}) on August 14 and September 5 is evident in the relatively low NO_x and NO concentrations observed near downtown source areas with high concentrations in downwind areas (vector average wind speeds are shown in Table 2). For example, on 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 (vector wind speeds of about 0.9 ms^{-1}), morning NO_x concentrations were around 200 ppb near downtown source areas. On the morning of September 5 (vector wind speeds greater than 1.5 ms^{-1}), the spatial characteristics in NO_x concentrations were similar to those on August 14. CO concentrations were also lower when wind speeds were higher.

In summary, on light-wind mornings when vector wind speeds were less than about 1.5 ms^{-1}, a "cloud" of ozone precursors with high NO_x, NO, and CO concentrations exists and is confined near the emissions source region (as observed on August 13). Higher precursor concentrations can lead to more NO-scavenging and lower ozone concentrations early in the day. Later, on these days, the high ozone precursor concentrations lead to high ozone concentrations with the highest ozone concentrations centered near or slightly downwind from the downtown area (Fig. 6). On days with moderate wind (vector wind speeds greater than about 1.5 ms^{-1}), the wind disperses the precursor 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 (Fig. 7).

5.6. Aloft Stability

Aloft warming contributes to atmospheric stability. During ozone episodes in the Paso del Norte study area, rawinsonde and RASS T_v data revealed warming in the aloft air mass. A comparison of the RASS T_v 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. Fig. 8 shows virtual potential temperature (in degrees K) profiles at 0600 MST on August 12 to 14 at the El Paso West site (see Brown et al. [2001] for a more detailed figure). As shown in Fig. 8, the aloft T_v on August 12 was 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 to 14 was also observed at the 850-mb altitude. 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). The increase in inversion strength was a result of the aloft warming rather than the surface cooling. Estimates of surface heat fluxes from radiation data indicate that the fluxes were similar each day; thus, day-to-day differences in the MGR and ultimate mixing height were controlled primarily by the day-to-day increase in aloft stability.

6. Summary and Conclusions

Based on the analyses and observations discussed in this paper, an assessment of the meteorological and air quality characteristics can be presented to explain causal factors during the high ozone concentration episode of August 13 and episodes under similar conditions.

Synoptic meteorological conditions were usually characterized by a 500-mb ridge over or just west of the Paso del Norte study area; this feature induced aloft warming and increased atmospheric stability in the study area. Weak surface pressure gradients were also associated with these synoptic high pressure conditions and, thus, with high ozone concentrations in the area. Maximum surface temperature were at least 32°C, with a diurnal temperature variation of at least 14°C; these conditions produced strong photochemistry and a strong nocturnal temperature inversion which trapped morning emissions. In addition to these basic conditions, slow mixing layer growth rates (less than about 150 mhr^{-1} during the morning) and light surface winds (vector averages less than about 1.5 ms^{-1}) allowed ozone precursors and ozone to accumulate near emissions source areas, thus contributing to maximum ozone concentration greater than 95 ppb.

On days with high ozone concentrations, high morning concentrations of CO, NO, and NO_x were observed near the emissions source regions of El Paso and Ciudad Juárez. A cloud of ozone precursors formed in the morning and remained confined to the source region due to a slow MGR and light winds. On days with lower ozone concentrations, higher wind speeds dispersed the source cloud and maximum precursor concentrations were about a factor of 2 lower, but more widely distributed. On days with high ozone concentrations, the midday ozone cloud with the highest concentrations was confined to the source region, or slightly downwind. On days with lower ozone concentrations, maximum ozone concentrations were lower, but more widely distributed.

Aloft ozone and ozone precursor concentrations during nights that preceded exceedance days (and during the early mornings of exceedance days) were significantly lower than the maximum ozone concentrations, with aloft ozone of about 45 to 65 ppb, NO_y of around 1 to 2 ppb, NO at approximately 0.1 to 0.2 ppb, and non-methane hydrocarbons at about 25 to 55 ppbC. These conditions were about the same on both high and low ozone days. In addition, these concentrations of ozone were less than about one-half the maximum ozone concentration on high ozone days; thus, carryover of ozone and precursors did not significantly influence ozone exceedances.

In conclusion, collecting and analyzing the meteorological and air quality data used to understand the processes that influence ozone in the Paso del Norte air basin assist in meeting the goals of Annex V of the La Paz Agreement. This understanding has helped guide the development of, and has been used to validate, meteorological and photochemical models. Currently, the photochemical models are being used to evaluate emission control strategies designed to reduce ozone pollution in the Paso del Norte air basin. Since the Paso del Norte air basin is in both Mexico and the United States, control of area, point and mobile source emissions on both sides of the border is being addressed.

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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 CAMS 41	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 Pas~~o Tillman, TX~~	TIL	31.7569	-106.4828									X
Ivanhoe Fire Station	IVH	31.7881	-106.3217									X

O_3 - 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; CAMS – Continuous Air Monitoring Station (TNRCC).

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

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

[c] Two 2-hour samples per day.

Table 2. Mixing height growth rates (MGRs) and maximum mixing heights at El Paso West; El Paso East; and El Paso Downtown; vector average surface winds for 0600-1000 MST; and peak ozone concentrations on August 12 to August 14 and September 4 to 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 Height Growth Rates (m/hr)							
El Paso West	320	80	220	120	130	130	120
El Paso East	370	50	50	60	80	100	80
El Paso Downtown	380	150	120	100	150	130	120
Average of all sites	357	93	130	93	120	120	107
Maximum Daytime Mixing Height (m) at El Paso Downtown							
	3800	3700	3600	3600	3500	3500	3500
Average of 4 sites 0600 through 1000 MST vector average wind speeds (sites used include 20/30 Club, El Paso Downtown, El Paso East, and El Paso UTEP)							
	1.3 m/sec	0.9 m/sec	2.0 m/sec	1.3 m/sec	1.6 m/sec	1.0 m/sec	1.0 m/sec
Peak Observed Ozone Concentration (ppb)							
	77	137	79	118	60	82	97

List of Figures

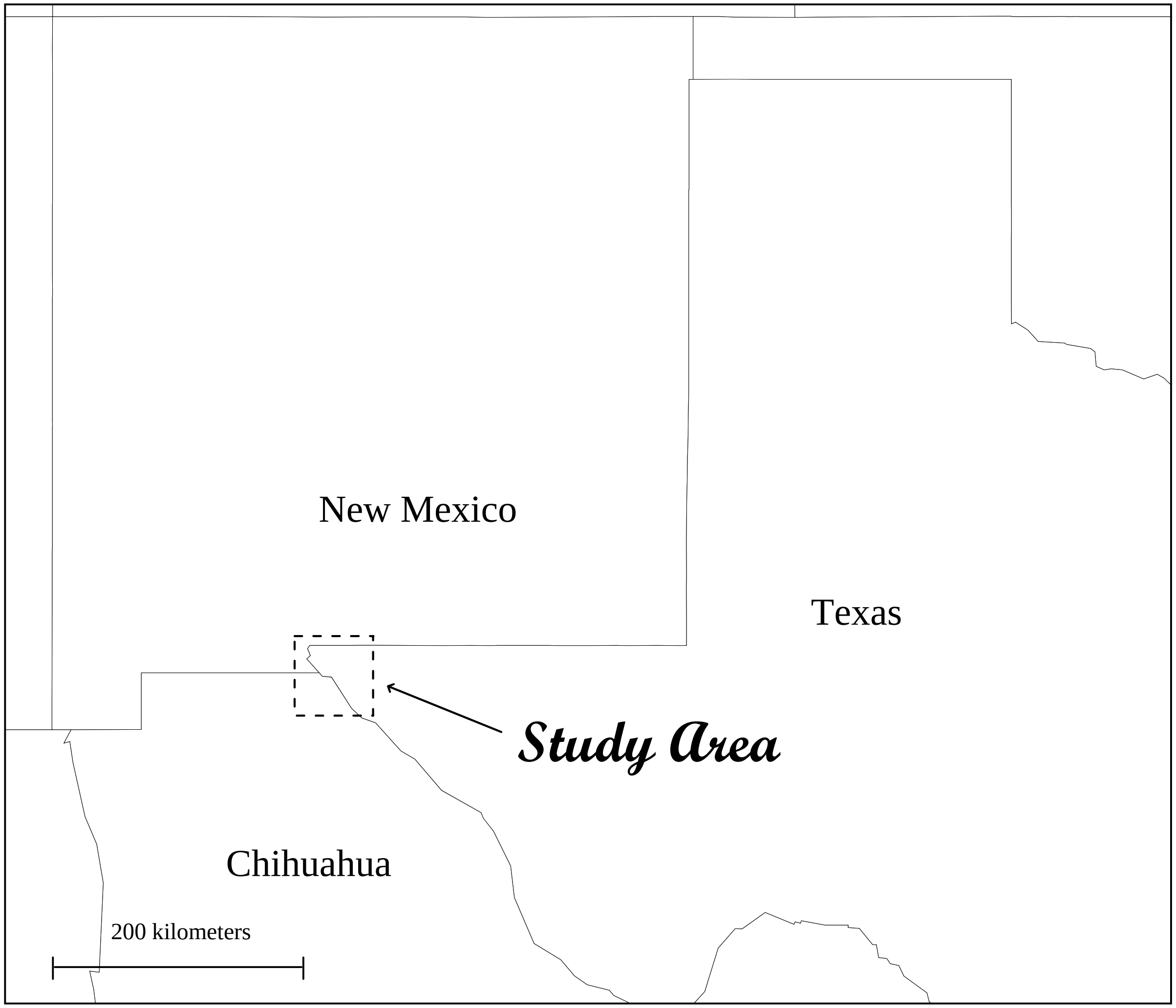
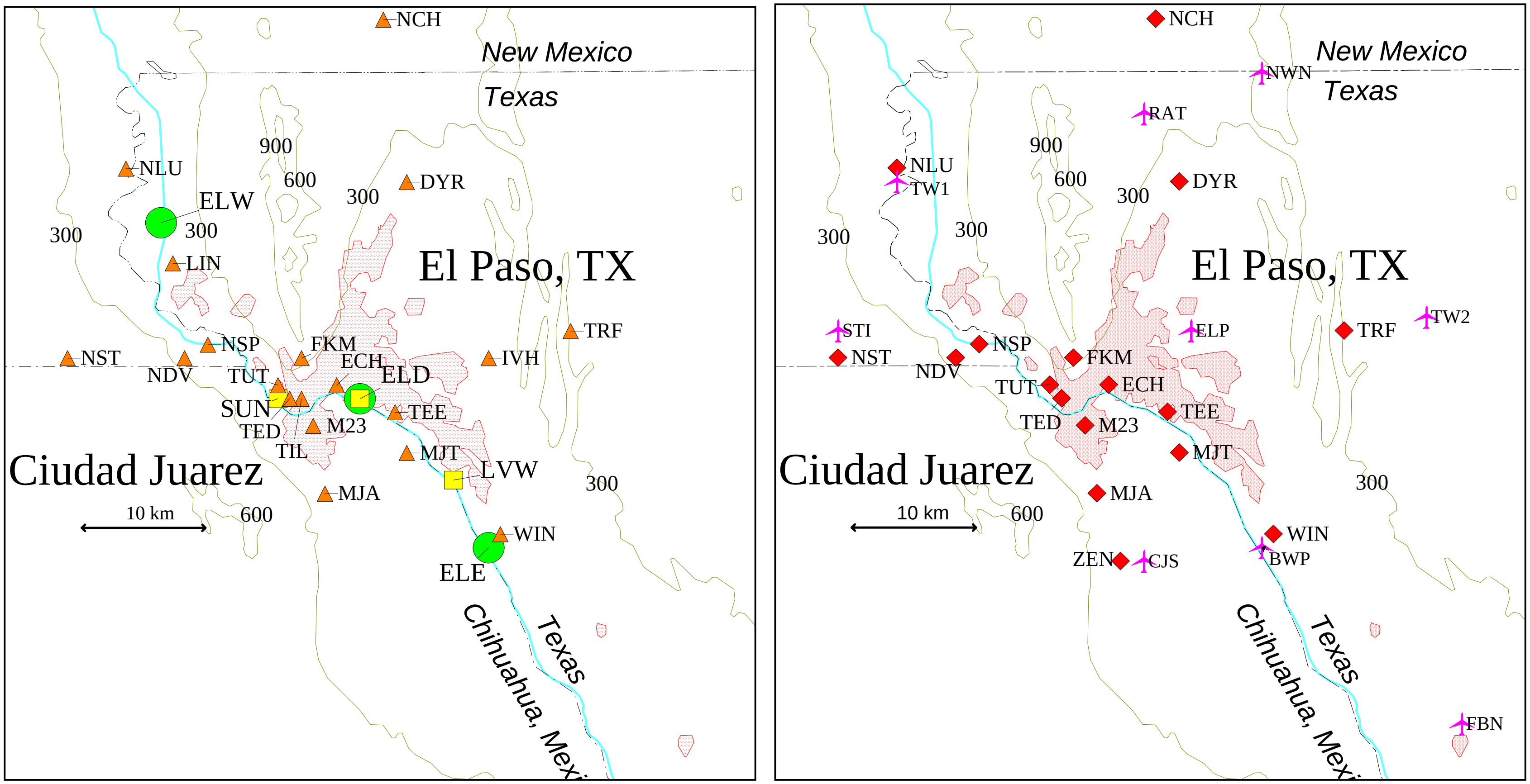


Fig. 1. The Paso del Norte Ozone Study area.



(a)

(b)

Fig. 2. Elevation contours (m agl) and 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 meteorology (circles); surface meteorology only (triangles); and sodars (squares). (b) Surface air quality stations (diamonds) and aircraft spiral positions (airplanes). Full names of surface meteorology and air quality stations are listed with these IDs in Table 1. Shaded areas are developed regions in El Paso and Ciudad Juárez.

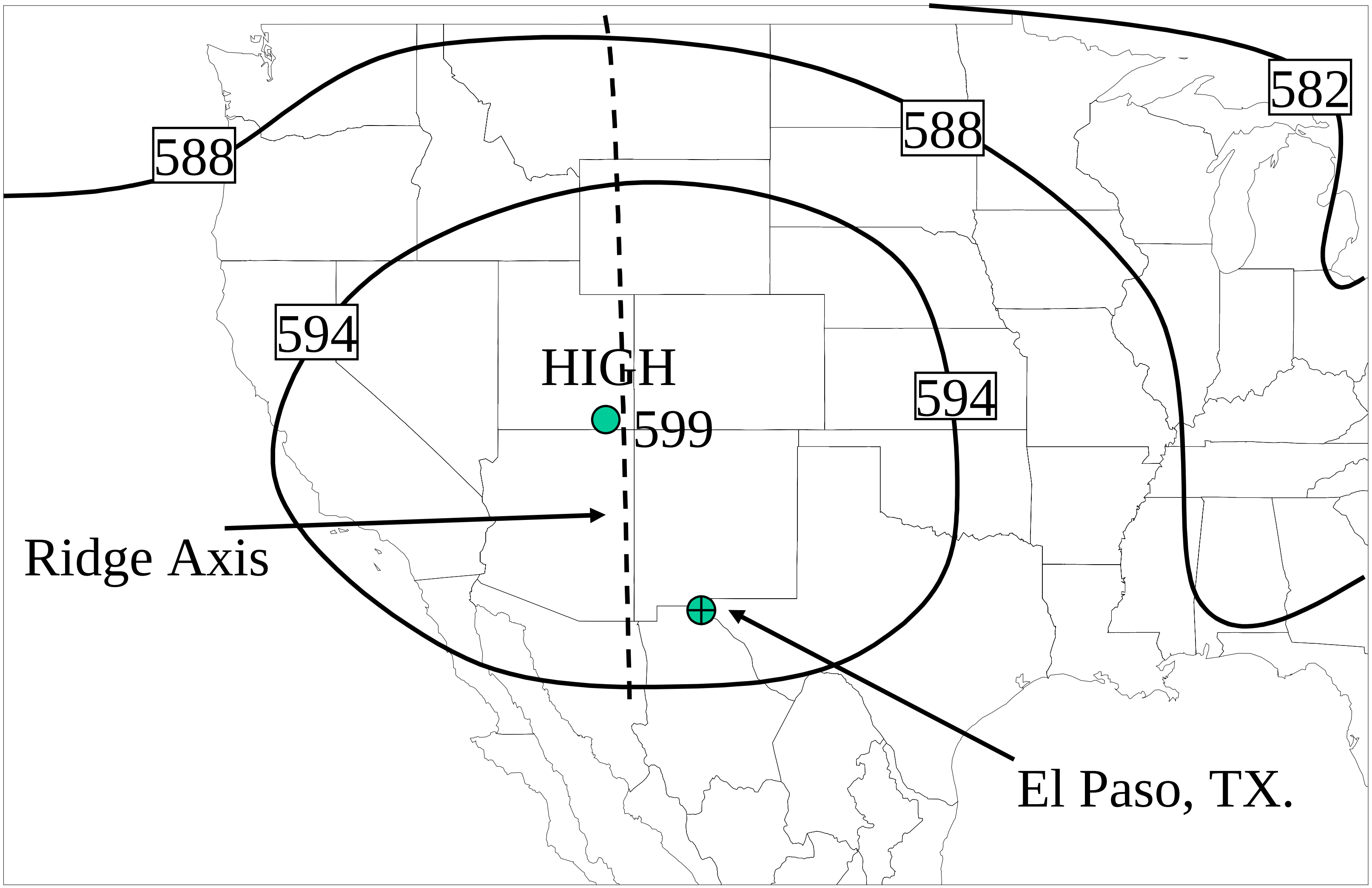


Fig. 3. 500-mb heights on August 13, 1996, at 1700 MST from the nested grid model initialization.

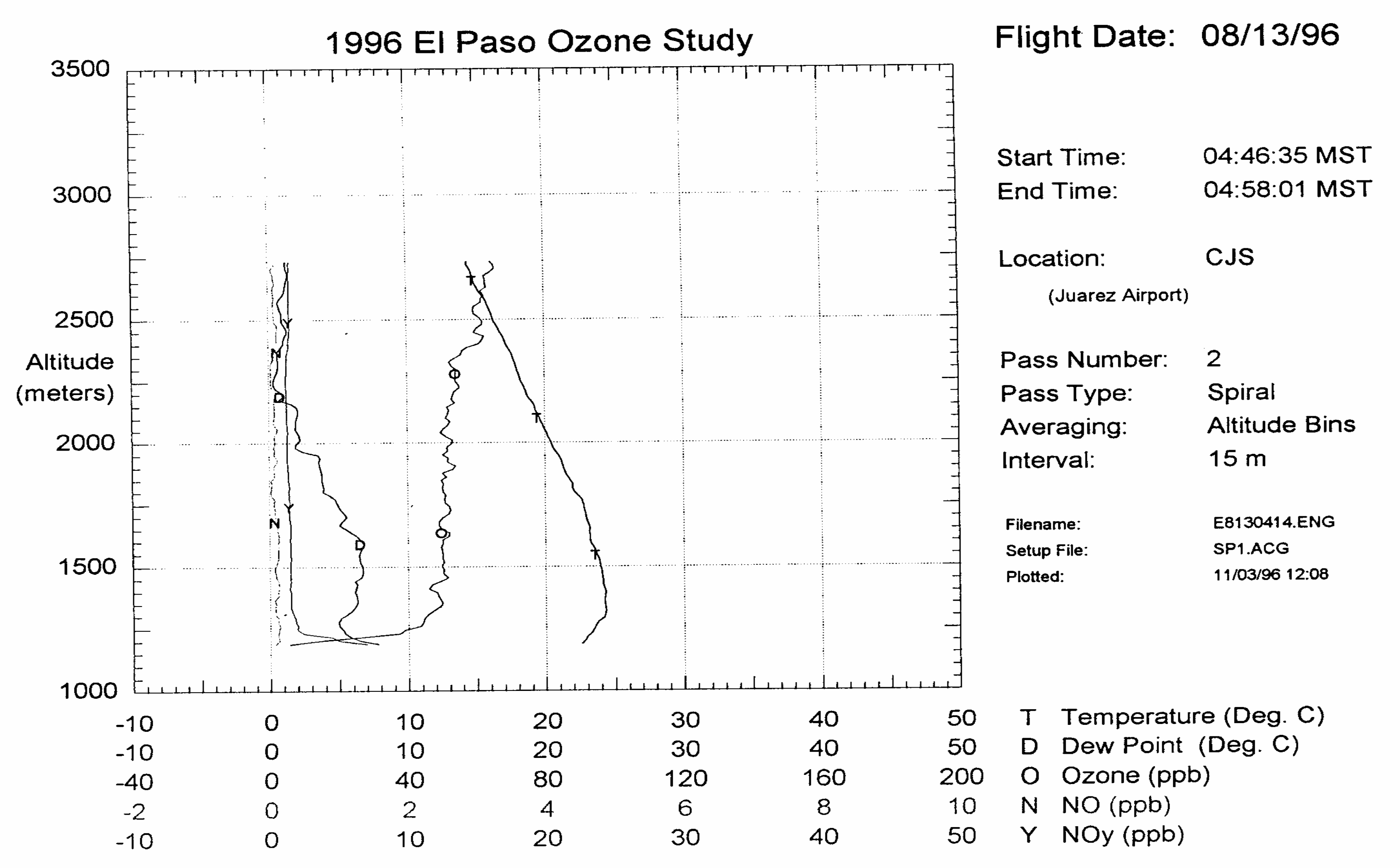


Fig. 4. Data collected during an aircraft spiral at Juárez Airport from 0446 to 0458 MST on August 13, 1996.

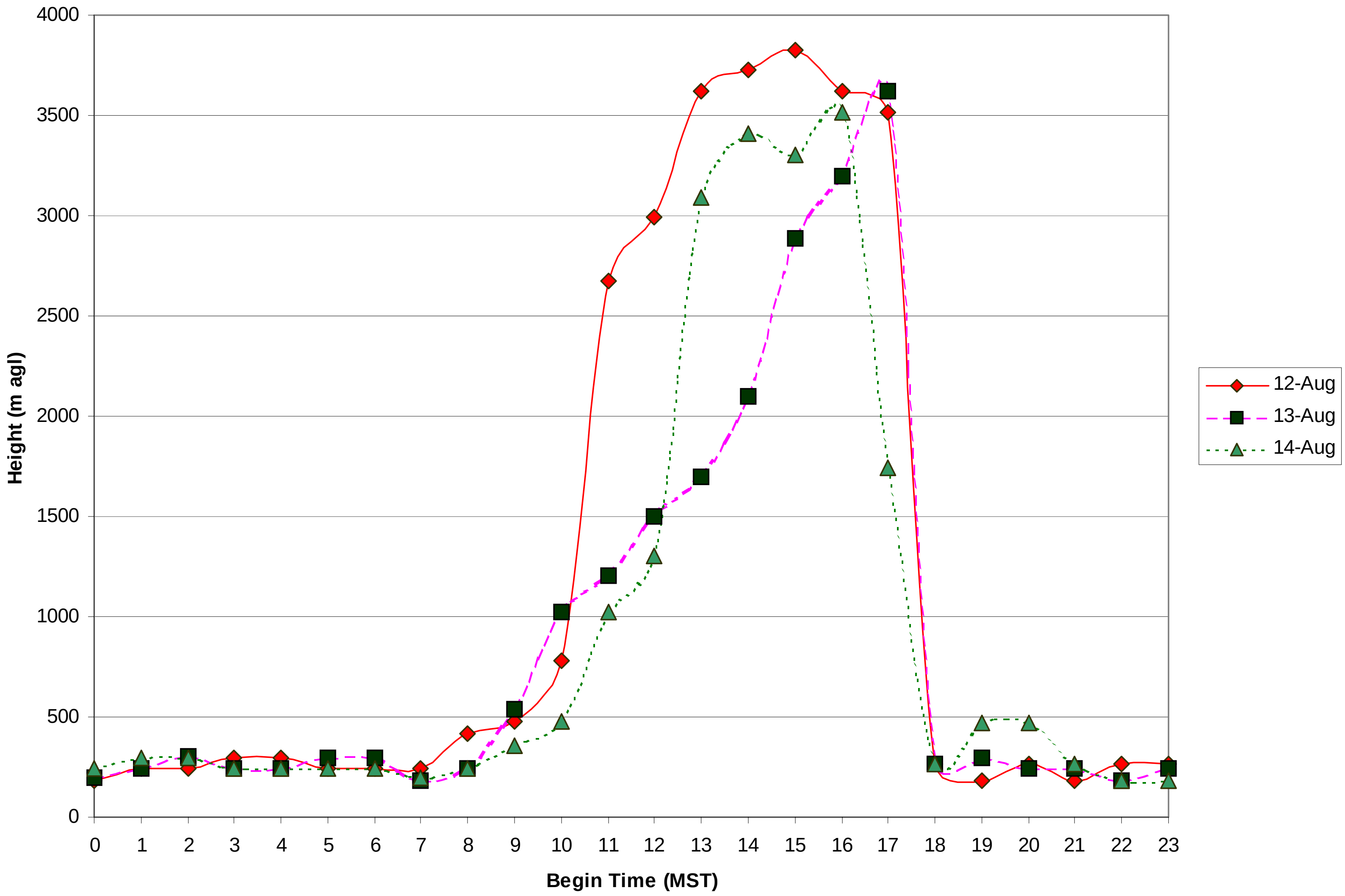


Fig. 5. Surface-based mixing heights at El Paso Downtown on August 12 to 14, 1996.

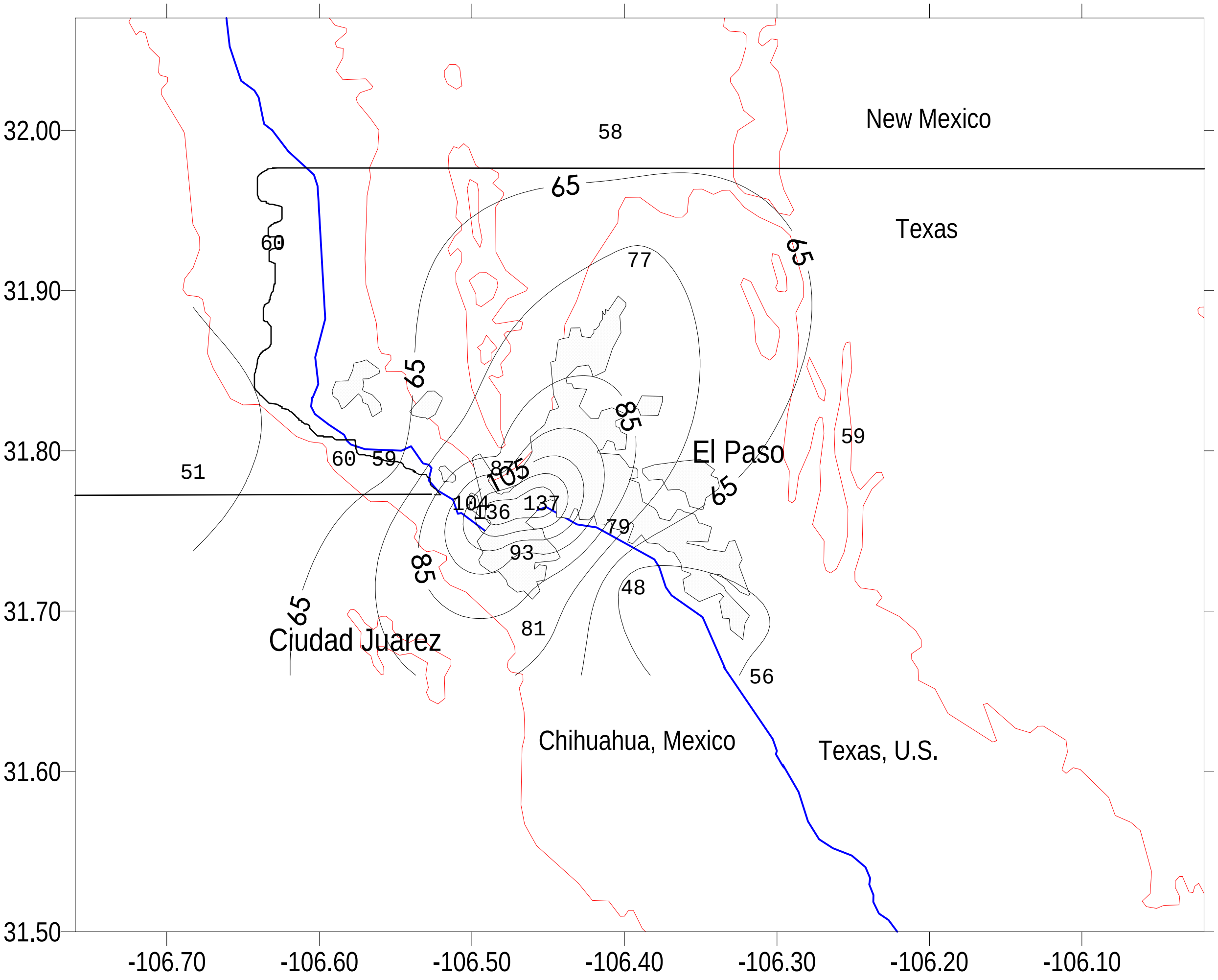


Fig. 6. Surface ozone concentrations (ppb), shown in plain text, and ozone concentration isopleths (ppb) estimated for August 13 at 1100 MST. The isopleths contour interval is 10 ppb. Shaded areas are developed regions in El Paso and Ciudad Juárez.

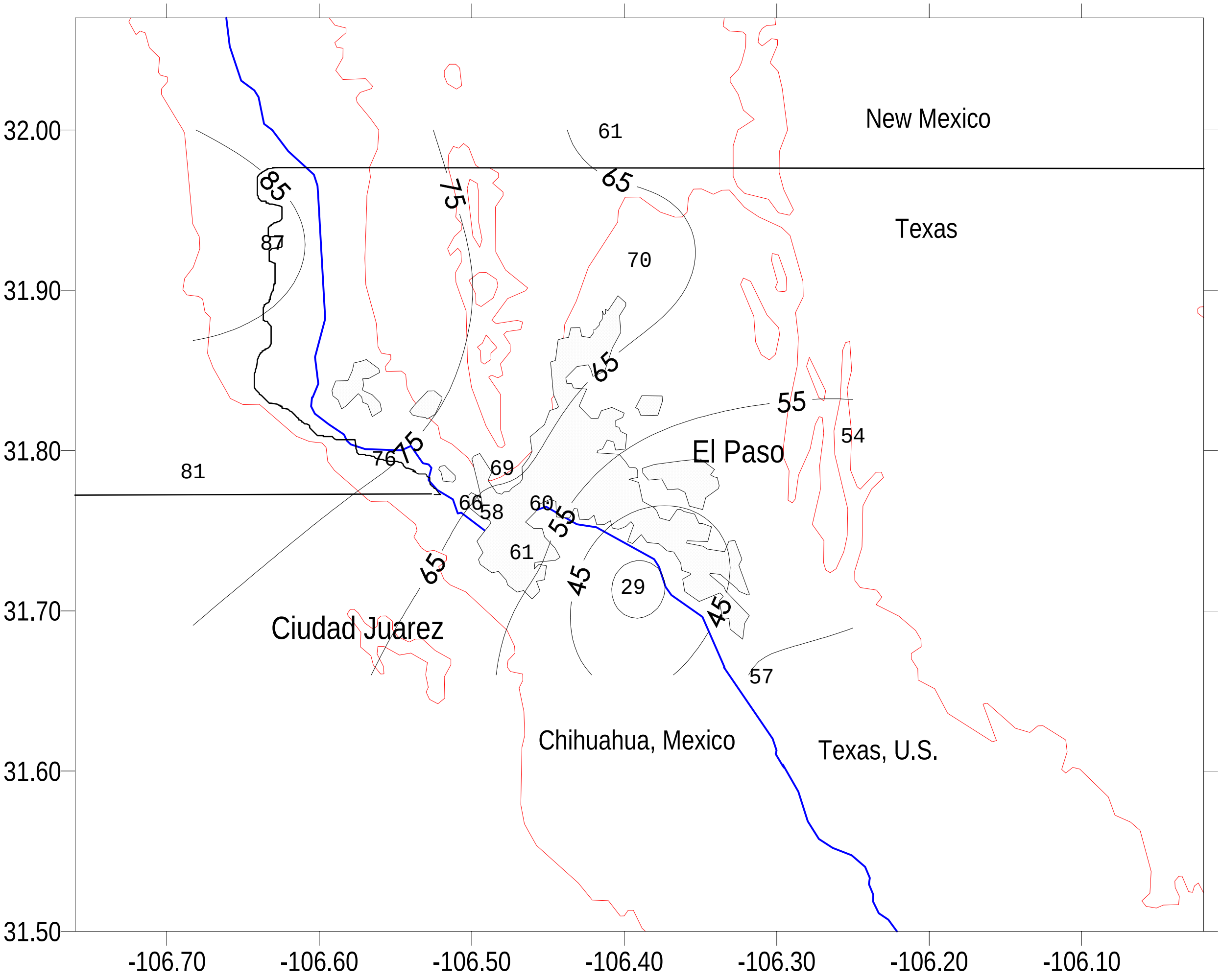


Fig. 7. Surface ozone concentrations (ppb), shown in plain text, and ozone concentration isopleths (ppb) estimated for August 14 at 1200 MST. The isopleths contour interval is 10 ppb. Shaded areas are developed regions in El Paso and Ciudad Juárez.

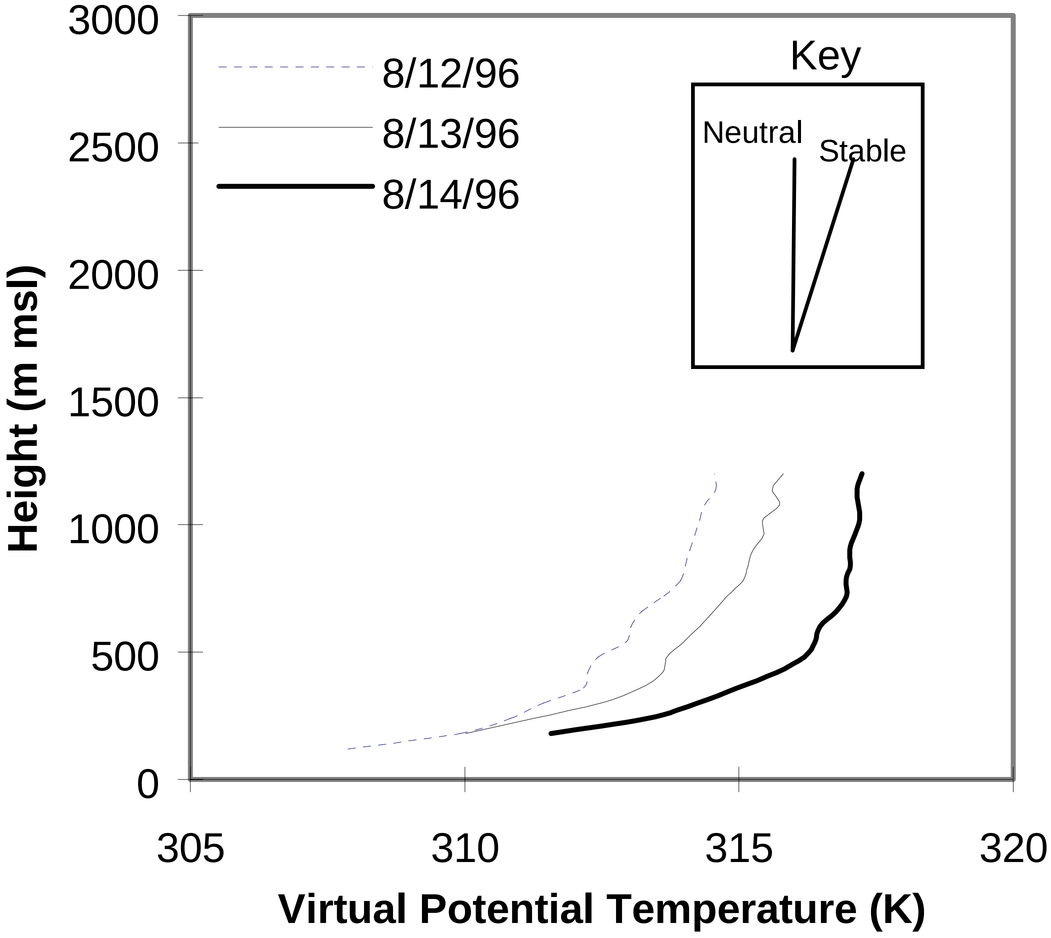


Fig. 8. Virtual potential temperature profiles computed from RASS measurements at El Paso West (ELW) from August 12 to 14, 1996 at 0600 MST. Positive slope = stable conditions; negative slope = mixing conditions; vertical slope = neutral conditions.