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OZONE CHARACTERIZATION STUDY

FINAL REPORT (P.O. 210324)

Prepared for:

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Senior Planner
Clark County
Air Quality — Protecting the air we share
Department of Air Quality & Environmental Management
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January 17, 2006

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ACKNOWLEDGEMENTS

This work was performed for the Clark County Department of Air Quality & Environmental Management under Purchase Order No. 210324. Messrs. Harish Agarwal and John Koswan provided overall project management. We wish to acknowledge the many contributions by Department staff members who participated in technical discussions and provided data, in particular, Mr. Pravin Pema. We wish to also acknowledge Mr. William Cates for providing comments to the initial draft version of this report.

Recognition is due to Ms. Elizabeth Niccum of the T&B Systems staff who assembled the data from a variety of sources and merged it into a consistent database, and to her and Ms. Shelley Tanenbaum for numerous data processing tasks performed during the course of this analysis. Again, many thanks to Ms. Susan Hynek who was central in compiling all the text, figures, and tables from various authors into a consistent format.

EXECUTIVE SUMMARY

During the last two and a half decades years, the Las Vegas Valley has emerged as one of the fastest growing metropolitan areas in the nation, leading to increased emissions into the atmosphere that are precursors to ozone production. In recent years, concentrations of ozone in Clark County have approached, and on occasion exceeded, the new 8-hour ambient air quality standard as defined by the recently adopted Federal Ozone Standard. These exceedances increase the potential for a violation of the federally mandated Clean Air Act, and the necessity for developing control strategies. Planning realistic, cost-effective control strategies requires a comprehensive understanding of the origin and fate of ozone and ozone precursors. The Clark County Department of Air Quality & Environmental Management (DAQEM) contracted Technical & Business Systems, Inc. (T&B Systems) to characterize the behavior of ambient ozone and associated meteorological features during high ozone events.

Characterizing ozone in Clark County and the Las Vegas Valley is a challenging process. Local airflow is a complex diurnal cycle resulting from mountain and valley dynamic influences when the area is under high-pressure weather systems that suppress regional airflow. Regional transport from nearby metropolitan areas, primarily in southern California, occurs in a complex structure of airflow in both the horizontal and vertical directions. Adding to this complexity is the limited amount of air quality and meteorological data available along transport pathways.

The primary objectives of the program were to evaluate data collected throughout Clark County, as well as data collected in source areas upwind of Clark County, to determine the nature of the ozone formation and interbasin transport. Specific objectives of the project were to:

- Examine the historical ozone and precursor trends in Clark County
- Determine annual ozone-cycle; establish when and where high ozone levels occur in Clark County
- Identify the meteorological features that affect ozone levels in Clark County (wind field patterns, mixing heights, etc.)
- Perform a descriptive analyses of high ozone events in Clark County that include events occurring over the ozone season under a variety of meteorological scenarios
- Develop methods to forecast the occurrence of high ozone levels
- Summarize what is known about the characteristics of ozone episodes and recommend additional measurements as necessary to further our understanding

Moreover, since the initiation of this analysis, the DAQEM has started planning a field measurement study for the 2005 ozone season. The results and recommendations of this analysis will also feed back into the field study design.

Both year-to-year differences and systematic trends were observed in the ambient concentrations of CO and NO_x. Declines in ambient CO concentrations occurred at 13 of 15 sites from 1996 through 2003. Four sites showed downward trends in NO_x levels and two sites showed upward trends. The median declines were 30 ppb per year for CO and 0.8 ppb per year for NO_x. Ambient ozone concentrations showed annual variations, but did not exhibit statistically significant trends over time. Since primary pollutant (CO and NO_x) concentrations changed over time but ozone levels did not, it is possible that the primary pollutant emission changes either did not affect ozone levels or that they affected ozone loss and formation in complex ways having little net change in the ambient ozone concentrations.

Ambient concentrations of both CO and NO_x showed statistically significant reductions on Sundays compared with Wednesdays. The median daytime decrease in ambient CO concentrations (21 percent) on Sundays was smaller than the corresponding daytime decreases of NO (38 percent) and NO_x (37 percent). In contrast, peak ozone levels increased on Sundays compared with Wednesdays. The increases in peak ozone levels on weekends, occurring in association with reduced weekend concentrations of ozone precursors, raise questions of relevance to possible future ozone control strategies. It is difficult to reconcile the observed weekday/weekend differences in precursor and ozone concentrations with a conceptual model of ozone formation in which ozone is produced locally and is limited by the availability of NO_x. Instead, the measurements show that the weekend reductions of NO_x changed the magnitudes of ozone loss due to titration by NO, thereby especially affecting the peak 8-hour ozone levels.

Using data from sites with measurements of ozone, NO, and NO_x, an observation-based method was applied for evaluating where and when ozone formation was limited by VOC and NO_x. On high-ozone days (top three peak 8-hour days per day of week per year), ozone formation was VOC-limited during early morning hours at all sites; ozone became NO_x-limited by late morning at Jean and by early afternoon at Apex. At Mesquite, Palo Verde, and Searchlight, ozone formation remained VOC limited throughout the day (sufficient NO_x was available to continue sustaining ozone formation), whereas Boulder City and JD Smith showed some afternoon hours that were transitional between VOC and NO_x limitation.

Synoptic weather patterns occurring over the Western U.S. were classified into particular pattern types with the objective of determining the relationship between large-scale weather features and ozone occurrences in the Las Vegas Valley. By examining the number of occurrences of the various weather types during the peak ozone months (May through August) for a 3-year period (2001 through 2003), it was postulated that significant relationships may be determined that will allow for the development of predictive models that can be used both for further analysis and operational applications. For the most part, high ozone events in Clark County occurred during three of the five weather types. Not unexpectedly, those weather types were characterized by high pressure that resulted in a stable atmosphere and light winds aloft.

Surface winds in Clark County are controlled by local terrain influences superimposed on the larger-scale synoptic and regional wind fields. Local influences include channeling of winds through passes and/or gaps in the terrain, and slope and valley wind systems. Slope and valley wind systems are local, thermally driven flow circulations that form in complex terrain areas. These processes directly affect the transport and dispersion of pollutants. The diurnal behavior of the prevailing Las Vegas Valley wind field is as follows: At night, when the atmosphere is most stable, local drainage flows dominate in the lower elevations. The flow appears to follow the terrain along the longitudinal axis of the Valley towards Lake Mead. The surface flow pattern during the stable nocturnal period is clearly decoupled from the stronger winds aloft, as seen from measurements at higher elevations around the Valley. By mid-morning, drainage flows cease and, due to solar-induced terrain heating, shift to an upslope flow, which most frequently is to the west and northwest. By mid-afternoon and continuing into evening, a rather uniform, moderately strong, southwest wind field prevails, as flows at all levels become strongly coupled. There appears to be a steady flux into the Valley from the southwest.

The only reliable upper-air meteorological measurements in Clark County are from the National Weather Service (NWS) rawinsonde at Desert Rock, Nevada (DRA), approximately 93 km northwest of Las Vegas in the southern end of the Nevada Test Site. Measurements of temperature, humidity and winds versus height are made routinely twice daily. However, the ability of DRA measurements to adequately describe the important meteorological features controlling dispersion in the Las Vegas Valley was questionable due to the complex terrain of Clark County. T&B Systems took a rawinsonde measurement from Las Vegas during the summer of 2004 which was compared to the corresponding DRA measurement. The primary shortcoming of the DRA sounding is the missing information between the surface height and DRA and Valley floor. The observed temperature and wind profiles were very similar above the initial surface layer.

CART® (Classification and Regression Trees) is an easy-to-use decision tree tool that can be used both for analyzing data and as a forecasting tool. CART automatically sifts large, complex databases, searching for and isolating significant patterns and relationships. Decision rules are derived from statistical relationships found between response (target) variables and predictors that minimize the variance in a training database. Approximately 70 predictors were selected from available datasets relevant to the study and used by CART to predict the existence or non-existence of ozone exceedances for the period of 1999 through 2003. The resulting decision tree classified all 27 exceedances for the period while misclassifying only 29 non-exceedance days, using 7 parameters and 10 decisions. The decisions could be essentially divided into two groups: those that favored transport as the cause of the exceedance, and those that favored local sources. Based on this grouping, the CART analysis implied 17 exceedance days resulting from predominantly local conditions and 10 exceedance days resulting predominantly from transport.

A major task of the study was to examine a set of high ozone events ranging in duration and occurrence within the ozone seasonal cycle. The temporal and spatial behavior of ozone and associated meteorology during ten events or episodes were analyzed in detail. The following table shows the dates that were included for study, the number of Clark County ozone monitoring stations that experienced an exceedance of the Federal 8-hour standard, and an assessment of the relative contributions from local sources and interbasin transport. During most episodes, the northwest quadrant of the Las Vegas Valley typically experienced the highest ozone levels. When interbasin transport was significant, sites throughout western Clark County had high ozone levels.

Interbasin transport of ozone played an important role on 9 of the 15 exceedance days examined during the case studies. In one instance, June 29, 2003, interbasin transport overwhelmed any local contribution to Clark County ozone levels. There were widespread exceedances occurring throughout the Clark County network preceded by stagnant flow conditions in the populated urban areas of California. Trajectory analyses, the timing and duration of ozone peaks, and the area of impact all infer overwhelming transport to Clark County. There is a definite Las Vegas urban ozone plume defined by the Clark County network. The relative contribution to the Clark County ozone burden from local versus transported sources is difficult to define. Nevertheless, our analyses suggested that the local contribution was significant on at least seven instances of the case study exceedance days.

Table ES-1. Summary of Ozone Episodic Case Studies

Date	# Sites >85ppb	Transport/Local Scenario
8/10/01	6	Significant local contribution
8/11/01	3	Significant local contribution
6/16/02	5	Interbasin transport significant contribution
6/27/02	5	Interbasin transport significant contribution
6/28/02	3	Interbasin transport significant contribution
8/11/02	3	Significant contribution from both interbasin transport and local sources
8/18/02	5	Interbasin transport significant contribution
5/26/03	3	Interbasin transport may be significant contribution
5/27/03	1	Significant local contribution
6/1/03	1	Interbasin transport significant contribution
6/3/03	1	Interbasin transport may be significant contribution
6/4/03	1	Significant local contribution
6/29/03	8	Overwhelming interbasin transport
7/9/03	2	Significant local contribution
7/21/03	7	Significant local contribution

One of the most interesting features of the meteorology on high ozone days was the prevailing southeasterly winds in the Las Vegas Valley when ozone production is active. The prevailing winds are generally from the southeast in the morning but by mid- to early-afternoon have shifted to southwesterly accompanied by increased speeds. However, on most of the high ozone days examined, southeasterly flow continued until late in the afternoon. Air mass trajectories beginning during the time of the morning commute initially meander in the downtown area before traveling upvalley (to the northwest) where and when maximum ozone levels usually occur. These features describe the general behavior of the Las Vegas urban plume.

The conceptual model for Clark County high ozone includes peak ozone levels in the northwest quadrant of the Valley supported by light southwest flows. During interbasin transport episodes, peak ozone levels may occur in other locations as well. Timing of ozone peaks typically occur mid-afternoon but again may vary considerably during interbasin transport scenarios.

Based on our analyses, several recommendations are put forth to fill the gaps in our knowledge of the air quality and meteorology:

- The origin and fate of pollutants in Clark County cannot be adequately understood without boundary layer measurements of temperature, winds, and ozone, at a minimum. The planned 2005 field monitoring study should include wind profiler/RASS and/or sodar/RASS or rawinsonde measurements from at least one site in the Las Vegas Valley and from one upwind location. Ozone monitoring sites should be placed at elevated platforms of opportunity (i.e., isolated hill tops or tall towers). Ozone aloft measurements using aircraft or ozonesondes is strongly recommended.
- Additional surface ozone monitoring should occur at locations at the extreme northwest and northwest of the Valley, and along the western foothills of the Valley to determine if the existing ozone network adequately characterizes peak levels.

- Analyses of day-of-week and trend variations in ozone and primary pollutant concentrations indicate that ozone levels at sites in and near Las Vegas may not respond to changes in local emissions in easily predictable ways. Further understanding of potential ozone responses to changes in emissions will require collocated measurements of ozone and precursor species, including hydrocarbons, at multiple sites representing different types of locations. Both long-term and episodic measurements would be of value.
- It is recommended that wind measurements be obtained from a site along the Las Vegas Wash, between Lake Mead and Las Vegas. The temperature gradients between Lake Mead and the Las Vegas basin is the likely mechanism for the southeasterly winds that dominate the meteorology during ozone exceedances, and the additional meteorological measurements will assist in confirming this mechanism and the role is has on ozone concentrations.
- The possibility of using the CART model as a forecasting tool should be further evaluated using 2004 data. Assuming it shows promise, the CART model should be utilized as an integral part in the 2005 field campaign. It is also recommended that further CART analysis be conducted for future seasons using additional predictor parameters that may be collected during the 2005 field study and future years. These parameters include upper-air meteorological data, temperature profiles, mixing heights, ozone concentrations aloft, VOC concentrations, and NO_y concentrations.

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1. INTRODUCTION

During the last two and a half decades, the Las Vegas Valley has emerged as one of the fastest growing metropolitan areas in the nation, leading to increased emissions into the atmosphere that are precursors to ozone production. In recent years, concentrations of ozone in Clark County have approached, and on occasion exceeded, the new 8-hour ambient air quality standard as defined by the recently adopted Federal Ozone Standard. These exceedances increase the potential for a violation of the federally mandated Clean Air Act, and the necessity for developing control strategies. Planning realistic, cost-effective control strategies requires a comprehensive understanding of the origin and fate of ozone and ozone precursors. The Clark County Department of Air Quality & Environmental Management (DAQEM) contracted Technical & Business Systems, Inc. (T&B Systems) to characterize the behavior of ambient ozone and associated meteorological features during high ozone events.

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Moreover, since the initiation of this analysis, the DAQEM has started planning a field measurement study for the 2005 ozone season. The results and recommendations of this analysis will also feed back into the field study design.

1.1 Topography of Clark County

The Las Vegas Valley is located in a broad desert valley, or more accurately a basin, within Clark County in extreme southern Nevada. The surrounding topography, shown in **Figure 1-1**, is extremely complex. Mountains surrounding the valley extend 2,000 to 10,000 feet above the valley floor. The Las Vegas Valley comprises about 600 square miles. Its longitudinal axis, depicted by the black line on the figure, runs from northwest to southeast. The Valley is bounded on the north by the Sheep Range, while Boulder City and the Lake Mead National

Recreation Area are generally considered its southern extent. From a hydrological (and meteorological) perspective, drainage from the valley is channeled into Lake Mead via the Las Vegas wash (shown as the eastern extension of the longitudinal axis line). To the west are the Spring Mountains, which include Mt. Charleston, the region's highest peak at 11,918 feet. Several smaller ranges line the eastern rim of the valley, including the Muddy Mountains, the Black Mountains and the Eldorado Range (Reference:*http://newweb.wrh.noaa.gov/vef/climate/pagei.php).*

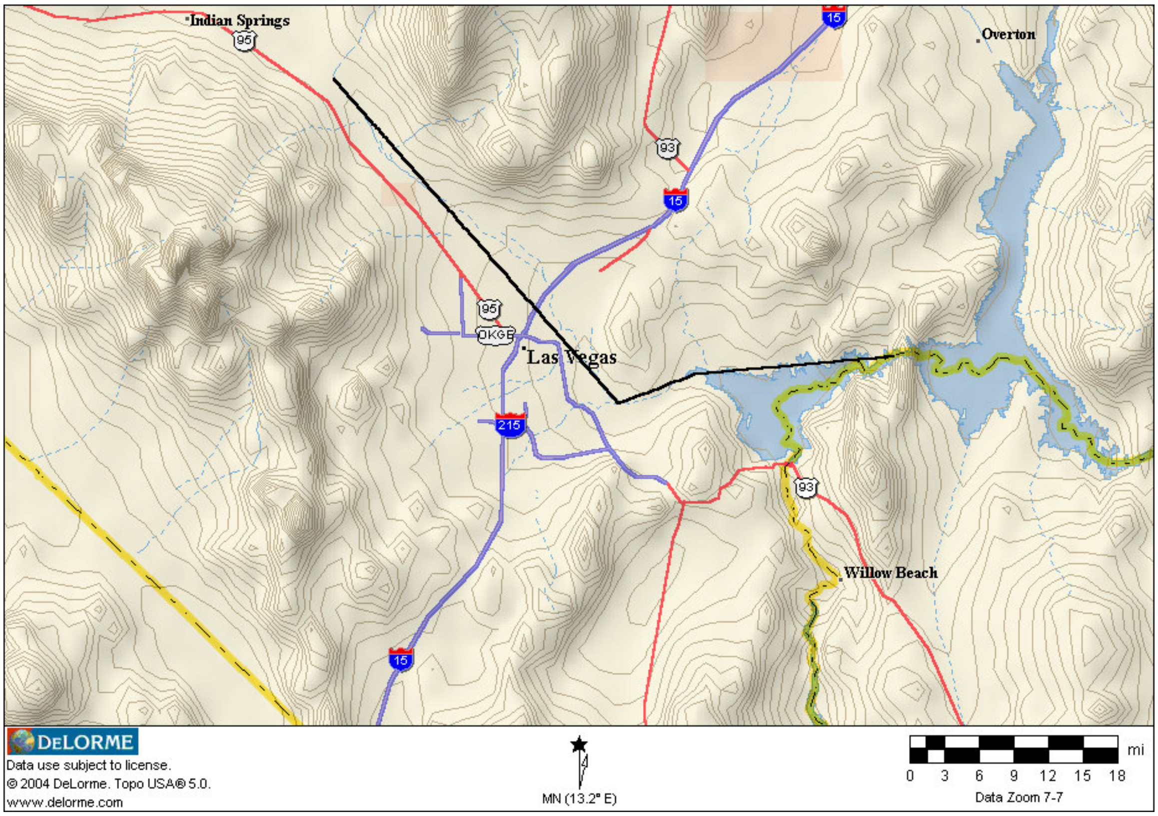


Figure 1-1. Map Showing the Topography of Las Vegas Valley and Adjacent Areas

The terrain of Las Vegas Valley rises significantly from approximately 1,200 ft at Lake Mead to 2,000 ft downtown Las Vegas to over 2,800 ft in the suburbs on the west side of the Valley. Also, the surface temperature of Lake Mead is a stark contrast to the heated desert surface. These are important features in understanding the local forces that drive the three-dimensional wind structure in the Valley.

1.2 Content of This Report

This report consists of five main sections in addition to this introduction. In Section 2, ambient measurements of ozone and primary pollutant concentrations are examined to evaluate how peak ozone concentrations have been responding to changes in ambient levels of ozone precursors. An overview of the meteorology in Clark County during the ozone season is presented in Section 3. Meteorological features are examined on the synoptic-scale, and local, terrain-driven wind fields are described. Weather pattern types are shown as well as prevailing flows over the diurnal cycle. The available upper-air data are also examined. Section 4 presents a method of statistically describing features during high ozone events that provides an objective forecasting tool. The CART method was employed in this task. A set of case studies of high ozone events in Clark County is contained in Section 5. The spatial and temporal behavior of ozone and associated meteorology for ten periods that experienced exceedances of the Federal Ozone Standard are examined therein. And lastly, in Section 6, a summary of findings and recommendations for the planned 2005 field campaign are given.

2. OZONE AND OZONE PRECURSORS

2.1 Overview

In this section, ambient measurements of ozone and primary pollutant concentrations are examined to evaluate how peak ozone concentrations have been responding to changes in ambient levels of ozone precursors. Three methods are used for empirically assessing the responses of ozone levels to precursor changes:

1. Comparison of weekend to weekday levels of air pollutants (Altshuler et al., 1995; Larsen, 1999; Fujita et al., 2002, 2003a, 2003b; Blanchard and Tanenbaum, 2003; Lawson et al., 2003; Pun et al., 2003; Croes et al., 2003);
2. Application of an observation-based procedure for qualitatively characterizing local ozone formation as VOC or NO_x limited (Blanchard et al., 1999);
3. Assessment of trends over time.

Since each approach has strengths and limitations, their conclusions are compared and contrasted at the end of this chapter.

2.2 Data and Statistical Methods

Hourly measurements of NO, NO_x, CO, SO_2, and ozone for all monitoring sites were obtained for the period 1998 through 2003; for trend analyses, data from 1996 and 1997 were also used. **Figure 2-1** shows the Clark County air-quality monitoring network.

Day-of-week averages were determined for each hour of each day of the week. Statistical comparisons between the average NO, NO_x, and CO concentrations on different days were made for the hours of 06 PST [indicative of fresh emissions, typically having maximum morning concentrations) and 12 PST (midday, higher photochemical activity), for three-hour periods 06 to 09 PST, 09 to 12 PST, 12 to 15 PST], and for 06 to 15 PST.

For ozone, day-of-week averages were determined for both peak 1-hour and peak 8-hour concentrations. Each of these metrics was each determined from three subsets of the data:

1. All measurements from the months of March through October of each year;
2. Twenty-one high-ozone days selected from each year by determining the top-3 ozone days for each day of the week and each year;
3. The top-10 high-ozone days per day-of-week per year.

The first subset provides information about averages, while the other two data subsets focus on conditions of greater regulatory interest. The procedures for selecting high-ozone days represent each day of the week and each year equally. The top-3 subset provides a set of about 9 percent of the 245 days from March through October, while the top-10 subset includes about 29 percent of the days.

For comparability with the ozone analyses, NO, NO_x, and CO measurements were also restricted to the months of March through October. Differences in weekday and weekend concentrations of the precursor compounds were determined using all days within the selected months to provide as large a data set as possible for quantifying the changes in precursor levels on weekends.

All statistical tests refer to t-tests of the differences between means. The data points constituting each mean were separated in time (e.g., Sunday 12 PST compared with Wednesday 12 PST) so that statistical assumptions of independence were not violated. Because large numbers of statistical tests were carried out, a stringent significance probability ($p<0.01$) was used to evaluate statistical significance. Using $p<0.01$, approximately one statistical test in one hundred is expected to yield an apparently significant result when no statistical difference actually exists.

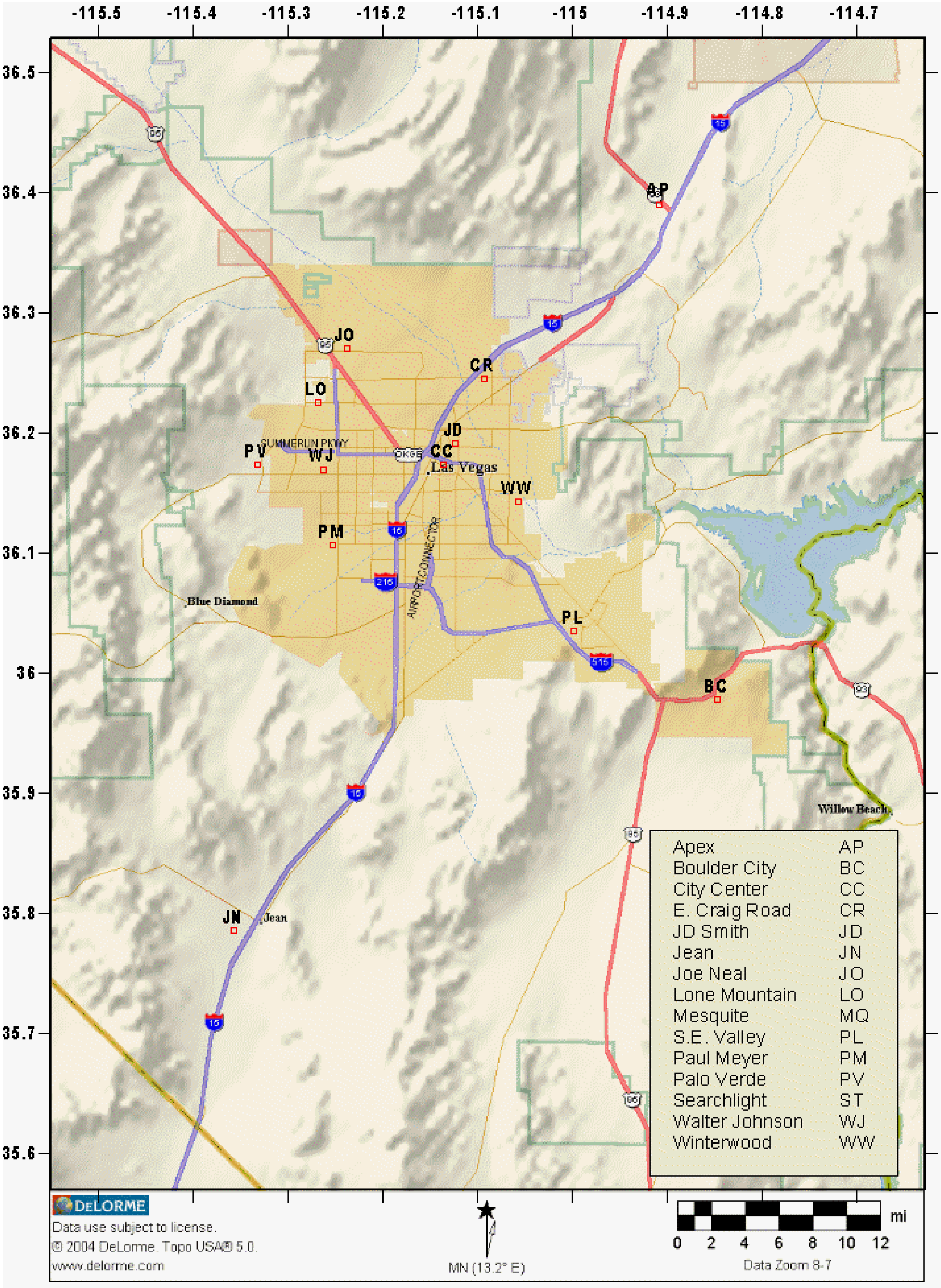


Figure 2-1. Clark County Air Quality Monitoring Network

2.3 Day-of-Week Variations in Primary Pollutant Concentrations

Mean day-of-week concentrations were determined for each day of the week and each monitoring location, and the magnitudes and statistical significance of day-of-week differences in the concentrations of primary pollutants were evaluated. The comparisons focus on contrasts between Wednesdays and Sundays. These days provide one weekday and one weekend day that each follows a day of the same type. For each monitoring site and each specified time of day, the differences between mean Wednesday and mean Sunday concentrations were determined and expressed as:

Difference = 100% x (Wednesday mean – Sunday mean)/(Wednesday mean)

Positive differences therefore represent decreases in ambient concentrations from Wednesdays to Sundays. For primary pollutants, ambient concentrations on Sundays were typically lower than on Wednesdays, so expressing the results as percent decreases allows most of the differences to be expressed as positive numbers.

The decreases in ambient concentrations of NO, NO_x, and NO_2 from Wednesdays to Sundays are summarized in **Tables 2-1 through 2-3**. As previously noted, the morning comparisons were made to capture a time period dominated by fresh emissions, whereas the 12 PST comparisons represent differences occurring close to the time of peak ozone formation or concentration. All sites showed statistically significant ($p<0.01$) lower levels of NO, NO_2, and NO_x at 06 PST on Sundays compared with Wednesdays, with median reductions of 37 to 55 percent. At 12 PST, the Sunday levels were also lower than on Wednesdays; all sites showed significantly lower levels of NO, NO_2, or NO_x except Jean (at Apex and Boulder City, the 12 PST NO or NO_2 declines were not statistically significant, but the NO_x decline was). The median decreases at 12 PST on Sundays ranged from 24 percent for NO_2 to 37 percent for NO.

While Tables 2-1 through 2-3 summarize the NO, NO_2, and NO_x declines at 06 PST and 12 PST on Sundays, average day-of-week concentrations were computed for each hour of each day. To check the representativeness of the results presented in Tables 2-1 through 2-3, we determined the NO and NO_x decreases for all monitors using several different averaging times: hourly (06 and 12 PST), 3-hour (06 to 09 PST, 09 to 12 PST, 12 to 15 PST), and 9-hour daytime (06 to 15 PST). Summary results are depicted in **Figures 2-2 through 2-4**. The results show that the 06 PST and 12 PST decreases bracket the daytime (06 through 15 PST) changes. The median daytime (06 through 15 PST) declines of NO, NO_x, and NO_2 were 38, 37, and 33 percent, respectively.

The changes in the ambient levels of NO and NO_x on Sundays compared with midweek were large enough, and lasted long enough throughout the portion of the day when ozone could form locally, that less local ozone formation would be expected if local ozone formation were sensitive to variations in NO and NO_x levels, i.e., if ozone were NO_x-limited. Conversely, if declines in ambient NO and NO_x levels on Sundays lead to increases in ambient ozone concentrations, then it is unlikely that local ozone formation was NO_x sensitive. As we discuss later, the role of fresh NO emissions in titrating ozone requires special consideration.

Table 2-1. Differences Between Mean Wednesday and Sunday NO Concentrations at 06 and 12 PST (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Difference (percent decrease)	
		NO 06 PST	NO 12 PST
AP/320030022	Apex, North Las Vegas	**35.4**	34.4
BC/320030601	Boulder City	**66.5**	24.2
FP/320030563	Freedom Park, Las Vegas	**16.8**	**40.4**
JD/320032002	J.D. Smith, Las Vegas	**23.9**	**41.1**
JN/320031019	Jean	**39.3**	10.5
MC/320030539	E. Sahara, Las Vegas	**18.9**	**33.5**
PV/320030073	Palo Verde, Las Vegas	**80.5**	**52.8**
ST/320030078	Searchlight	**48.3**	**39.5**
	Mean	41.2	34.5
	Median	37.3	36.9

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from all days during March through October 1998-2003 from sites with 3 or more years of data in Clark County.

Table 2-2. Differences Between Mean Wednesday and Sunday NO_x Concentrations at 06 and 12 PST (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Difference (percent decrease)	
		NO_x 06 PST	NO_x 12 PST
AP/320030022	Apex, North Las Vegas	**37.4**	**21.6**
BC/320030601	Boulder City	**55.9**	**27.4**
FP/320030563	Freedom Park, Las Vegas	**53.7**	**31.8**
JD/320032002	J.D. Smith, Las Vegas	**54.9**	**36.2**
JN/320031019	Jean	**34.8**	13.3
MC/320030539	E. Sahara, Las Vegas	**45.6**	**31.9**
PV/320030073	Palo Verde, Las Vegas	**69.4**	**37.4**
ST/320030078	Searchlight	**57.2**	**34.0**
	Mean	51.1	29.2
	Median	54.3	31.8

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from all days during March through October 1998-2003 from sites with 3 or more years of data in Clark County.

Table 2-3. Differences Between Mean Wednesday and Sunday NO_2 Concentrations at 06 and 12 PST (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Difference (percent decrease)	
		NO_2 06 PST	**NO_2 12 PST**
AP/320030022	Apex, North Las Vegas	**39.5**	13.0
BC/320030601	Boulder City	**47.7**	**24.1**
FP/320030563	Freedom Park, Las Vegas	**64.9**	**21.5**
JD/320032002	J.D. Smith, Las Vegas	**63.7**	**28.8**
JN/320031019	Jean	**30.4**	16.6
MC/320030539	E. Sahara, Las Vegas	**50.8**	**28.5**
PV/320030073	Palo Verde, Las Vegas	**58.6**	**26**
ST/320030078	Searchlight	**63.9**	**23.6**
	Mean	52.4	22.8
	Median	54.7	23.8

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from all days during March through October 1998-2003 from sites with 3 or more years of data in Clark County.

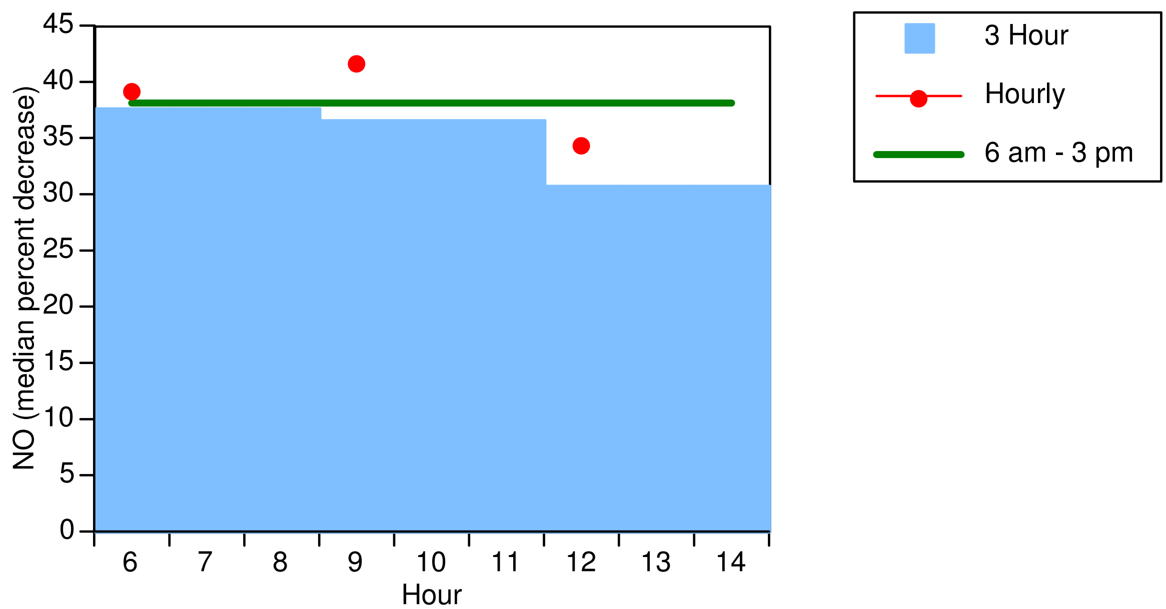


Figure 2-2. Median Percent Decrease in Ambient NO Concentrations from Wednesdays to Sundays in Clark County

Medians were determined from all the results from all monitoring sites for three 3-hour periods (06 to 9 PST, 9 to12 PST and 12 to 15 PST), hourly (at 06, 09, and 12 PST), and averaged over the period 06 to 15 PST. The data are from the period March through October 1998 to 2003.

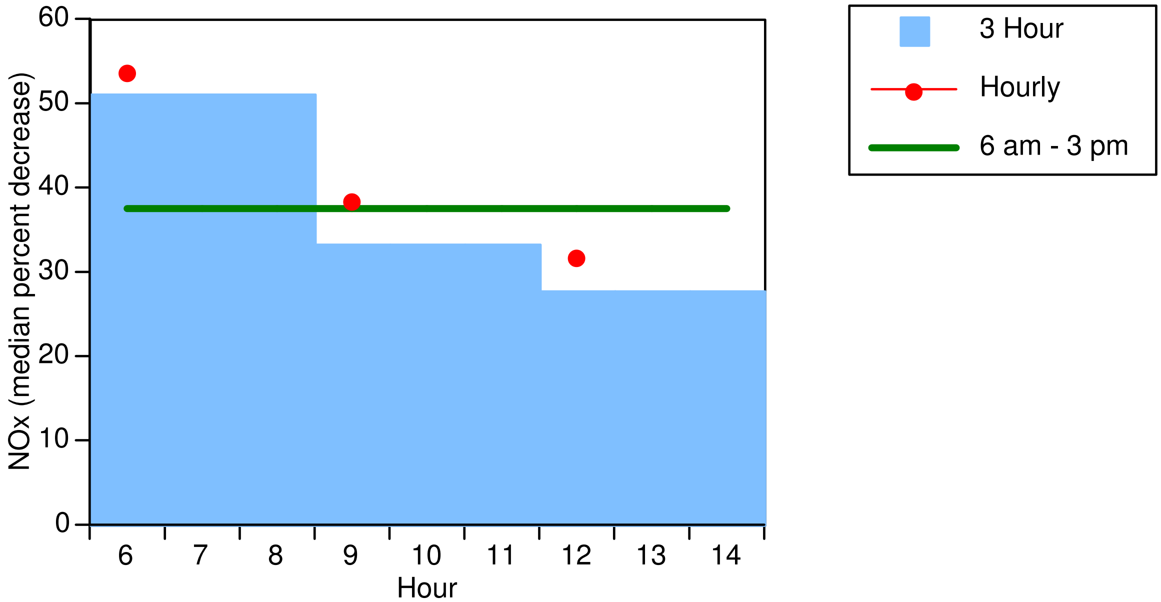


Figure 2-3. Median Percent Decrease in Ambient NO_x Concentrations from Wednesdays to Sundays in Clark County

Medians were determined from all the results from all monitoring sites for three 3-hour periods (06 to 9 PST, 9 to12 PST and 12 to 15 PST), hourly (at 06, 09, and 12 PST), and averaged over the period 06 to 15 PST. The data are from the period March through October 1998 to 2003.

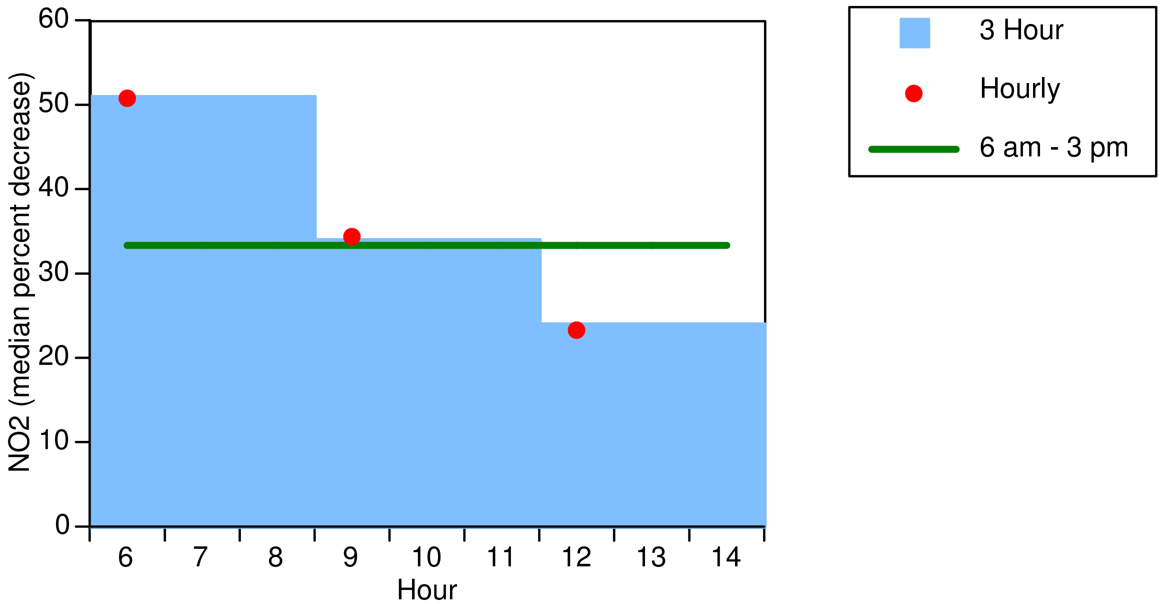


Figure 2-4. Median Percent Decrease in Ambient NO_2 Concentrations from Wednesdays to Sundays in Clark County

Medians were determined from all the results from all monitoring sites for three 3-hour periods (06 to 09 PST, 9 to12 PST and 12 to 15 PST), hourly (at 06, 09, and 12 PST), and averaged over the period 06 to 15 PST. The data are from the period March through October 1998 to 2003.

A more complete understanding of the weekend ozone responses requires consideration of changes in hydrocarbon levels on weekends. Because hydrocarbon data were not available, we examined weekend changes in ambient CO concentrations, which correlate highly with automotive exhaust hydrocarbon emissions. Note that actual changes in weekend hydrocarbon levels may have differed from the CO changes.

The decreases in average ambient concentrations of CO from Wednesdays to Sundays are summarized in **Table 2-4**. At 06 PST, all sites showed statistically significant weekday/weekend differences in ambient CO concentrations. The median CO reduction at 06 PST on Sundays was 36 percent. None of the Wednesday/Sunday decreases was statistically significant at 12 PST. The median difference at 12 PST was a 3.5 percent decrease, but some sites exhibited increases and others decreases in the ambient CO concentrations at 12 PST on Sundays. We also determined the CO decreases for all monitors using several different averaging times: hourly (06 PST and 15 PST), three-hour (06 to 9 PST, 9 to 12 PST, 12 to 15 PST), and 9-hour daytime (06 to 15 PST). Summary results are depicted in **Figure 2-5.** The median decreases at 06 PST and 12 PST bracketed the median daytime (06 to 15 PST) decrease, which was a 21 percent decline from Wednesdays to Sundays.

Table 2-4. Differences Between Mean Wednesday and Sunday CO Concentrations at 06 and 12 PST (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Difference (percent decrease)	
		CO 06 PST	CO 12 PST
BC/320030601	Boulder City	1.4	-6.3
BS/320030020	E. Craig, North Las Vegas	**29.4**	-2.2
CC/320030016	City Center, Las Vegas	**52.8**	22.5
CW/320030562	Crestwood	**34.7**	0.3
FL/320031022	E. Flamingo, Las Vegas	**25.2**	0.5
FP/320030563	Freedom Park, Las Vegas	**54.4**	4.9
GV/320030298	Green Valley, Henderson	**37.8**	8.1
JD/320032002	J.D. Smith, Las Vegas	**60.7**	21.4
MC/320030539	E. Sahara, Las Vegas	**37.2**	0.0
MG/320031023	S. L.V. Blvd., Las Vegas	**30.8**	9.7
PL/320030007	S.E. Valley, Henderson	**52.1**	1.0
PM/320030043	Paul Meyer, Las Vegas	**29.7**	-1.9
PT/320030107	Pittman	**51.1**	1.8
SA/320030561	Sunrise Acres, Las Vegas	**46.3**	7.8
SL/320030021	Shadow Lane	**33.1**	6.0
WW/320030538	Winterwood, Las Vegas	**30.4**	-22.5
	Mean	37.9	3.2
	Median	35.9	1.4

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from all days during March through October 1998 to 2003 from sites with three or more years of data in Clark County.

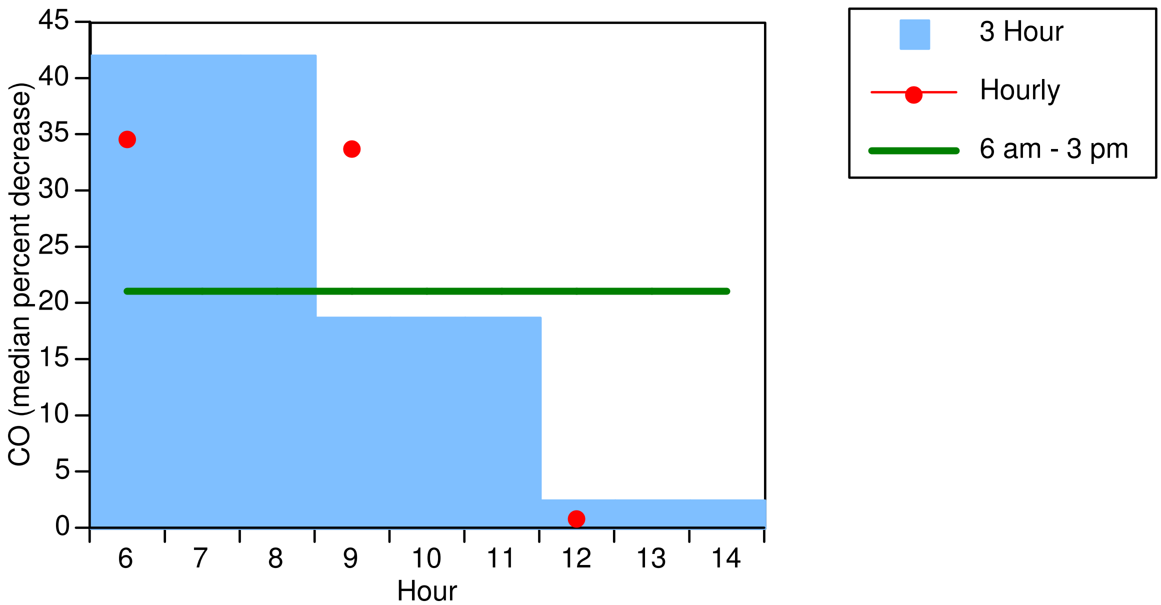


Figure 2-5. Median Percent Decrease of Ambient CO Concentrations from Wednesdays to Sundays in Clark County

Medians were determined from all the results from all monitoring sites for three 3-hour periods (06 to 9 PST, 09 to12 PST and 12 to 15 PST), hourly (at 06, 09, and 12 PST), and averaged over the period 06 PST to 15 PST. The data are from the period March through October 1998 to 2003.

The median daytime decrease in ambient CO concentrations (21 percent) on Sundays was smaller than the corresponding daytime decreases of NO (38 percent) and NO_x (37 percent). However, the Sunday morning declines in ambient CO levels were statistically significant, suggesting that motor vehicle emissions of hydrocarbons also declined on Sunday mornings.

The weekend CO declines implies that declining weekend emissions from gasoline vehicles (the principal source of CO) contributed in part to the ambient NO and NO_x declines on Sundays. Because the CO declines were smaller than the NO and NO_x declines, though, weekend changes in motor vehicle NO_x emissions cannot account for the full weekend decrease in ambient NO and NO_x concentrations; the most likely cause of the other portion of the ambient NO and NO_x decreases on weekends would be changes in diesel emissions on weekends.

Ambient measurements of SO_2 were available for two sites, Apex and East Sahara. Concentrations of SO_2 were significantly ($p<0.01$) lower at East Sahara at 06 PST Sundays than at 06 PST Wednesdays; otherwise, weekend SO_2 concentrations were not significantly different from midweek levels (Table 2-5). These results suggest the presence of a local source with a weekly emissions cycle affecting the site at East Sahara. Possibly, these variations could also contribute to weekly changes in NO_x levels at East Sahara, depending upon the emissions characteristics of the local source.

Table 2-5. Differences Between Mean Wednesday and Sunday SO_2 Concentrations at 06 and 12 PST (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Difference (percent decrease)	
		SO_2 06 PST	SO_2 12 PST
AP/320030022	Apex, North Las Vegas	1.6	1.5
MC/320030539	E. Sahara, Las Vegas	**28.2**	-4.3
	Mean	14.9	-1.4
	Median	14.9	-1.4

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from all days during March through October 1998 to 2003 from sites with three or more years of data in Clark County.

2.4 Day-of-Week Variations in Peak Ozone Concentrations

In contrast to the weekend changes in ozone precursor concentrations, peak ozone levels increased on Sundays compared with Wednesdays (**Table 2-6**). The ozone increases occurred for both peak 1-hour and 8-hour ozone levels at all monitoring sites, and for both ozone-season averages and high-ozone days (the only exception was at Shadow Lane). For the high-ozone (top-3) days, the mean peak 8-hour concentrations on Sundays exceeded 80 ppbv at four sites (**Figure 2-6**).

Diurnal variations of ozone, NO, and NO_x concentrations on high-ozone days (top-3 per day-of-week per site per year) show the influence of morning titration of ozone by NO (Figure 2-7). At five of the six sites with NO and NO_x measurements, lower levels of NO and NO_x on Sunday mornings were associated with higher morning levels of ozone (Figure 2-7). For these sites, the mean 8-hour ozone maxima were greater on Sundays primarily because ozone levels recovered from their morning minima earlier on Sundays. Smaller increases were observed between the Wednesday and Sunday mean 1-hour peak ozone levels (**Table 2-6**).

The increases in peak ozone levels on weekends, occurring in association with reduced weekend concentrations of ozone precursors, raise questions of relevance to possible future ozone control strategies. We expect that future weekday emission levels will differ from current weekend emission levels in both the times of the day when emissions occur and the relative amounts of VOC and NO_x emitted. Therefore, current weekend days do not provide an exact predictor for future ozone responses on weekdays. Nonetheless, it is difficult to reconcile the observed weekday/weekend differences in precursor and ozone concentrations with a conceptual model of ozone formation in which ozone is produced locally and is limited by the availability of NO_x. Instead, the results show that the weekend reductions of NO_x changed the magnitudes of ozone loss due to titration by NO. In principle, it is hypothetically possible that no local formation of ozone occurred and the weekday/weekend differences in ozone were entirely due to interactions of background ozone with local NO emissions (later sections of this report address the question of ozone transport). It is also possible that some local ozone formation occurred, but that it was not usually NO_x-limited, as will be discussed next.

Table 2-6. Differences Between Mean Wednesday and Sunday Maximum 1-hour and 8-hour Ozone Concentrations (percent declines relative to Wednesday levels). Positive numbers represent higher Wednesday concentrations.

ID/AIRS	SITE	Wednesday – Sunday Peak Difference (percent decrease)					
		All Days		Top-10 Days per Day-of-week per Year		Top-3 Days per Day-of-week per Year	
		8-Hour Ozone	1-Hour Ozone	8-Hour Ozone	1-Hour Ozone	8-Hour Ozone	1-Hour Ozone
AP/320030022	Apex, North Las Vegas	-2.7	-1.2	-2.1	-1.2	-1.4	-0.5
BC/320030601	Boulder City	-4.3	-3.2	-3.4	-3.2	-3.2	-3.0
BS/320030020	E. Craig, North Las Vegas	**-13.8**	**-8.1**	**-8.6**	-5.1	-7.1	-3.8
CC/320030016	City Center, Las Vegas	**-19.9**	**-11.3**	**-12.0**	**-6.3**	**-10.4**	-5.3
JD/320032002	J.D. Smith, Las Vegas	**-10.0**	-4.8	**-5.7**	-4.4	-4.5	-1.0
JN/320031019	Jean	-2.3	-1.0	**-4.3**	-1.7	**-5.6**	-3.1
JO/320030075	Joe Neal, Las Vegas	**-8.2**	-6.6	-6.0	-6.1	-5.8	-4.6
LO/320030072	Lone Mountain, Las Vegas	**-8.0**	-5.5	-4.4	-3.0	-3.5	-0.9
PL/320030007	S.E. Valley, Henderson	**-6.5**	-3.9	**-4.2**	-3.7	-5.3	-2.7
PM/320030043	Paul Meyer, Las Vegas	**-6.8**	-3.4	-3.6	-0.5	-3.8	-0.2
PV/320030073	Palo Verde, Las Vegas	**-7.1**	-5.4	**-5.9**	-3.9	**-6.0**	-5.1
SL/320030021	Shadow Lane	**-14.9**	**-7.2**	-5.1	-1.2	-1.4	3.1
ST/320030078	Searchlight	-3.9	-2.6	**-7.6**	-5.1	-6.7	-5.1
WJ/320030071	Walter Johnson, Las Vegas	**-9.3**	-6.5	**-5.7**	-3.2	-4.7	-1.6
WW/320030538	Winterwood, Las Vegas	-5.0	-3.0	**-5.1**	-2.8	-5.0	-3.0
	Mean	-8.2	-4.9	-5.9	-3.8	-5.3	-3.0
	Median	-7.1	-4.8	-5.4	-3.5	-5.1	-3.0

Statistically significant ($p<0.01$) differences are shown in bold. The averages were determined from days as noted during March through October 1998 to 2003 from sites with three or more years of data in Clark County.

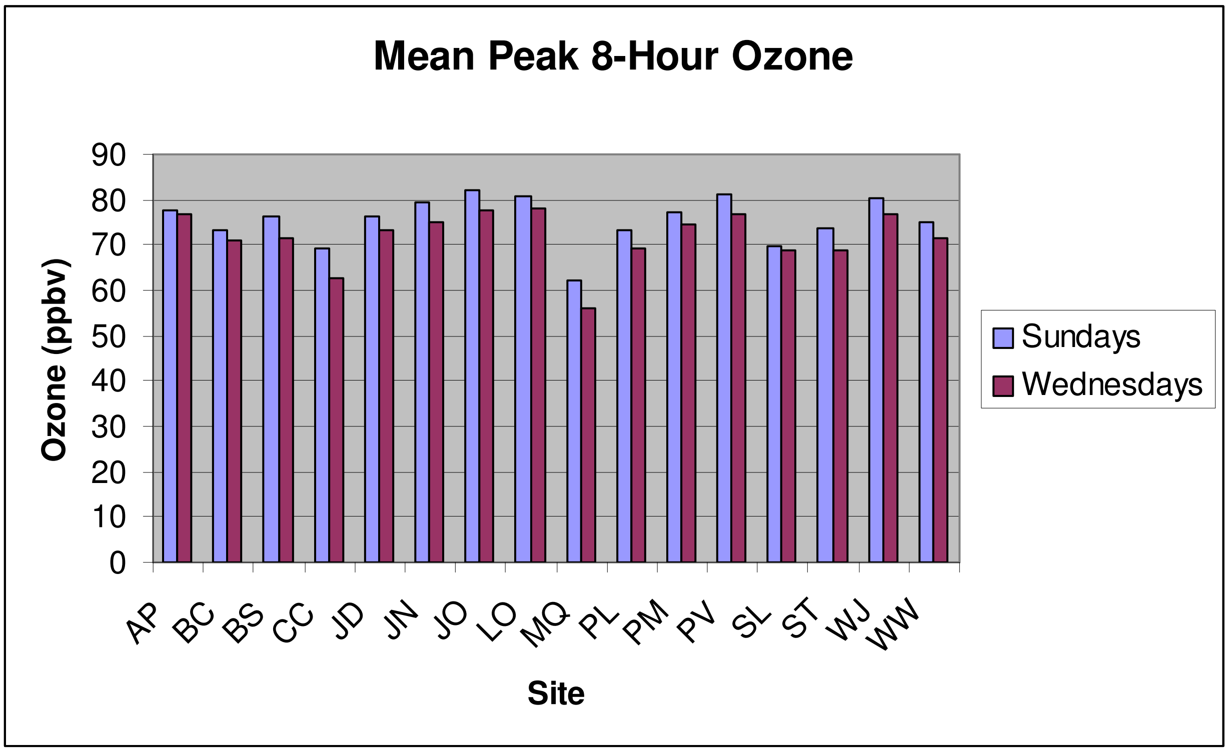


Figure 2-6. Mean Peak 8-hour Ozone Concentrations on Wednesdays and Sundays at Monitoring Sites in Clark County

For each site, means were determined for the top-3 peak 8-hour ozone days per day-of-week per year. The data are from the period March through October 1998 to 2003.

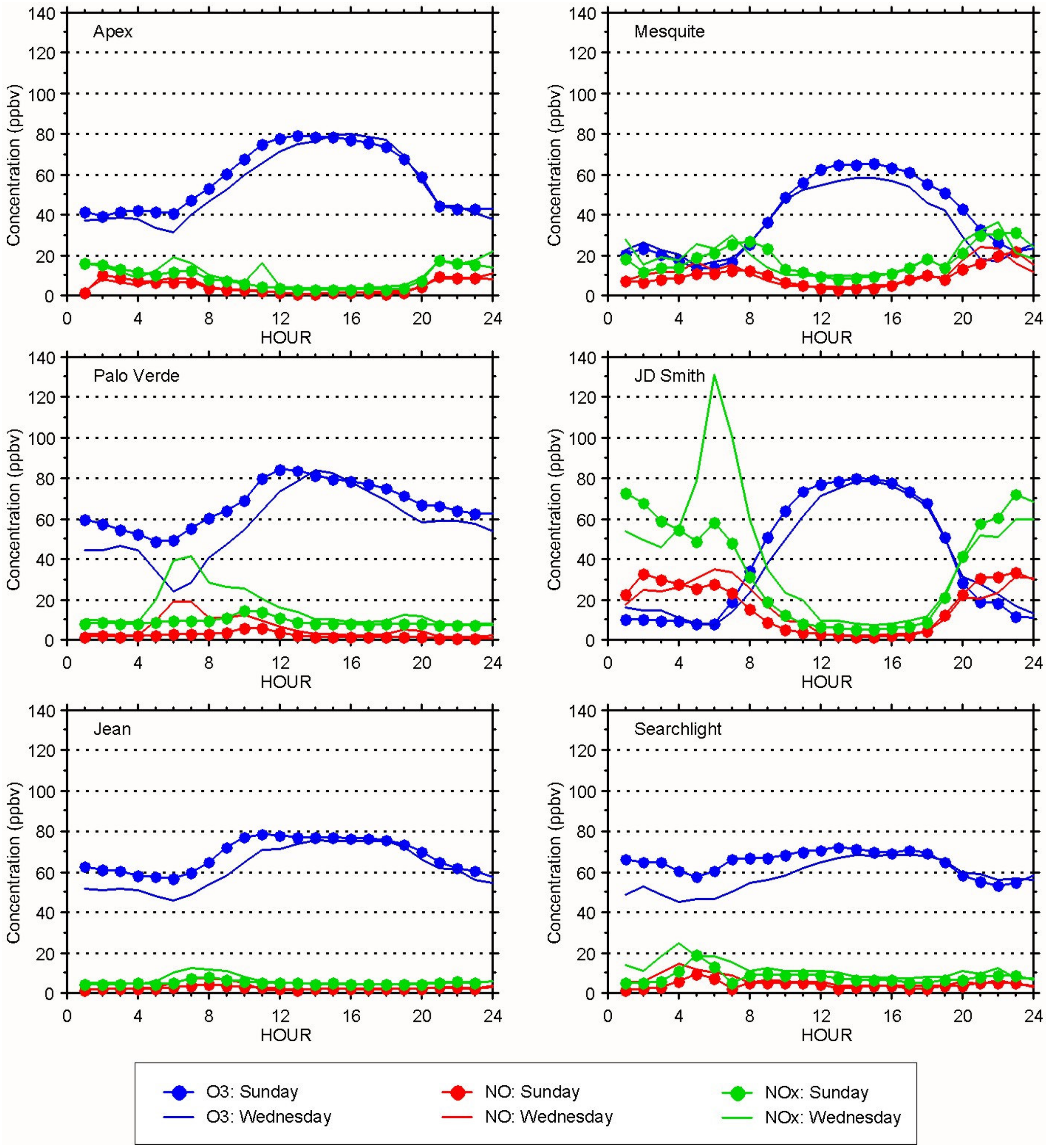


Figure 2-7. Mean Concentrations of Ozone, NO, and NO_x on Wednesdays and Sundays versus Hour of the Day

The data are from all sites having measurements of ozone, NO, and NO_x. The averages were determined from the high-ozone days at each site (top-3 peak 8-hour ozone days per day-of-week per year).

2.5 VOC and NO_x Limitation of Ozone Formation

In an air mass with fresh anthropogenic emissions, new ozone formation is limited by the availability of free radicals, rather than by the concentrations of VOC and NO_x, which are typically present in excess. However, because ozone formation is initially limited each morning by the availability of free radicals, and because hydrocarbon compounds are a source of free radicals, the radical-limited phase is commonly called VOC-limited. Free radical production depends upon the cumulative radiation flux, so in an air mass containing ample fresh emissions, ozone levels increase as a function of cumulative radiation. Photolysis reactions yield free radicals, which in turn fuel the conversion of NO to NO_2 (without consumption of ozone); subsequent photolysis of NO_2 yields atomic oxygen and thence ozone. More reactive hydrocarbon species are converted to less reactive species as an air mass ages. Also, NO_2 molecules are eventually removed from NO – NO_2 interconversion by reaction with OH radical to yield nitric acid (HNO_3). Whereas aging of an air mass tends to convert hydrocarbons to less reactive species, but not to remove them entirely, aging removes NO_x. Therefore, as an air mass ages, it becomes more NO_x-limited in the absence of ongoing fresh emissions.

A variety of indicators of air mass aging may be used to provide empirical assessments of the sensitivity of local ozone formation to VOC or NO_x. Aging is sometimes characterized using ratios of more reactive to less reactive hydrocarbon compounds (e.g., xylenes/benzene). One commonly used definition of chemical age is $1 - NO_x/NO_y$ (which varies from zero when all NO_y is present as NO and NO_2 up to one when all NO_y is present as NO_x reaction products). A calculated quantity known as "extent of reaction" provides another measure of aging that has been used to delineate the transition between younger, VOC-limited air masses and more aged, NO_x limited air masses (see appendix in Section 2.8). Other indicators that have been applied to delineate VOC and NO_x limitation include ambient VOC/NO_x ratios and ratios of other compounds such as ozone/NO_x, ozone/NO_y, and H_2O_2/HNO_3.

The available measurements in Clark County were suitable for calculating the extent of reaction because estimates could be made using the existing NO_x data (as noted in the appendix, these data are biased measures of true NO_x, which is the sum of NO plus true NO_2, but the calculation permits use of such data). The methods are briefly summarized in the appendix, which also identifies literature references that provide full methodological details. For the present application, an additional uncertainty arose due to rounding conventions: values for NO, NO_2, and NO_x below 5 ppbv were reported as 0 ppbv in the data for 1998-2001; all such values were treated as one-half the detection limit, recoding them as 2.5 ppbv. The reported values for NO were recovered by taking the difference between $NO_x - NO_2$ if NO was reported as below detection limits but the other two species were not.

The calculations for the higher ozone days (top-3 peak 8-hour ozone days per day-of-week per year per site) were carried out. At all sites, ozone formation began in a VOC-limited state (extent less than 60 percent) during early morning hours (**Figure 2-8**). Ozone became NO_x limited (extent greater than 80 percent) by late morning at Jean and by early afternoon at Apex. Ozone formation reached a transitional state (extent greater than 60 percent and less than 80 percent) by early afternoon at Boulder City and JD Smith; ozone formation then returned to a VOC-limited state at JD Smith during the later afternoon as fresh NO_x emissions occurred. At Mesquite, Palo Verde, and Searchlight, ozone formation remained VOC limited throughout the day (sufficient NO_x was available to continue sustaining ozone formation).

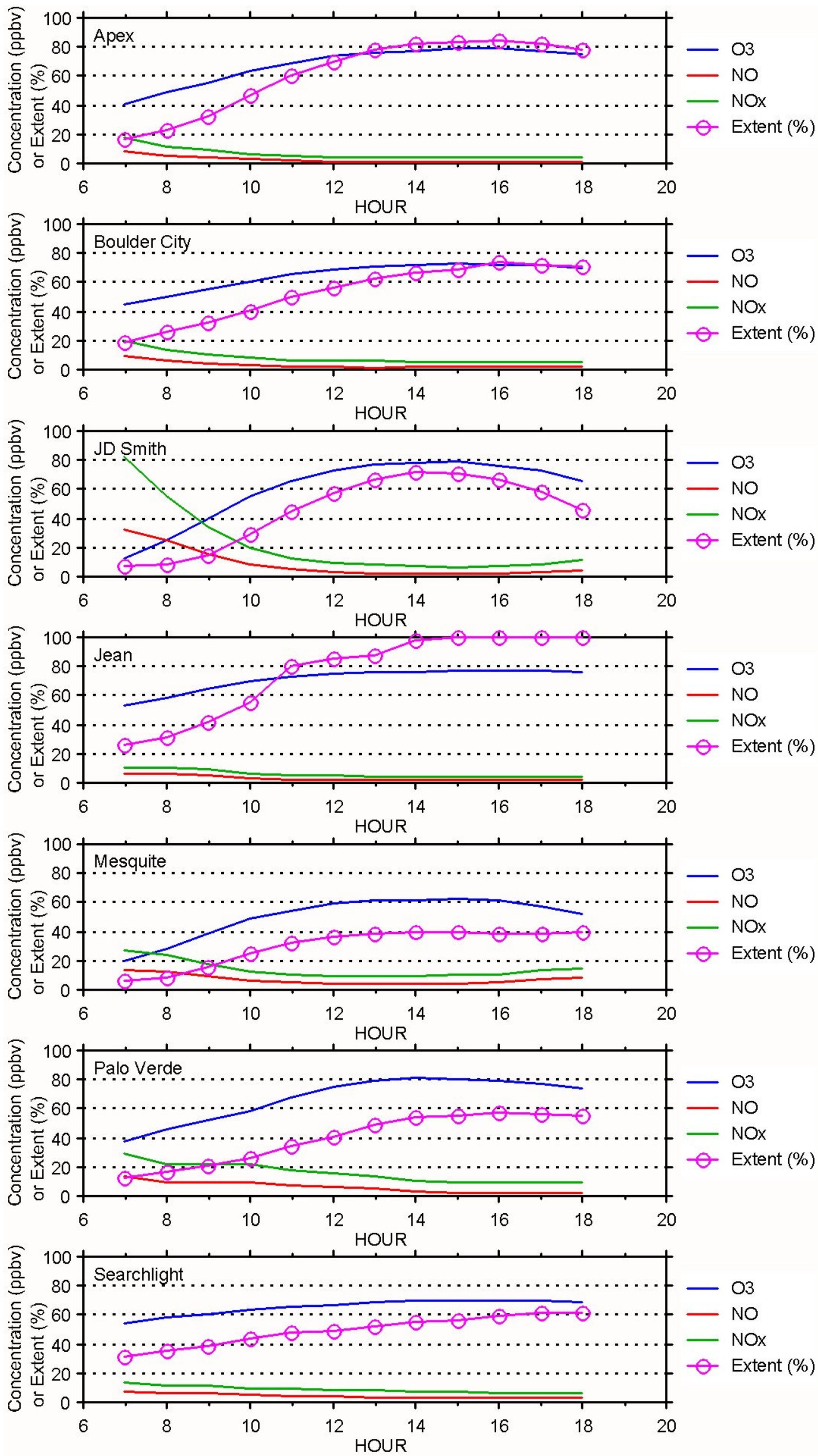


Figure 2-8. Mean Extent of Reaction versus Hour of the Day

The averages for each site were determined from the top-3 peak 8-hour ozone days per day-of-week per year. The calculations were carried out for all sites having measurements of ozone, NO, and NO_x according to the methods discussed in the text and in the appendix. Ozone formation is VOC-limited when the extent of reaction is less than 60 percent, transitional when extent is between 60 and 80 percent, and NO_x-limited when extent exceeds 80 percent.

The estimates of the extent of reaction exhibit a relationship to the changes in peak 8-hour ozone levels from Wednesdays to Sundays (**Figure 2-9**). As indicated, with the exception of Jean, the amount of the peak ozone increase on Sundays compared with Wednesdays was largest for the sites with the lowest mean extent of reaction (i.e., where ozone formation during the peak 8-hour periods was the most VOC-limited). The exception – Jean – is a site where ozone levels are expected to be influenced by long-range transport, and where weekend/weekday changes in NO_x levels were less pronounced than at other sites (**Tables 2-1** through **2-3**).

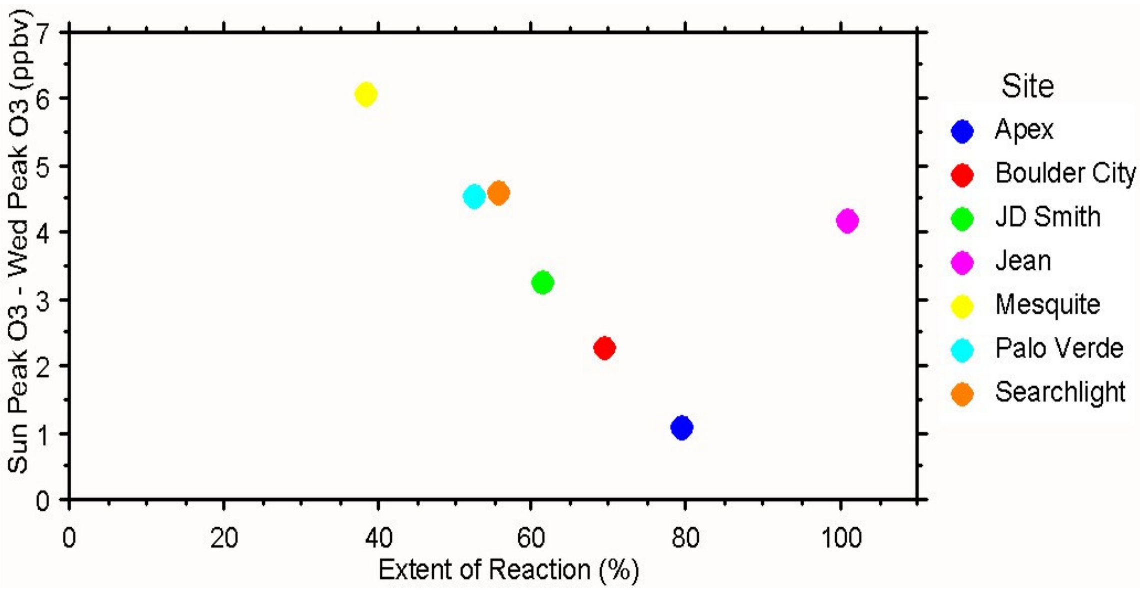


Figure 2-9. Difference Between Mean Peak 8-Hour Ozone Levels on Wednesdays and Sundays Versus Mean Extent of Reaction

The peak ozone differences were calculated as the Sunday mean minus the Wednesday mean, so that positive values indicate higher peak 8-hour ozone levels on Sundays. The mean extent of reaction was determined from the same hours and days used for computing the mean peak 8-hour ozone levels.

The relationship shown in Figure 2-9 demonstrates consistency between the weekday/weekend ozone response and the estimated extent of reaction. At locations where ozone formation is VOC (or radical) limited, lowering NO_x levels can increase ozone concentrations either by decreasing the amount of ozone titrated by fresh NO (Fujita et al., 2003a) or by increasing the number of ozone molecules that are formed from each NO molecule (Reynolds et al., 2004). While the extent of reaction calculations do not distinguish between these two possibilities, the earlier discussion demonstrates the influence of NO titration on ozone at sites in Las Vegas.

2.6 Trends in Primary Pollutants and Peak Ozone Levels

Diurnal profiles show decreases in the average CO concentrations at all hours of the day from 1996 through 2003 (**Figure 2-10**). Year-to-year differences in NO_x levels were also seen, but downward trends were not as evident (**Figure 2-11**). Changes over time were formally evaluated using quarterly average concentrations, which exhibited downward trends for CO at most locations during both summer and winter months (**Figure 2-12 and Table 2-7**). The median rate of decrease in ambient CO concentrations was 30 ppbv per year, with 13 of 15 sites showing declines (Table 2-7). Without measurements of hydrocarbon compounds, it is not possible to determine if hydrocarbon concentrations declined in parallel with the decreases in ambient CO levels.

The quarterly-average NO_x concentrations showed increasing trends at Palo Verde and Apex, but declines at JD Smith, East Sahara, Boulder City, and Jean (**Figure 2-13** and Table 2-7). The geographical variations suggest that the changes in ambient NO_x levels may reflect site-specific factors, possibly indicating the effects of growth and development in the western (Palo Verde) and northeastern (Apex) parts of the valley. The median rate of decrease in ambient NO_x levels was 0.8 ppbv per year.

In contrast to the differences between ambient concentrations on weekdays and weekends, the time trends show more prominent decreases of ambient CO than NO_x concentrations.

Ambient ozone concentrations showed annual variations, but did not exhibit systematic trends over time (**Figures 2-14** through **2-16**). These figures depict trends in the 2nd and 4th highest annual peak hourly ozone levels (Figure 2-14), the mean ozone concentrations by hour (Figure 2-15), and the maximum ozone concentrations by hour (Figure 2-16). None of these measures exhibited systematic trends over time. Since primary pollutant (CO and NO_x) concentrations changed over time but ozone levels did not, it is possible that the primary pollutant emission changes either did not affect ozone levels or that they affected ozone loss and formation in complex ways having no net change in the ambient ozone concentrations.

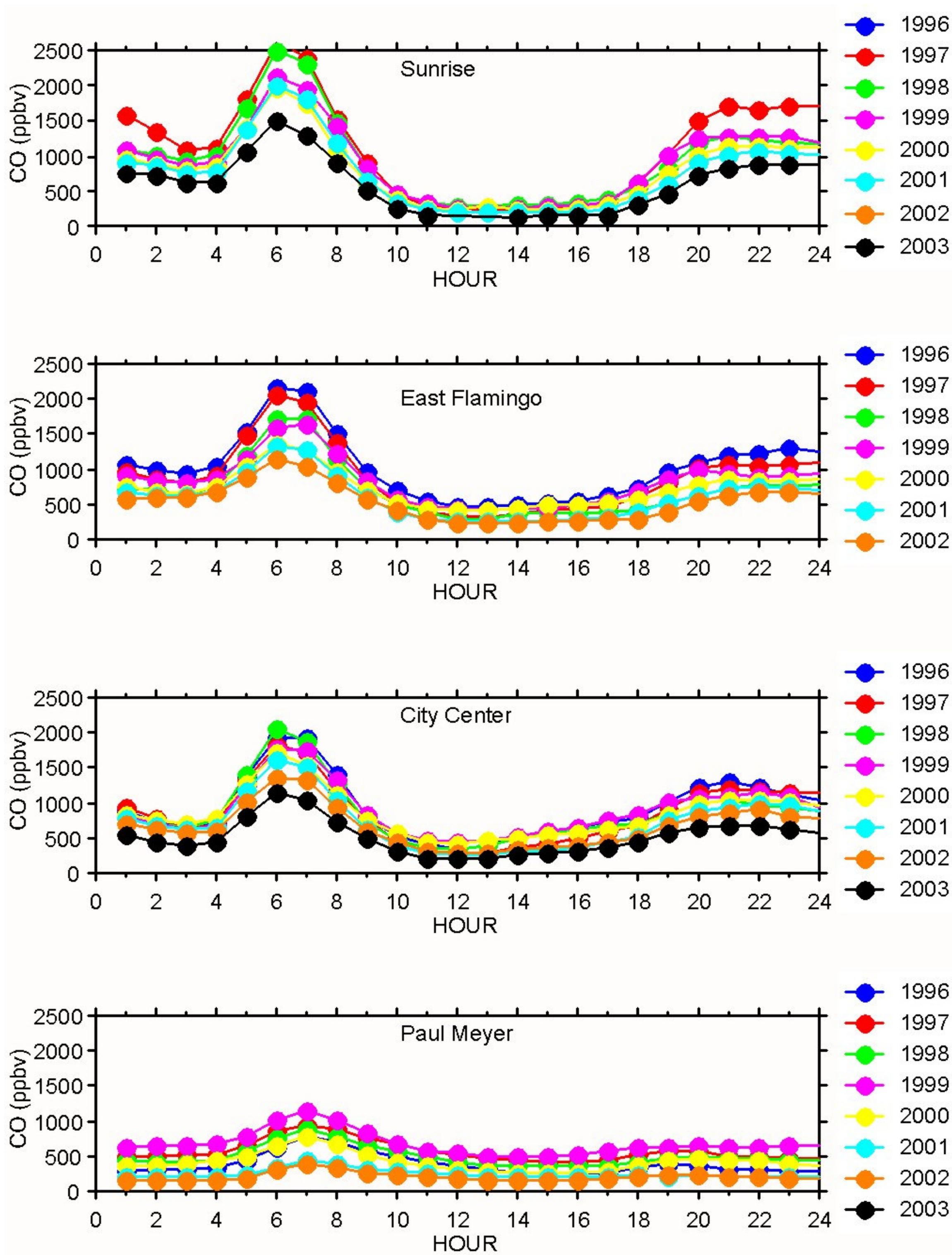


Figure 2-10. Diurnal Profiles of CO Concentrations by Year at Four Sites

The measurements are from weekdays during March through October of each year. Averages were excluded if fewer than 50 percent of the possible measurements were available.

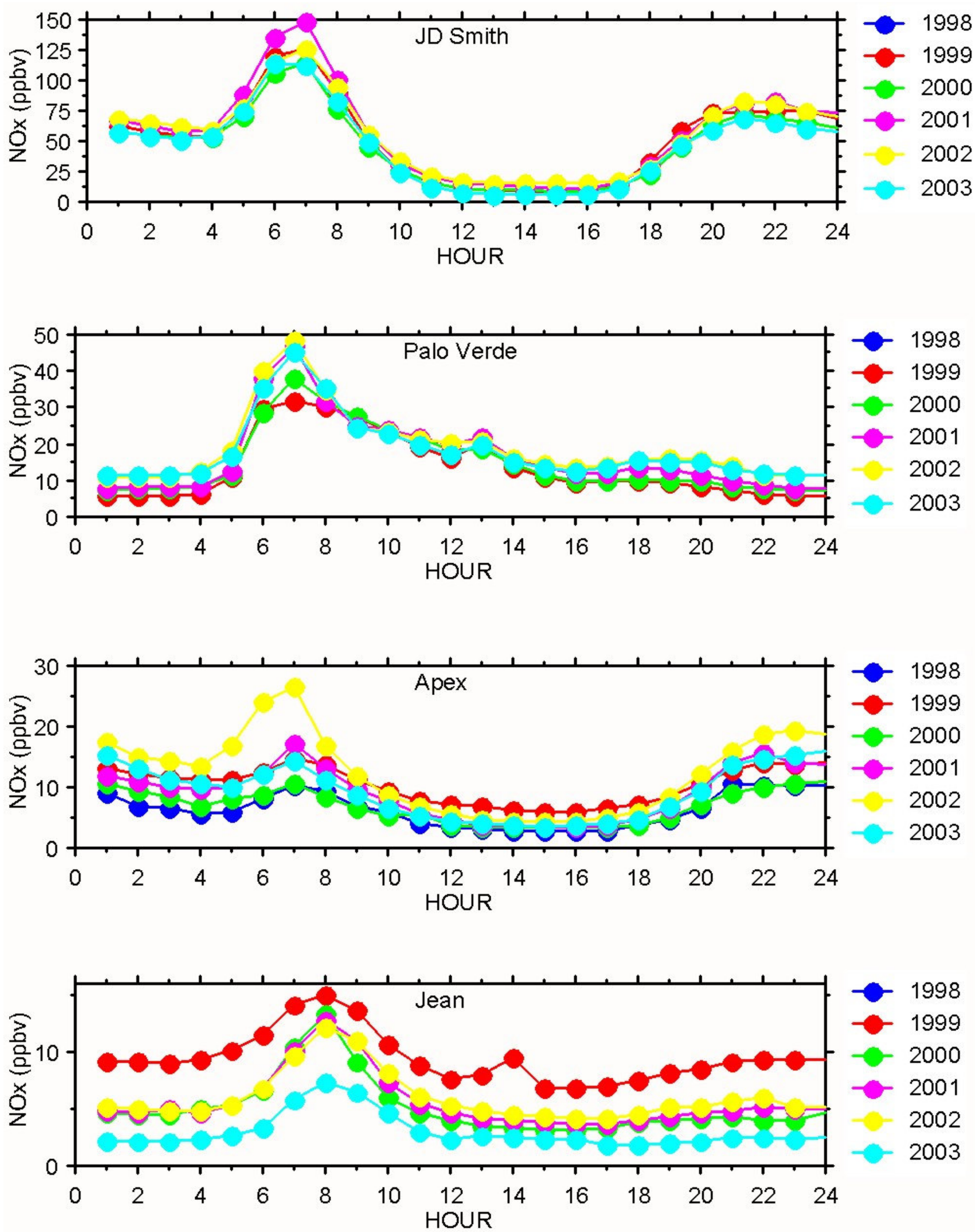


Figure 2-11. Diurnal Profiles of NO_x Concentrations by Year at Four Sites

The measurements are from weekdays during March through October of each year. Averages were excluded if fewer than 50 percent of the possible measurements were available.

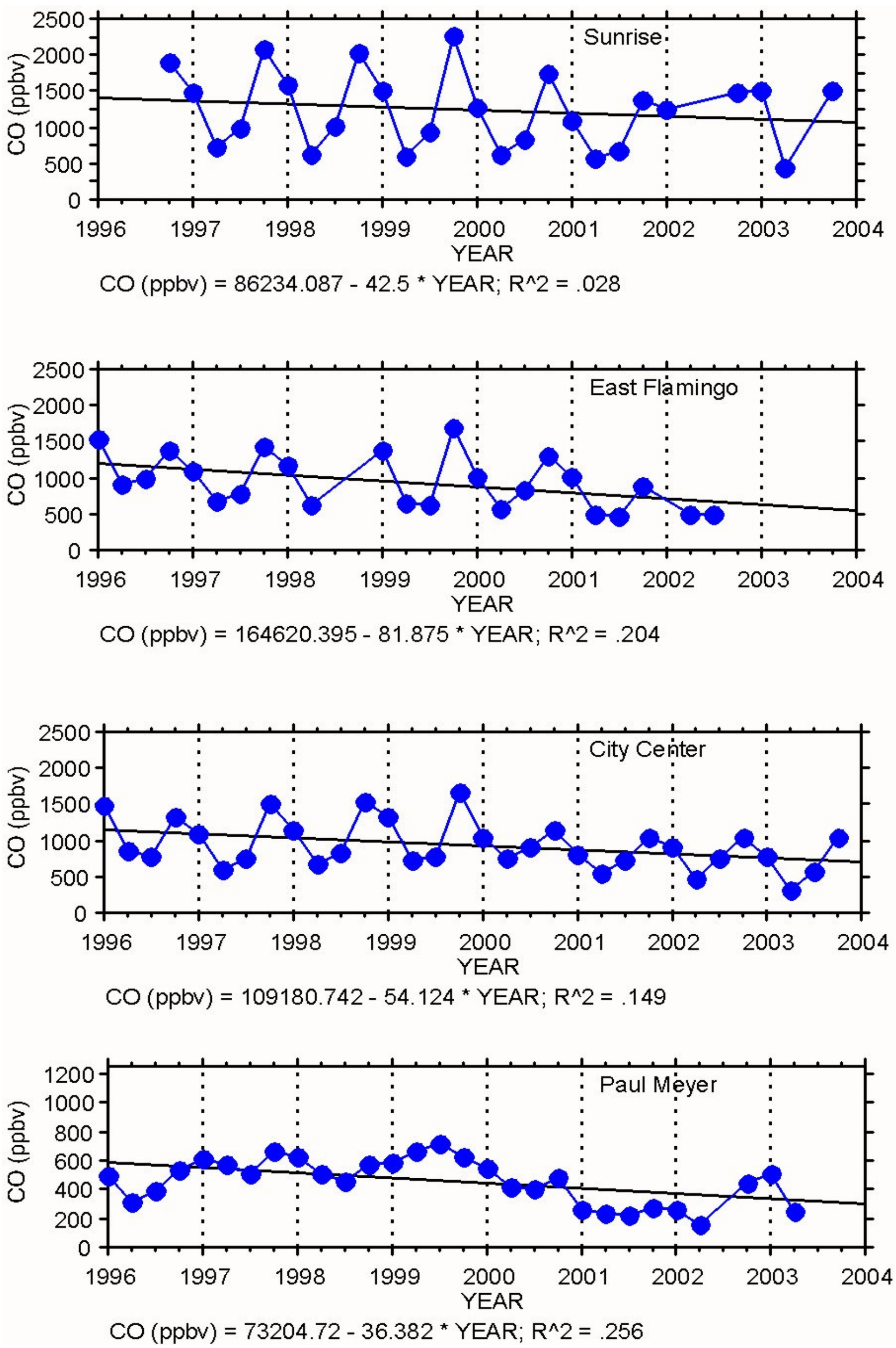


Figure 2-12. Quarterly Average CO Concentrations at Four Sites

The measurements are from all days of each year. Quarterly averages were compiled from monthly averages and quarters were excluded if fewer than two monthly averages were available. Monthly averages were compiled from daily averages and months were excluded if fewer than 22 daily averages were available (75 percent of 30 days). Daily averages were computed if at least 18 hourly measurements (75 percent) were available.

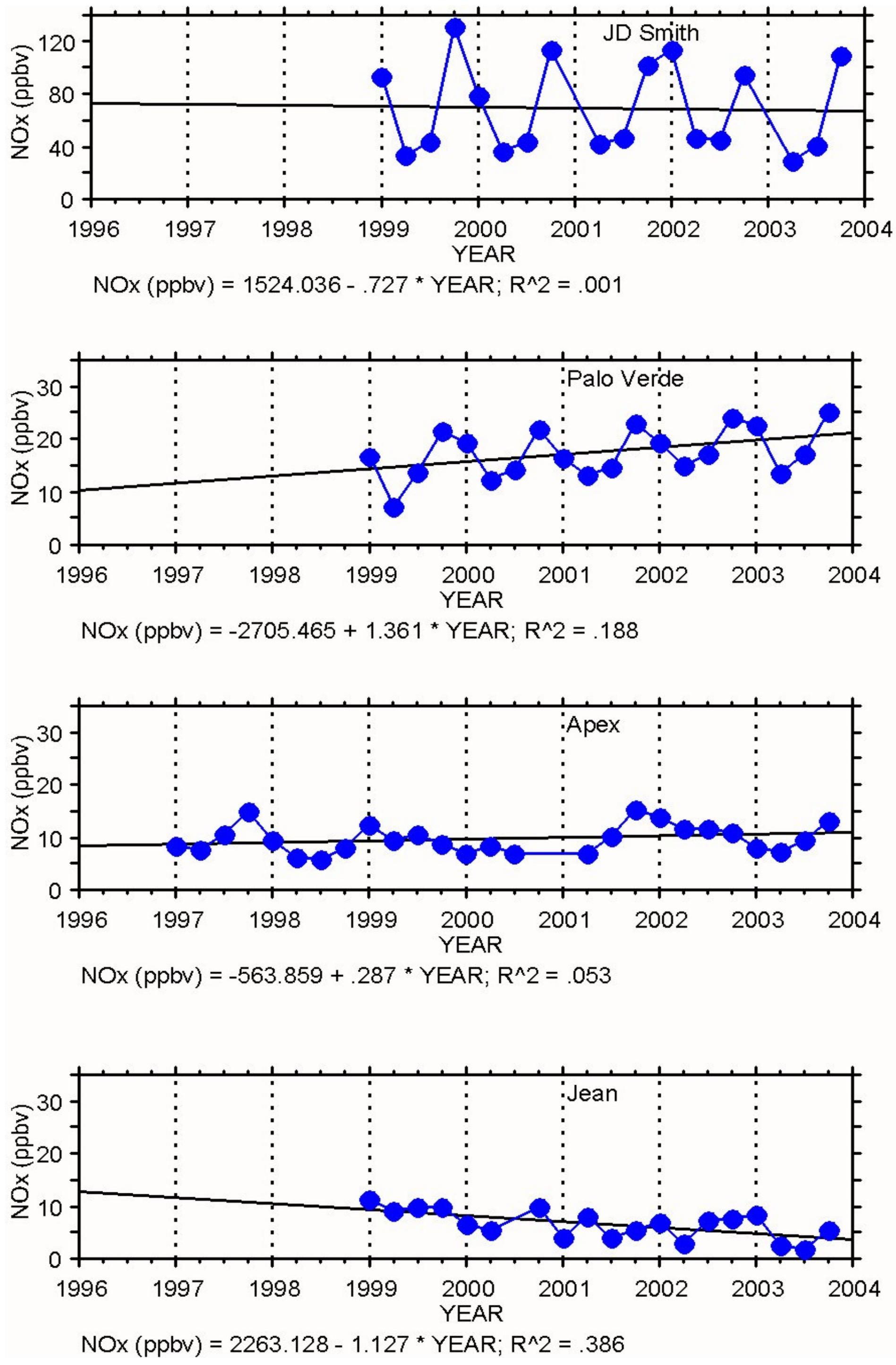


Figure 2-13. Quarterly Average NO_x Concentrations at Four Sites

The measurements are from all days of each year. Quarterly averages were compiled from monthly averages and quarters were excluded if fewer than two monthly averages were available. Monthly averages were compiled from daily averages and months were excluded if fewer than 22 daily averages were available (75 percent of 30 days). Daily averages were computed if at least 18 hourly measurements (75 percent) were available.

Table 2-7. Rates of Change of Ambient CO and NO_x Concentrations, 1996-2003

SITE	Code	NOx		CO	
		Slope (ppbv/year)	Significance Level	Slope (ppbv/year)	Significance Level
Apex	AP	0.29	0.26		
Boulder City	BC	-0.89	0.16	7.0	0.08
City Center	CC			**-54.1**	**0.03**
E. Craig	CR			-3.8	0.59
Crestwood	CW			-29.5	0.60
E. Sahara	ES	-0.91	0.85	-46.2	0.22
E. Flamingo	FL			**-81.9**	**0.03**
Green Valley	GV			6.5	0.62
J.D. Smith	JD	-0.73	0.90	-21.4	0.73
Jean	JN	**-1.13**	**0.005**		
S. L.V. Blvd.	MG			**-157.9**	**1.58E-6**
Paul Meyer	PM			**-36.4**	**0.005**
Pittman	PT			-22.8	0.33
Palo Verde	PV	1.36	0.06		
Sunrise Acres	SA			-42.5	0.41
S.E. Valley	SE			-8.7	0.38
Shadow Lane	SL			-53.7	0.15
Winterwood	WW			-5.5	0.82

The rates were determined by linear regression using the quarterly average concentrations described in Figures 2-12 and 2-13. Sites were excluded if fewer than 16 quarters of data were available. Statistically significant ($p<0.05$) trends are shown in bold type.

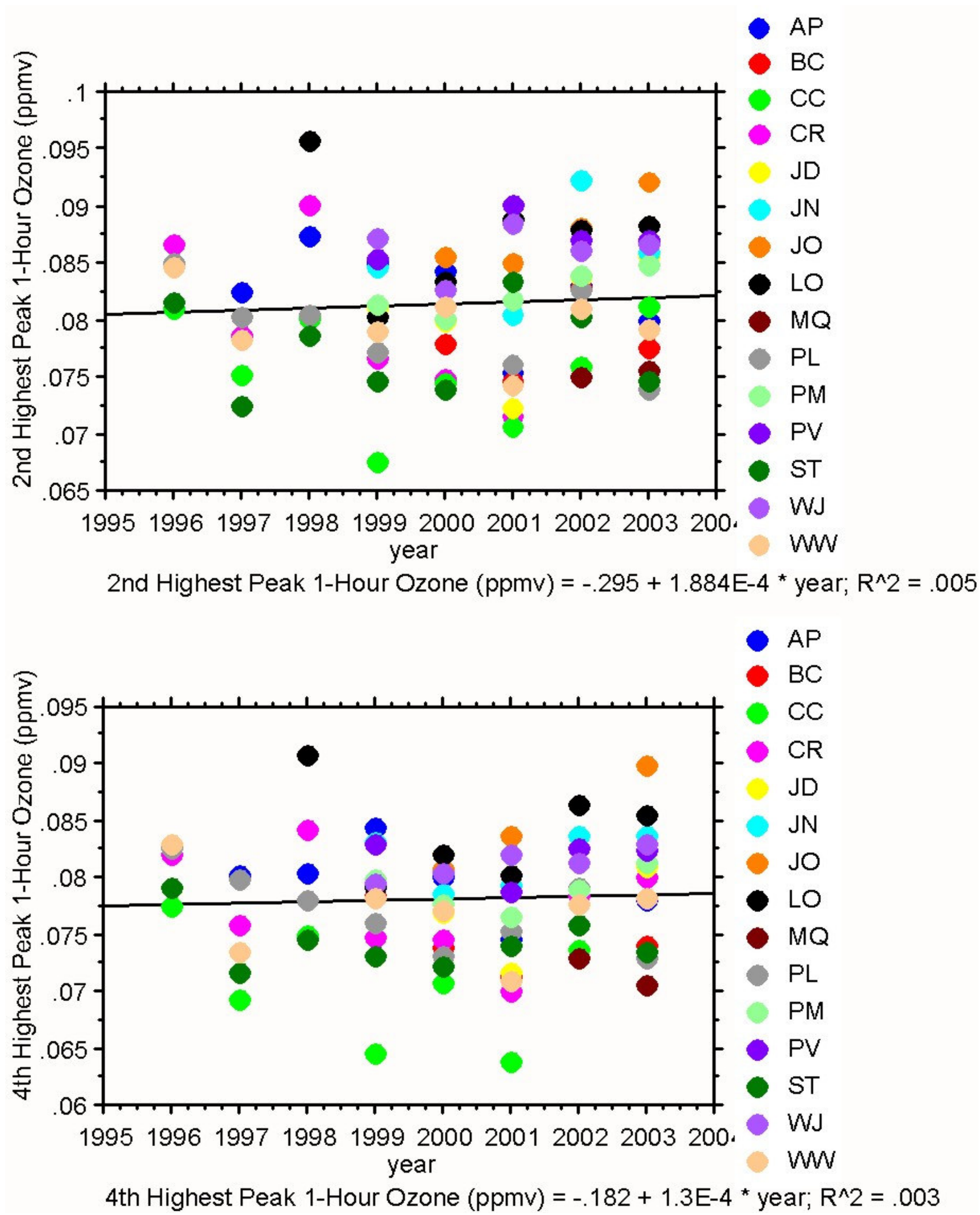


Figure 2-14. Trends in the Annual 2nd and 4th Highest Peak Hourly Ozone Concentrations versus Year

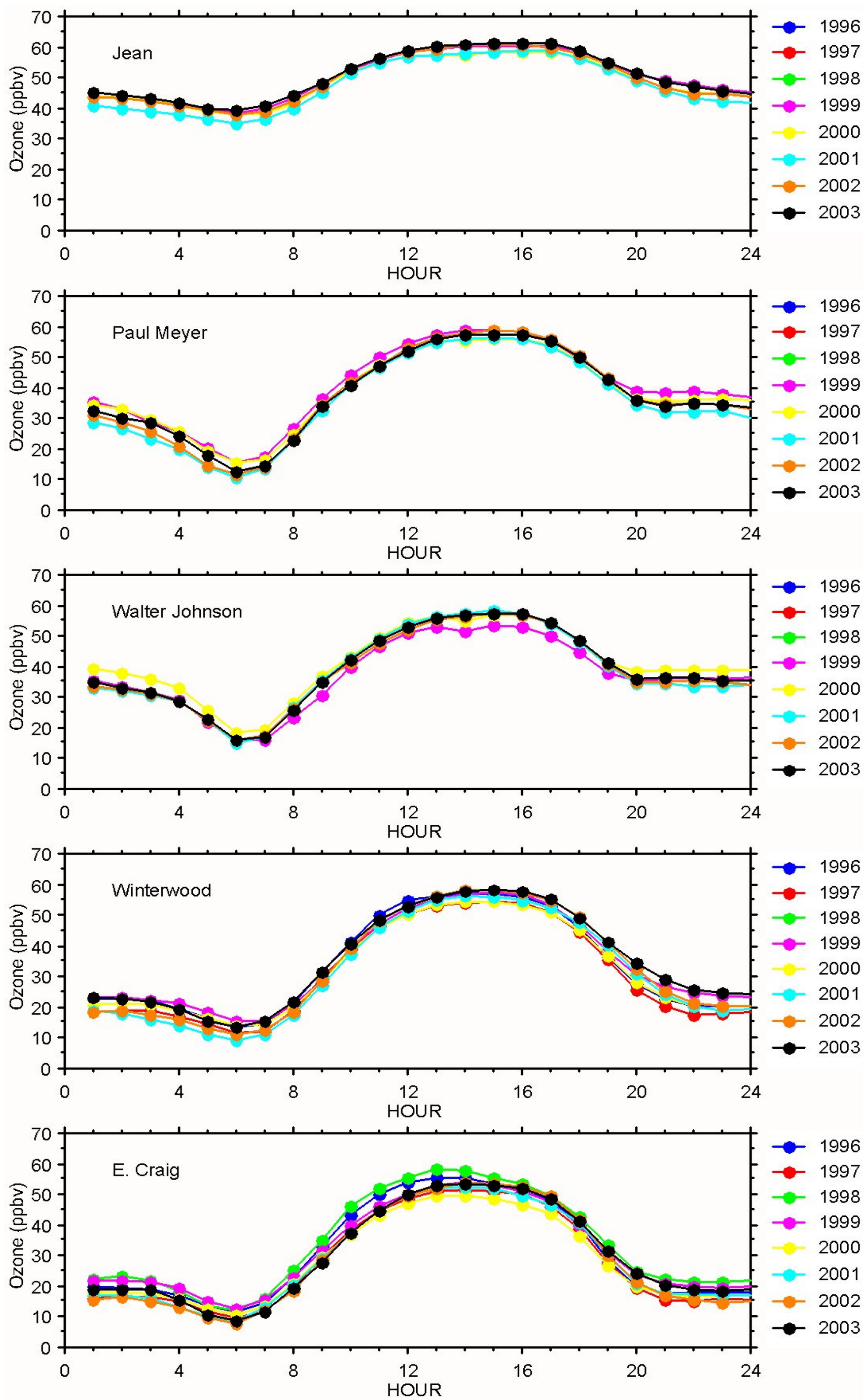


Figure 2-15. Diurnal Profiles of Mean Ozone Concentrations by Year at Five Sites

The measurements are from weekdays during March through October of each year. Averages were excluded if fewer than 50 percent of the possible measurements were available.

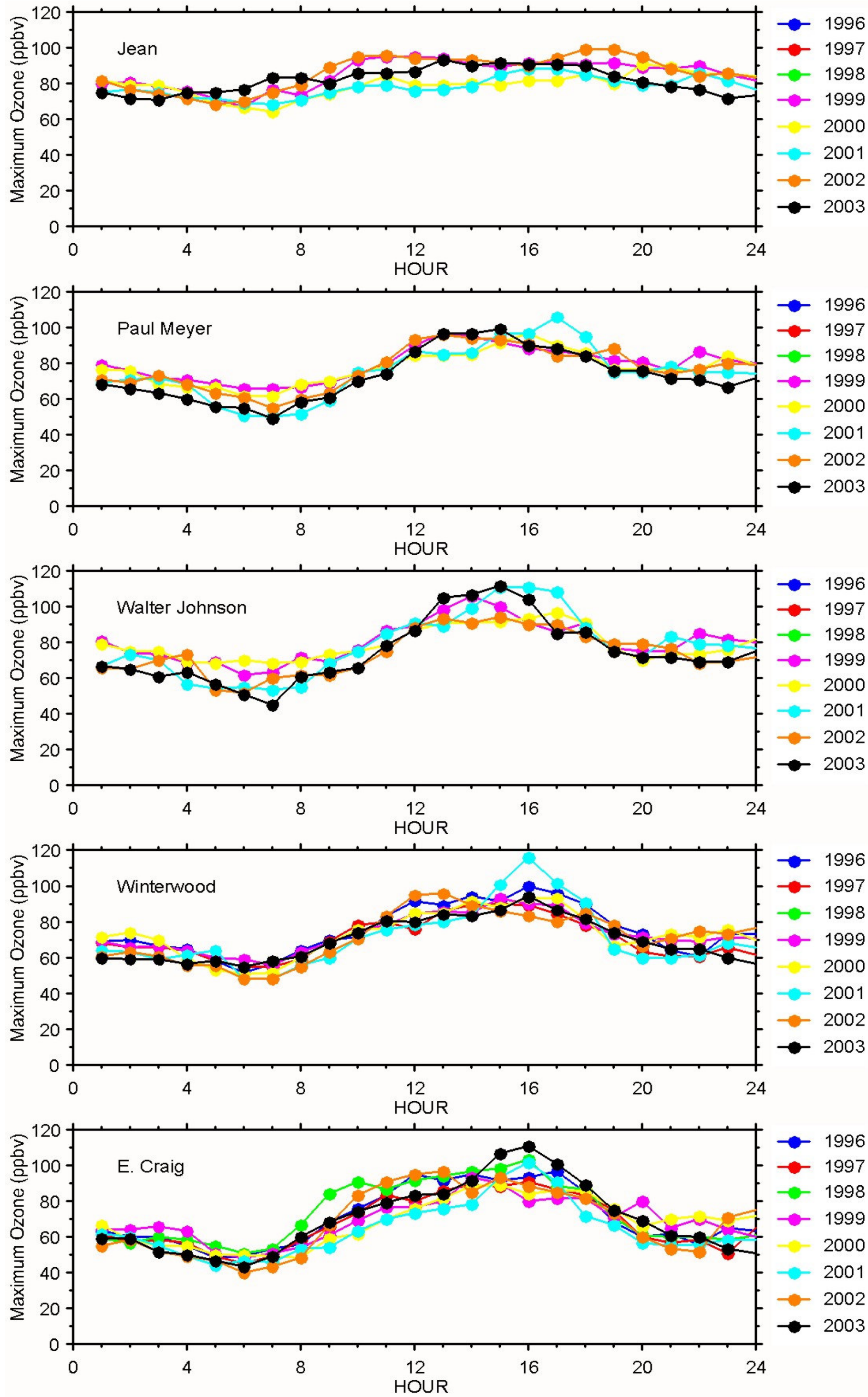


Figure 2-16. Diurnal Profiles of Maximum Ozone Concentrations by Year at Five Sites

The measurements are from weekdays during March through October of each year. Data were excluded if fewer than 50 percent of the possible measurements were available. For each site and year, each hourly maxima was determined independently. As a result, the values shown for the individual hours for a given year may have been obtained from measurements made on different days.

2.7 Section Summary

Ambient concentrations of both CO and NO_x showed statistically significant reductions on Sundays compared with Wednesdays. The median daytime decrease in ambient CO concentrations (21 percent) on Sundays was smaller than the corresponding daytime decreases of NO (38 percent) and NO_x (37 percent). In contrast, peak ozone levels increased on Sundays compared with Wednesdays. The ozone increases occurred for both peak 1-hour and 8-hour ozone levels at all monitoring sites, and for both ozone-season averages and high-ozone days.

The increases in peak ozone levels on weekends, occurring in association with reduced weekend concentrations of ozone precursors, raise questions of relevance to possible future ozone control strategies. We expect that future weekday emission levels will differ from current weekend emission levels in both the time of day when emissions occur and relative amounts of VOC and NO_x emitted; therefore, current weekend concentrations do not provide an exact predictor for future weekday ozone levels. Nonetheless, it is difficult to reconcile the observed weekday/weekend differences in precursor and ozone concentrations with a conceptual model of ozone formation in which ozone is produced locally and is limited by the availability of NO_x. Instead, the weekend results show that the weekend reductions of NO_x changed the magnitudes of ozone loss due to titration by NO.

Both year-to-year differences and systematic trends were observed in the ambient concentrations of CO and NO_x. Declines in ambient CO concentrations occurred at 13 of 15 sites from 1996 through 2003. Year-to-year differences in NO_x levels were also seen, with four sites showing downward trends and two sites showing upward trends. The median declines were 30 ppbv per year for CO and 0.8 ppbv per year for NO_x. In contrast to the differences between ambient concentrations on weekdays and weekends, the time trends showed more prominent decreases of ambient CO than NO_x concentrations.

Ambient ozone concentrations showed annual variations, but did not exhibit systematic trends over time. Since primary pollutant (CO and NO_x) concentrations changed over time but ozone levels did not, it is possible that the primary pollutant emission changes either did not affect ozone levels or that they affected ozone loss and formation in complex ways that did not result in changes in the ambient ozone concentrations.

An observation-based method for evaluating where and when ozone formation was limited by VOC and NO_x was applied. At all sites, ozone formation began in a VOC-limited state during early morning hours; it became NO_x-limited by late morning at Jean and by early afternoon at Apex. Ozone formation reached a transitional state by early afternoon at Boulder City and JD Smith; ozone formation then returned to a VOC-limited state at JD Smith during the later afternoon as fresh NO_x emissions occurred. At Mesquite, Palo Verde, and Searchlight, ozone formation remained VOC limited throughout the day (sufficient NO_x was available to continue sustaining ozone formation).

In summary, the weekday/weekend analyses, trend assessments, and estimation of VOC and NO_x limitation together indicate that ozone levels at sites in and near Las Vegas may not respond to changes in local emissions in easily predictable ways. Further understanding of potential ozone responses to changes in emissions would benefit from continuous measurements of multiple species, including hydrocarbons, at multiple sites representing different types of locations. Both long-term and episodic measurements would be of value.

2.8 Appendix: Extent of Reaction

Calculation of the extent of reaction, its use in delineating VOC- and NO_x-limitation, and comparisons with modeling studies are described in full in Blanchard et al. (1999), Blanchard (2000), and Blanchard and Stoeckenius (2001).

The smog production (SP) algorithm was applied to the data from all sites having measurements of ozone, NO, and either NO_2, NO_x, or NO_y. In summary, the extent of reaction is defined as:

(1) $Extent(t) = SP(t)/SP_{max}$

Smog Produced (SP) is defined as (Johnson, 1984):

(2) $SP(t) = O_3(t) + DO_3(t) – O_3(0) + NO(0) – NO(t)$

In application to ambient measurements, Blanchard et al. (1999) describe procedures for estimating the background ozone and ozone lost to deposition, i.e., $O_3(0)$ and $DO_3(t)$. The initial NO, or the NO input, i.e., NO(0), is estimated as $F*NO_x(0)$, where F=0.95, and additional equations are used to estimate $NO_x(0)$. The estimated $NO_x(0)$ is also used for calculating the denominator of the extent of reaction, namely, SP_{max}:

(3) $SP_{max} = B*NO_x(0)^{\alpha}$

where $B = 19$ and $\alpha = 2/3$ (Blanchard et al., 1999).

When NO_y data are available, the $NO_x(0)$ is estimated as the sum of NO_y and the cumulative mass of NO_y lost to deposition (Blanchard et al., 1999):

(4) $NO_x(0) = NO_y(t) + DNO_y(t)$

When true NO_x ($NO + NO_2$) data are available, the $NO_x(0)$ is estimated from:

(5) $NO_x(0) = NO_x(t) + [B/3F]^3 * [2X + 1]^3$

where:

$X = \cos[(4\pi + \cos^{-1}C)/3]$
$C = 1 – (27\gamma/F)/\{2*(B/F)^3\}$ for $–1 <= C <= 1$
$\gamma = \{O_3(t) + DO_3(t) – O_3(0) + B*NO_x(t) – NO(t) \}/ (B – F)$

There are typographical errors in these equations as published in Blanchard et al., (1999), and the correct version (above) was used for this project.

As indicated by Equations 1 through 5, the SP algorithm requires accurate measurements of ozone, NO, and either NO_x or NO_y. However, measurements of true NO_x ($NO + NO_2$) or NO_y (the sum of NO_x and NO_x reaction products) are not routinely available from compliance monitors. The standard NO_x monitor measures NO_x plus unquantified fractions of NO_x reaction products, such as peroxyacetylnitrate (PAN) and nitric acid (HNO_3) (Winer et al., 1974). For AIRS sites, these routine "NO_x" data were used to provide upper and lower bounds on the extent of reaction. The lower bound for extent was computed by using the measurements of "NO_x" as if they were true NO_x in Equation 5 above. The upper bound for extent was computed by using the measurements of "NO_x" as if they were true NO_y in Equation 4 above. The extent of reaction was estimated as the mean of the upper and lower bounds. In previous work, we have found good agreement between the mean of the upper and lower bounds and the extent of reaction calculated from true NO_y.

3. OVERVIEW OF METEOROLOGY

3.1 Synoptic Weather Typing

Synoptic weather patterns occurring over the western U.S. were classified into particular pattern types with the objective of determining the relationship between large-scale weather features and ozone occurrences in the Las Vegas Valley. By examining the number of occurrences of the various postulated weather types during the peak ozone months (May through August) for a 3-year period (2001 through 2003), significant relationships may be determined that will allow for the development of predictive models that can be used both for further analysis and operational applications.

3.1.1 Typing Criteria

The basic premise of the classification scheme is that the synoptic scale weather characteristics, as depicted by the 500 mb constant pressure patterns, are very influential in determining the onset and duration of high ozone occurrences in the Las Vegas Valley and surrounding areas. This constant-pressure surface (~18,000 ft or 6,000 m) is commonly used by the meteorology community to describe the major features of the atmosphere and for weather prediction. Five different 500 mb synoptic patterns were postulated:

1. Pacific Trough (PT)
2. Interior Trough (IT)
3. Pacific Ridge (PR)
4. Interior Ridge (IR)
5. Flat Ridge (FR)

The 500 mb synoptic weather pattern at 00 UTC (16 PST) and 12 UTC (04 PST) for each day during the ozone season over a 3-year period were examined and classified into one of the five categories. Twice daily National Weather Service (NWS) generated 500 mb constant-pressure maps were examined and the weather patterns were subjectively determined by experienced meteorologists. In addition, the data set for typing included specific measured weather parameters including the 500 mb height and the ambient air temperature at the 700 mb level at the Desert Rock NWS upper-air site. Temperatures aloft at that level are indicative of the mixing potential (stability) of the regional air mass presiding in the area at the time of measurement. Warmer air at 700 mb (~10,000 feet or 3,000 meters) is indicative of a stable atmosphere and poor dispersion conditions, while cooler air aloft is associated with more vigorous vertical mixing of pollutants and thus better dispersion.

The characteristics and criteria for each weather type are described below:

<u>Pacific Trough (PT)</u>

The axis of the long-wave 500 mb trough, or series of short wave troughs, is located off or along the Pacific Coast, producing falling 500 mb heights and increases from a westerly to a southwesterly flow. By convention, it was decided that the lowest 500 mb heights during this weather type are west of the Sierra Nevada Mountains. This type of trough influences atmospheric dispersion conditions in the interior southwestern U.S. by slowly eroding the strength and longevity of stable anti-cyclonic air masses, which results in the breaking down of the broad scale subsidence needed to sustain poor dispersion conditions. The PT designated weather type, also by convention, includes zonal flow situations characterized by light to moderate straight west to east flow across the western U.S. The southerly component of the onshore flow characteristic of the PT weather type may also open the door for increased moisture aloft over the interior regions. In general, the 700 mb temperature at the Desert Rock upper-air station is less than 10^{o} C during PT occurrences.

Interior Trough (IT)

When the axis of a long or short wave trough, or a closed cyclonic system, resides in the interior of the southwestern U.S., the synoptic weather type is designated to be an Interior Trough (IT). In this type, the lowest 500 mb heights are east of the Sierra Nevada Mountains. The most significant characteristic of this pattern is the advent of cool air aloft in the interior southwest, and the resultant well-mixed dispersion conditions. Temperatures at 700 mb are usually below 8^{o} C, and may be as low as 0^{o} C during the early part of the ozone season. When advected moisture is available aloft, considerable cloudiness and escalated precipitation potential may also accompany the IT synoptic type.

Pacific Ridge (PR)

The Pacific Ridge (PR) synoptic weather type is directly associated with the mean eastern Pacific ridge, with the axis of highest pressure situated along or west of the Pacific coast. The convention for this feature requires that the highest 500 mb heights be located west of the Sierra Nevada Mountains. The maximum 500 mb heights usually exceed 5900 meters near the core of the ridge, but at the Desert Rock upper-air site, heights may be considerably lower. Another convention for the PR designation requires that the 500 mb flow over southern Nevada be from a northerly direction (west-northwesterly to northeasterly), reflecting the counter-clockwise motion around the anti-cyclonic air mass to the west. During the first half of the ozone season, the northerly flow aloft will result in the advection of cooler, less stable air into the region, while during the later half of the season, the northerly flow often brings in warmer drier air. The Desert Rock 700 mb temperature may be as high as 12^{o}C (late season), or as low 5^{o}C (early season). The PR weather type usually marks the beginning of an anti-cyclonic situation, and often will follow a cyclonic event, especially in the earlier part of the season. It is also not unusual for this type to be the result of the retro-gradating of a ridge located farther east. The PR weather type is usually more transient than other ridging situations, and thus tends to occur for shorter durations, often as a transition into other longer-lived anti-cyclonic regimes.

Interior Ridge (IR)

The primary characteristic of the Interior Ridge (IR) weather type is the existence of a discernable high-pressure ridge at the 500 mb level over the interior southwestern U.S.. The convention for this feature is that the highest 500 mb heights be located east of the Sierra Nevada Mountains. Typically, the interior ridge occupies the Great Basin and Inter-Mountain region and is often centered near the Four Corners area east of Las Vegas. The height of the 500 mb surface over the Desert Rock upper-air site is usually greater than 5900 m, and sometimes as high as 5990 m. The 700 mb temperature in this situation usually exceeds 12^{o} C, and can be as high as 16^{o} C. The warm temperatures aloft are indicative of strong air mass subsidence in the interior region, and thus valley capping and limited thermodynamic mixing is prevalent. However, because of the lack of cool air advection, the hottest local surface temperatures of the year are usually recorded during IR events, but mixing-layer depths may sometimes be deeper due to intense surface heating. Flow aloft at Desert Rock during IR situations is usually very light and possibly variable when the ridge axis is over southern Nevada and easterly to southeasterly when the ridge center is father east.

Flat Ridge (FR)

When the eastern Pacific ridge broadens to extend over the ocean and the interior west, with little transitory movement, this weak anti-cyclonic air mass is classified as a Flat Ridge (FR). In this pattern, all of the synoptic scale energy is well to the north and the pressure gradients, both at the surface and aloft, are very weak. The 500 mb surface may not always be as high as in the stronger ridging types (such as the PR and IR), but they still are typically greater than 5900 m over most of the region. Because this is still a weak anti-cyclonic situation, significant air mass subsidence is prevalent, and as a result, the interior valleys remain capped and stable. This scenario is the most conducive to increased episodic pollution carry-over from one day to the next.

3.1.2 Frequency of Weather Types and Relation to Ozone

The occurrence of each type for each month for the 3-year period is summarized in **Table 3-1**. As expected, troughs are a more frequent occurrence earlier in the season with June and August having a comparable number with the lowest frequency in July. Conversely, weather types featuring long-wave ridges and flat pressure gradients are most frequent in mid-season, peaking in July, and less frequent in May and early June.

Table 3-2 presents the number of exceedances or near-exceedances that are associated with each weather type. The table also lists the percent of the total occurrences of a given type associated with high ozone. (Note that when reviewing both Tables 3-1 and 3-2 there are two weather types associated with each day or exceedance/near-exceedance – one for the early morning (12 GMT) and one for the afternoon (0 GMT).) As anticipated, the bulk (almost 90 percent) of the high ozone days are associated with ridges, with approximately 40 percent of the high ozone days occurring during interior ridging (IR). Beyond that, it is difficult to draw any firm conclusions regarding weather type using just the five types investigated, since approximately 85 percent of the ridge occurrences did not result in exceedances or near exceedances. It is likely that further sub-classifications of the ridge types will provide results that are more conclusive. Based on results of other tasks of this study, possible type classifiers could include the presence of a thermal low near Las Vegas, more specific ridge location information, the strength of pressure gradients, the month, and transition between types information (persistence of a given type).

Table 3-1. Monthly Frequency of Weather Types for 3-year Period 2001-2003

Month	PT	IT	PR	IR	FR
May	40	58	24	37	26
June	20	37	18	52	51
July	26	13	5	103	38
August	38	24	23	46	53
Total	124	132	70	238	168

Table 3-2. Frequency of Weather Types versus Daily Maximum 8-Hour Ozone Concentration for 3-year Period 2001-2003

Maximum 8-hr Avg.	PT	IT	PR	IR	FR	Total
80 – 85 ppb	7	2	8	24	19	60
>85 ppb	1	1	10	16	10	38
Total	8	3	18	40	29	98
% of High Ozone Cases	8.1%	3.1%	18.4%	40.8%	29.6%	
% of Type Cases	6.5%	2.3%	25.7%	16.8%	17.2%	

3.2 Discussion of the Wind Data Used in the Database

The primary source of data for the analysis was data from the Clark County DAQEM's ambient monitoring network. Data from this network was readily available from 1996 to the present. However, sites were still being added to the network up until 1999. Thus, data prior to 1999 were not reviewed extensively. The case study investigation was conducted using episodes from 2001 through 2003, as was the weather typing effort, concentrating on the most recent and likely most relevant years of data available. For the CART analysis, data from 1999 through 2003 were used in order to maximize the number of exceedance and near-exceedance days available for this statistical method.

Early in the review of the DAQEM data it was noted that a problem existed with the wind direction data from several of DAQEM sites. This includes primarily the wind direction data from the following sites:

- Joe Neal
- Apex
- Lone Mountain
- Walter Johnson
- City Center
- E Charleston
- Sunrise Acres
- Landfill
- Green Valley

The data from these sites were deemed invalid and, thus, not used herein. Therefore, the use of data from other meteorological networks within the basin was investigated. Three other sources of meteorological data were identified, and are briefly described below:

- FAA/NWS – The National Weather Service operates meteorological stations at three airports within the Las Vegas Valley: McCarran, North Las Vegas, and Nellis AFB. This data seemed for the most part reasonable and was included in our database.
- RAWS - Remote Automated Weather Stations (RAWS) are operated for land management applications in the western United States. Two sites were located within our study domain and merged into our database.
- Clark County Regional Flood Control District (CCRFL) - The District operates a network of precipitation and meteorological monitoring sites throughout the Las Vegas basin. While data quality appears good, the collection of data is event-driven and not

continuous. While not totally appropriate for all data uses, it was satisfactory for examining the prevailing winds and was very useful where there were no other data. It should be noted that the data were checked by comparing sites that were close to other sites that were using conventional monitoring methods.

The sites actually used in this analysis are listed in **Table 3-3**, and their locations mapped on **Figure 3-1**. The table includes the site ID, which is plotted on the figures, the site name, site coordinates, and the site operator.

Table 3-3. Site Names and Locations

Site ID	Name	Lat	Long	Source	
BC	Boulder City	35.97889	-114.84417	DAQEM	
FL	E. Flamingo	36.11444	-115.16250	DAQEM	
FP	Freedom Park	36.18500	-115.10320	DAQEM	Note1
JD	JD Smith	36.19111	-115.12222	DAQEM	
JN	Jean	35.78000	-115.34000	DAQEM	
MC	E. Sahara	36.14390	-115.08560	DAQEM	
MCC	McClellen	36.09300	-115.16300	NWS	
MS	Charleston	36.15890	-115.11080	DAQEM	Note1
NEL	Nellis	36.24920	-115.03500	NWS	
NLV	No. Las Vegas AP	36.20750	-115.19600	NWS	
NVAL	North Valley	36.34317	-115.16672	CCRFC	
OR	Orr	36.12052	-116.13103	DAQEM	
PL	S.E. Valley	36.03500	-114.99810	DAQEM	
PM	Paul Meyer	36.10806	-115.25361	DAQEM	
PT	Pittman Rd	36.05444	-114.99722	DAQEM	
PV	Palo Verde	36.17306	-115.33167	DAQEM	
RM	Mountain Springs	36.02340	-115.51570	RAWS	
RR	Red Rock	36.07553	-115.44410	RAWS	
SA	Sunrise Acres	36.16306	-115.11444	DAQEM	Note1
SL	Shadow Lane	36.16361	-115.16222	DAQEM	
SLOA	Sloan	35.92742	-115.19431	CCRFC	
TORT	Desert Tortoise Center	35.97522	-115.25131	CCRFC	
WW	Winterwood	36.14306	-115.05167	DAQEM	

Note 1: Some site locations have been changed slightly to allow for clearer plotting on Figure 3-1.

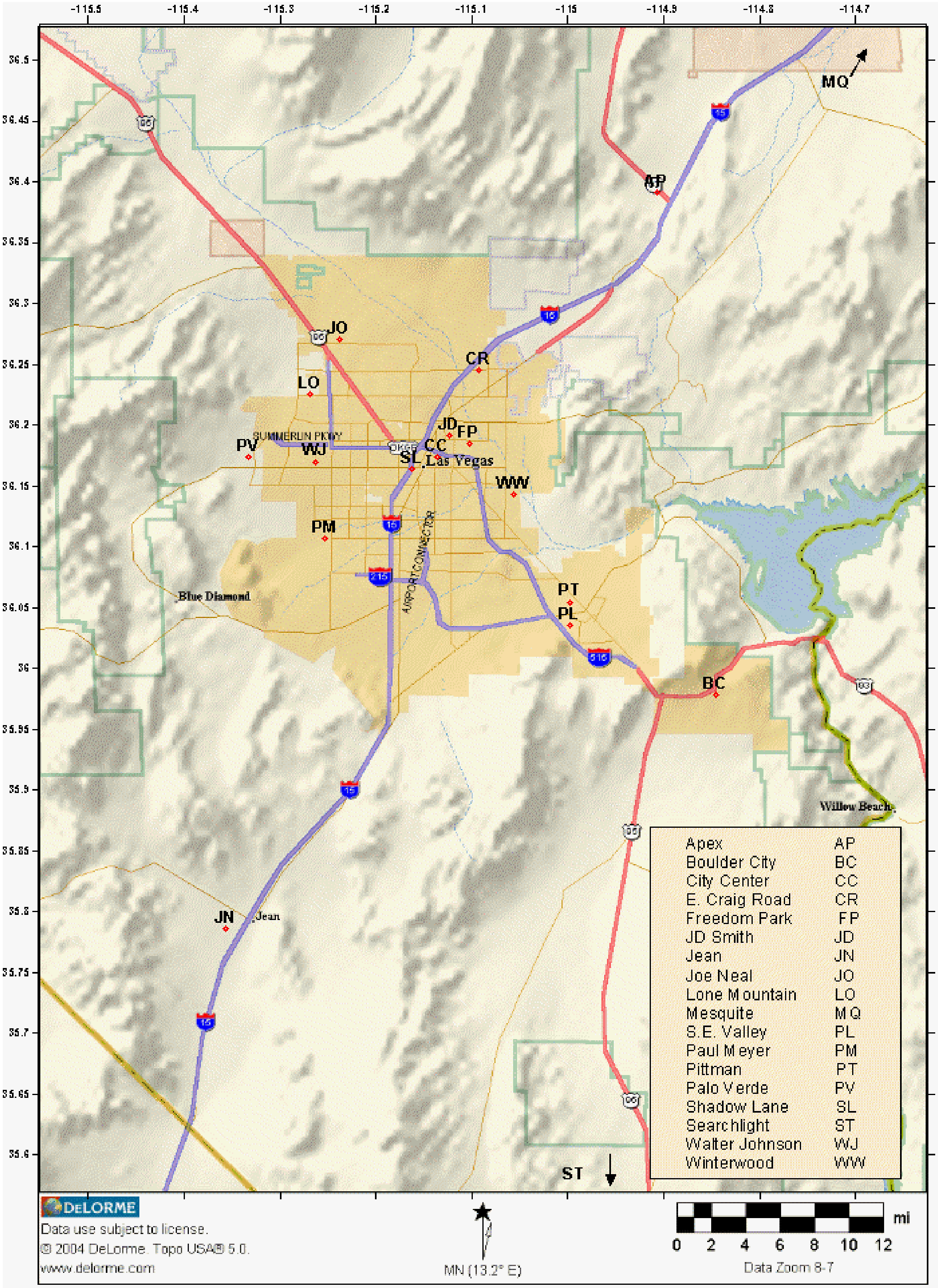


Figure 3-1. Map Showing Las Vegas Valley Surface Meteorological Network

3.3 Surface Winds

Surface winds in Clark County are controlled by local terrain influences superimposed on the larger-scale synoptic and regional wind fields. Local influences include channeling of winds through passes and/or gaps in the terrain, and slope and valley wind systems. Slope and valley wind systems are local, thermally driven flow circulations that form in complex terrain areas (Whitman, 1990). These processes directly affect the transport and dispersion of pollutants. An overview of the variability of the winds in Clark County are depicted in the sets of wind roses on **Figures 3-2 through 3-4.** The figures show the frequency of wind direction from each of the 16 compass points that are further classified by wind speed. Both nighttime and daytime measurements are given on separate windrose diagrams. Data are presented for two sites in the Las Vegas Valley; JD Smith and Palo Verde, and for one outside of the Valley (Jean). The JD Smith site is in downtown Las Vegas, Palo Verde is located on the west side of the Valley near the foothills, and Jean is southwest of the Las Vegas Valley east of the California-Nevada state line. All three sites are operated by the DAQEM and appear to produce valid data.

The windrose diagrams for all three sites show distinct diurnal variations. The Las Vegas Valley sites (Figures 3-3 and 3-4) exhibit characteristics that can be attributed to both local terrain effects and regional-scale winds. Prevailing winds (most frequent) at the JD Smith sites experience a 180 degree direction shift between day and night. At night, the wind is most often downvalley (along the longitudinal axis) to the southeast, reflecting a drainage flow. During the day, unequal heating of the terrain by insolation cause the flow to be directed upvalley (to the northwest). As can be seen, drainage winds are associated with low wind speeds. When wind speeds increase at night, it is typically due to larger-scale phenomena becoming more dominant.

Similarly, the winds at Palo Verde are usually dominated by local terrain-driven features. During the day, winds are primarily upvalley (from the southeast). At night, the prevailing wind is more westerly than in downtown. This is most likely due to the stronger slope flow influence from the ridges that define the western boundary of the Las Vegas Valley and reinforced by the prevailing southwest regional winds. The different locations of the two Valley sites can account for observed features, and also account for the stronger wind speeds observed.

The observed winds at Jean (Figure 3-4) are very different from those in the Valley. The overwhelming occurrence of winds from the west observed at night is pretty much as expected from west coast wind climatology (Hayes et al., 1984). The high incidence of southerly winds measured during the daytime is rather surprising but in reasonable agreement with the winds aloft discussed below in Section 3.5. The Desert Rock rawinsonde measurements exhibit a low-level prevailing wind from the south-southwest. Typically, winds back counter-clockwise approaching the surface due to surface friction, which in this case implies becoming more southerly. Paramount to this feature is that during the day, when rigorous vertical mixing occurs, there exists a physical coupling between surface winds and winds aloft within the boundary layer. At night, as the atmosphere stabilizes, the shallow surface boundary layer and the flow aloft are decoupled. Often this decoupling creates a nocturnal low-level wind jet in valleys. Unfortunately, there are no detailed measurements of the winds aloft over the Las Vegas Valley to observe if such a feature exists.

3.3.1 Prevailing Wind Flow

The prevailing winds were developed from the hourly data for the summer period June to September in the same manner as the data discussed in the prior section. The frequency of wind direction from each of the 16 compass points was computed along with the average wind speed in each direction category. Frequency statistics were computed for each hour for the following data sets:

- 15 DAQEM sites for which valid data was available (see section 3.2)
- 3 NWS/FAA sites (No. Las Vegas Airport, Nellis, and McCarren Field)
- 2 RAWS sites that were within map domain, and
- 3 CCRFC agency sites that were not noticeably dominated by local terrain features and which were located where no other data were available.

Streamlines were drawn to the prevailing winds and contours of average wind speed (isotachs) constructed. The diurnal variation of the prevailing flow is illustrated in the sequence of charts in **Figures 3-5 through 3-10**, which start late in the day after the peak ozone concentrations are normally measured. In the late afternoon/early evening, the prevailing winds are uniformly southwest throughout the region as shown on Figure 3-5. There is some divergence at the eastern side of the Valley as indicated by the stream flow turning more northerly in the north and more westerly in the south. Wind speeds are rather brisk, averaging 4-6 m/s in the Valley.

It should be noted that Nellis winds were inconsistent with the other data throughout the day, but were accounted for in the streamline analyses. While we have no reason to discount the data, it is difficult to explain in context with the other winds. Apex measurements were omitted from the final data set due to problems explained above. However, the winds from Apex were very similar in both speed and direction to Nellis, adding confidence to both data sets. Channeling of the air by the adjacent terrain may create the observed winds.

By late night when the atmosphere has become more stable, low-level convergence of flows in the Valley develop as illustrated on Figure 3-6. Within the Valley, drainage winds are evident converging on the east side. It is likely that the drainage flow follows the terrain towards Lake Mead but no measurements were available along that path. Winds are generally light (less than 2 m/s) in the Valley. Moderate southwest winds continue to prevail outside the Valley and at the higher elevations. This suggests that at 01 PST the low-level winds in the lower valley floor are decoupled from the winds aloft, and infer that a temperature inversion has developed in parts of the Valley but not at other higher locations.

Near sunrise at 06 PST (Figure 3-7), drainage winds dominate the Valley. The flow is seen to converge near the Las Vegas wash. Winds are generally very light. By contrast, the prevailing wind at Sloan (2745 ft) is still from the southwest and speed has not diminished at all (over 4 m/s). This would suggest that on average any nocturnal surface temperature inversion is very weak or non-existent at Sloan.

By mid-morning, prevailing winds in the Valley have already changed dramatically (Figure 3-8). Surface winds are being directed towards the east facing slopes along the west side, and upvalley (southeast to northwest). There appears to be decoupling of the winds aloft as reflected at Sloan and the Desert Tortoise Center where winds are south-southwest at more than 4 m/s. At the same time, the Nellis prevailing winds remained from the south at speeds in excess of 6 m/s.

On the 12 PST chart (Figure 3-9), an organized, widespread upvalley (SE) flow is illustrated. Air from the downtown area moves to the northwest along the Valley's axis while another streamline moves air from south Las Vegas into the foothills south of Summerlin. A northern branch transports air towards Apex. Wind speeds are generally 2 to 4 m/s during this time period. It now appears the flow at the surface has coupled with the winds aloft, indicating that the morning transition has taken place. This noontime wind flow pattern is particularly significant in light of the "typical" areal distribution of ozone, which is discussed in detail in Section 5.

By mid-afternoon (15 PST), the prevailing winds are mostly southwest throughout the domain. As can be seen from Figure 3-10, the wind field is relatively uniform with the exception of a veering of the flow northerly in the northwest quadrant of the Valley. The average wind speed from the prevailing directions is moderately strong and uniform at 4-6 m/s. This is particularly noteworthy when comparing with the afternoon winds on ozone exceedance days (Section 5).

Time-series plots showing the diurnal variation of the prevailing winds in the Las Vegas Valley are shown on **Figure 3-11**. The JD Smith site is representative of winds within the urban core; Palo Verde representative of winds along the west side of the Valley, and Sloan of air flowing into the Valley. Wind direction is shown on the top panel of the figure, and wind speed on the bottom panel. JD Smith and Palo Verde both show dramatic diurnal change. After sunrise, prevailing westerly flows switch to southeasterly at JD Smith and northeasterly at Palo Verde---Palo Verde becoming southeast also by 10 PST. Both sites thereafter have upvalley or southeast winds until 14 PST, and then shift to westerly. Southwest to northwest winds prevail throughout the late afternoon and night. Note the sharp increase in wind speed that accompanies the afternoon direction shift. From midnight until late morning, winds in the urban core are very light (< 2 m/s).

Sloan is located in a pass at the southwestern edge of the Valley, immediately off Interstate 15. Air flow is channeled by the surrounding terrain and shows no diurnal cycle in wind direction. As can be seen from the figure, the prevailing winds are southwest throughout the daily cycle. Wind speed is relatively constant as well, between 4-5 m/s, except in late evening.

In summary, the diurnal behavior of the prevailing Valley wind field is as follows: At night when the atmosphere is most stable, local drainage flows dominate in the lower elevations. The flow appears to follow the terrain along the longitudinal axis of the Valley towards Lake Mead. The surface flow pattern during the stable nocturnal period is clearly decoupled from the stronger winds aloft, as seen at higher elevations around the valley. By mid-morning, drainage flows cease and, due to solar-induced terrain heating, shift to an upslope flow, which most frequently is to the west and northwest. By mid-afternoon and continuing into evening, a rather uniform, moderately strong, southwest wind field prevails, as flows at all levels become strongly coupled. There appears to be a steady flux into the Valley from the southwest as evidenced at Sloan.

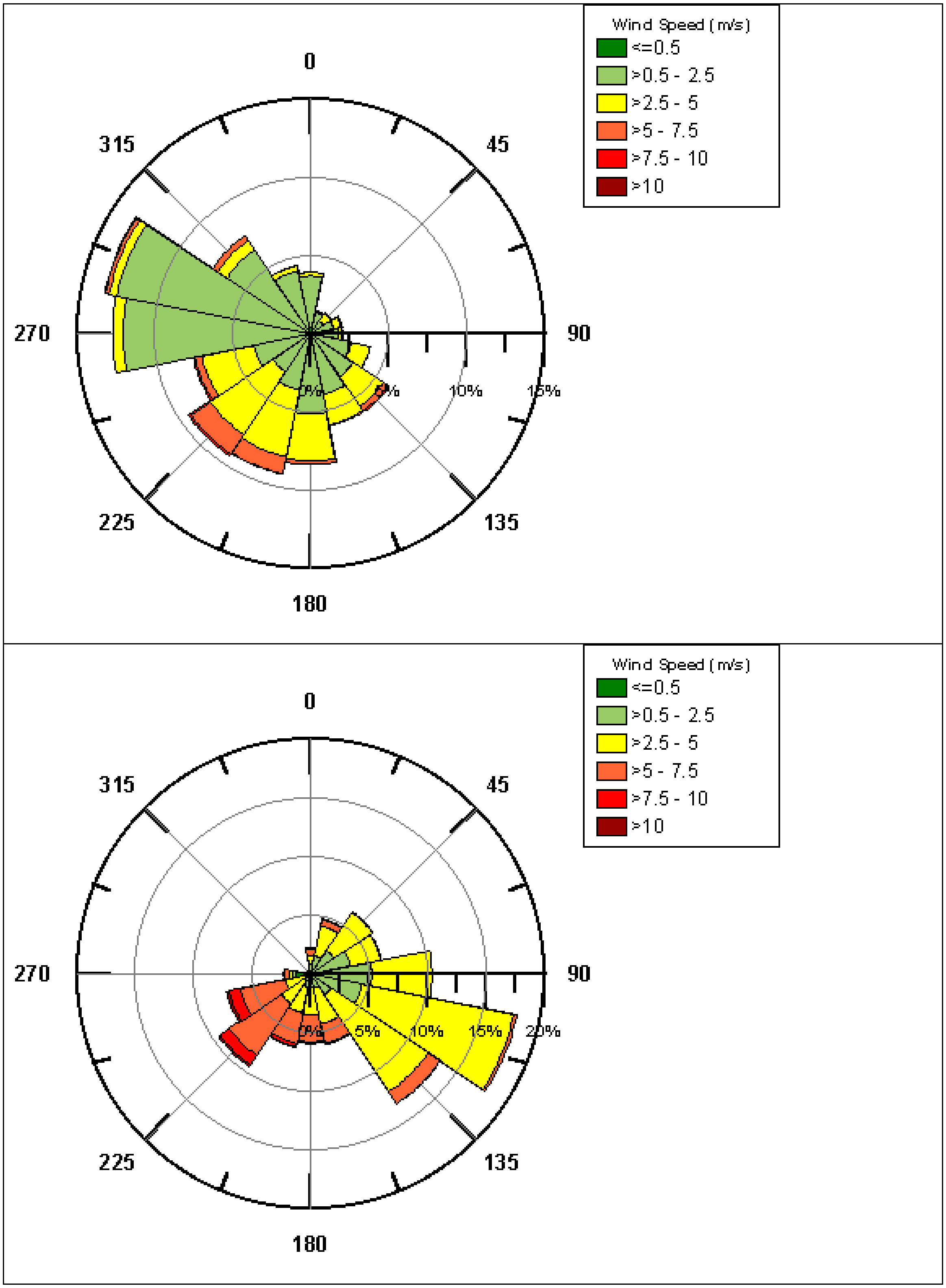


Figure 3-2. Windrose Diagrams for JD Smith Site – May through September, 2001-2003
Top panel shows nighttime winds and bottom panel shows daytime winds.

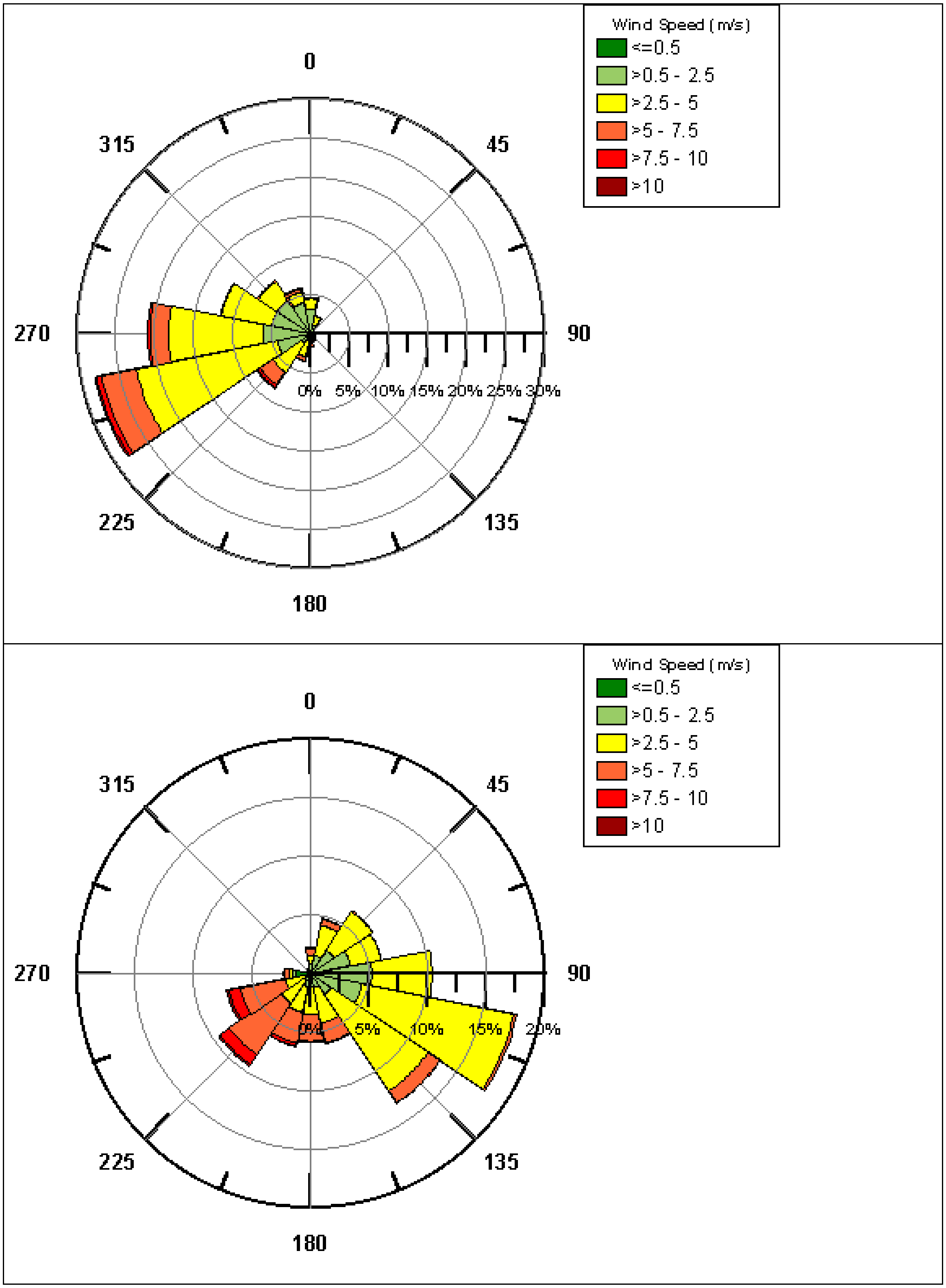


Figure 3-3. Windrose Diagrams for Palo Verde Site – May through September, 2001-2003
Top panel shows nighttime winds and bottom panel shows daytime winds.

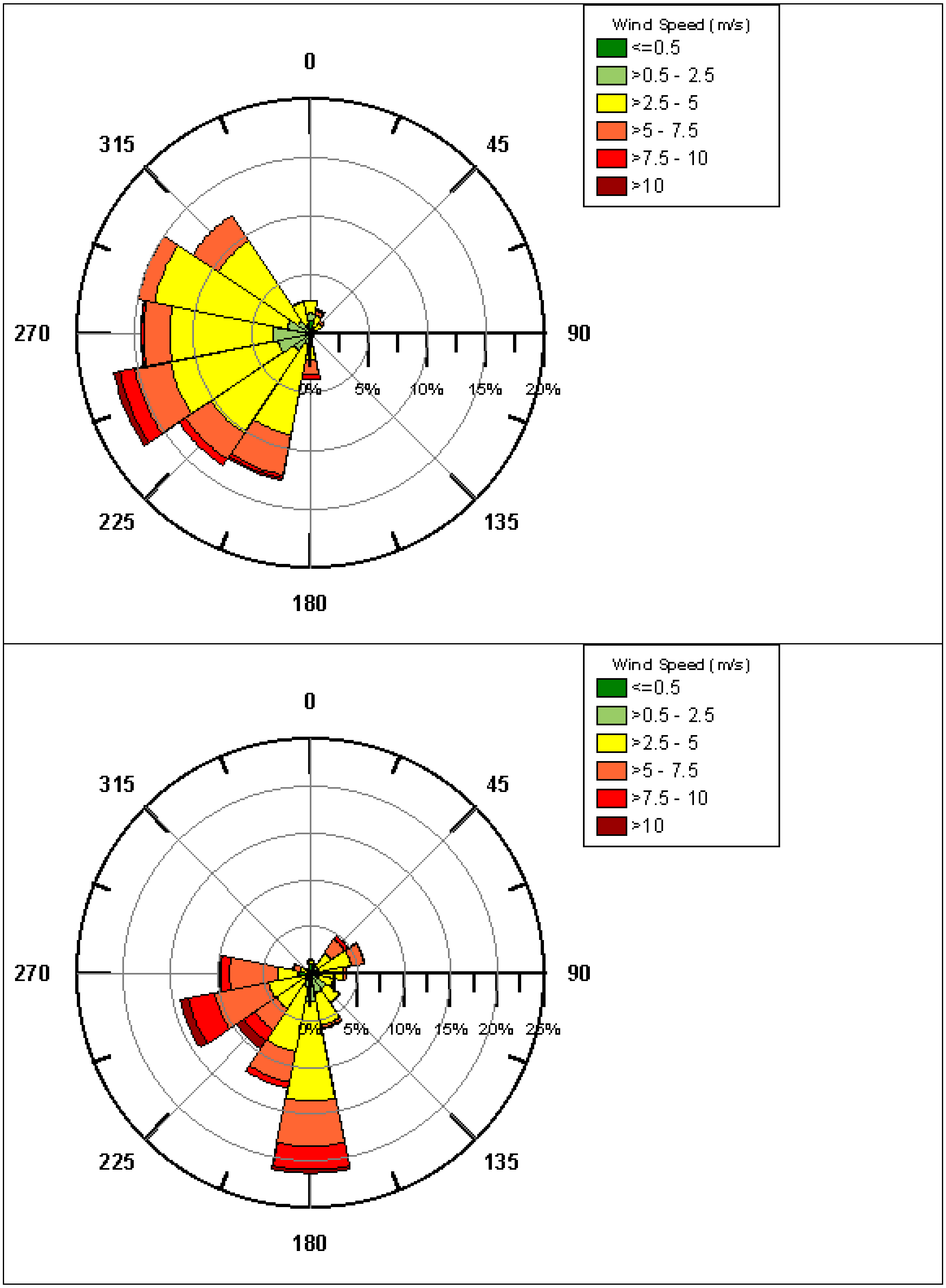


Figure 3-4. Windrose Diagrams for Jean Site – May through September, 2001-2003
Top panel shows nighttime winds and bottom panel shows daytime winds.

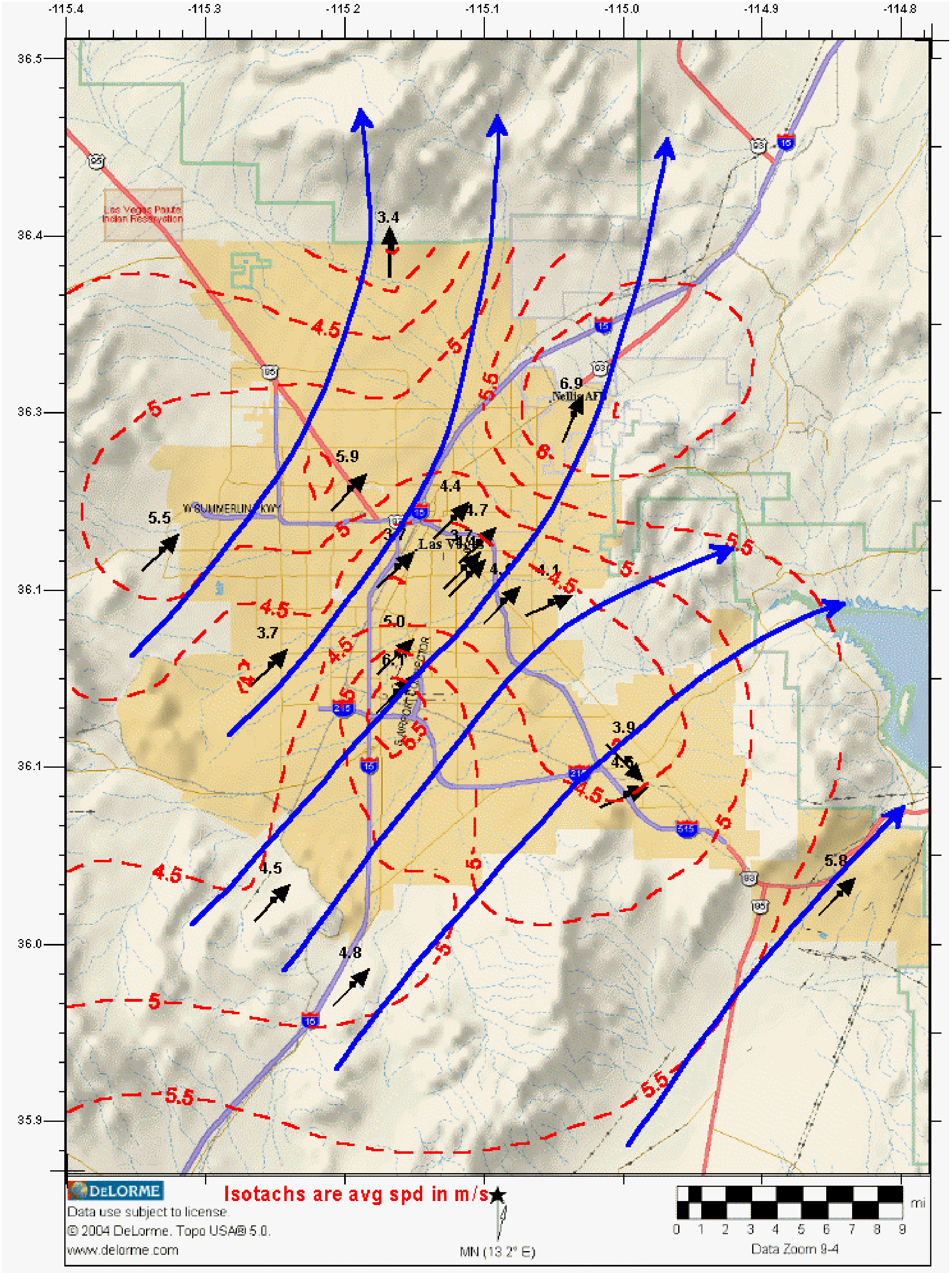


Figure 3-5. Las Vegas Valley Prevailing Winds at 18 PST

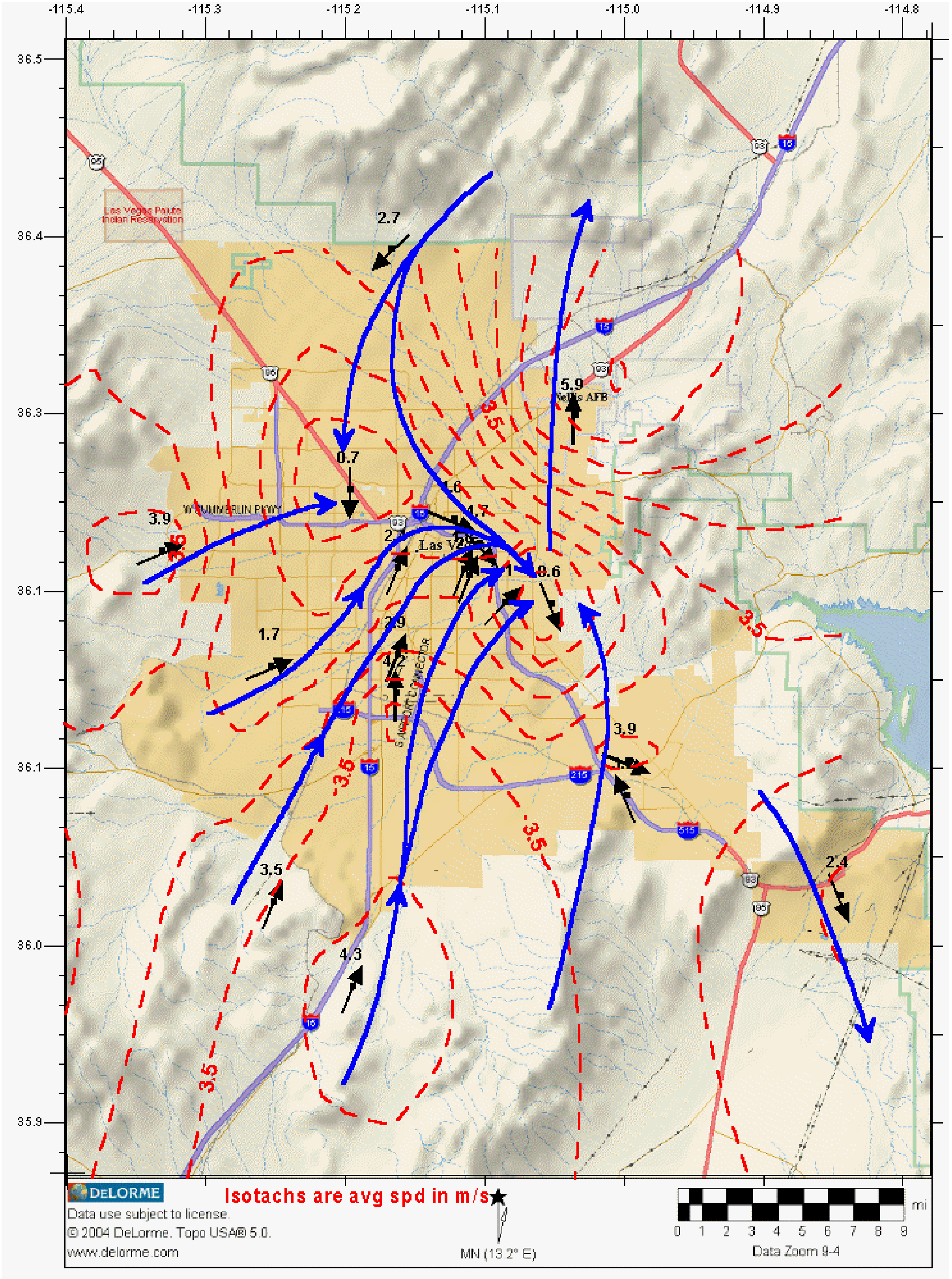


Figure 3-6. Las Vegas Prevailing Winds at 01 PST

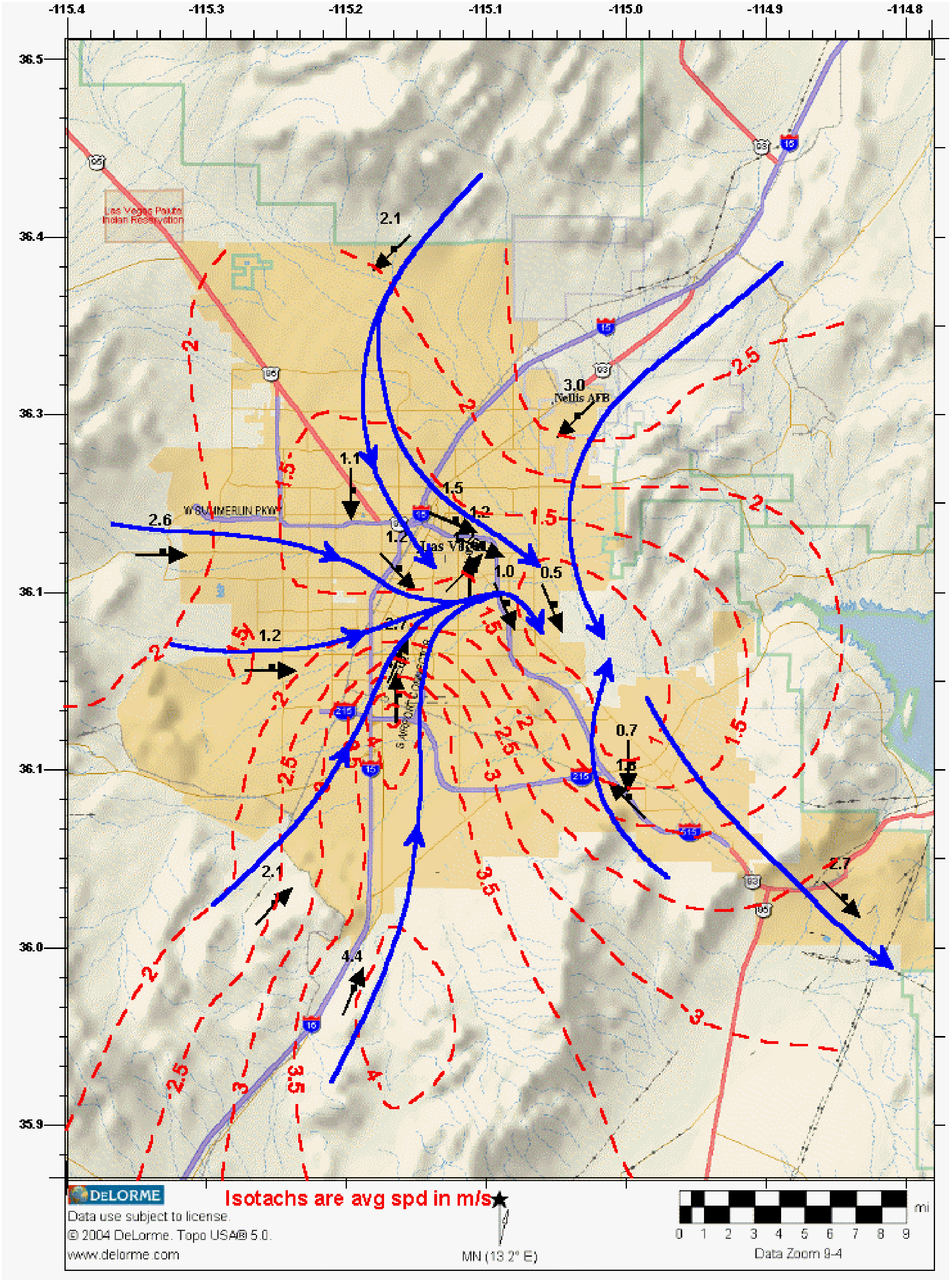


Figure 3-7. Las Vegas Prevailing Winds at 06 PST

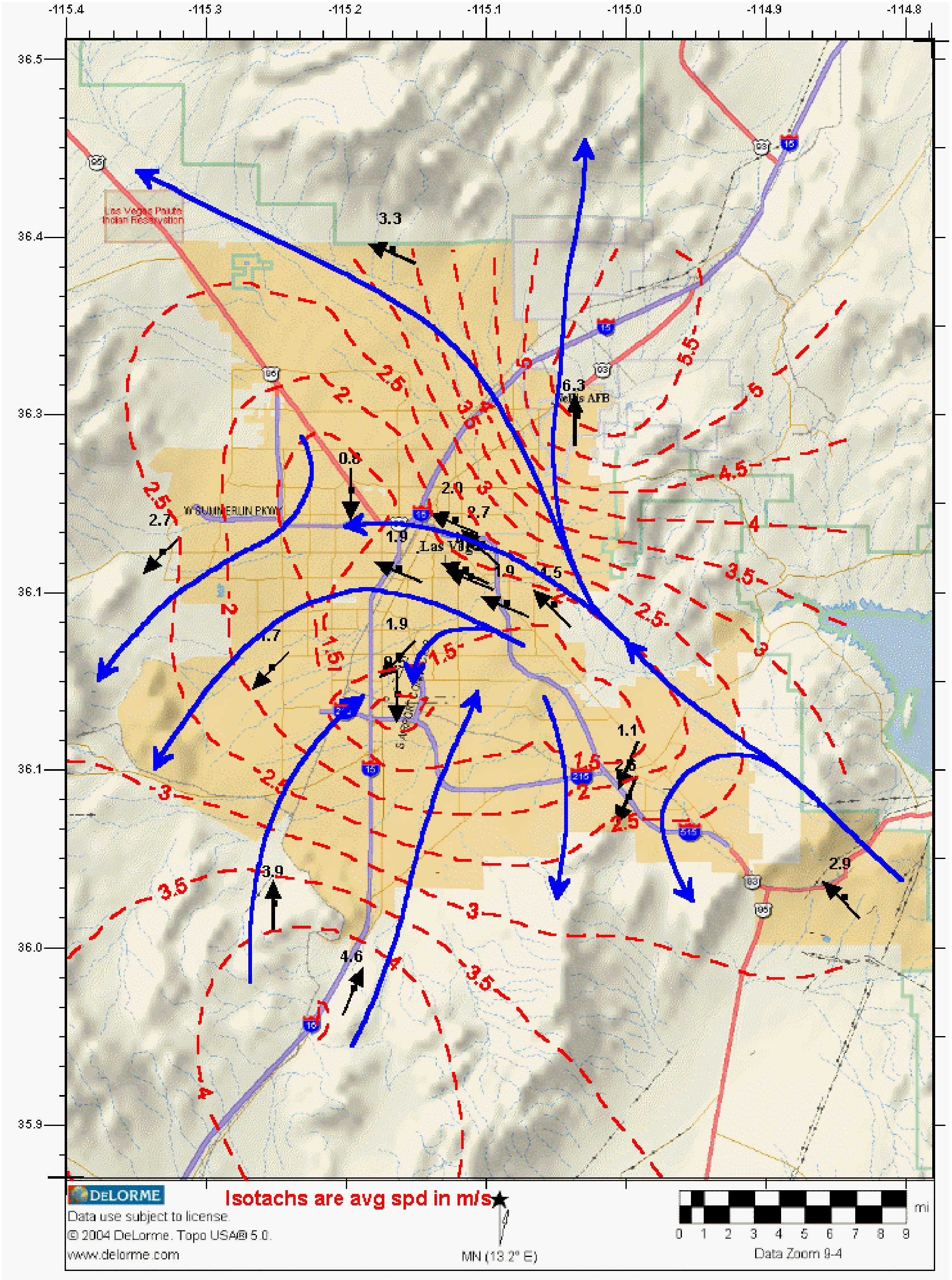


Figure 3-8. Las Vegas Prevailing Winds at 09 PST

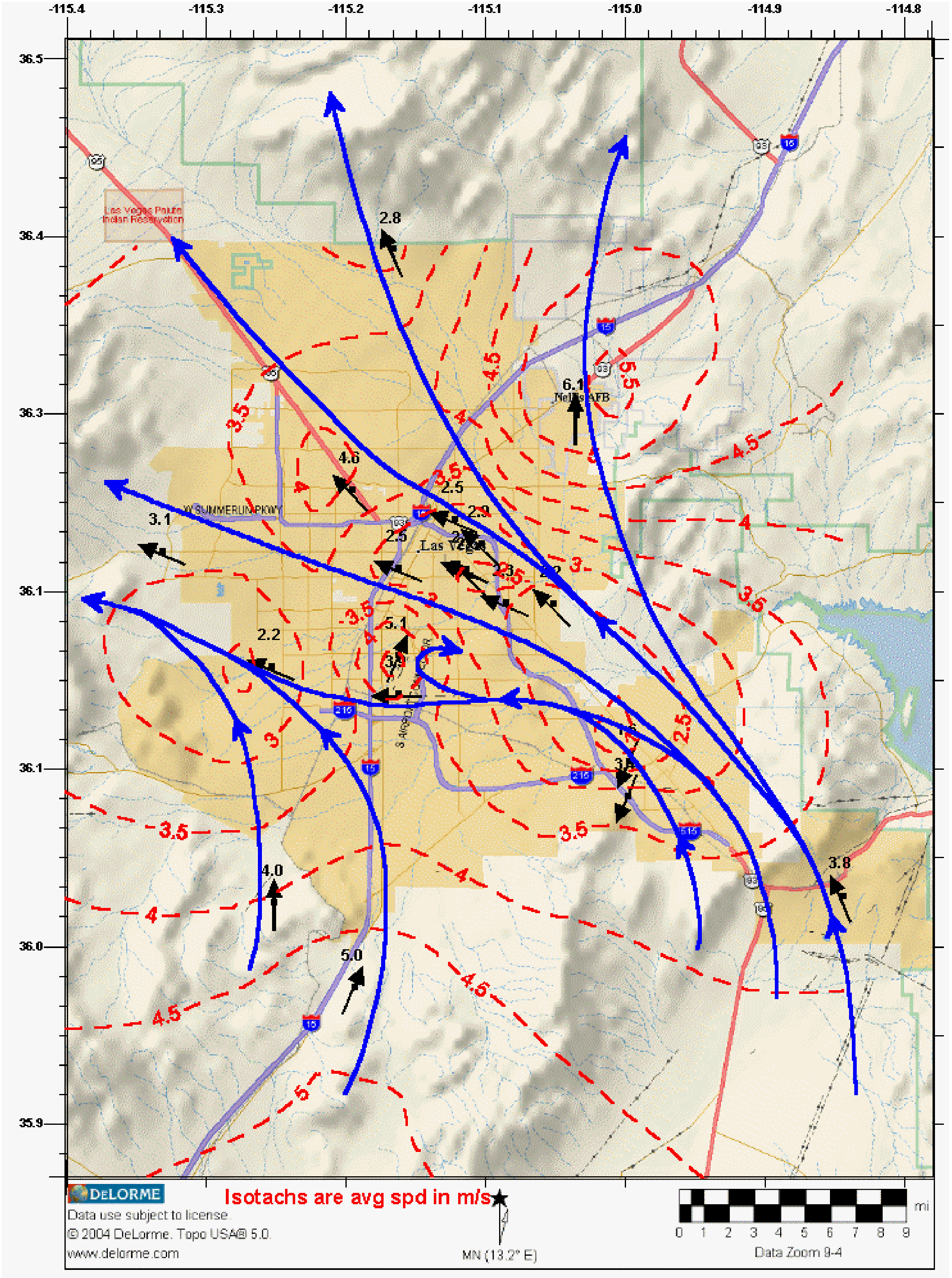


Figure 3-9. Las Vegas Prevailing Winds at 12 PST

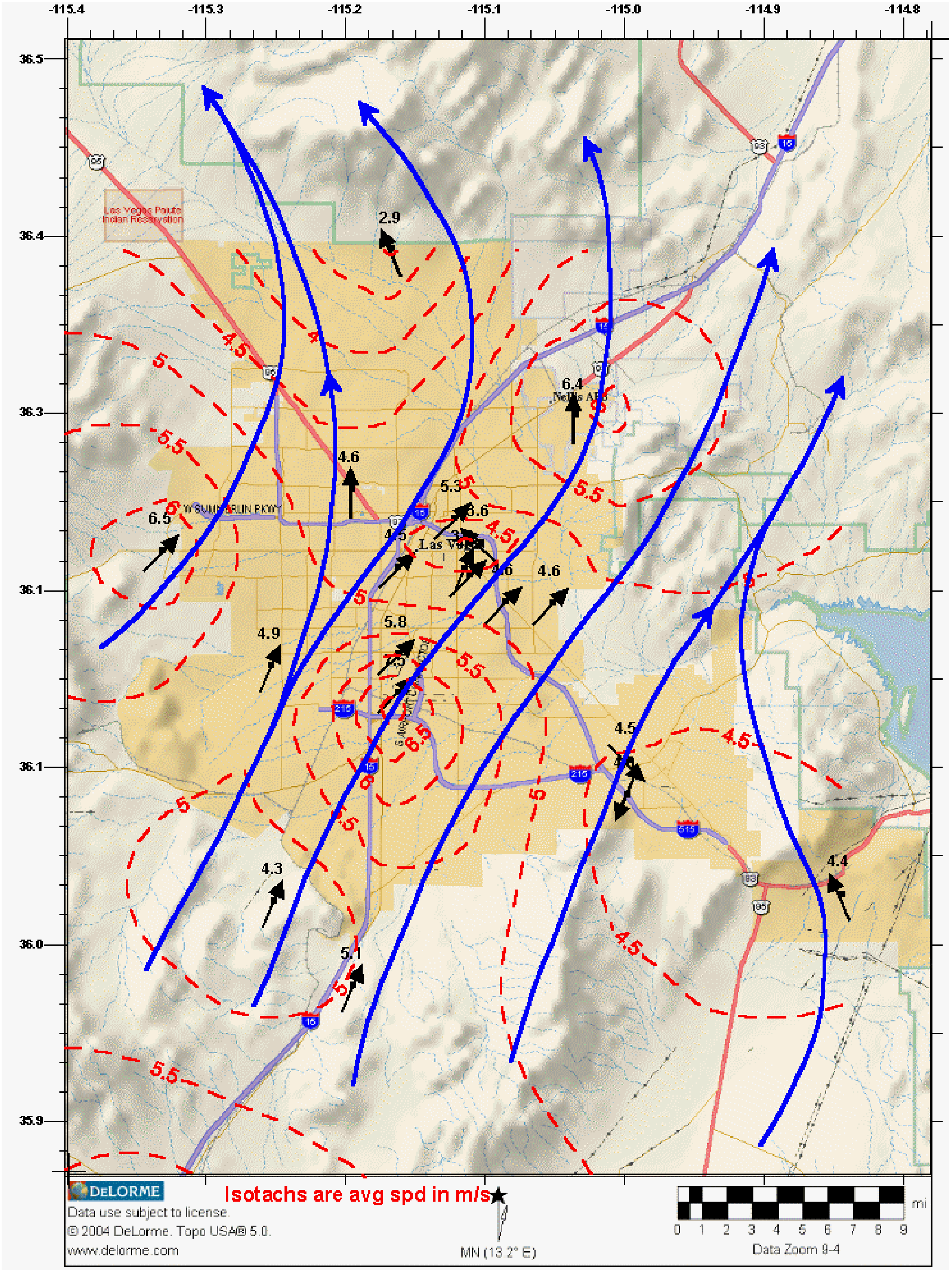
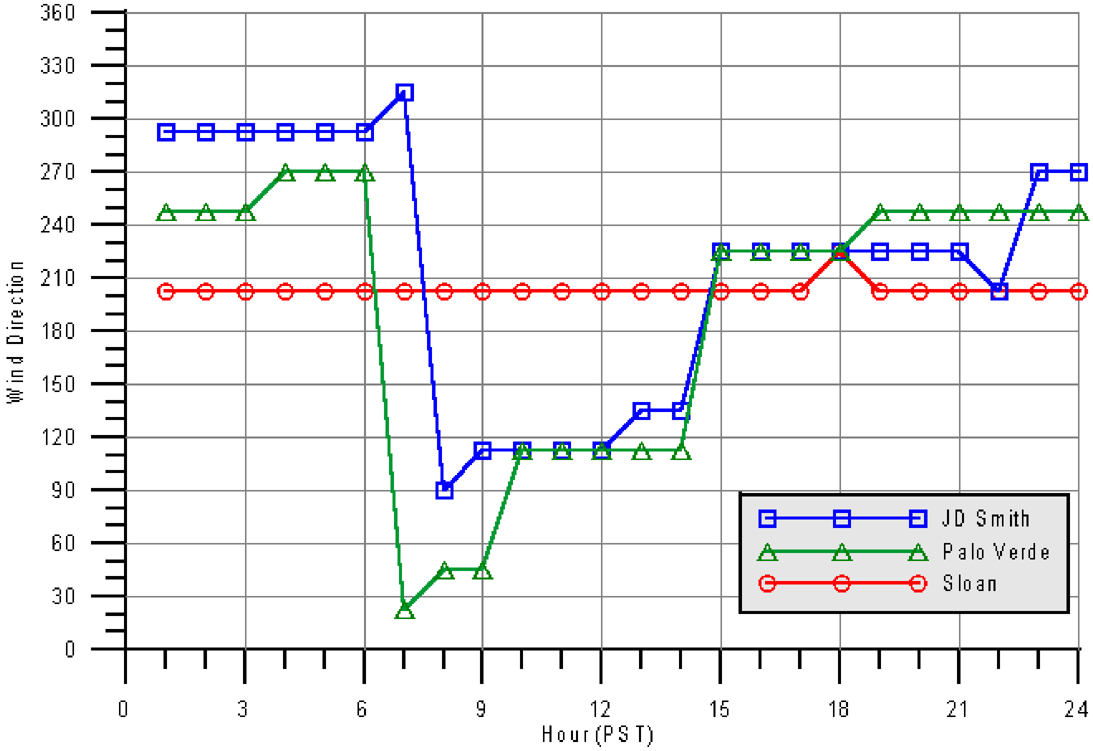


Figure 3-10. Las Vegas Valley Prevailing Winds at 15 PST



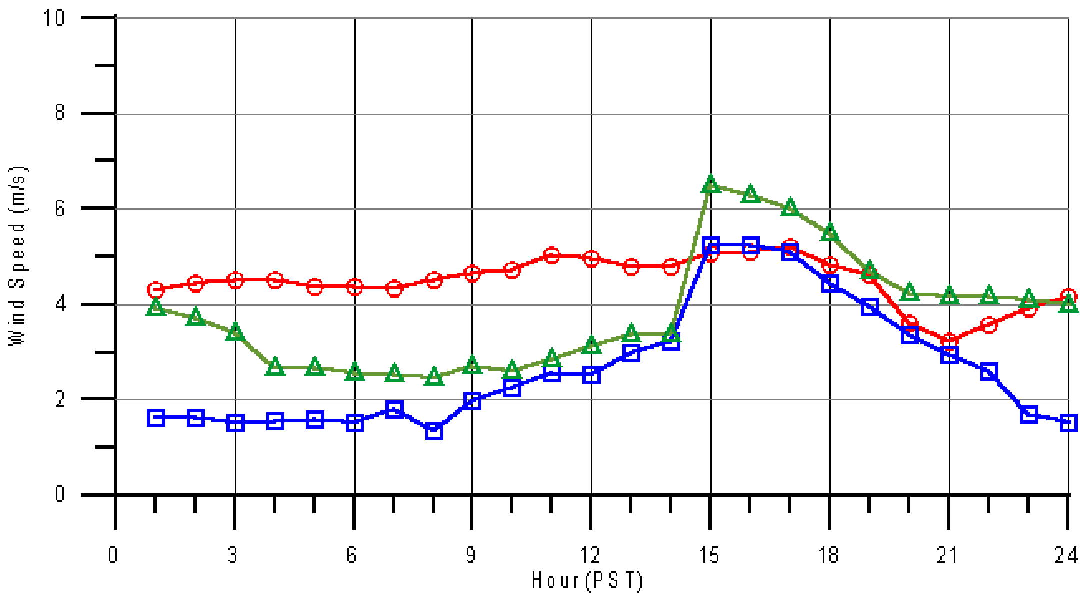


Figure 3-11. Diurnal Variation of Wind Direction (Top) and Speed (Bottom) at Select Sites

3.4 Upper-Air Meteorology

The only reliable upper-air meteorological measurement available was the National Weather Service (NWS) rawinsonde at Desert Rock, Nevada. Desert Rock (DRA) is located approximately 93 km northwest of Las Vegas in the southern end of the Nevada Test Site. Measurements (soundings) are made routinely twice daily at 00 GMT and 12 GMT (16 PST and 04 PST). Temperature, humidity, and winds are measured as a function of height.

Data were acquired for the 10-year period from 1994 through 2003. Soundings made during the warm months (May-September) were examined and are summarized statistically below. As complex terrain comprises southern Nevada, the representativeness of the lower boundary layer relative to the Las Vegas Valley is unknown. T&B Systems had an opportunity to make a rawinsonde measurement one day last summer at the DAQEM offices in downtown Las Vegas. This sounding was coordinated with the afternoon (00 GMT) observation at Desert Rock, thus offering a comparison.

3.4.1 Desert Rock Sounding Climatology

The ozone season (May 1 to October 31) was examined for the 10-year period. A summary of the 700 mb and 500 mb surfaces are provided in this section. The 700 mb pressure surface can, during periods of deep mixing, be within the boundary layer. To illustrate this point, **Table 3-4** lists the estimated maximum convective boundary layer for a 2-week period (June 2003) based on the DRA soundings. Typically, during this period, the 700 mb surface ranges between 3100 to 3200 m-msl. As can be seen from the data in Table 3-4, the 700 mb level is within the mixed layer on all days. Therefore, only the 500 mb information relates directly to synoptic-scale conditions whereas the 700 mb data is influenced significantly by local conditions as well.

Table 3-4. Maximum Mixing Heights During a 15-day Period at Desert Rock

DRA	700 mb Height	Boundary Layer Height
	MH(m-agl)	MH(m-msl)
15-Jun	3500	4509
16-Jun	2800	3809
17-Jun	3600	4609
18-Jun	4700	5709
19-Jun	3700	4709
20-Jun	3700	4709
21-Jun	1350	2359
22-Jun	2100	3109
23-Jun	2500	3509
24-Jun	2800	3809
25-Jun	3500	4509
26-Jun	3000	4009
27-Jun	3100	4109
28-Jun	3700	4709
29-Jun	>4500	>5500
30-Jun	3800	4809

The atmosphere is most stable on a synoptic-scale during mid-summer and dominated by high pressure. The 500 mb temperature and height averages by month for each year of the 10-year period at DRA are shown in **Table 3-5.** Peak temperatures and heights occur in July and August: -7.1°C and 5899 m, respectively.

Table 3-5. 500 mb Height and Temperature Statistics for Desert Rock, NV

Heights in meters

Year	May	June	July	August	September	October
1994	5727	5882	5916	5911	5844	5738
1995	5675	5784	5892	5895	5854	5806
1996	5759	5844	5915	5902	5813	5738
1997	5790	5787	5865	5889	5837	5760
1998	5680	5778	5901	5915	5795	5736
1999	5729	5811	5888	5873	5837	5835
2000	5782	5854	5888	5891	5840	5716
2001	5806	5853	5872	5916	5853	5815
2002	5737	5849	5924	5879	5818	5725
2003	5758	5825	5933	5904	5872	5832
Avg	5744	5827	5899	5897	5836	5770

Temperatures in °C

Year	May	June	July	August	September	October
1994	-15.0	-6.8	-7.0	-6.8	-10.1	-13.4
1995	-16.2	-11.7	-8.0	-5.6	-8.8	-10.2
1996	-12.3	-9.3	-6.4	-7.5	-9.0	-13.9
1997	-12.3	-9.8	-8.5	-7.7	-8.1	-12.1
1998	-15.7	-10.6	-7.1	-6.4	-9.4	-13.0
1999	-13.5	-9.9	-7.1	-8.2	-8.8	-10.4
2000	-10.9	-8.7	-7.9	-7.7	-8.2	-15.0
2001	-11.9	-8.5	-8.1	-6.5	-8.6	-10.9
2002	-14.1	-7.9	-6.5	-7.7	-10.1	-14.6
2003	-13.1	-9.3	-6.2	-6.6	-7.4	-9.0
Avg	-13.5	-9.2	-7.3	-7.1	-8.9	-12.2

Although there were year-to-year variations in the monthly averages, July or August were always the most stable months over the seasonal cycle. Peak monthly average 500 mb temperatures were experienced in August 1995 (-5.6°C) and July 2003 (-6.2°C). The daily medians, extremes, and quartiles are given in **Table 3-6.** Noteworthy is that six of the ten warmest 500 mb temperatures occurred during July of 1998 and 1999. The warmest 500 mb temperature (-1.5°C) occurred on September 19, 2000. The minimum temperature measured was -29.3°C on October 26, 1996. Cold temperatures of this magnitude are typically measured during extreme winter storm events.

Table 3-6. Daily Sounding Statistics for Desert Rock, May to October 1994 to 2003

	500 mb Height (m)	500 mb Temperature (°C)
Min.	5454	-29.3
1st Quartile	5782	-11.5
Median	5850	-8.8
3rd Quartile	5896	-7
Max	6016	-1.5

The wind direction and speed distribution over the 10-year period for both 700 mb and 500 mb levels are shown on **Figure 3-12**. The prevailing wind direction at 700 mb is south-southwest. Winds were from the southwest quadrant on 50 percent of the soundings. Wind speed was generally light to moderate. Winds were greater than 20 m/s on less than 1 percent of the soundings. The winds exhibited more variability at 500 mb. The prevailing wind direction was southwest with a secondary prevailing direction of west-southwest. Speeds were generally higher at 500 mb than at 700 mb--in excess of 20 m/s over 9 percent of the time.

The so-called monsoon season occurs during July and August. Monsoon periods are characterized by a low-level fetch from the Sea of Cortez that causes extensive cloudiness, atmospheric instability, and showery precipitation. Hence, the winds of this two-month subset were examined separately. Wind roses at 700 mb and 500 mb during July-August are shown on **Figure 3-13**. The winds during the monsoon period are much the same as over the entire ozone season and differences in the wind statistics are difficult to discern. At 700 mb, winds from the SW quadrant are even more persistent than for the ozone season (62 percent). The wind at 500 mb is again more variable than at 700 mb, and is somewhat more westerly than over the entire ozone season. Prevailing wind direction is west-southwest during the monsoon months as opposed to southwest over the 6-month ozone season.

Due to the occurrences of monsoon events in July and August, it was expected that low-level humidities would be increased with respect to the other months that comprise the ozone season (May, June, September and October). However, significant differences in the overall statistics for the two periods are not evident. The frequency of southwesterly winds during July and August is increased relative to the remainder of the ozone season. Correspondingly, winds with a northerly component are decreased. However, high humidity was associated with all wind directions. Relative humidity (RH) wind roses for the 700 mb heights are shown on **Figure 3-14.** In this type of diagram, RH is plotted instead of wind speed. The left panel shows the statistics for July and August whereas the right panel gives statistics for the other four months. The percentage of RH readings exceeding 60 percent RH is surprisingly the same. Without determining the actual frequency of occurrence at Desert Rock, it is assumed that monsoon conditions are relatively infrequent.

3.4.2 Las Vegas versus Desert Rock Sounding

The purpose of the sounding conducted on June 18 was to assess if the sounding, specifically the Las Vegas Valley, performed on a routine basis at Desert Rock is representative of conditions in Clark County where our ozone analysis is focused. While only a single sounding was conducted, it does provide the first step in assessing the usability of the large database of information available from the routine measurements collected by the National Weather Service (NWS).

The Las Vegas rawinsonde was taken from the County Government Center. The NWS site at Desert Rock is about 93 km (58 miles) to the northwest and about 417 m (1368 feet) higher in elevation than the Clark County sounding site. This elevation and distance difference is expected to produce differences in the first few hundred meters above ground level, but above that initial surface layer, we would hope that the temperature data from the two sounding locations would match reasonably well.

Figure 3-15 shows the sounding data collected. The NWS data is shown as "X" and our data is shown as a continuous line. It should be noted that the data resolution, or the amount of data reported, from our rawinsonde system is much finer, with significantly more data points than that reported from the NWS soundings. The NWS soundings report "significant levels" which is intended for an analysis of general weather patterns. As a consequence, the spacing between the data points from the NWS data can be from only a few 10s of meters to 100s of meters. Data from our system reports at intervals of about 5 to 10 meter increments. The overall profile reported from the NWS sounding does provide the resolution needed for our calculation of mixing height. The key for our analysis is how well the profile collected from Desert Rock represents the profile collected at the Clark County site. It is clear from the plot in Figure 3-13 that the data collected at the Desert Rock site in the first several kilometers (~10,000 ft) above ground level closely matches the sounding taken at the Clark County location. The only exception may be reported values from Desert Rock in the first 10s of meters above ground level where the profile will be different due to the differences in ground elevation between the sites and the strong surface heating that occurs within this layer. The primary shortcoming of the DRA sounding is the missing information between the surface height and DRA and Valley floor.

Based on the sounding performed, the observed temperature profiles between the Desert Rock and Clark County sites were very similar above the initial surface layer. This initial surface layer is only a few 10s of meters thick, with values above this layer showing minimal differences in the first several thousand meters of altitude. This similarity gives us much more confidence in using the database of information from Desert Rock to help analyze the mixing properties and related ozone concentrations within the Clark County region.

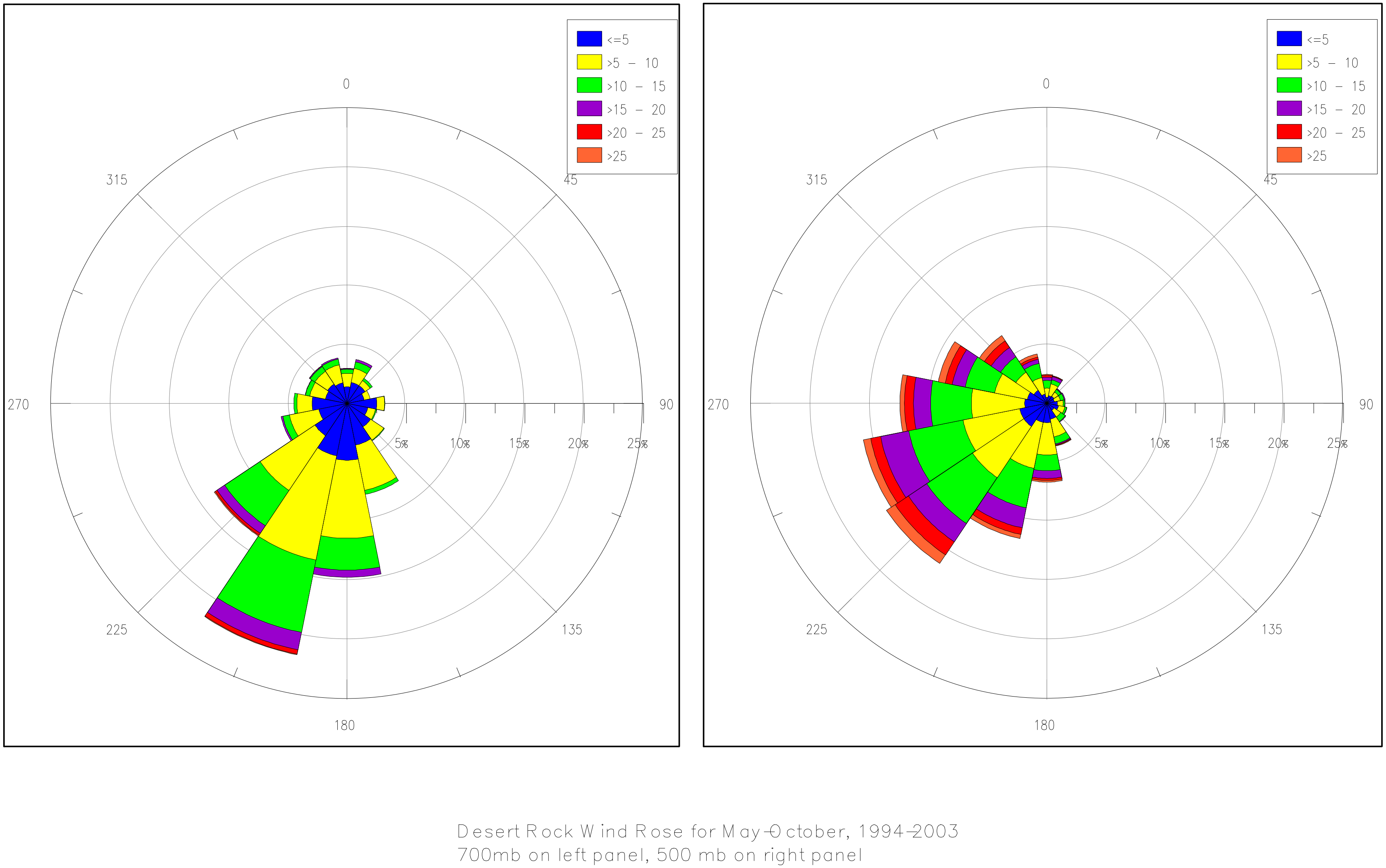
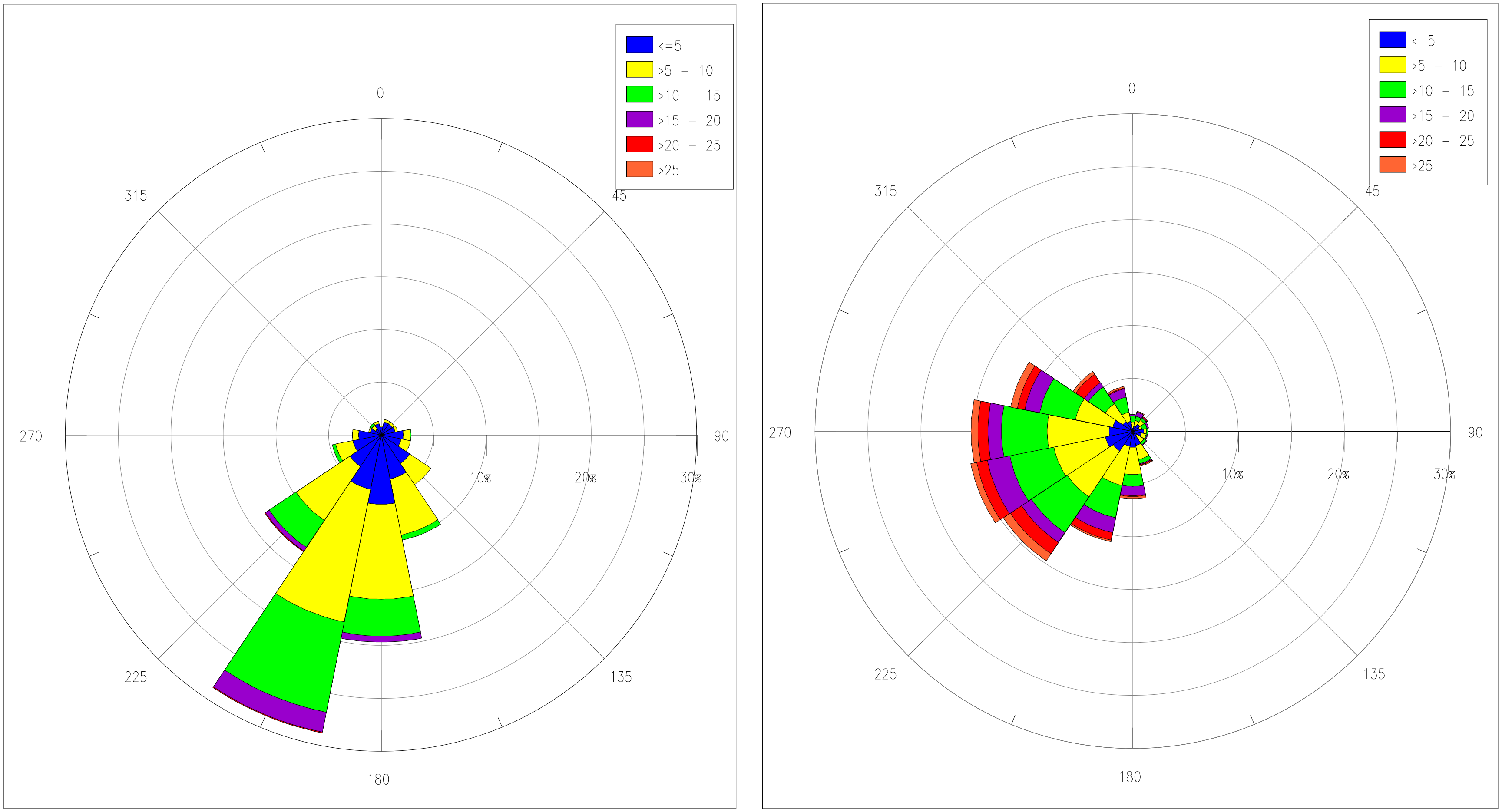


Figure 3-12. Desert Rock Wind Rose for May – October 1994-2003 (700 mb on left panel, 500 mb on right panel)



Desert Rock Wind Rose for July-August, 1994-2003
700mb on left panel, 500 mb on right panel

Figure 3-13. Desert Rock Wind Rose for July – August 1994-2003 (700 mb on left panel, 500 mb on right panel)

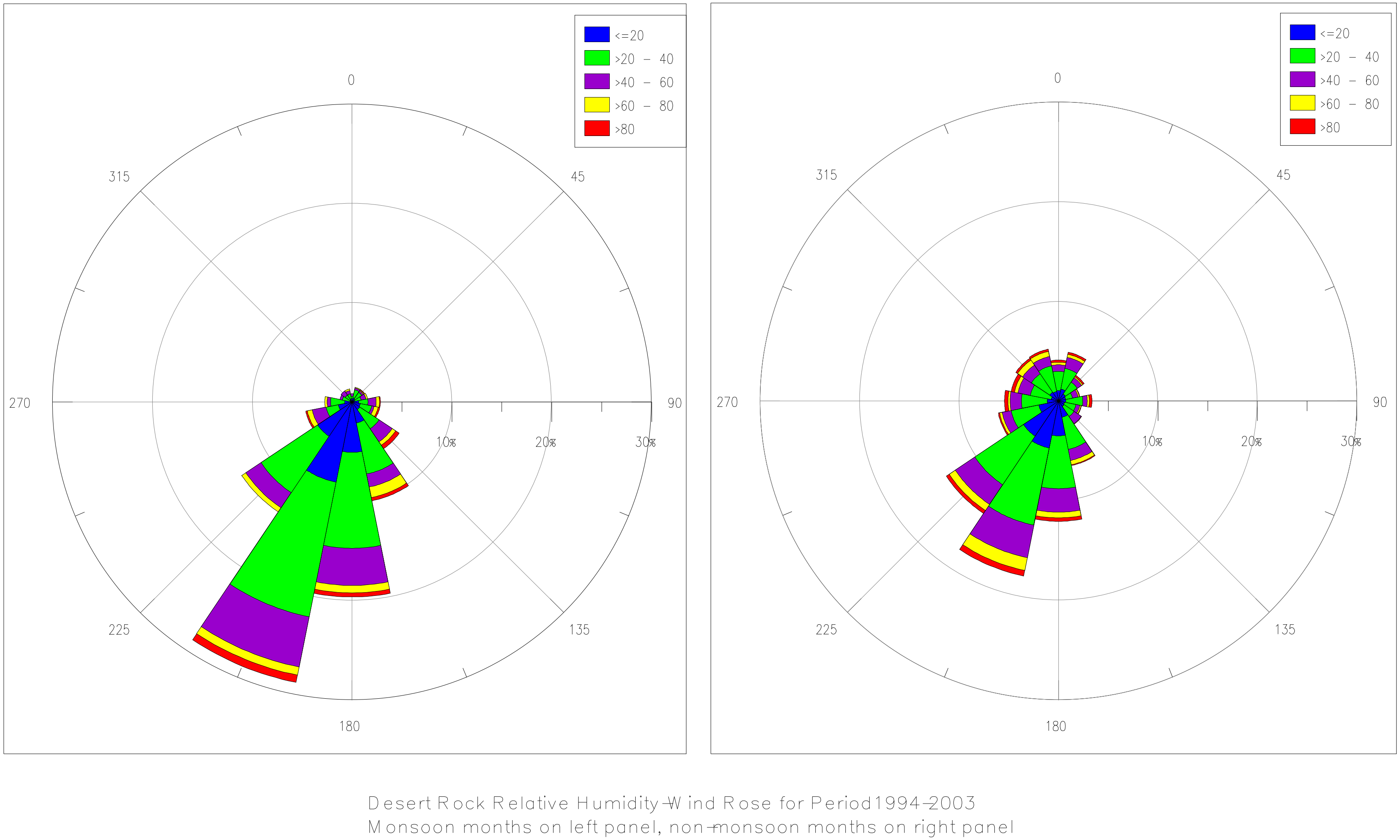


Figure 3-14. Desert Rock Relative Humidity-Wind Rose for Period 1994-2003
(Monsoon months on left panel, non-monsoon months on right panel)

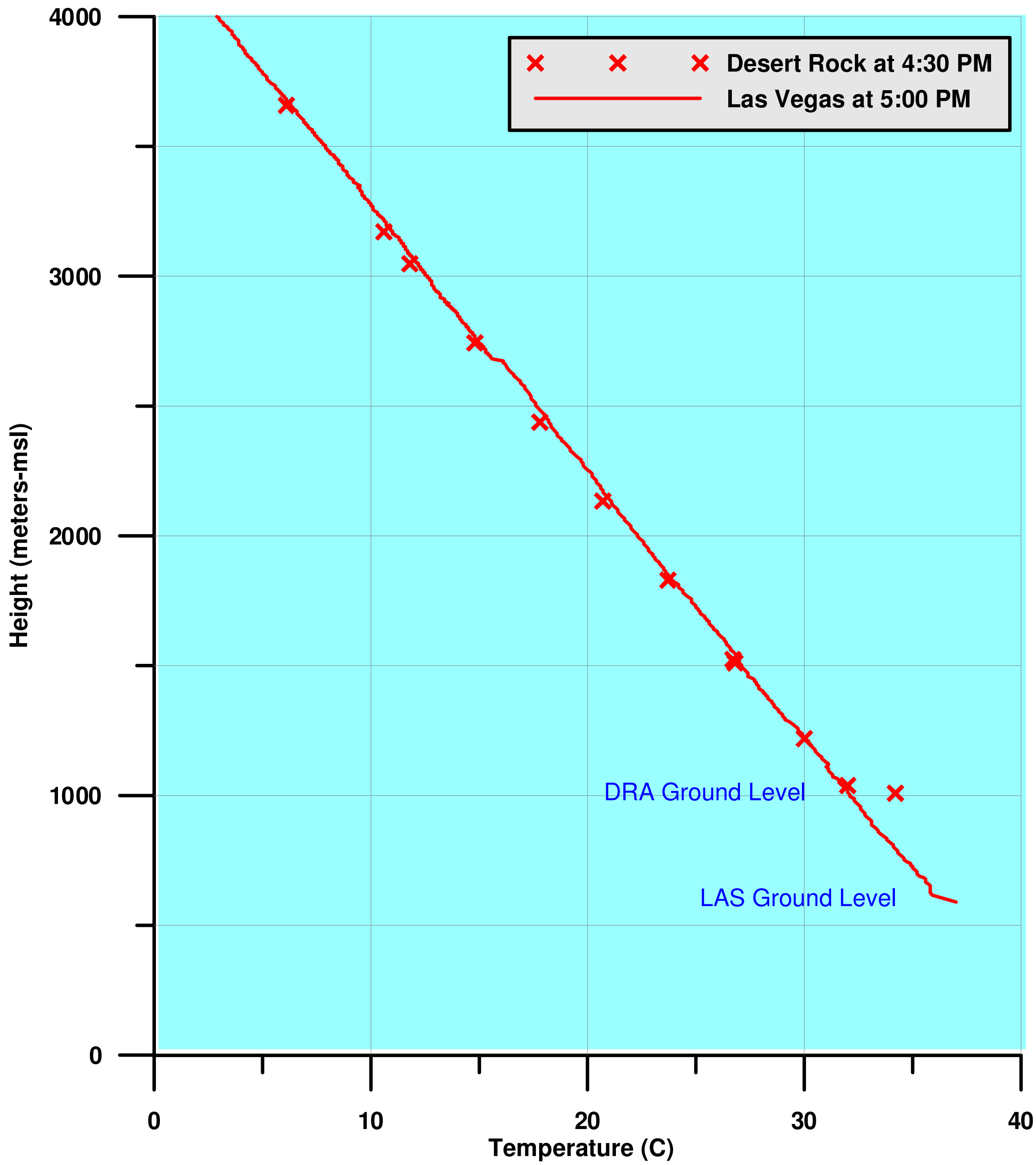


Figure 3-15. Sounding Plot Showing the Desert Rock and Clark County Offices (shown as LAS) Soundings

4. CART ANALYSES

4.1 Methodology

CART® (Classification and Regression Trees) is a robust, easy-to-use decision tree tool that automatically sifts large, complex databases, searching for and isolating significant patterns and relationships. Decision rules are derived from statistical relationships found between response (target) variables and predictors that minimize the variance in a training database. The key elements of a CART analysis are a set of rules for:

- splitting each node in a tree into "child" nodes;
- deciding when a tree is complete; and
- assigning each terminal node to a class outcome (or predicted value for regression)

To split a node into two child nodes, CART always asks questions that have a "yes" or "no" answer. For example, the question might be: is the maximum temperature <= 100 ^{o}F?
The CART splitting rule is to look at all possible splits for all variables included in the analysis. For example, consider a data set with 215 cases and 19 variables. CART considers up to 215 times 19 splits for a total of 4085 possible splits. Any problem will have a finite number of candidate splits and CART will conduct a brute force search through them all.

CART's next activity is to rank order each splitting rule on the basis of a quality-of-split criterion. The default criterion used in CART is essentially a measure of how well the splitting rule separates the classes contained in the parent node.

Once a best split is found, CART repeats the search process for each child node, continuing recursively until further splitting is impossible or stopped. Splitting is impossible if only one case remains in a particular node or if all the cases in that node are exact copies of each other (on predictor variables). This becomes the "terminal" node. Figure 4-1 is an example of a CART decision tree. Splitting decisions are presented in the blue boxes, with terminal nodes identified by red boxes.

The initial step in the CART process was to assemble a database containing parameters that potentially have effects on ozone concentrations within Clark County (predictors). Also at this time, the target parameters have to be chosen. For the purposes of ozone forecasting, the obvious target is whether or not there is an exceedance. Several studies using CART have used measured concentrations at individual sites as individual target variables. However, given the relatively small number of exceedances in Clark County, it was determined that looking at the basin as a whole was both the most effective approach and most likely to produce meaningful results. Thus, the target variable chosen was the existence of an exceedance anywhere in the network. An exceedance was defined as a daily maximum 8-hour concentration greater than or equal to 85 ppb at any site. In the CART database, these exceedances were given a categorical value of "2". Additionally, daily maximum 8-hour concentrations between 80 and 85 ppb were given a categorical value of "1" to identify periods that easily could have become exceedance days. The remaining data (less than 80 ppb) were assigned a categorical value of "0", and are hereafter referred to as "non-exceedance days." In the terminal nodes of the CART decision trees presented on Figures 4-1 to 4-12, exceedance days are depicted as a green bar, near-exceedance days as a blue bar, and non-exceedance days as a red bar. The total number of cases for a given terminal node is presented as "W".

A significant portion of this effort was spent collecting and merging the candidate predictor variables into one database. **Table 4-1** presents the list of variables included. Particular emphasis was placed on variables that could potentially be predicted, allowing the decision trees to act as forecasting tools. Again, network-wide meteorological measurements have, in general, been averaged, partly because of the pooled strategy mentioned above and partly because basin-wide meteorology is in general easier to predict than conditions at a given site.

The actual running of a CART model is relatively fast – typically only taking about 15 seconds. Thus, CART model runs were conducted frequently throughout the effort as the data were assembled. Presented below are descriptions of 12 model runs that represent the overall approach used to conduct the CART analysis. The model runs are summarized in **Table 4-2**. Associated with each of the model runs discussed is a chart depicting the decision tree, presented as **Figures 4-1 through 4-12**. Note that when reviewing the decision trees a "true" response to the presented criteria branches to the left.

4.2 Results

Model 1. This model used all of the available variables over the period from 2000 though 2003. For this and all of the runs presented below, only data from May 20 through August 20 were used, since no exceedances have been recorded beyond these dates. Twenty-two exceedances were reported during the years 2000 through 2003, leaving 346 non-exceedance days. Data from these years were initially chosen because it was hoped that results from this period could be tested using the 1996 through 1999 data.

The results show the expected result that ozone exceedances on a given day are strongly dependent on how high the ozone gets the previous day. Beyond that, the model selects data from California desert locations for the previous day(s), implying a transport role. The apparent criterion involving lower ozone concentrations at Twentynine Palms is misleading. The decision only removes three non-exceedances, and is thus not particularly significant. Not apparent on the decision tree plot is the existence of one exceedance for both Node 3 and Node 11. If these are ignored, the model identifies 20 of the 22 exceedances, while misclassifying only 23 non-exceedance days. Seventeen of the exceedances fall into one node (Node 5).

Model 2. It is possible in the CART model to change the "cost" of misclassifying one category as another. For this analysis, it is more critical to differentiate between exceedance days and non-exceedance days than it is to differentiate between exceedance days and near exceedance days, or near-exceedance days and non-exceedance days. CART will initially come up with decisions that minimize the misclassification of any category (exeedance, near-exceedance or non-exceedance). This model was run with an increased "cost" for misclassifying exceedance days as non-exceedance days, and vice-versa, forcing the program to come up with decisions that, for example, minimize the number of non-exceedances that show up in an exceedance-dominated terminal node, at the expense (or cost) of allowing more near-exceedances to show up in that node. Results are even better than for Model 1, with all exceedances identified in only two nodes, and only 21 misclassified non-exceedances. Note again that the decision using the Twentynine Palms data is basically not needed – removing only 3 non-exceedance days.

Model 2 also shows a decision that frequently shows up as either a primary or secondary splitter – low afternoon surface wind speeds. The importance of this splitter is emphasized by noting that by using just two criteria (yesterday's maximum 8-hour average greater than 70 ppb and average afternoon wind speed less than 3 m/s) 18 of 22 exceedances and 19 of 38 marginal days are identified, while misclassifying only 38 of 308 non-exceedance days.

Model 3. The problem with Models 1 and 2 is that the variable used for the primary split (maximum 8-hour average from the previous day) may not be suitable for forecasting applications. The maximum 8-hour average likely will not be known until the evening, making distribution of forecast results for the next day problematic. Thus, for this run, Model 2 was again run, discounting the maximum 8-hour average variable, as well as the previous day's 24-hour averages for the transport sites. This forces the inclusion of other ozone variables, such as the peak 1-hour average, which should be typically known by 15 or 16 PST.

As can be seen, the number of misclassified non-exceedance days increases, but is still relatively low. Decisions are similar to the previous models, with high concentrations during previous days and low afternoon wind speeds. A new decision has emerged involving the wind direction at 10 PST, with ozone exceedances occurring when winds have a southeasterly component (category 2 and 3 – category 0 is 0° to 45°, category 1 is 45° to 90°, etc.). Only one of the 17 exceedances on this branch occurred during category 7 wind directions (315° to 360°), and one during category 0 directions. This is consistent with observations noted during independent detailed analysis of the meteorology during exceedance days.

Model 4. One of the outputs from the CART software is a table presenting "variable importance." The output for Model 1 is shown below:

Variable Importance

<table>
<tr><th>Variable</th><th>Score</th><th></th></tr>
<tr><td>MAX_____</td><td>100.00</td><td>||||||||||||||||||||||||||||||||||||||||||</td></tr>
<tr><td>T_ANOMALY</td><td>89.12</td><td>|||||||||||||||||||||||||||||||||||||</td></tr>
<tr><td>AVG_____</td><td>64.13</td><td>|||||||||||||||||||||||||||</td></tr>
<tr><td>MAX_1HR__1</td><td>60.92</td><td>|||||||||||||||||||||||||</td></tr>
<tr><td>OZONE_15__1</td><td>57.02</td><td>||||||||||||||||||||||||</td></tr>
<tr><td>AVG_MAX_1HR__1</td><td>44.18</td><td>||||||||||||||||||</td></tr>
<tr><td>DEATH_VALLEY_AVG__1</td><td>40.82</td><td>|||||||||||||||||</td></tr>
<tr><td>DEATH_VALLEY_AVG__2</td><td>40.56</td><td>||||||||||||||||</td></tr>
<tr><td>DR500_RH_11</td><td>31.94</td><td>|||||||||||||</td></tr>
<tr><td>WS_AFT</td><td>31.35</td><td>||||||||||||</td></tr>
<tr><td>TRONA_AVG__2</td><td>28.54</td><td>|||||||||||</td></tr>
<tr><td>TRONA_AVG__1</td><td>27.06</td><td>|||||||||||</td></tr>
<tr><td>TYPE_23$</td><td>26.14</td><td>||||||||||</td></tr>
<tr><td>TYPE_11$</td><td>26.14</td><td>||||||||||</td></tr>
<tr><td>BARSTOW_AVG__1</td><td>24.73</td><td>||||||||||</td></tr>
<tr><td>JOSHUA_TREE_AVG__1</td><td>22.34</td><td>|||||||||</td></tr>
<tr><td>DR700_WD_11</td><td>20.88</td><td>||||||||</td></tr>
<tr><td>_9_PALMS_AVG__1</td><td>20.76</td><td>||||||||</td></tr>
<tr><td>DR500_WD2_23</td><td>19.34</td><td>|||||||</td></tr>
<tr><td>DR700_T_11</td><td>16.85</td><td>||||||</td></tr>
<tr><td>T_12</td><td>16.61</td><td>||||||</td></tr>
<tr><td>DEATH_VALLEY_O3_MAX__1</td><td>16.43</td><td>||||||</td></tr>
<tr><td>DR700_WD_23</td><td>16.37</td><td>||||||</td></tr>
<tr><td>T_MAX</td><td>15.95</td><td>||||||</td></tr>
<tr><td>DR500_WD2_11</td><td>13.39</td><td>|||||</td></tr>
<tr><td>TWENTY_NINE_PALMS_O3_MAX__1</td><td>13.36</td><td>|||||</td></tr>
<tr><td>DR500_T_23</td><td>13.03</td><td>|||||</td></tr>
<tr><td>_9_PALMS_AVG__2</td><td>11.80</td><td>||||</td></tr>
<tr><td>DR700_T_23</td><td>11.51</td><td>||||</td></tr>
<tr><td>DR700_WS_23</td><td>11.30</td><td>||||</td></tr>
<tr><td>WS_16</td><td>8.75</td><td>|||</td></tr>
<tr><td>DR700_HT_11</td><td>8.49</td><td>|||</td></tr>
<tr><td>WS_10</td><td>7.75</td><td>||</td></tr>
<tr><td>DR500_T_11</td><td>7.75</td><td>||</td></tr>
</table>

Variable	Score	
WD_16	7.38	||
DR500_HT_11	7.09	||
MOJAVE__2	6.07	||
JOSHUA_TREE_AVG__2	4.15	|
DR500_WS_11	0.59	
DR500_WD_23	0.29	
DR700_RH_23	0.00	
T_DIFF	0.00	
RR_RH_AFT	0.00	
RR_RAD_AFT	0.00	
MOJAVE__1	0.00	
DR700_HT_23	0.00	
DR500_WS_23	0.00	
DR500_RH_23	0.00	
DR500_HT_23	0.00	
VICTORVILLE_AVG__1	0.00	
DR700_WS_11	0.00	
DR700_RH_11	0.00	
VICTORVILLE_AVG__2	0.00	
BARSTOW_O3_MAX__1	0.00	
DR500_WD_11	0.00	
JOSHUA_TREE_O3_MAX__1	0.00	
TRONA_O3_MAX__1	0.00	
WD_10	0.00	
BARSTOW_AVG__2	0.00	
T_MAX_NORM	0.00	
CLOUDS	0.00	
SOLAR	0.00	
DR700_WD2_11	0.00	
JULIAN_DAY	0.00	
DR700_WD2_23	0.00	
WD2_10	0.00	
WD2_16	0.00	
DAY_OF_WEEK	0.00	
DATE	0.00	

Many of the variables have an indicated importance of “0.00”. Note, however, that several of the “unimportant” variables frequently show up in the decision tree, so determining the unimportance of a given variable was also based on results from test runs.

Model 1 was run again after removing several “unimportant” variables. The model does a good job of identifying all of the exceedances, with only 13 misclassified non-exceedance days. However, the decision tree is complicated, presenting the possibility that the decisions, while mathematically correct for the given data set, may not be applicable in the real world. This decision tree should be compared against the 2004 data set to see how well it stands up.

Model 5. One of the sets of data that showed up as being of relatively low importance was the 500 mb data for 2300Z. Model 4 was rerun with this data removed. Results show a slight improvement over the Model 4 results. In particular, by ignoring the one exceedance in Node 15, there are 21 exceedances identified, with only 8 misclassifications of non-exceedance days. Note also that if decision Nodes 6, 7 and 8 are removed, 20 of 22 exceedance days are identified while only misclassifying 10 non-exceedance days, using 8 variables and 9 decisions.

Model 6. In the results for Model 5, only the Trona transport site data shows up in the decision tree criteria. For this model, the role of transport was further investigated by removing all transport site data and rerunning Model 5. This seems to have had a slight detrimental effect on the results, with more misclassified non-exceedance days.

Model 7. One of the conclusions from the independent project effort to classify the ozone season days by weather type was that the 700 mb data was much more important for performing the classifications than the 500 mb data. Thus, for this model, Model 6 was rerun after removing all remaining 500 mb data. Overall, this did not improve results. However, it is interesting to note that 17 of the 22 exceedances can be identified using just three variables (daily 1-hour maximum, afternoon wind speed, and the 700 mb temperature).

Model 8. As mentioned above, it was hoped that the 1996 through 1999 data could be used to validate results from the above model runs. Results from this validation effort were not encouraging. After further review, it was decided that the data collected from 1996 through 1998, when the network was still under development and many of the current sites were non-existent, were different enough from the 1999 through 2003 data to make such validation questionable. However, no reason could be seen for excluding the 1999 data from the analysis. Thus, CART models were run incorporating the 1999 data to assure the use of all available data. For the 1999 through 2003 period, there were 27 exceedance days and 430 non-exceedance days. Model 8 is a rerunning of Model 2 (all variables) with the new data set. Results are not as good as for Model 2.

Model 9. Similar to Model 3, this is a rerunning of Model 8 after removing the previous day's maximum 8-hour average, as well as the previous day's average concentrations for the transport sites, from consideration. Again, results are not quite as good as they were when just the 2000 through 2003 data were used, with a noticeably higher number of misclassified non-exceedance days. The model includes several decisions that do not immediately seem relevant, using variables such as the normal maximum temperature.

Model 10. This Model 9 run without the 500 mb data. The number of misclassified non-exceedance days remains higher than the similar run using the 2000 to 2003 data.

Model 11. This is Model 10 run without transport sites and several "unimportant" variables. Contrary to the trend, this model has noticeably better results than its 2000 to 2003 counterpart (Model 7), though the number of decisions may be high. However, the fact that all but one of the exceedances fall into just three nodes implies that there may be some validity to the decisions.

Having explored several different model scenarios, a final set of models was run using only parameters that showed up in the CART trees for the most successful runs. Emphasis was placed on using the parameters preferred for Models 9 and 11, as they were particularly successful and used the longer-term database (1999 to 2003). Not all parameters that showed up in the decision trees were used. An effort was made to remove parameters that resulted in decisions that seemed contrary to conditions associated with the formation and transport of ozone. For example, in Model 9, there would seem to be no logical reason why the normal maximum temperature would play any role in the resulting concentrations on any given day. As with Models 9 and 11, the "cost" for differentiating between exceedance days and non-exceedance days was increased.

The decision tree for **Model 12**, showing the CART decision tree of the most successful of these final runs, is presented in Figure 4-12. A complete breakdown of the results for each of the displayed terminal nodes is also present in **Table 4-3**. As shown in Table 4-3, all 27 of the exceedances fall into four terminal nodes, while misclassifying only 22 non-exceedance days. However, in reviewing the decision tree, it would seem to make sense to simplify the decision tree in the following ways; First, the Node 4 decision could be eliminated, primarily because it is not obvious why drier afternoon conditions would result in fewer exceedances. Eliminating this decision node reduces the terminal nodes with exceedance to three. While the excellent results of Terminal Node 3 are somewhat diluted, the resulting node results are still good, and the existence of several near-exceedance days is further acknowledged. Second, a previous CART run showed a possibly more relevant decision for Node 9. Using the decision "Ozone 15_1<=101.5", virtually all of the non-exceedance days are identified in Terminal Node 9, leaving one exceedance along with one non-exceedance in Terminal Node 10.

4.3 Summary

Employing the above changes, the resulting decision tree classifies all 27 exceedances in three nodes while misclassifying 29 non-exceedance days, using seven parameters. These three scenarios are summarized below:

Scenario 1

- The 15 PST regional ozone reading from the previous day greater than 68.5 ppb
- The regional afternoon wind speed less than 2.5 m/s
- The 23 GMT 500 mb RH less than 39.8%

The majority of the exceedanes fall into this case. As with all of the cases, relatively high ozone readings on the previous day are critical. Low afternoon wind speeds and dry conditions as evidenced by low relative humidity aloft create the classic ozone conditions.

Scenario 2

- The 15 PST regional ozone reading from the previous day greater than 68.5 ppb
- The regional afternoon wind speed greater than or equal to 2.5 m/s
- The 11 GMT 700 mb RH between 14.5 and 21%
- The 11 GMT 500 mb RH less than or equal to 21.3%
- Maximum 1-hour ozone concentration at Joshua Tree for the previous day greater than 86.5 ppm

If afternoon wind speeds are higher, transport appears to play a critical role. Consistent with this, the atmospheric conditions during the morning appear to increase in importance. Still lower relative humidity conditions are also important, though Node 8 implies that extremely dry conditions may not be conducive to high ozone concentrations.

Scenario 3

- The 15 PST regional ozone reading from the previous day greater than 101.5 ppb
- The regional afternoon wind speed greater than or equal to 2.5 m/s
- The 11 GMT 700 mb RH less than 21%

On those rare occasions when exceedances are noted during less dry, windier conditions, the occurrence of the exceedance appears to be based solely on carry-over from the previous, very high ozone concentration day.

All of these scenarios are consistent with the findings of the case studies.

Table 4-1. CART Database. Variables in upper case indicate variables used during model runs.

Variable	Description
DATE	Date
JULIAN_DATE	Julian Day
EXCEEDANCE	Network Maximum 8-hr ozone average >85 ppb =1, 80 - 85 pbb=1, <80 ppb =0
Max	Network maximum daily 8-hr ozone average
Average	Network average of daily maximum 8-hr ozone average from all sites
MAX__1	"Max" for previous day
AVG__1	"Average" for previous day
SOLAR	Sin(Julian day - Julian day Marc h 21) x 2 PI / 365
CLOUDS	Clouds, based on >10% drop in daily average solar radiation (1 for cloudy, 0 for clear)
T_12	Network average temperature at 1200 PST from all sites
T_MAX	Network average of maximum temperature from all sites
T_MAX_NORM	Normal maximum temperature for Las Vegas
T_ANOMALY	"T max" - "T max Norm"
WS_AFT	Network average afternoon (1000 - 1600 PST) wind speed from all sites
DR500_HT_23	Desert Rock 500 mb height, 1100 Z
DR500_T_11	Desert Rock 500 mb temperature, 1100 Z
DR500_RH_11	Desert Rock 500 mb RH, 1100 Z
DR500_WD_11	Desert Rock 500 mb wind direction, 1100 Z
DR500_WD2_11	Desert Rock 500 mb WD (categorical - 8 point compass, 0 = 0-45 deg), 1100 Z
DR500_WS_11	Desert Rock 500 mb wind speed, 1100 Z
DR700_HT_11	Desert Rock 700 mb height, 1100 Z
DR700_T_11	Desert Rock 700 mb temperature, 1100 Z
DR700_RH_11	Desert Rock 700 mb RH, 1100 Z
DR700_WD_11	Desert Rock 700 mb wind direction, 1100 Z
DR700_WD2_11	Desert Rock 700 mb WD (categorical - 8 point compass), 1100 Z
DR700_WS_11	Desert Rock 700 mb wind speed, 1100 Z
DR500_HT_23	Desert Rock 500 mb height, 2300 Z
DR500_T_23	Desert Rock 500 mb temperature, 2300 Z
DR500_RH_23	Desert Rock 500 mb RH, 2300 Z
DR500_WD_23	Desert Rock 500 mb wind direction, 2300 Z
DR500_WD2_23	Desert Rock 500 mb WD (categorical - 8 point compass), 2300 Z
DR500_WS_23	Desert Rock 500 mb wind speed, 2300 Z
DR700_HT_23	Desert Rock 700 mb height, 2300 Z
DR700_T_23	Desert Rock 700 mb temperature, 2300 Z
T_DIFF	Dirfference between "DR700 T 23" and "T max"
DR700_RH_23	Desert Rock 700 mb RH, 2300 Z
DR700_WD_23	Desert Rock 700 mb wind direction, 2300 Z
DR700_WD2_23	Desert Rock 700 mb WD (categorical - 8 point compass), 2300 Z
DR700_WS_23	Desert Rock 700 mb wind speed, 2300 Z
WS_10	Average wind speed for 1000 PST at Craig Rd
WD_10	Average wind direction for 1000 PST at Craig Rd
WD2_10	Average WD (categorical - 8 point compass) for 1000 PST at Craig Rd
WS_16	Average wind speed for 1600 PST at Craig Rd
WD_16	Average wind direction for 1600 PST at Craig Rd
WD2_16	Average WD (categorical - 8 point compass) for 1600 PST at Craig Rd
RR_RH_AFT	Red Rock average RH, 1000 - 1400 PST
RR_RAD_AFT	Red Rock average solar radiation, 1000 - 1400 PST

Table 4-1. CART Database (continued)

Variable	Description
Mojave O3 max	Maximum 8-hour average ozone - Mojave
Mojave avg	Daily average ozone - Mojave
MOJAVE__1	Daily average ozone, previous day - Mojave
MOHAVE__2	Daily average ozone, two days prior - Mojave
Barstow avg	Daily average ozone - Barstow
Death Valley avg	Daily average ozone - Death Valley
Joshua Tree avg	Daily average ozone - Joshua Tree
Trona avg	Daily average ozone - Trona
29 Palms avg	Daily average ozone - 29 Palms
Victorville avg	Daily average ozone - Victorville
BARSTOW_AVG__1	Daily average ozone, previous day - Barstow
DEATH_VALLEY_AVG__1	Daily average ozone, previous day - Death Valley
JOSHUA_TREE_AVG__1	Daily average ozone, previous day - Joshua Tree
TRONA_AVG__1	Daily average ozone, previous day - Trona
_9_PALMS_AVG__1	Daily average ozone, previous day - 29 Palms
VICTORVILLE_AVG__1	Daily average ozone, previous day - Victorville
BARSTOW_AVG__2	Daily average ozone, two days prior - Barstow
DEATH_VALLEY_AVG__2	Daily average ozone, two days prior - Death Valley
JOSHUA_TREE_AVG__2	Daily average ozone, two days prior - Joshua Tree
TRONA_AVG__2	Daily average ozone, two days prior - Trona
_9_PALMS_AVG__2	Daily average ozone, two days prior - 29 Palms
VICTORVILLE_AVG__2	Daily average ozone, two days prior - Victorville
OZONE_15__1	Network average ozone at 1500 PST from all sites
TYPE 11	Weather typing - 1100 PST
TYPE 23	Weather typing - 2300 PST
Barstow O3 max	Daily maximum 1-hr ozone average, Barstow
Death Valley O3 max	Daily maximum 1-hr ozone average, Death Valley
Joshua Tree O3 max	Daily maximum 1-hr ozone average, Joshua Tree
Trona O3 max	Daily maximum 1-hr ozone average, Trona
Twenty-nine Palms O3 max	Daily maximum 1-hr ozone average, Twenty-nine Palms
MOJAVE_03_MAX__1	Daily maximum 1-hr ozone average, previous day, Mojave
BARSTOW_03_MAX__1	Daily maximum 1-hr ozone average, previous day, Barstow
DEATH_VALLEY_O3_MAX__1	Daily maximum 1-hr ozone average, previous day, Death Valley
JOSHUA_TREE_O3_MAX__1	Daily maximum 1-hr ozone average, previous day, Joshua Tree
TRONA_O3_MAX__1	Daily maximum 1-hr ozone average, previous day, Trona
TWENTY_NINE_PALMS_03_MAX__1	Daily maximum 1-hr ozone average, previous day, Twenty-nine Palms
MAX_1HR__1	Network maximum 1-hour average, previous day
AVG_MAX_1HR__1	Average Network maximum 1-hour average, previous day

Table 4-2. Summary of CART Model Runs

	Description	Nodes with Exceedances	Exceedance Predicted	Miscassified Non-Exceedances	Parameters	Decisions
Model 1	2000 to 2003 data, all variables	4	22	72	10	10
		2	20	23	9	9
Model 2	Model 1 with increased 0/2 mismatch cost	2	22	21	8	8
Model 3	Model 2, MAX__1, AVG__1 removed	3	22	41	10	10
		2	21	27	10	10
Model 4	Model 3, “important” variables, unit costs	5	22	13	13	13
Model 5	Model 4, 23-hr 500 mb data removed	5	22	15	11	12
		4	21	8	10	11
		3	20	8	9	10
		3	20	10	8	9
		2	17	7	6	7
Model 6	Model 5, transport sites data removed	6	22	60	6	10
		4	20	17	6	10
		3	19	11	6	10
		2	16	10	5	7
Model 7	Model 6, 500 mb data removed	5	22	>100	5	7
		4	21	45	7	8
		3	20	38	6	7
		2	19	31	5	6
		1	17	27	3	4
Model 8	1999-2003 data, all variables with increased 0/2 mismatch cost	6	27	>200	8	8
		5	26	65	8	8
		2	23	17	8	8
Model 9	Model 8, MAX__1, AVG__1 removed	5	27	>150	9	9
		2	24	15	9	9
Model 10	Model 9, 500 mb removed	5	27	50	9	9
		3	25	23	9	9
Model 11	Model 10, transport sites data and other Selected parameters removed	4	27	26	9	11
		3	26	18	9	11

Table 4-3. Summary of Terminal Nodes for CART Model 12

Terminal Node	**< 80 ppb**	**80 – 85 ppb**	**=> 85 ppb**
1	163	5	0
2	7	6	1
3	11	3	16
4	9	3	0
5	12	2	0
6	7	1	0
7	10	1	8
8	10	0	1
9	77	15	1
10	82	4	0
9 alternate	158	19	0
10 alternate	1	0	1
Total	388	45	27

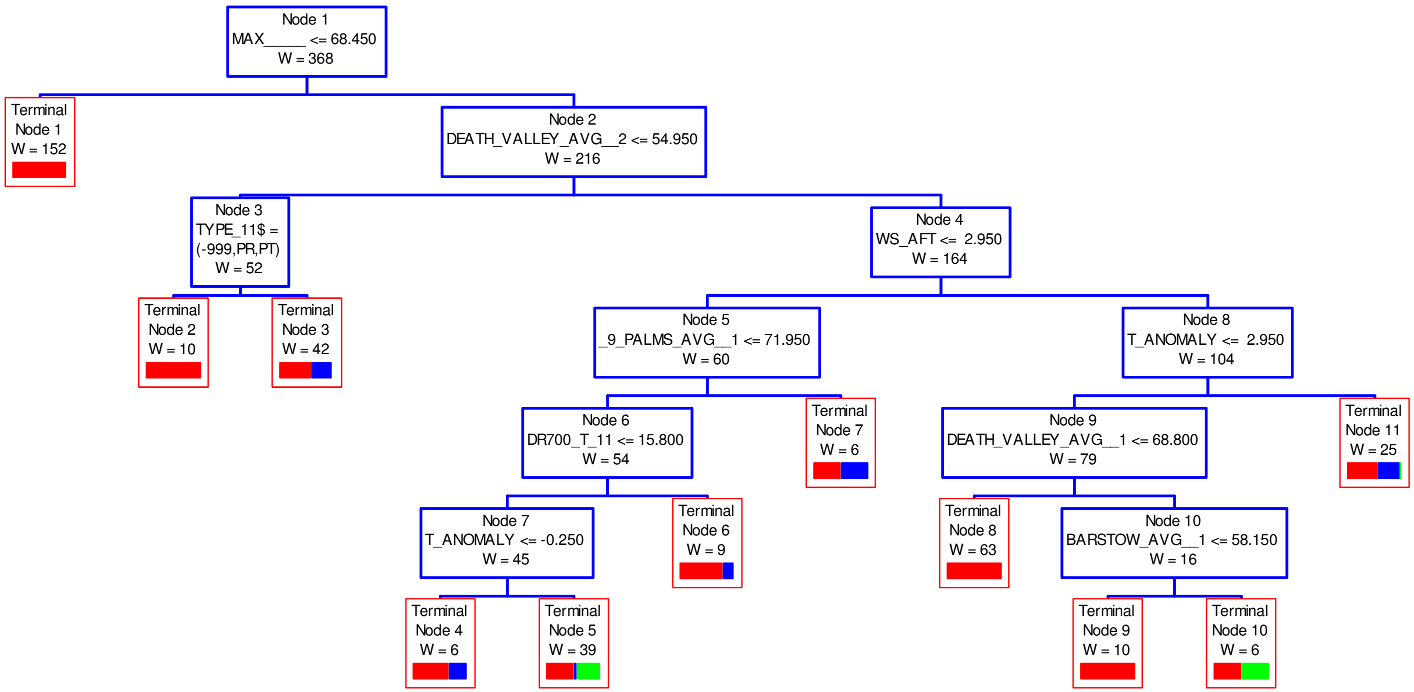


Figure 4-1. CART Model 1

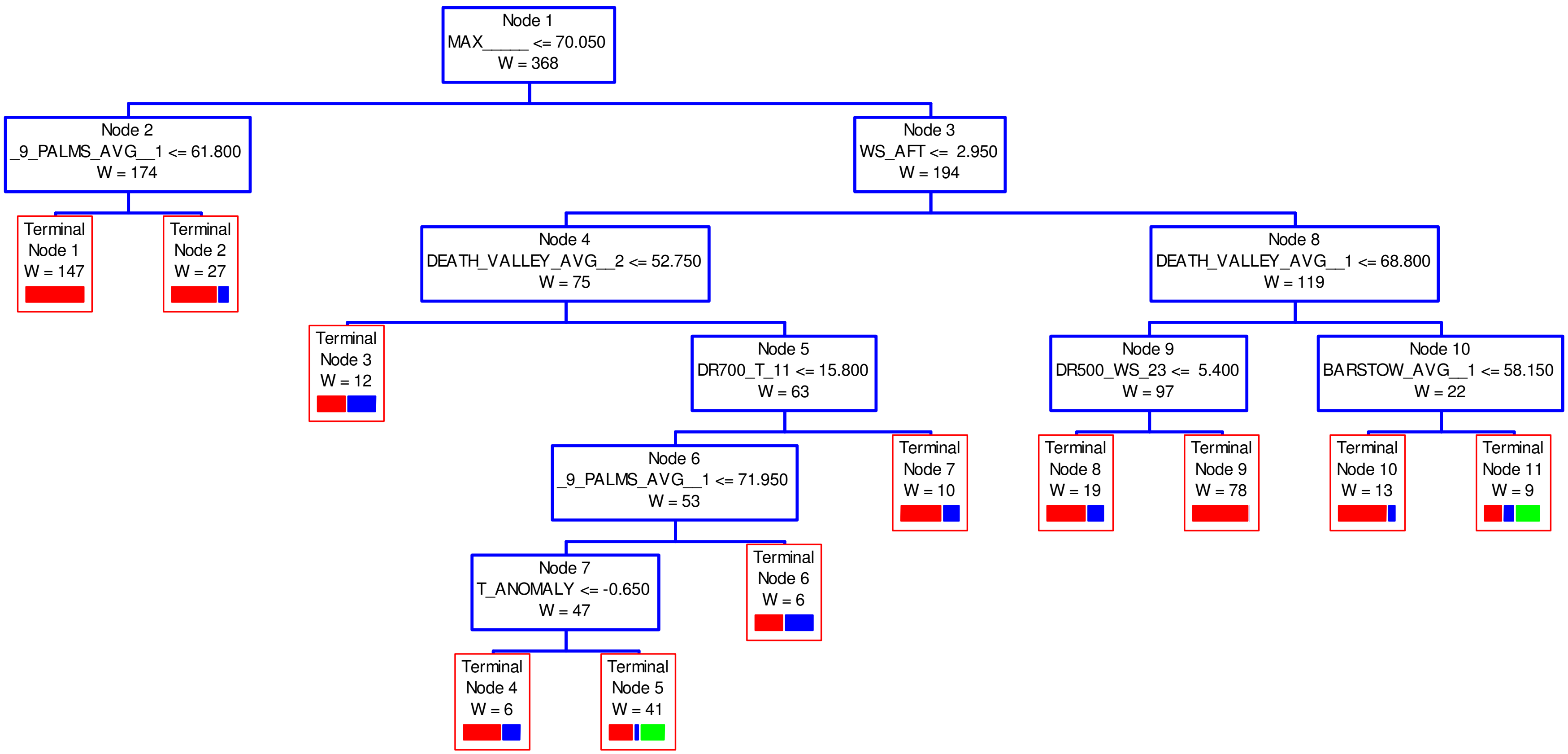


Figure 4-2. CART Model 2

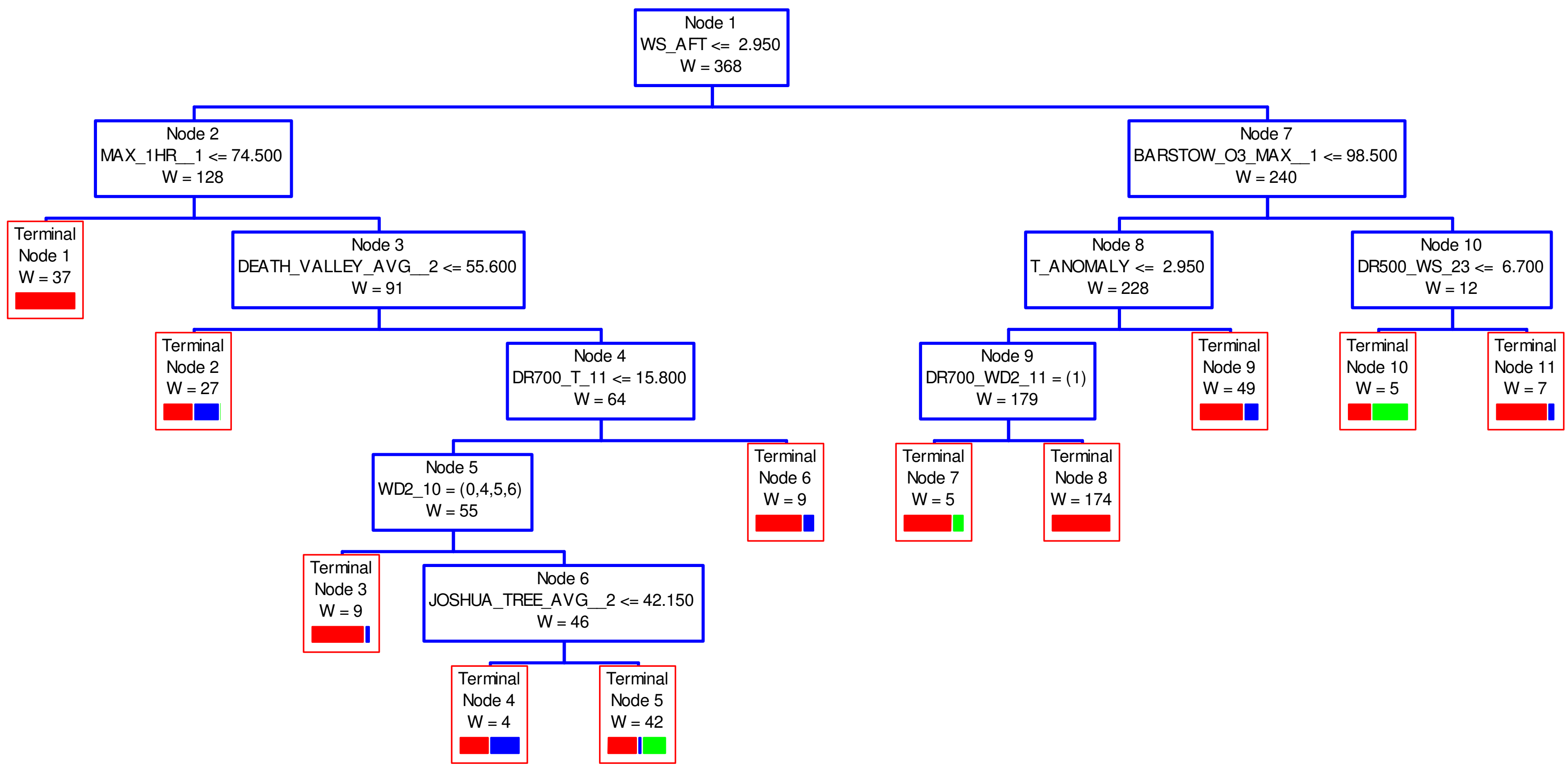


Figure 4-3. CART Model 3

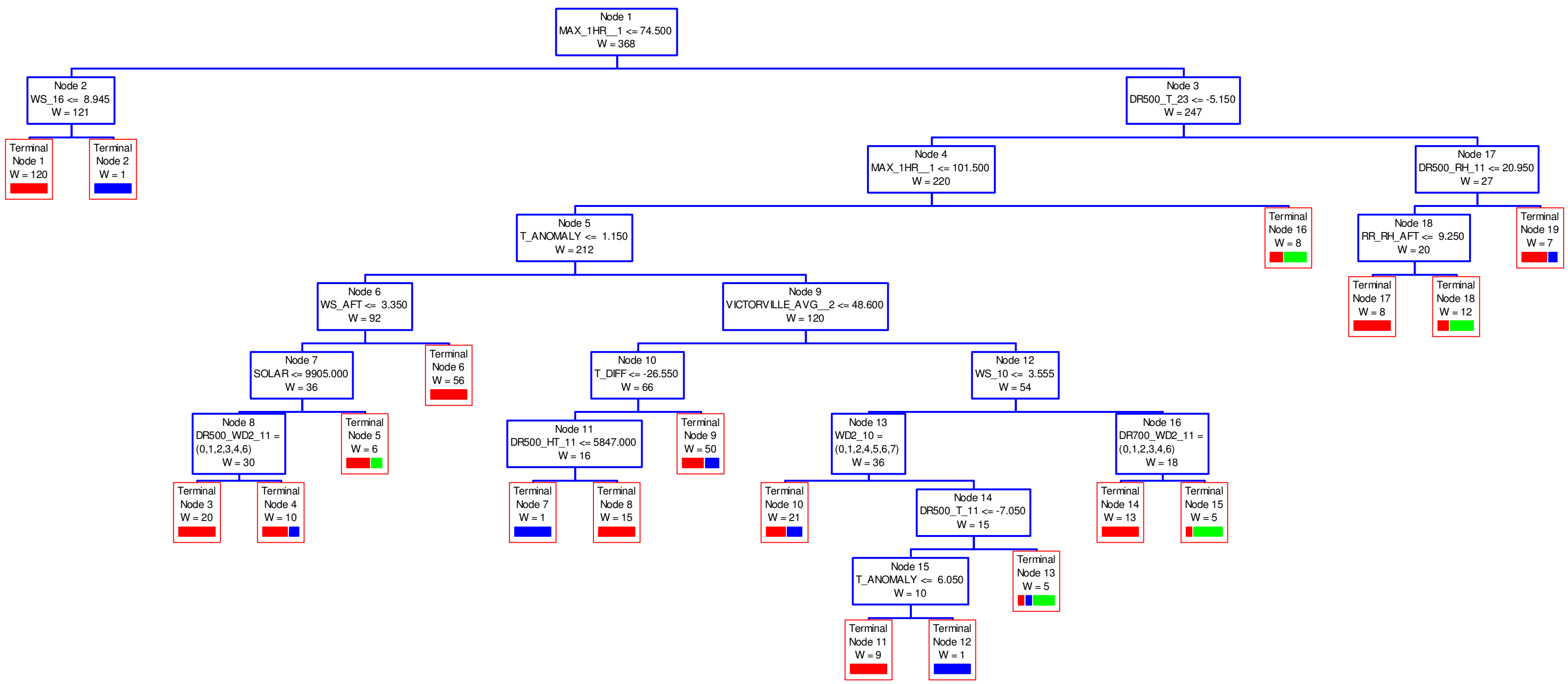


Figure 4-4. CART Model 4

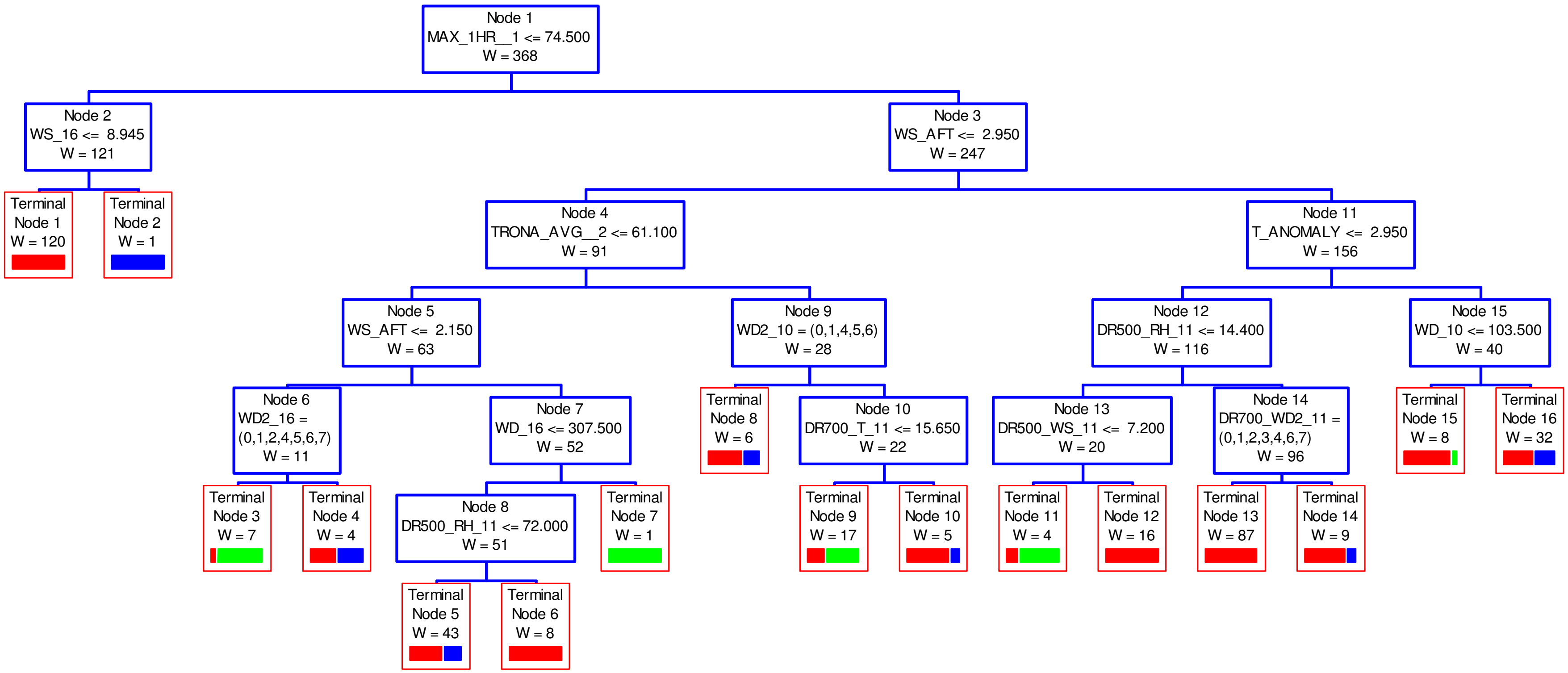


Figure 4-5. CART Model 5

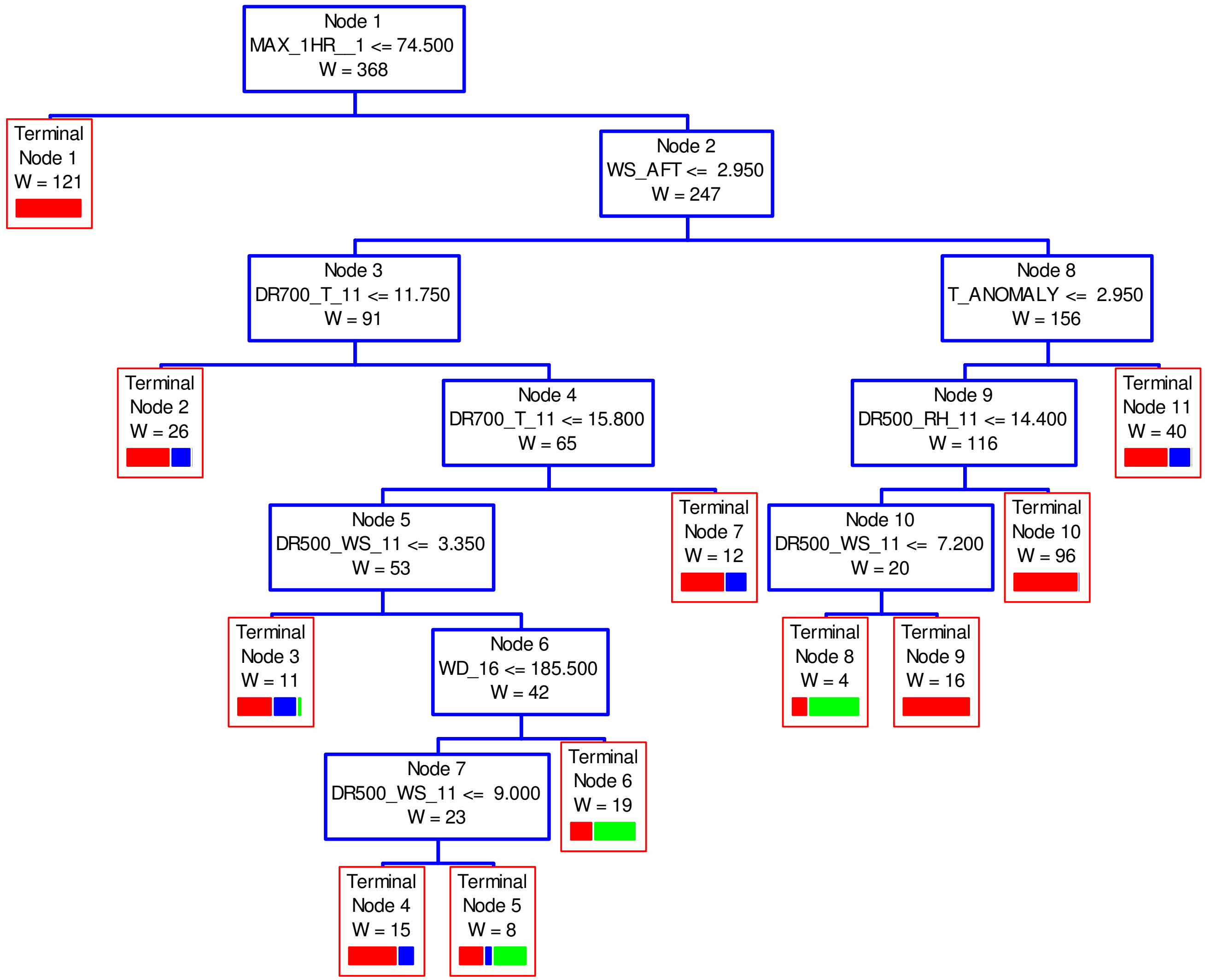


Figure 4-6. CART Model 6

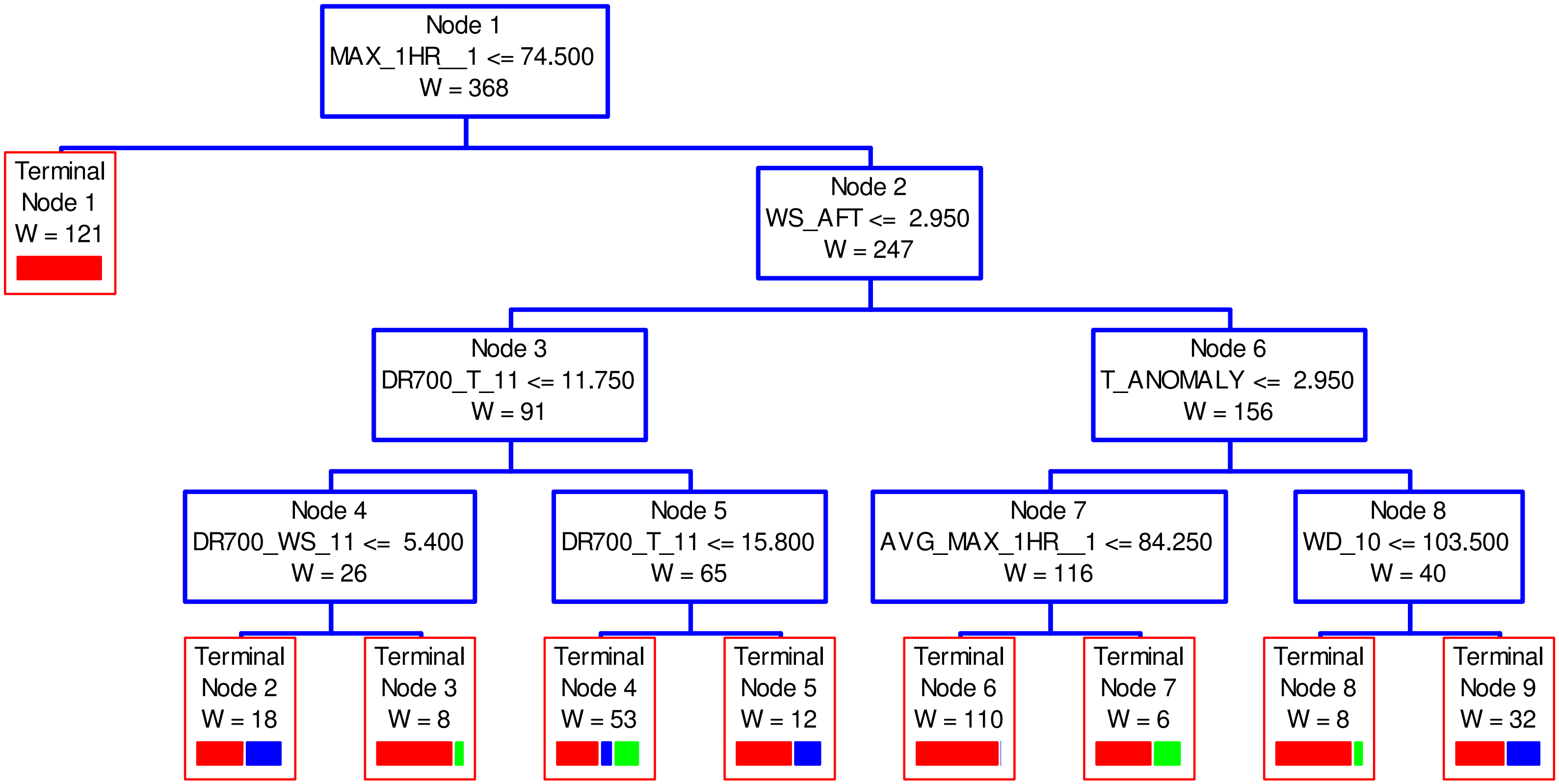


Figure 4-7. CART Model 7

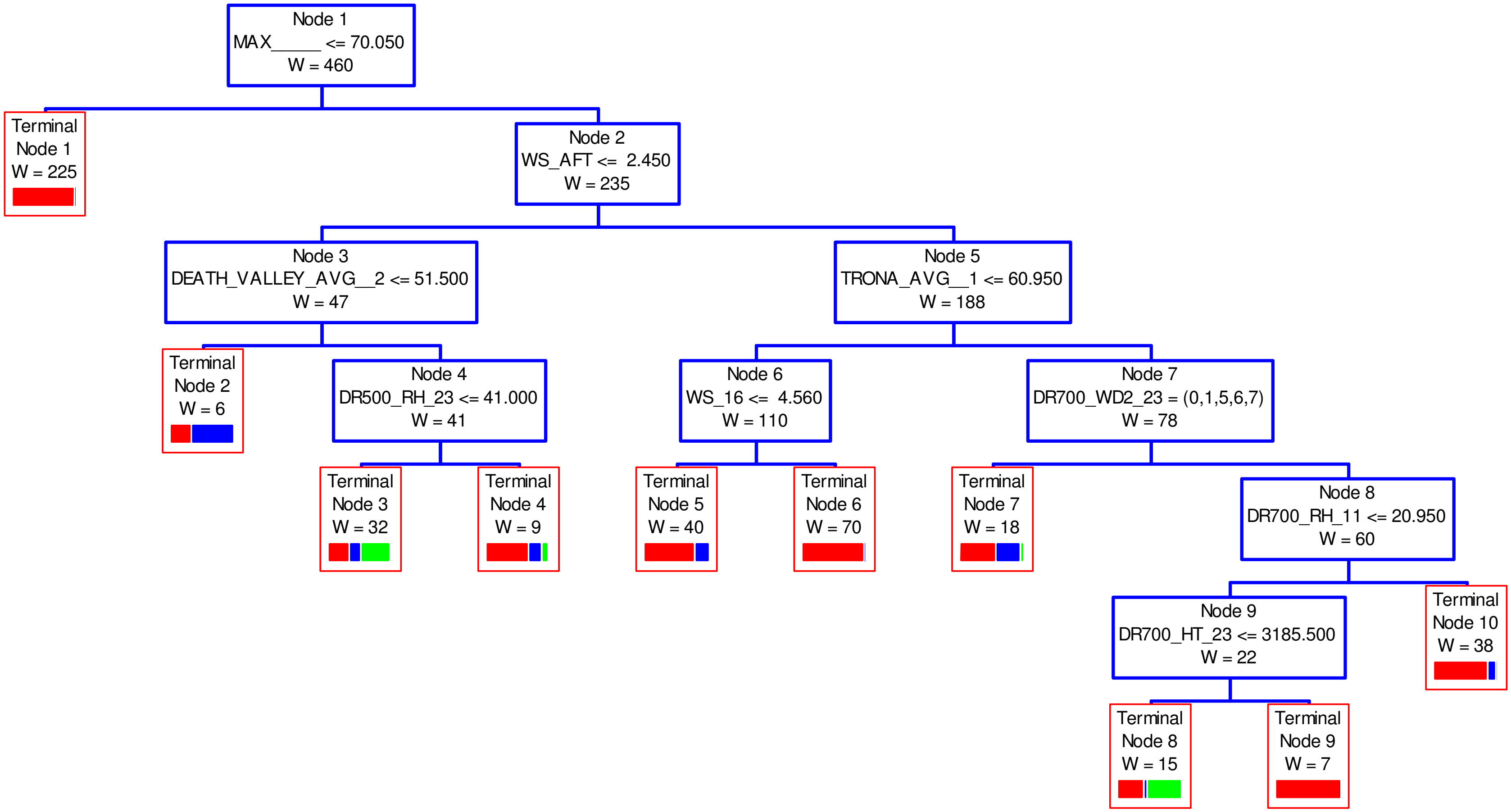


Figure 4-8. CART Model 8

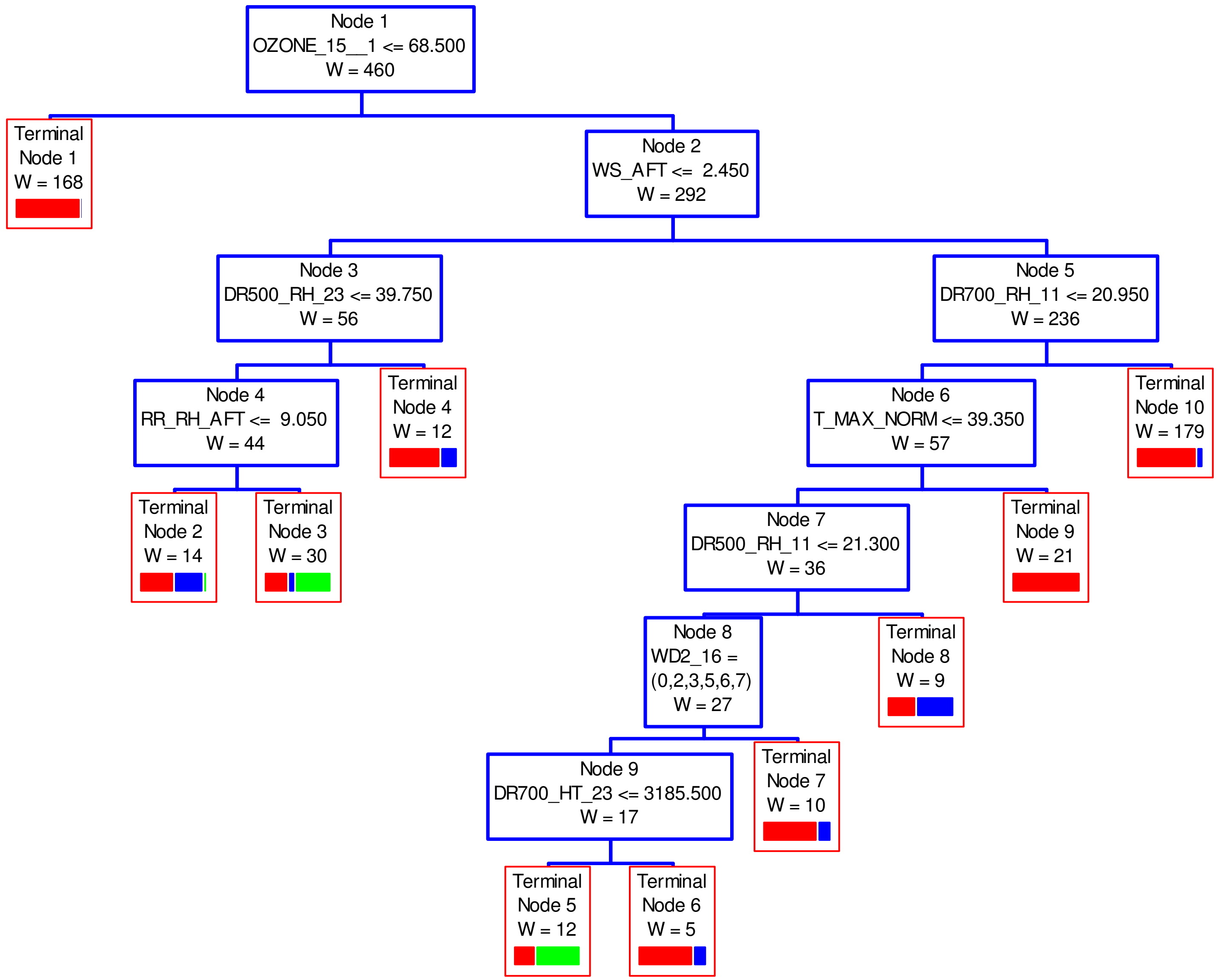


Figure 4-9. CART Model 9

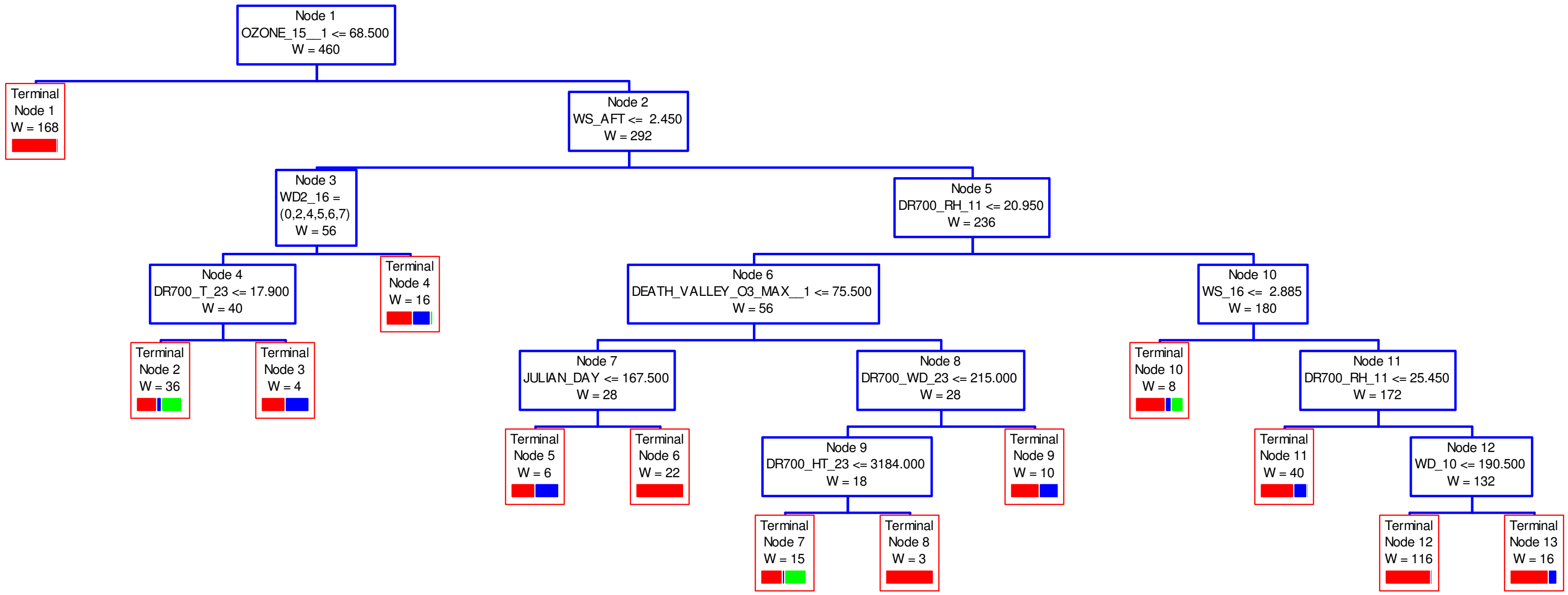


Figure 4-10. CART Model 10

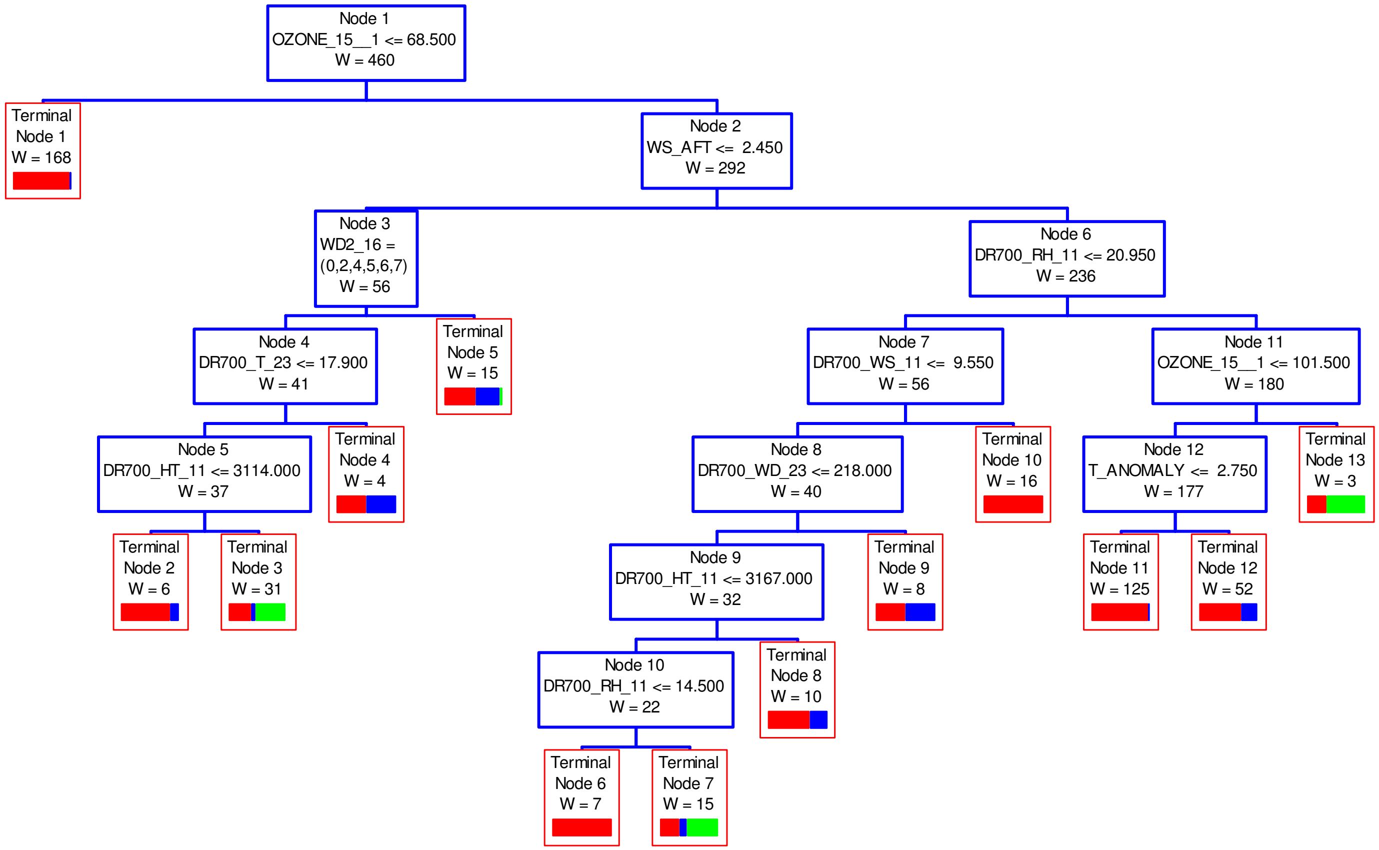


Figure 4-11. CART Model 11

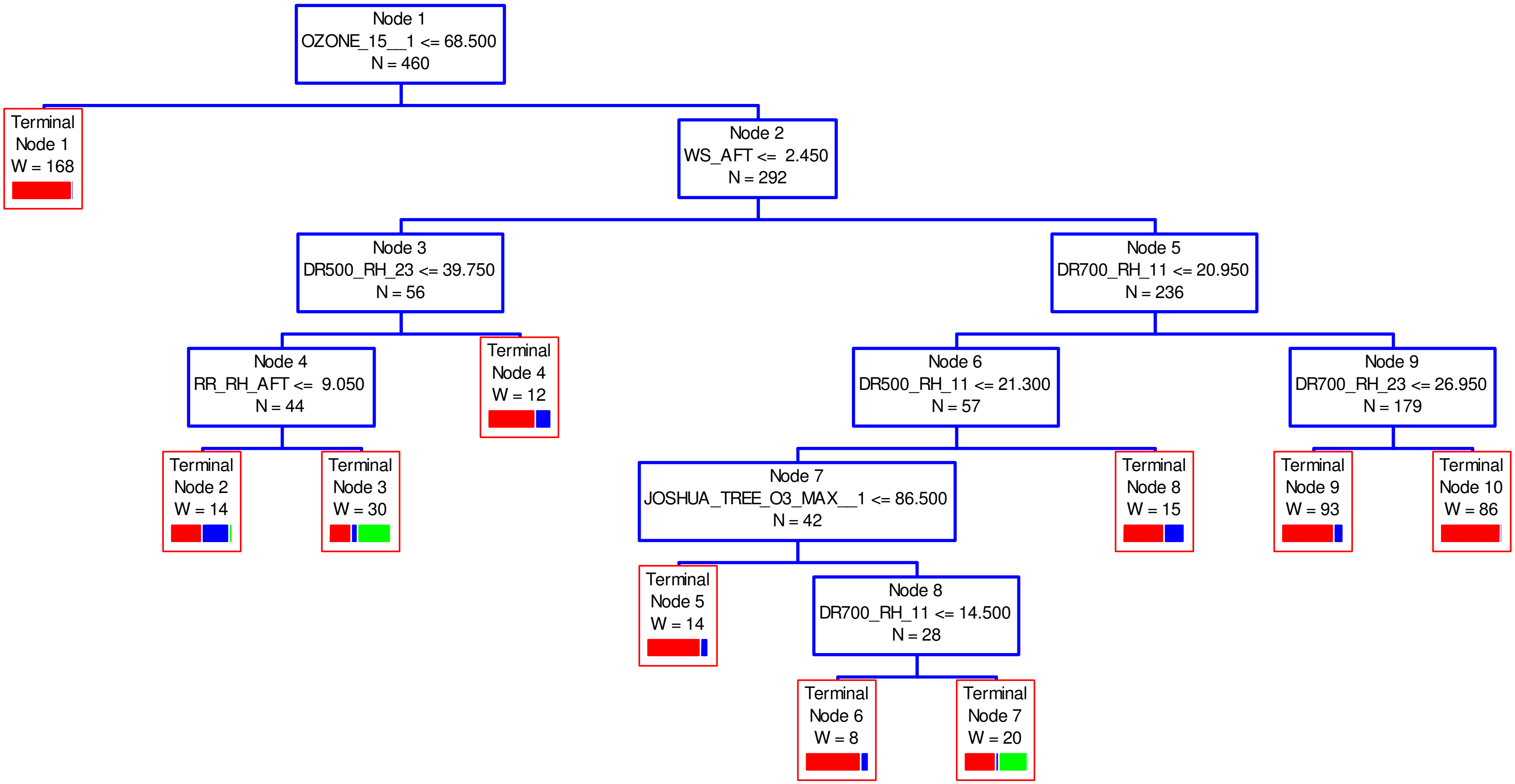


Figure 4-12. CART Model 12

5. CASE STUDIES

This section is comprised of the ten ozone episodes selected for study. An exceedance of the 8-hour Federal Ozone Standard of at least one site in the Clark County monitoring network occurred in each of the episodes. A primary goal of the case study selection process was to examine a range of episodes in terms of duration and occurrence within the ozone season cycle. The dates of each episode and duration in days are:

1. August 10-11, 2001 – 2 day
2. June 16, 2002 – 1 day
3. June 27-28, 2002 – 2 day
4. August 11, 2002 – 1 day
5. August 18, 2002 – 1 day
6. May 26-27, 2003 – 2 day
7. June 1-4, 2003 - 4 day (only 3 out of 4 days had an exceedance)
8. June 29, 2003 – 1 day
9. July 9, 2003 – 1 day
10. July 21, 2003 – 1 day

For each episode, there is a detailed discussion of the areal distribution of ozone and timing of the peaks, and the synoptic-scale and local meteorology that affected Clark County air quality, including estimated surface air-parcel trajectories.

An initial objective of the study was to develop a list of candidate periods for case studies. The case studies were selected to be representative of ozone episodes over the ozone season in order to characterize the range of meteorological conditions that can lead to episodic conditions.

Our approach was to generate a data set that consisted of the four highest 8-hour averages and dates for each monitoring site. Episodic conditions were considered to have occurred when several sites within the network experienced their highest levels. This was done for two ozone seasons, 2002 and 2003, when it was felt the temporal and spatial characteristics of area emissions were most similar to current conditions.

As it turned out, four episodes each year experienced the bulk of ozone exceedances. These periods are listed above. The five 2003 episodes included 72 of the 77 occurrences of ozone exceeding 85 ppb. In 2002, the four episodes listed accounted for all but one exceedance of the 8-hour ozone standard. DAQEM staff added the August 10-11, 2001 episode for case study.

The multi-day episodes all occurred during May and June (with exception of the 2001 episode). The July and August episodes were generally shorter in duration.

The representativeness of the candidate episodes was evaluated by examining the temporal distribution of high levels over the 8-year period of record that comprises our database. This information is summarized in three tables that are shown below. **Table 5-1** gives the number of network exceedances of the 8-hour ozone standard. June experienced the greatest number of exceedances (16) followed closely by July (13). There were no exceedances experienced in September or October during the 8-year period examined.

Since there were only 43 exceedances during this period, it was useful to examine the temporal distribution of network peaks greater or equal to (GE) 80 ppb. The number of occurrences increased to 117 and provided more resolution. As can be seen from **Table 5-2**, high ozone levels occurred most frequently in June—approximately twice as often as in May, July and August during which high ozone occurred with similar frequency. There were no occurrences of ozone concentrations in excess of 80 ppb in September and only one instance in October.

The duration of episodes (GE 80 ppb) was also examined (**Table 5-3**). Most episodes persisted for only 1-2 days but, as can be seen from the table, multi-day episodes are not uncommon. Two episodes persisted on 5 consecutive days. Thirteen of the 24 multi-day episodes occurred in June.

The episodes selected comprise a representative sample of the statistical distribution of high ozone over the historical period considered. That is to say, most are June episodes and May, July, and August episodes are included on the list. Moreover, candidate episodes include one 4-day episode, two 3-day episodes, three 2-day episodes, and four 1-day episodes. This distribution of episode duration is consistent with the long-term record.

Two high ozone days not included in this study are noteworthy because they occur at somewhat anomalous dates: April 15 and October 15. Whereas October has been previously defined as part of the ozone "season", the April occurrence is prior to the start of the season. Neither event exceeded the Federal Ozone Standard but is nevertheless interesting. **Table 5-4** provides the peak 1-hour averaged ozone and corresponding hour for the sites within the network for these events. Ozone levels were generally high in Clark County on April 15, 1999. Apex, Mesquite, and Joe Neal all experienced ozone levels greater than 90 ppb. Station maximum readings all occurred late in the afternoon (16-17 PST). The western-most site, Jean, was the only site that experienced high ozone (89 ppb) on October 15, 2002. The remaining sites in the network experienced seasonal levels.

Table 5-1. Network Maximum 8-Hour Ozone Concentrations GE 85 ppb

#Sites	Season	May	June	July	Aug	Sept	Oct	Totals
5	**1996**	1	2	1	1	0	0	5
6	**1997**	1	0	0	0	0	0	1
6	**1998**	0	2	6	0	0	0	8
13	**1999**	1	3	2	0	0	0	6
15	**2000**	0	0	1	2	0	0	3
15	**2001**	0	0	0	3	0	0	3
15	**2002**	0	3	1	2	0	0	6
15	**2003**	2	6	2	1	0	0	11
	Totals	5	16	13	9	0	0	43

Table 5-2. Network Maximum 8-Hour Ozone Concentrations GE 80 ppb

#Sites	Season	May	June	July	Aug	Sept	Oct	Totals
5	**1996**	2	6	3	1	0	0	12
6	**1997**	2	3	1	0	0	0	6
6	**1998**	1	5	6	4	0	0	16
13	**1999**	6	8	2	2	0	1	19
15	**2000**	3	3	1	4	0	0	11
15	**2001**	2	4	3	5	0	0	14
15	**2002**	1	7	4	5	0	0	17
15	**2003**	6	10	3	3	0	0	22
	Totals	23	46	23	24	0	1	117

Table 5-3. Duration of Ozone Maxima GE 80 ppb

Duration (Days)	May	June	July	August
2	2	7	2	3
3		4		2
4		2		
5	1		1	

Table 5-4. Anomalous Ozone Events (1-hour averages)

	15-Apr-99		**15-Oct-02**	
	Max O3	**Hr(PST)**	**Max O3**	**Hr(PST)**
AP	91	16	78	16
BC	85	17	71	16
CC	62	16	64	14
CR	77	16	58	15
JD	82	16	75	15
JN	87	16	89	13
JO	92	15		
LO	83	16	66	16
MQ	91	17		
PL	80	16	61	16
PM	83	16	72	16
PT				
PV	88	16	72	16
SL			65	15
ST	79	17		
WJ	87	16	70	15
WW	80	17	73	15

5.1 August 10 to 11, 2001 Episode

Ozone Levels

The Federal Ozone Standard of 85 ppb 8-hour running average was exceeded on both August 10 and 11, 2001. Exceedances of the 8-hour standard were measured at CC, JO, LO, WJ, PV, and WW (PM reached 85.0 ppb) on the 10^{th}, and at LO, PV, and WJ on the 11^{th}. Maximum ozone levels are listed in **Table 5-5** ordered by site I.D. In the last row of the table, the number of sites exceeding the 8-hour ozone standard is given.

Table 5-5. Maximum 8-Hour Ozone (ppb) – Case Study 1

Site Name	Site ID	8/9/01	8/10/01	8/11/01	8/12/01
Apex	AP	65.5	68.8	68.4	61.3
Boulder City	BC	52.6	69.8	66.6	56.1
E Craig Rd	BS	67.0	78.4	70.0	57.8
City Center	CC	57.0	83.9	70.6	49.5
JD Smith	JD	56.5	80.8	72.4	52.3
Jean	JN	62.1	72.1	75.3	65.3
Joe Neal	JO	85.0	94.0	84.1	69.1
Lone Mt	LO	82.7	90.6	88.9	69.4
Mesquite	MQ	Nd	Nd	Nd	nd
SE Valley	PL	61.0	76.6	67.1	59.4
Paul Myer	PM	69.4	85.0	81.8	63.8
Palo Verde	PV	78.1	91.1	90.1	69.6
Shadow Lane	SL	61.0	87.0	73.3	56.3
Searchlight	ST	49.0	66.5	61.5	53.3
Walter Johnson	WJ	75.4	92.5	88.5	66.5
Winterwood	WW	61.9	85.9	66.4	56.0
Network Max		85.0	94.0	90.1	69.6
# Sites Exceeded		0	6	3	0

nd = no data

Charts showing the Las Vegas Valley and adjacent regions peak ozone spatial pattern are shown on **Figures 5-1 and 5-2**. The left panels show daily maximum 8-hour averaged levels and contours of constant ozone. The right panels give daily maximum 1-hour averaged levels, contours of constant ozone, and the time of the peak (PST). The highest 8-hour peak for the episode was 94.0 ppb measured at Joe Neal on the 10^{th}. It is noteworthy in that this episode experienced the only exceedance at City Center during the 3-year period from which the case studies were drawn. It is also noteworthy that the maximum 1-hour ozone was measured at Winterwood (116 ppb), which was unique for this period as well. The 1-hour ozone standard was not exceeded. Peak ozone was experienced late in the afternoon (16 to 17 PST) on the 10^{th} and in the early afternoon on the 11^{th}. Ozone levels south of the city were generally in the seventies on August 10 and in the mid-sixties on the following day. A noteworthy difference in the spatial ozone distribution during this episode is the northwest to southeast gradient (to lower levels) on the 10^{th} becoming a more west to east gradient on the 11^{th}. Both patterns are repeated in the other case studies but the northwest to southeast gradient was the most frequently observed.

Time-series plots of hourly ozone at select sites in the city are shown on **Figure 5-3**. The complete 2-day cycle is shown. During the late night and early morning, ozone levels reach a minimum and do not indicate any overnight carryover at the surface. (In rural locations where reduction mechanisms are not active, ozone levels often remain high and contribute to the ambient ozone burden on the following day.) At the City Center, ozone levels are near zero, which is characteristic at locations exposed to fresh NO emissions when ozone production is inactive as it is during the night.

Meteorology

The synoptic pattern at the 500 mb level (~18,000 ft) in the southwestern U.S. previous to and including August 10th and 11th indicated that a Flat Ridge (FR), with minimal horizontal pressure gradient, was the dominant feature. During August 8th, the pressure gradient over the entire western U.S. south of 45 degrees was extremely flat, resulting in very light winds. On August 9th, the weather pattern evolved into a broad Interior Ridge (IR) configuration, with the 500 mb heights higher over southern Nevada than anywhere else. By the afternoon of the 10th, the peak 500 mb heights had shifted to the west of Las Vegas, over southern California, a pattern that continued into the 11th. As a result of this sequence, flow aloft over southern Nevada increased from light and variable on the 8th to a light northwesterly wind on the 9th becoming slightly stronger northwesterly by the afternoon of the 10th and the morning of the 11th. By the afternoon of the 11th, a flat ridge again developed and drifted back toward the east, resulting in the highest 500 mb heights being again located over southern Nevada. At that time, the flow at 500 mb diminished and switched to northeasterly. **Figure 5-4(a&b)** shows the 500 mb pattern for the mornings of August 9 and 10, and **Figure 5-5(a&b)** shows the 500 mb maps for the morning and afternoon of the 11th.

The general FR pattern was likewise discernable at lower levels in the atmosphere, including at the 700 mb level (~10,000 ft-agl), where the ridge also appeared to undergo a subtle shift to the west on the 9th and 10th. This triggered an increase of light northerly flow aloft over southern Nevada. By the 11th, however, the ridge seemed to mirror the 500 mb feature and built back toward the east. Flow over southern Nevada at 700 mb became almost light and variable as the ridgeline expanded over the area. The temperature aloft at 700 mb increased slightly on the 10th (14.1 to 14.6), indicating that the stability in the boundary layer did not change appreciably from the previous day. However, the 700 mb temperature increased by 1.2° C (14.6 to 15.8) by the afternoon of the 11th, as the ridgeline passed overhead.

A major low-level synoptic feature was a thermal low, evident on the 850 mb (~5,000 ft-msl) plot, in southwestern Nevada and eastern California on the 9th that may be a mechanism that provides some regional dispersion. On the 10th and 11th, the thermal low was not evident and winds appeared light and variable providing for poor ventilation. **Figure 5-6** shows the 850 mb maps for the afternoon of the 9th and 10th. The winds at 850 mb on the 10th and 11th at the Desert Rock upper-air site were very light and somewhat variable from the southwest.

Backward trajectories from the City Center were constructed using the HYSPLIT Model and are shown on **Figures 5-7 and 5-8** for August 10 and 11, respectively. Shown are trajectories ending at the surface at 16 PST, starting 24 hours earlier. Thus, the trajectory on Figure 5-7 starts at 17 PST on the 9th and the trajectory on Figure 5-8 starts at 17 PST on the 10th. The number of hours back from 16 PST is posted along the trajectories. As can be seen from the figures, beginning in the early morning of the 10th and continuing through the afternoon of the 11th, transport winds were extremely light. Therefore, it is unlikely that interbasin transport can account for the high ozone levels measured.

Local afternoon surface wind direction and speed for August 10 are plotted on **Figure 5-9**. Isotachs constructed from the measured wind speed are shown as well. Of particular significance are the light winds that were measured, ranging from 1 to 2 m/s, and variable wind direction in the city and suburbs. The surface winds on the 11th were also relatively light but direction of the flow was more organized and generally to the west and northwest.

Mixing heights, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures ranged from 3,300 m-agl on the 10th to 3,850 m-agl on the 11th.

<u>Summary</u>

- Exceedances of the 8-hour ozone standard were experienced on both August 10 and 11, 2001. Six sites had exceedances on the 10th and one site on the 11th.

- The spatial ozone pattern was typical on the 10th in that peak levels were in the northwest sector of the Valley with a primarily northwest to southeast gradient. On the 11th, the ozone gradient was west to east, with peak levels on the west side of the Valley.

- This episode took place during a period categorized as FR (Flat Ridge). The air mass dominating southern Nevada was quite stable and stagnant during the period, with warm air aloft prevailing. There is some evidence that the presence of a thermal low over the region could provide a ventilation mechanism, and that when it is not present—such as on August 10 to 11—dispersion is significantly weakened.

- There is no evidence of interbasin transport based on trajectory estimates and local wind fields.

- Both days fell into CART class Terminal Node 3. This terminal node is consistent with locally generated ozone concentrations.

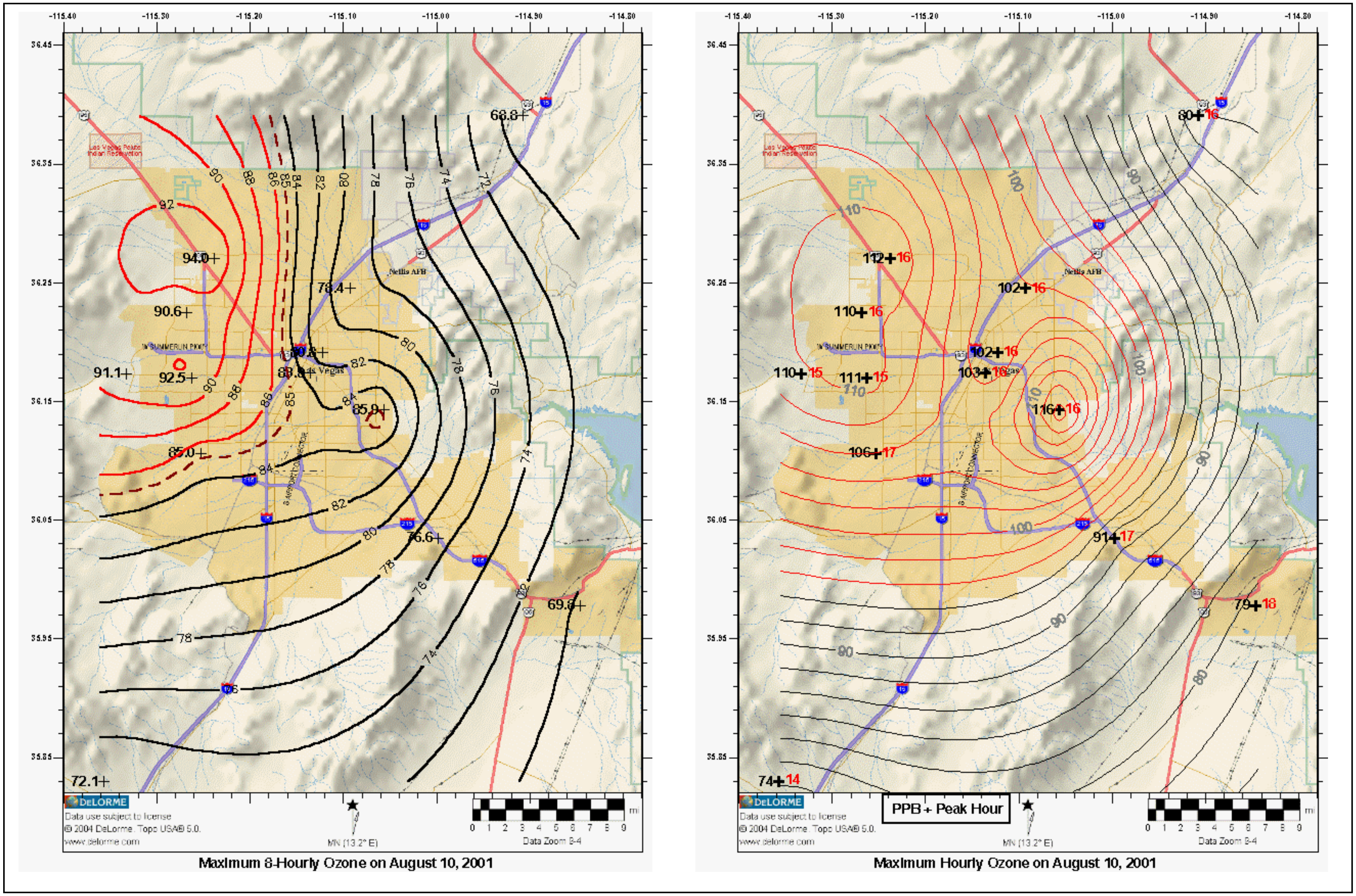


Figure 5-1. Peak Ozone for August 10, 2001

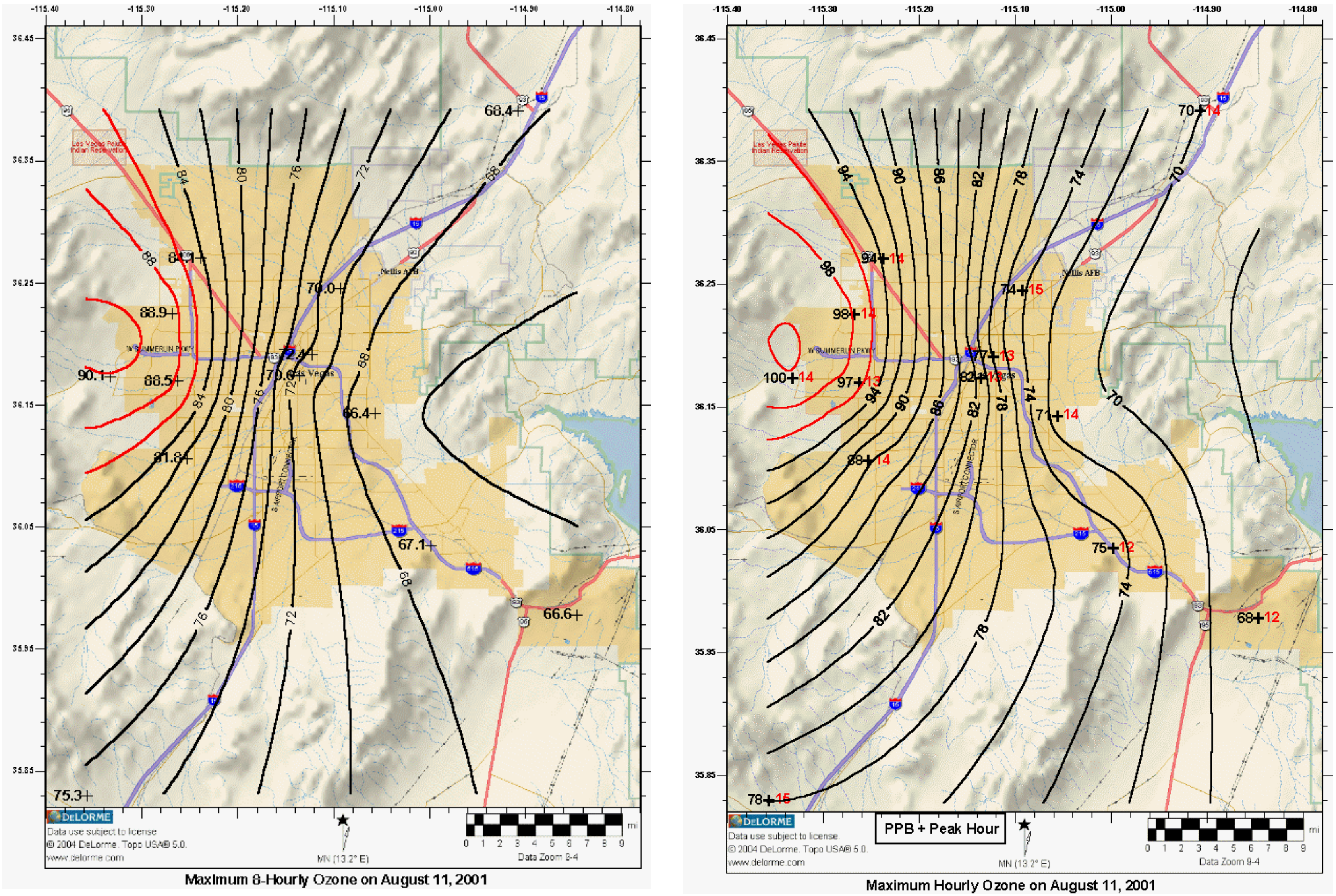


Figure 5-2. Peak Ozone for August 11, 2001

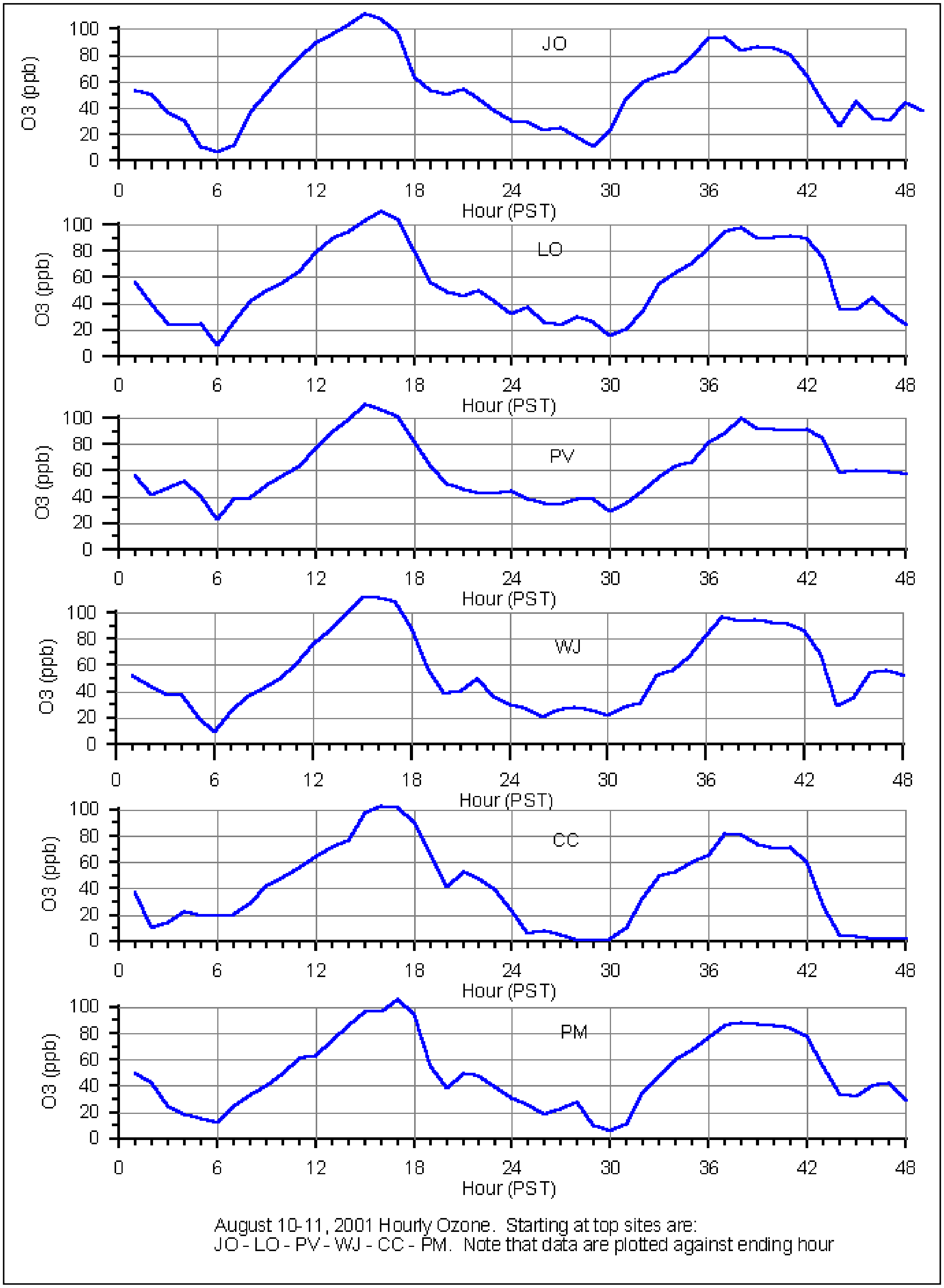


Figure 5-3. August 10-11, 2001 Hourly Ozone

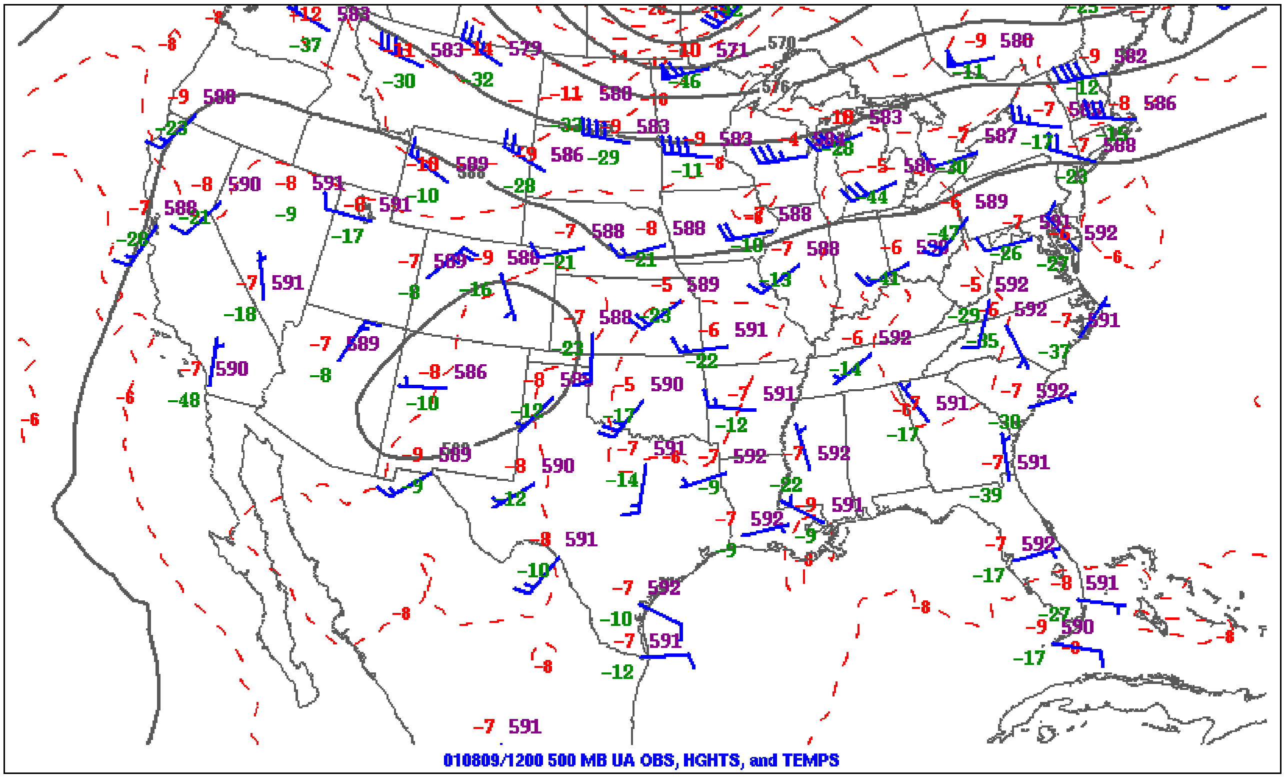


Figure 5-4(a). NWS 500 mb Constant Pressure Map for Morning of August 9, 2001

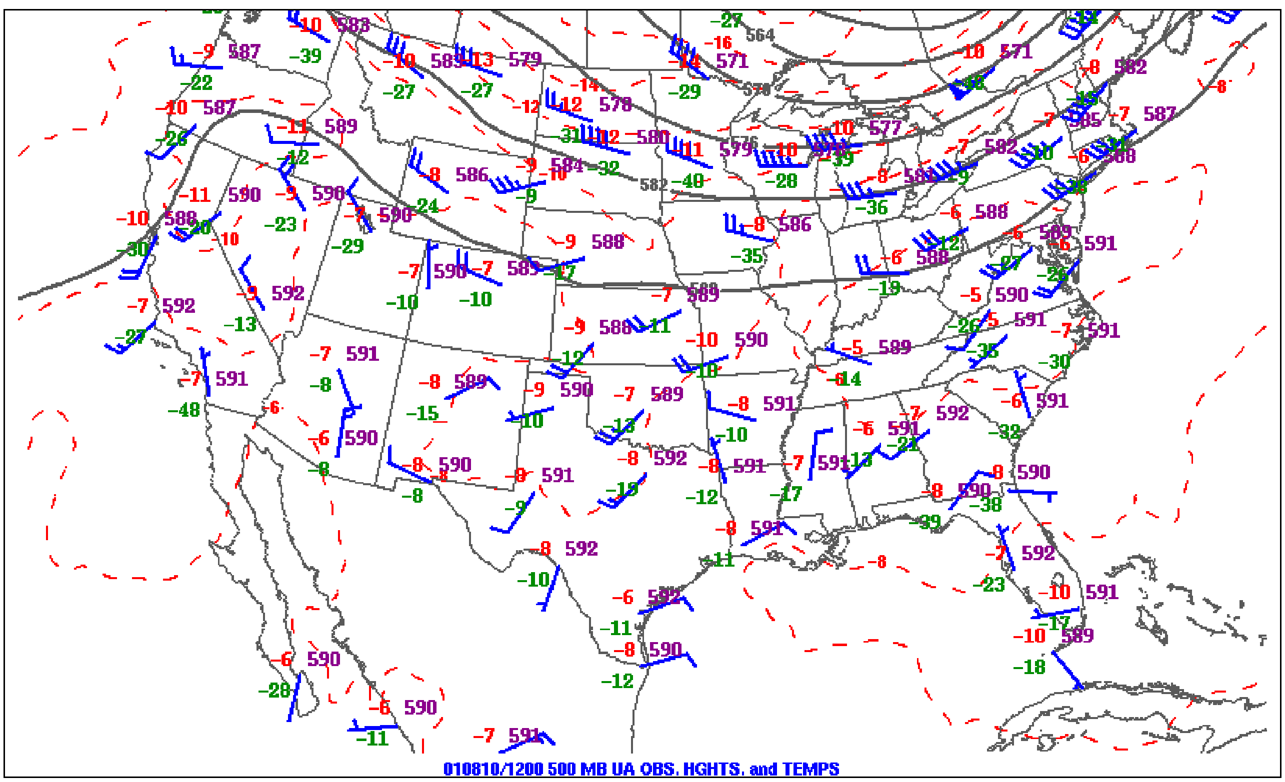


Figure 5-4(b). NWS 500 mb Constant Pressure Map for Morning of August 10, 2001

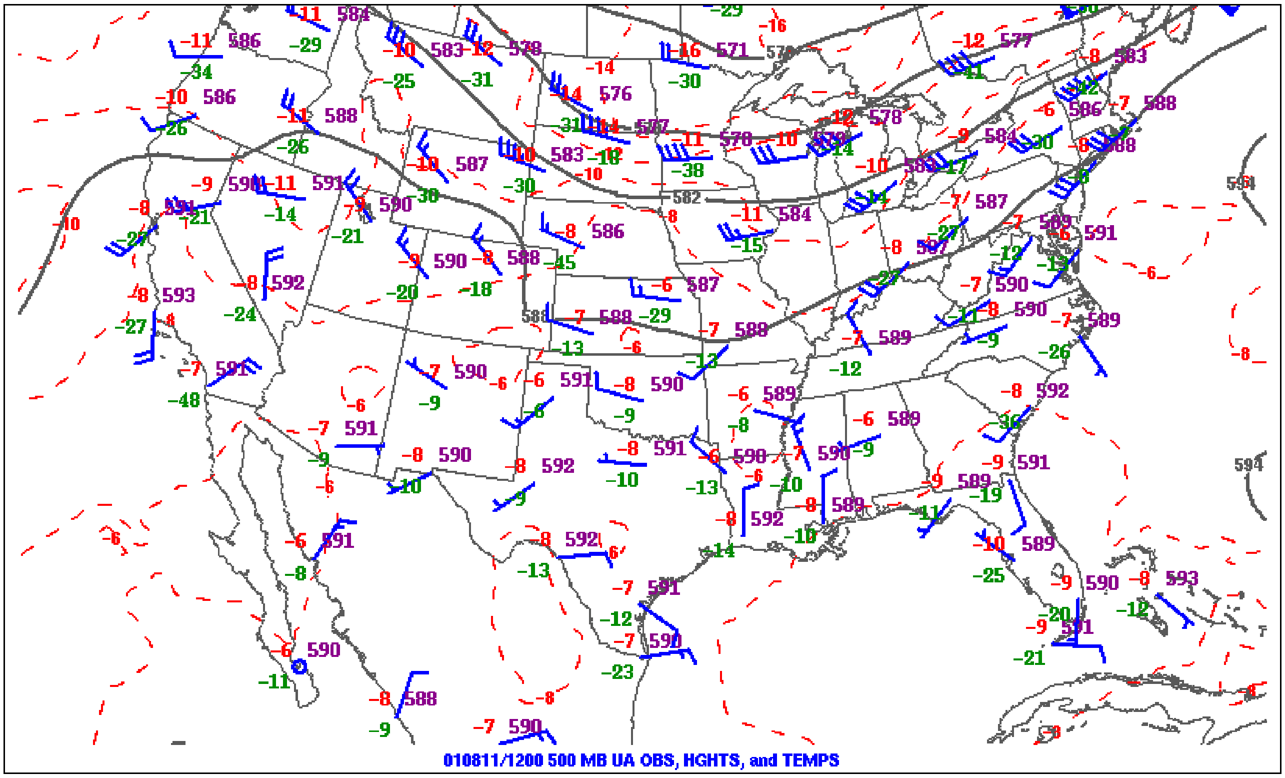


Figure 5-5(a). NWS 500 mb Constant Pressure Map for Morning of August 11, 2001

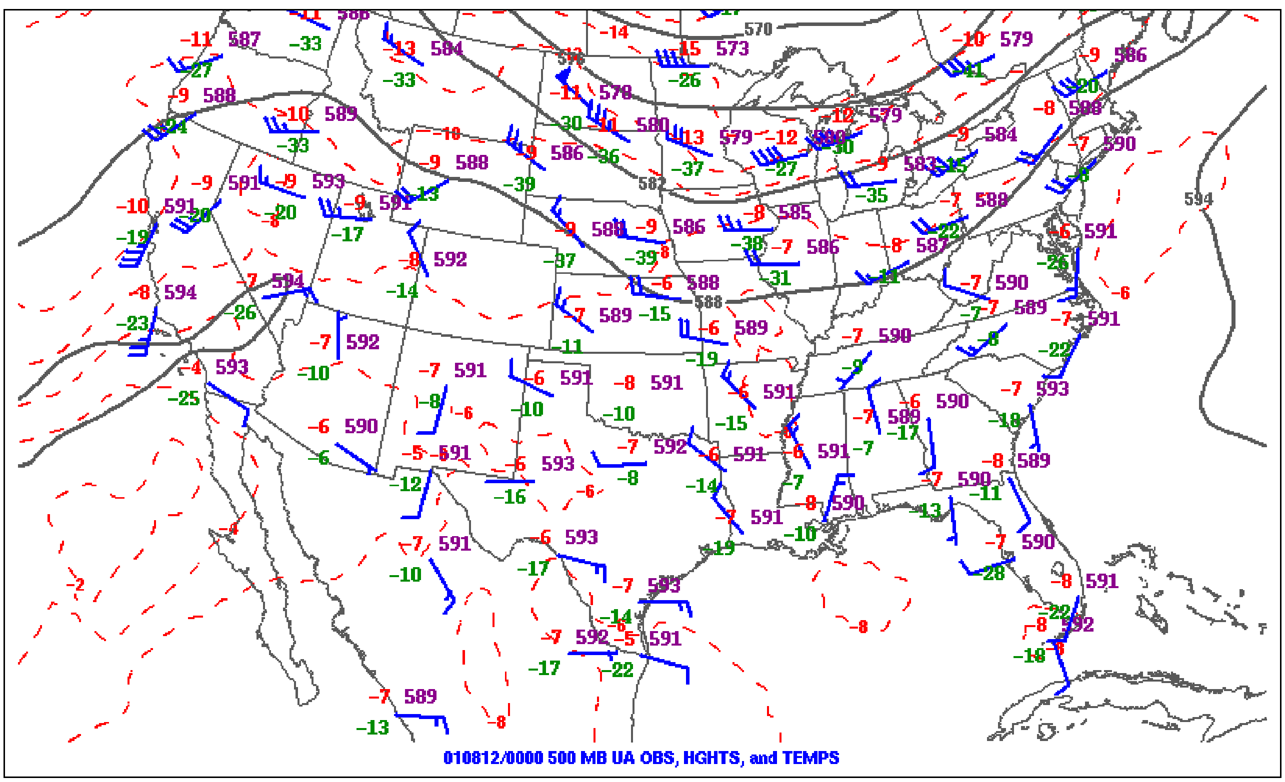


Figure 5-5(b). NWS 500 mb Constant Pressure Map for Afternoon of August 11, 2001

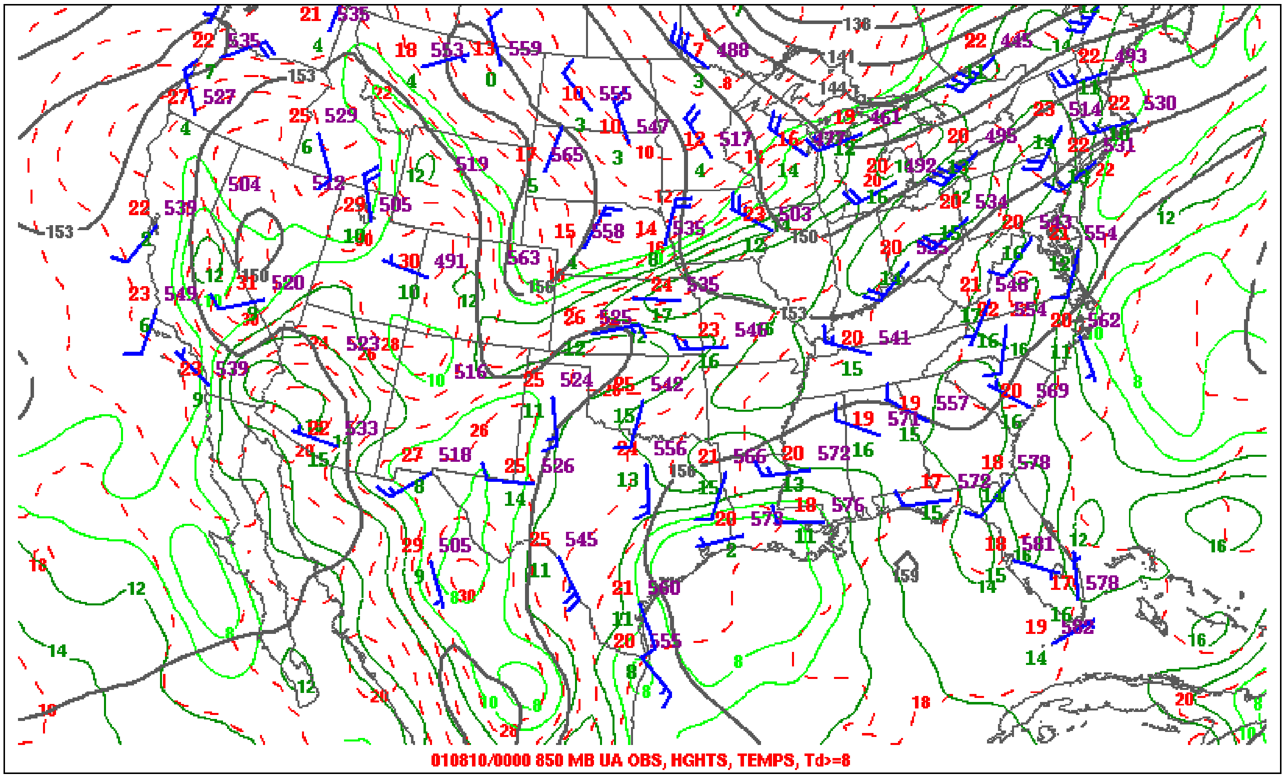


Figure 5-6(a). NWS 850 mb Constant Pressure Map for Afternoon of August 9, 2001

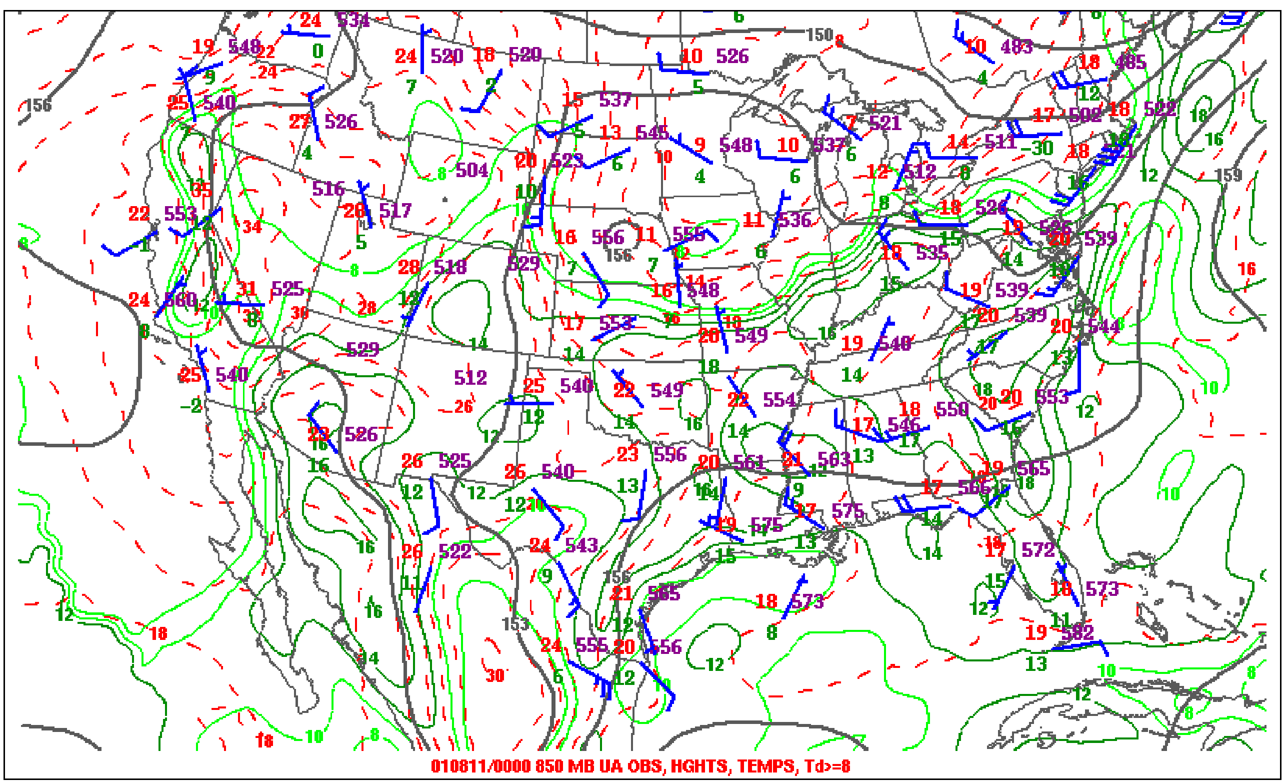


Figure 5-6(b). NWS 850 mb Constant Pressure Map for Afternoon of August 10, 2001

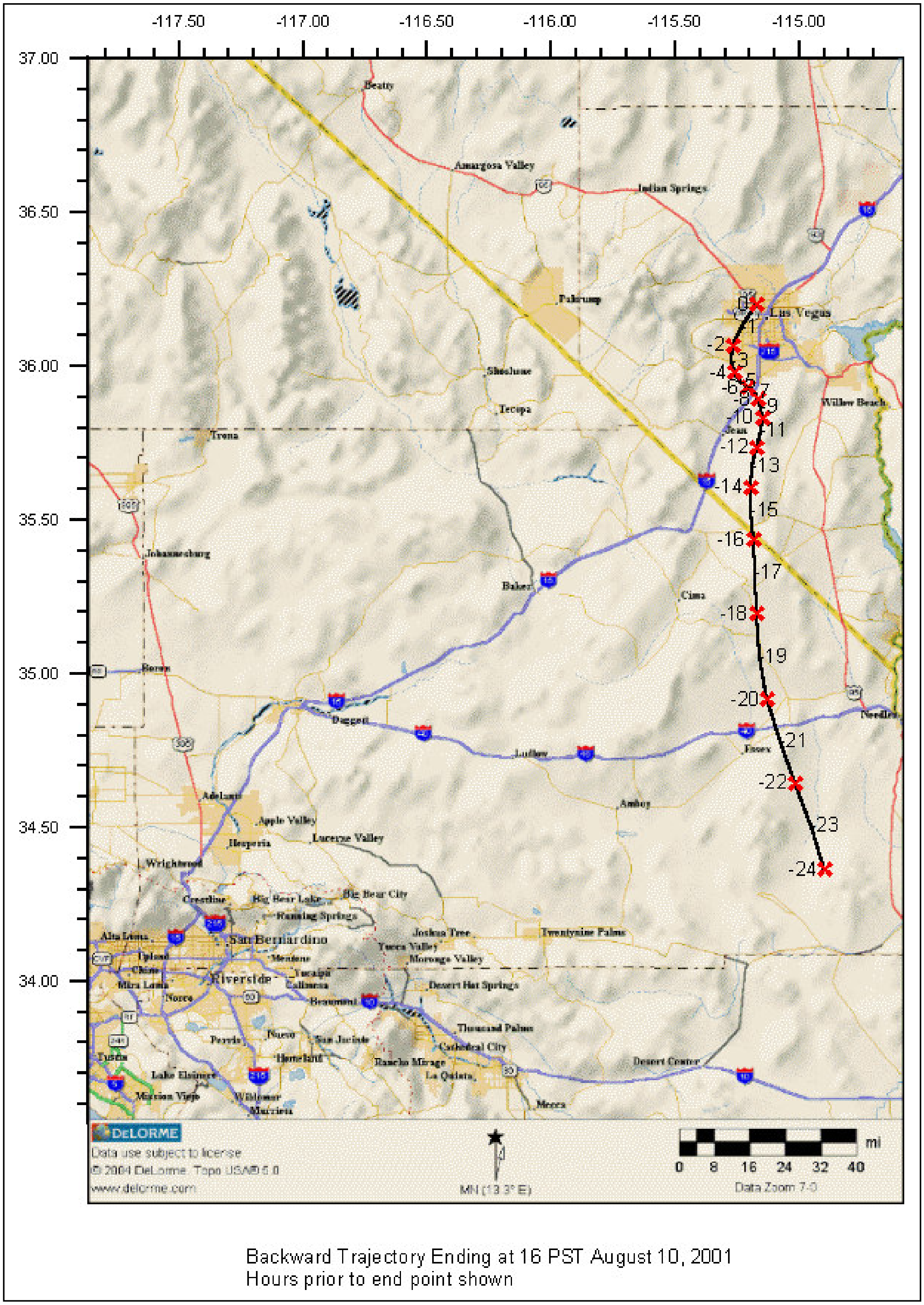
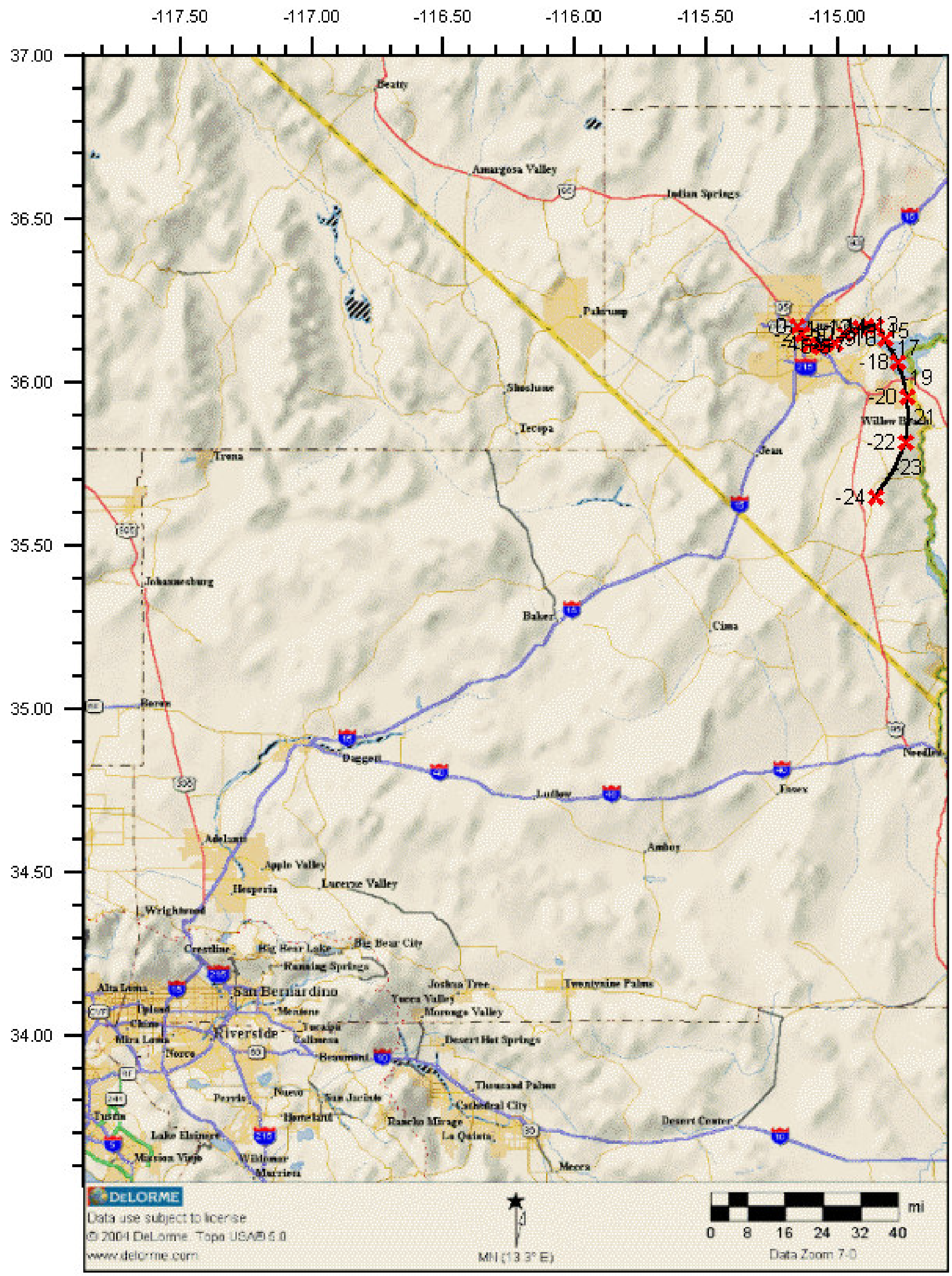


Figure 5-7. Backward Trajectory Ending at 16 PST, August 10, 2001



Backward Trajectory Ending at 16 PST August 11, 2001
Hours prior to end point shown

Figure 5-8. Backward Trajectory Ending at 16 PST, August 11, 2001

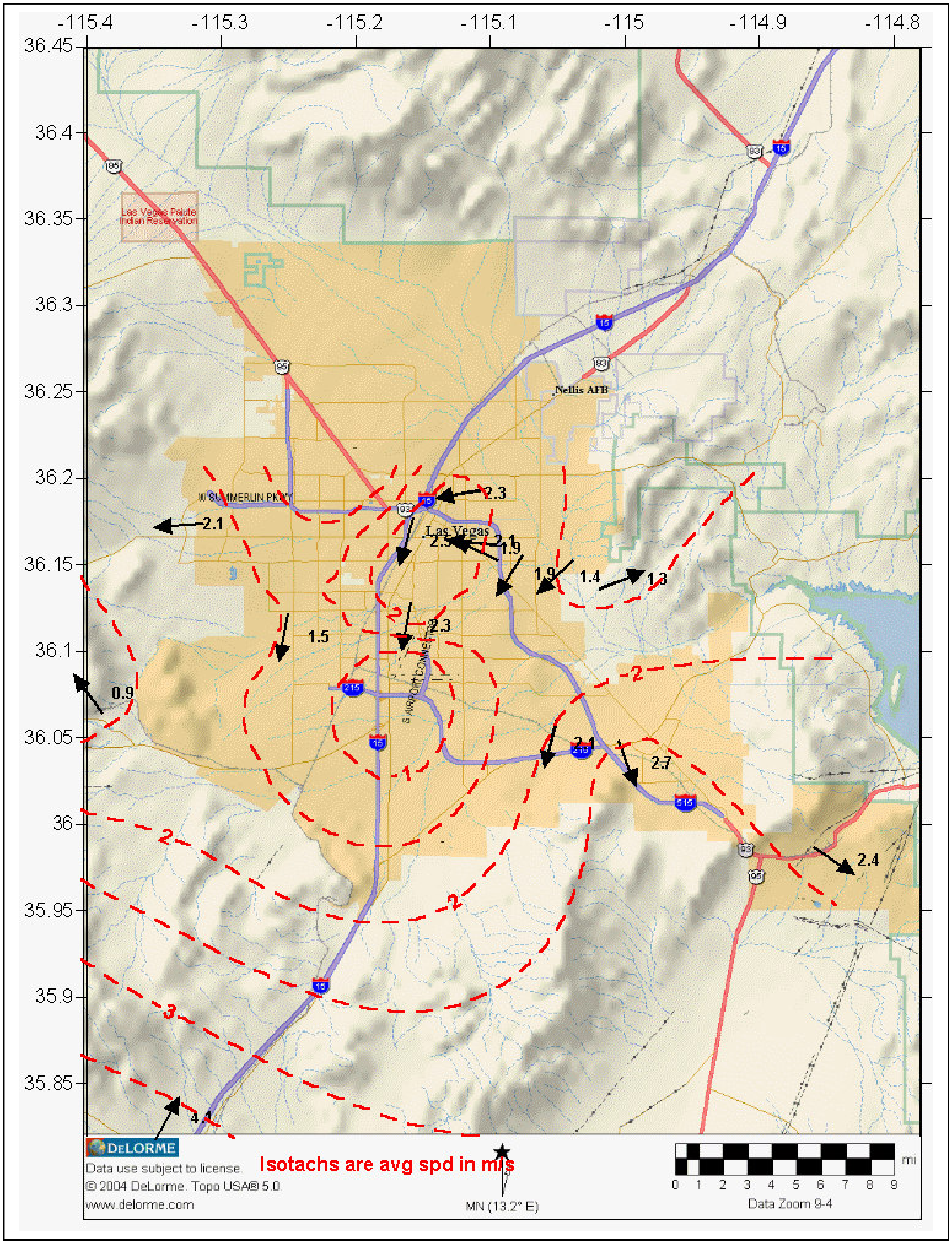


Figure 5-9. Las Vegas Valley Surface Winds at 16 PST on August 10, 2001

5.2 June 16, 2002 Episode

Ozone Levels

The Federal Ozone Standard of 85 ppb 8-hour running average was exceeded June 16, 2002. **Table 5-6** shows the daily maximum ozone at the Clark County monitoring network sites on the day prior, the exceedance day, and day after. On the 16th, exceedances of the 8-hour standard were measured at five site; AP, CR, JD, JO, and WW. Charts showing the Las Vegas Valley and adjacent regions peak ozone spatial pattern are shown on **Figure 5-10**. The left panel shows daily maximum 8-hour averaged levels and contours of constant ozone. The right panel gives daily maximum 1-hour averaged levels, contours of constant ozone, and the time of the peak (PST). The spatial pattern for ozone peaks in this episode was unique relative to the other case studies in that the highest 8-hour peak for the episode was measured at Apex (90.5 ppb) and at Craig Road (89.9). Hourly peak levels were experienced in the north and northwest of downtown as well, although the maximum was measured at Joe Neal. Craig Road and Apex hourly peaks were very nearly as high. Both the 8-hour and 1-hour daily maximum spatial gradients tend to be from lower values in the southwest to higher values in the northeast.

An interesting feature of this episode is the relatively high background ozone levels throughout the California desert and Clark County. Time-series plots of hourly ozone levels over June 14 to 15 are shown on **Figure 5-11**. Ozone at Victorville (VICT) and Joshua Tree (JSN) are particularly high. Barstow, located on a known transport path between the South Coast and San Joaquin Valley air basins, measured ozone in excess of 95 ppb. Even Death Valley (DVL) and Jean measured persistent ozone in the 70 to 80 ppb range. As will be discussed further, the meteorology supports interbasin transport during the period.

Table 5-6. Maximum 8-Hour Ozone (ppb) – Case Study 2

Site Name	Site ID	6/15/02	6/16/02	6/17/02
Apex	AP	83.1	90.5	81.3
Boulder City	BC	81.5	82.9	81.4
E Craig Rd	BS	78.5	89.9	77.8
City Center	CC	63.5	76.0	63.1
JD Smith	JD	74.5	85.9	76.5
Jean	JN	71.9	79.3	81.5
Joe Neal	JO	72.9	88.1	84.4
Lone Mt	LO	59.5	74.9	19.8
Mesquite	MQ	71.6	76.8	69.5
SE Valley	PL	77.6	82.6	75.8
Paul Myer	PM	65.3	79.0	78.9
Palo Verde	PV	68.9	80.1	79.0
Searchlight	ST	71.4	75.9	70.0
Walter Johnson	WJ	64.5	78.8	76.0
Winterwood	WW	76.0	86.6	77.6
Network Max		83.1	90.5	84.4
# Sites Exceeded		0	5	0

Meteorology

The synoptic pattern at the 500 mb level on June 16, 2002 showed an Interior Ridge (IR) of high pressure with a rather well-defined axis situated over Nevada and the Great Basin. The ridge developed over the region during the 15th, having evolved from a flatter configuration the day before. **Figure 5-12(a & b)** shows the NWS 500 mb constant pressure maps for the afternoons of the 15th and 16th. The peak 500 mb heights were located well south of Nevada over the Gulf of California during the period, while the northward extending axis of the ridge migrated slowly from west of Las Vegas on the 15th to east of the area on the 16th. During both days, winds at the 500 mb level over the Desert Rock upper-air site were west-northwesterly and moderately strong at around 18 m/s, and the 500 mb heights remained higher than 5,900 m. By the morning of the 17th, 500 mb heights were starting to drop as the center of the ridge consolidated over the central Gulf of California, and a more zonal flow configuration sunk into Nevada from the northwest.

Below the 500 mb level, the general interior ridging configuration, with the center of the high well south over the northern Gulf of California, was also apparent. **Figure 5-13(a & b)** shows the NWS constant level charts for the 700 mb and 850 mb levels during the morning of the 16th. The 700 mb temperature over Desert Rock at that time was 15.0^{o} C, compared to 13.1^{o}C 24 hours before. The warmest 700 mb temperatures on the map were located in a pocket over southern California and Nevada, and western Arizona. Wind flow at that level over the Desert Rock site was southeasterly at around 25 knots.

Just above the surface at 850 mb the general high pressure ridge, with the center over central Baja, was still discernable, and the warm air pocket over southern Nevada was also apparent in **Figure 5-13(b).** A thermal trough is indicated on the morning of the 16th, with an axis that runs from the Death Valley area in California north northeastward over southern Nevada and into western Utah. With the axis of the trough just north and west of the Las Vegas Valley, rather strong low-level southwesterly winds (20 to 40 knots) were recorded at the Desert Rock NWS site at about 220 m to 430 m above the ground, providing a mechanism for interbasin transport.

The air parcel backward trajectory from downtown Las Vegas shown on **Figure 5-14** was constructed using the HYSPLIT Model. The trajectory depicts the prior 24-hour movement of a surface (10 m) parcel of air beginning at 16 PST when peak ozone levels are commonly measured. The number of hours prior to 16 PST is posted along the trajectory. As can be seen, the trajectory originates 24 hours earlier near the town of Mojave at the outlet of Tehachapi Pass. Several studies have identified Tehachapi Pass as a major transport corridor from the heavily polluted southern San Joaquin Valley to the desert. It is suspected that the high ozone levels at sites downwind of the South Coast Air Basin contributed to high background levels in Clark County as well.

An examination of the local afternoon winds on June 16 tend to support the higher ozone levels at Craig Road and Apex as opposed to the more typical peak in the northwest quadrant of the Valley. The 16 PST surface winds shown on **Figure 5-15**, although highly localized, show transport to the northeast from downtown area at moderate speeds (3 to 4 m/s).

Mixing heights, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, was 2,850 m-agl—the lowest mixing height of the case study episodes.

Summary

- This was a one-day episode occurring on June 16 on which exceedances of the 8-hour ozone standard were experienced at five sites. The maximum level was 90.5 ppb measured at Apex. Levels at Craig Road were nearly as high (89.9 ppb).

- Relative to the other case study days, the spatial ozone pattern was not typical. Peak levels were experienced northeast of downtown Las Vegas rather than northwest. Local surface winds generally support transport of the urban plume northeast.

- This episode took place during a period categorized as IR (Interior Ridge). The center of the ridge was well south of southern Nevada and the northern axis was over or just east of the area. The air mass dominating southern Nevada was quite thermodynamically stable with warm air aloft prevailing. There is strong evidence of a thermal trough just northwest of the Las Vegas Valley during the early hours of the 16th. This feature may have induced some significant southwesterly flow just above the terrain in southern Nevada and eastern California.

- The HYSPLIT Model trajectory indicates transport from the San Joaquin Valley to Clark County. Ozone levels experienced in the California desert support transport from the South Coast and San Joaquin Valley air basins to the desert.

- June 16, 2002 fell into CART class Terminal Node 7. This terminal node is consistent with ozone transport to the Las Vegas Valley.

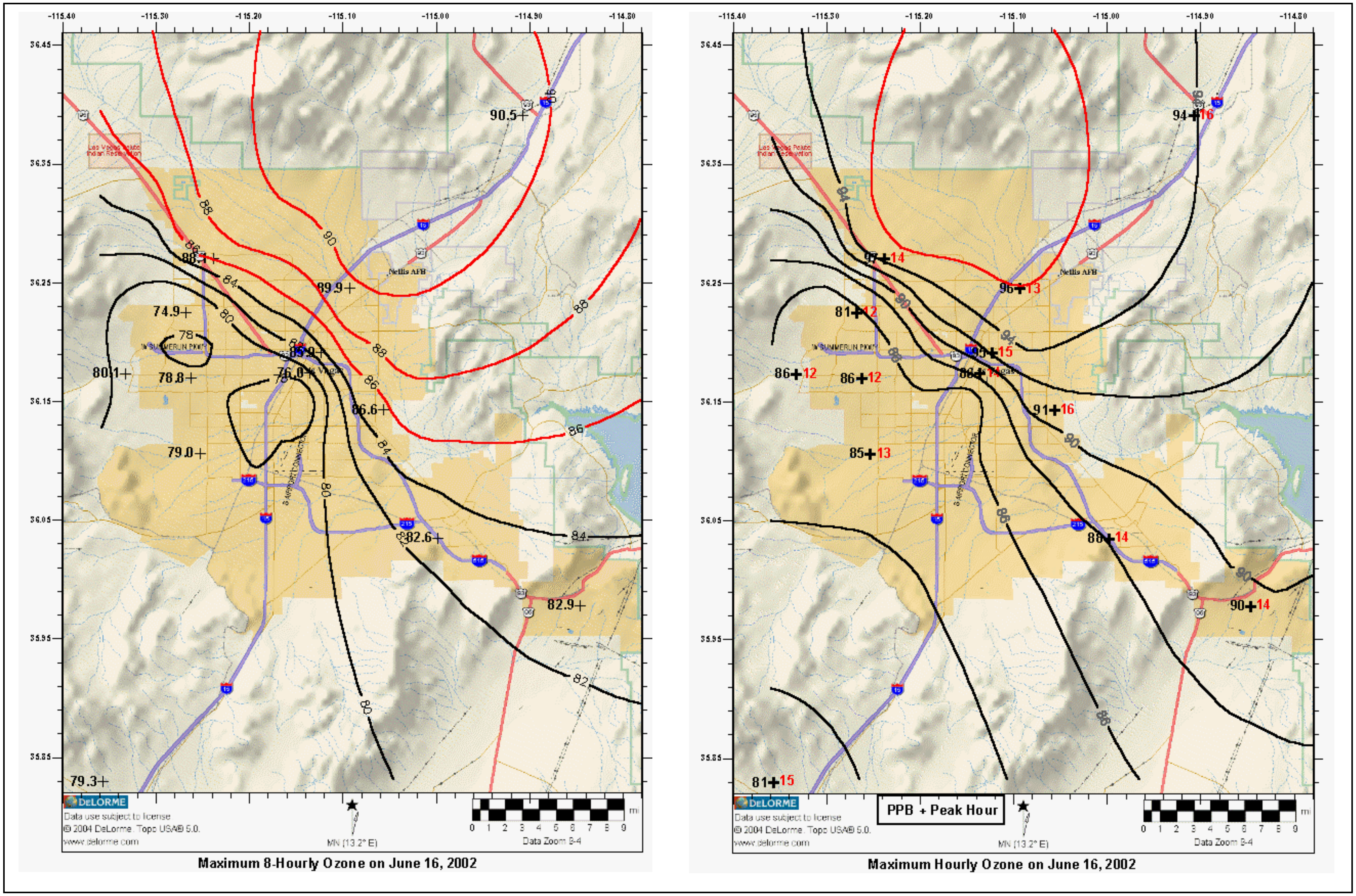


Figure 5-10. Peak Ozone for June 16, 2002

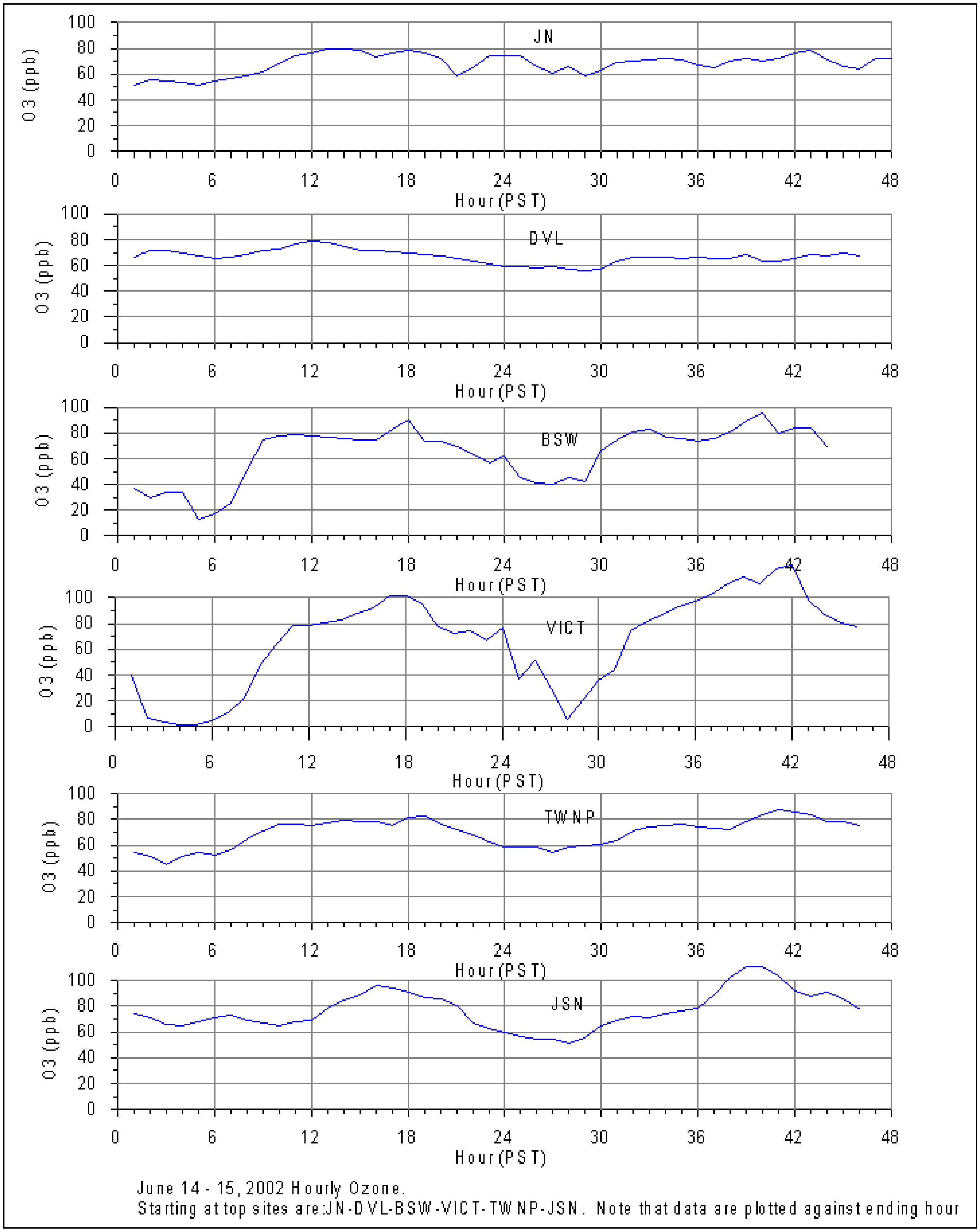


Figure 5-11. Hourly Ozone for June 14-15, 2002

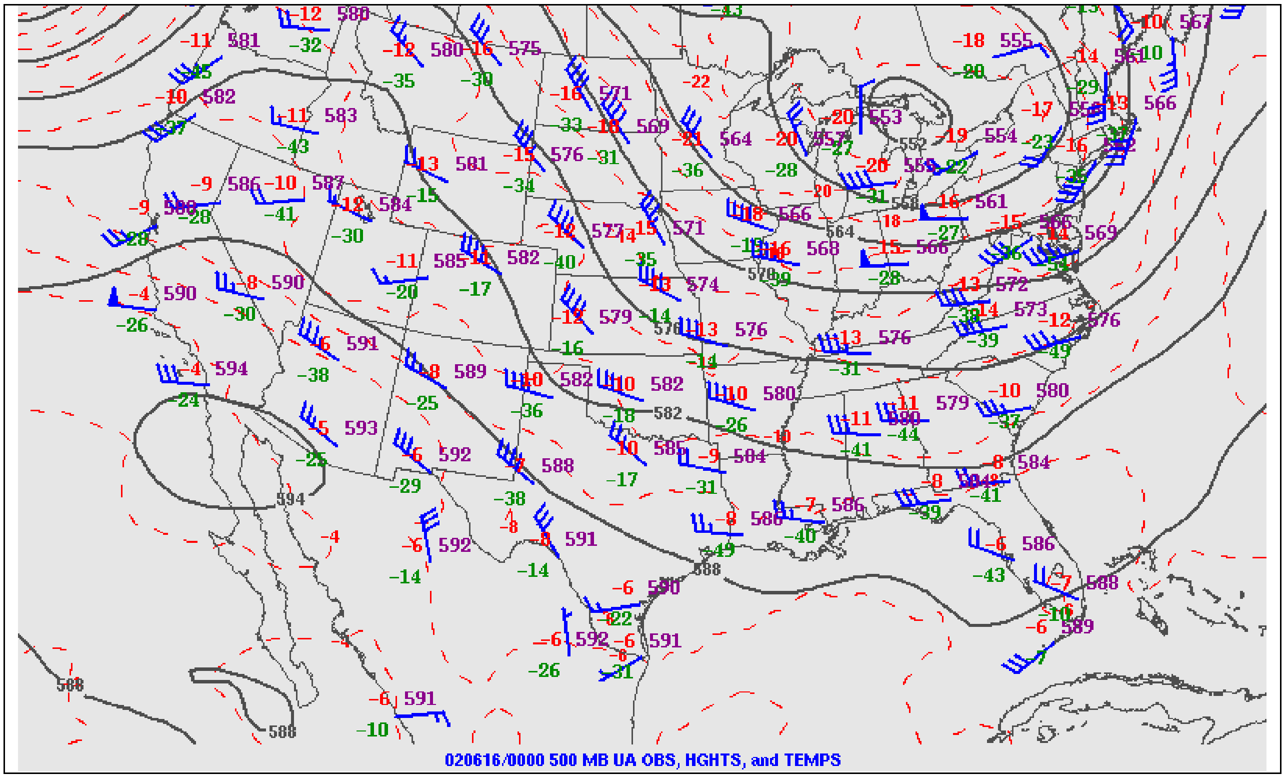


Figure 5-12(a). NWS 500 mb Constant Pressure Map for Afternoon of June 15, 2002

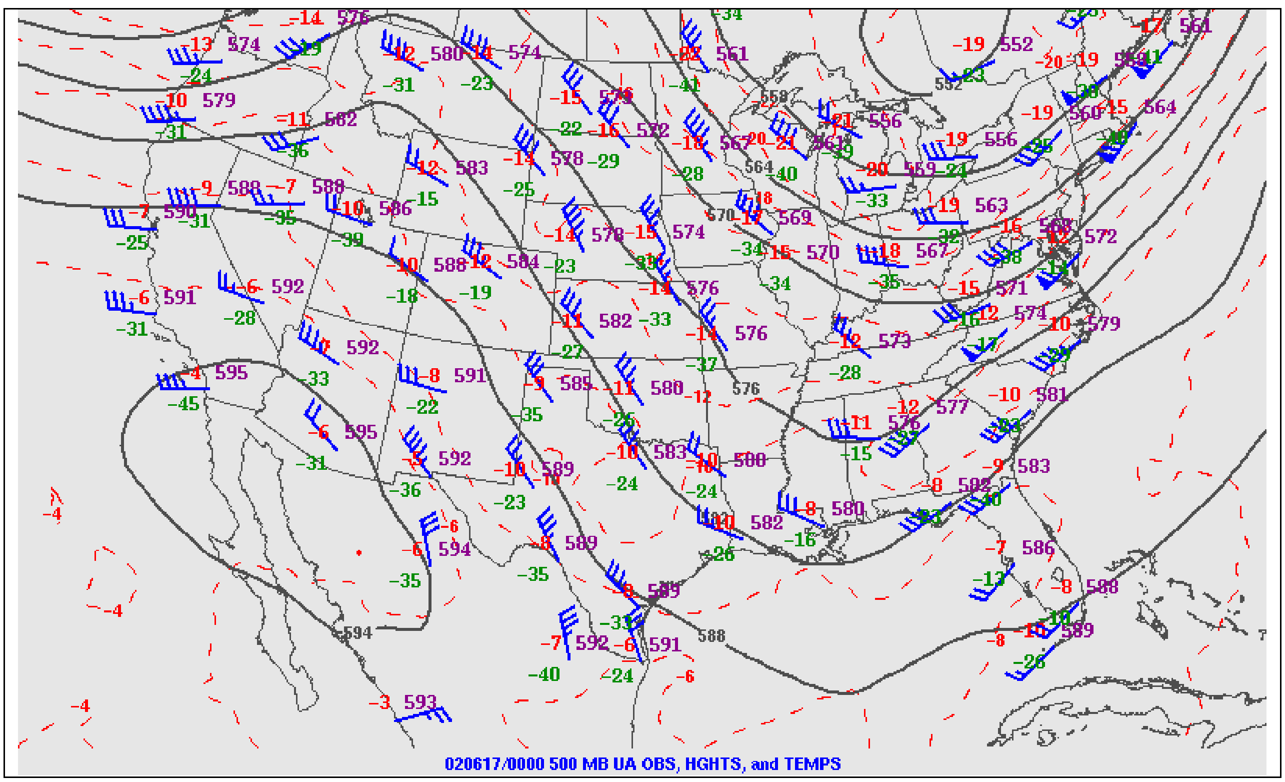


Figure 5-12(b). NWS 500 mb Constant Pressure Map for Afternoon of June 16, 2002

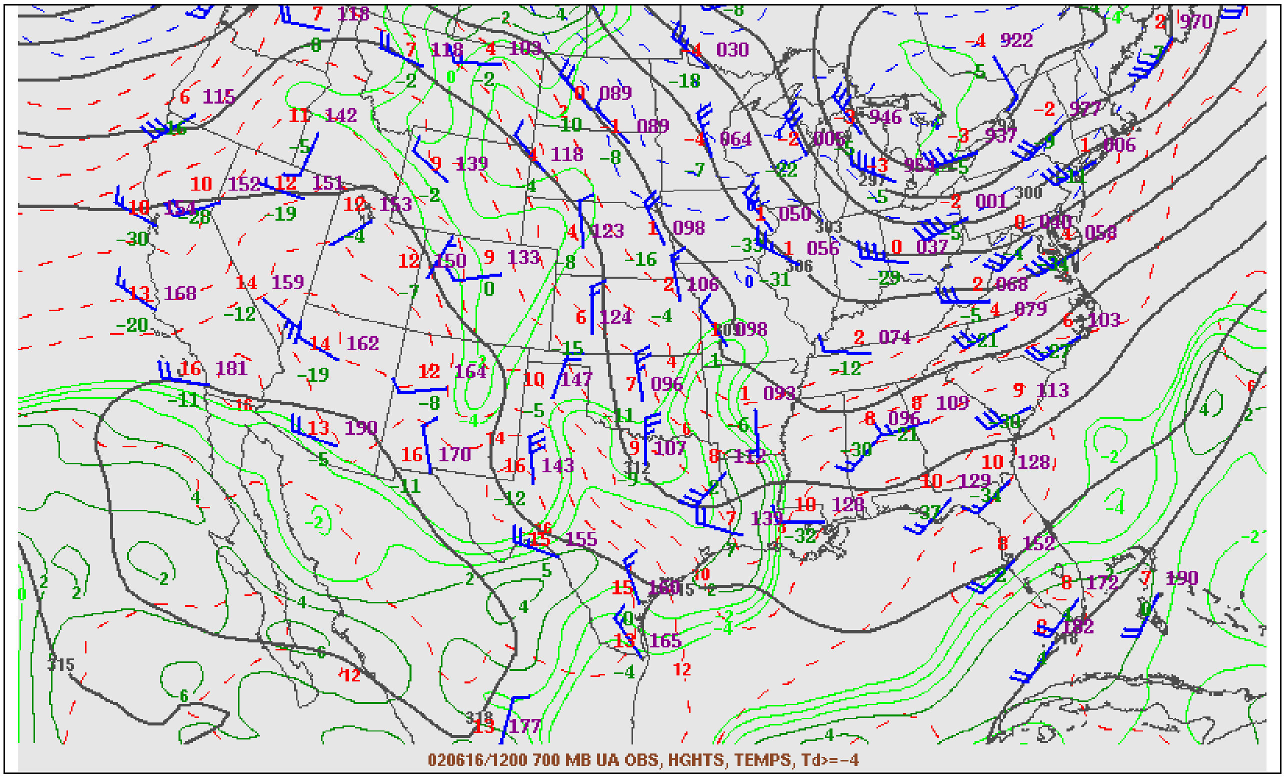


Figure 5-13(a). NWS 700 mb Constant Pressure for the Morning of June 16, 2002

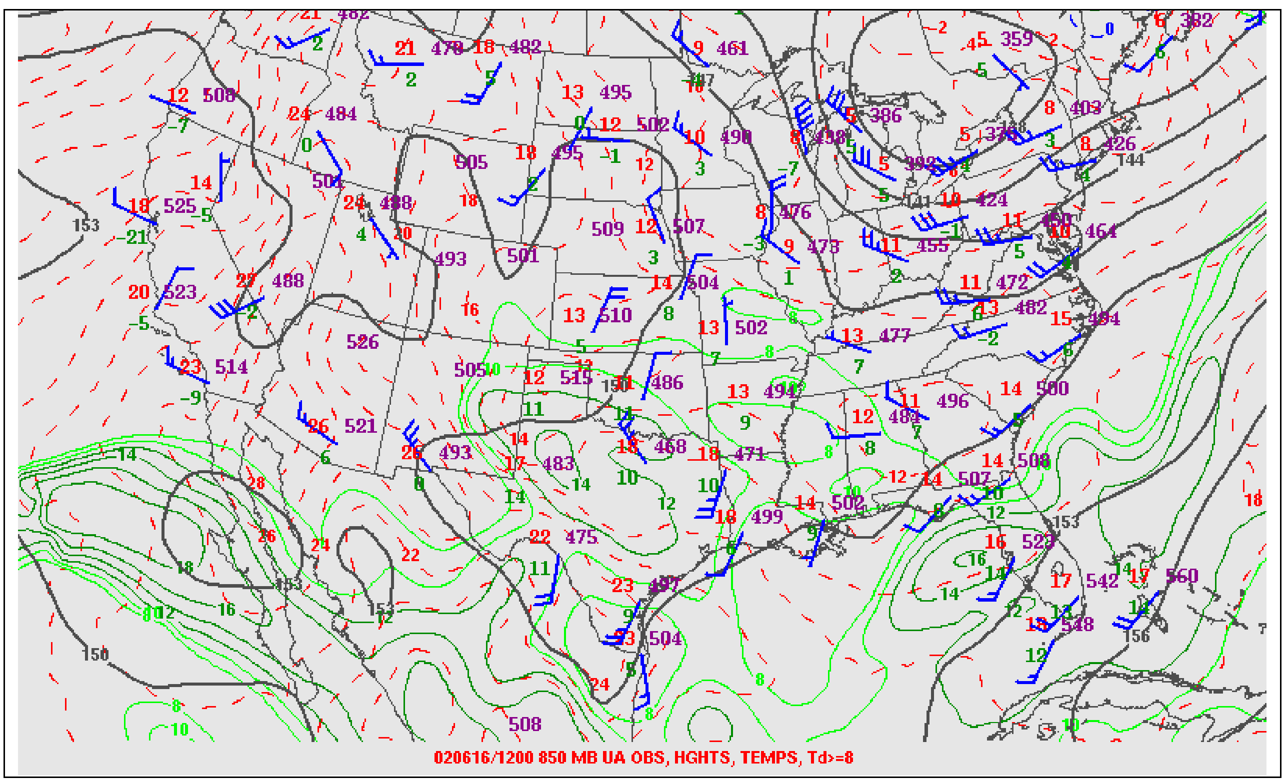


Figure 5-13(b). NWS 850 mb Constant Pressure for the Morning of June 16, 2002

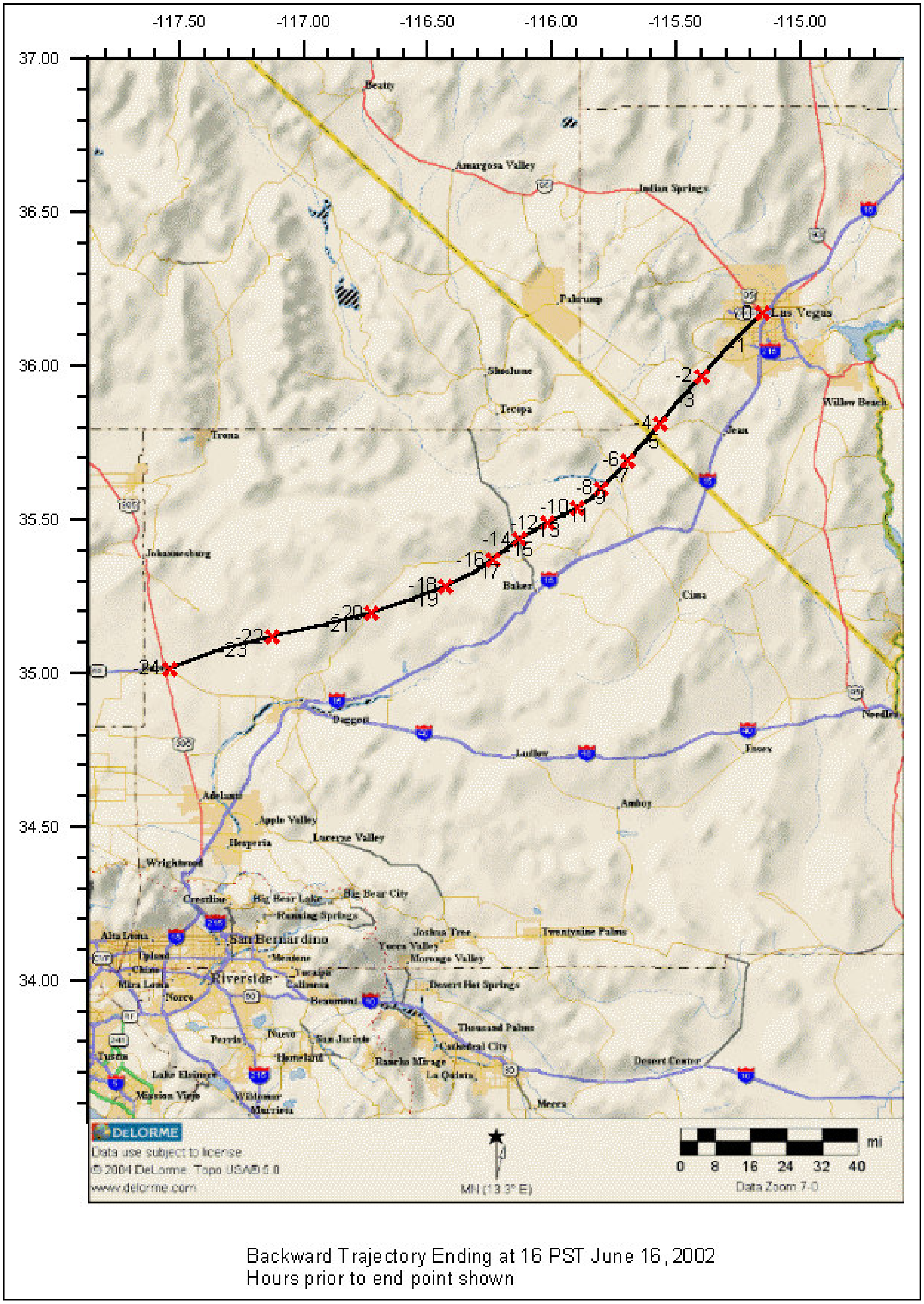


Figure 5-14. Backward Trajectory at 16 PST, June 16, 2002

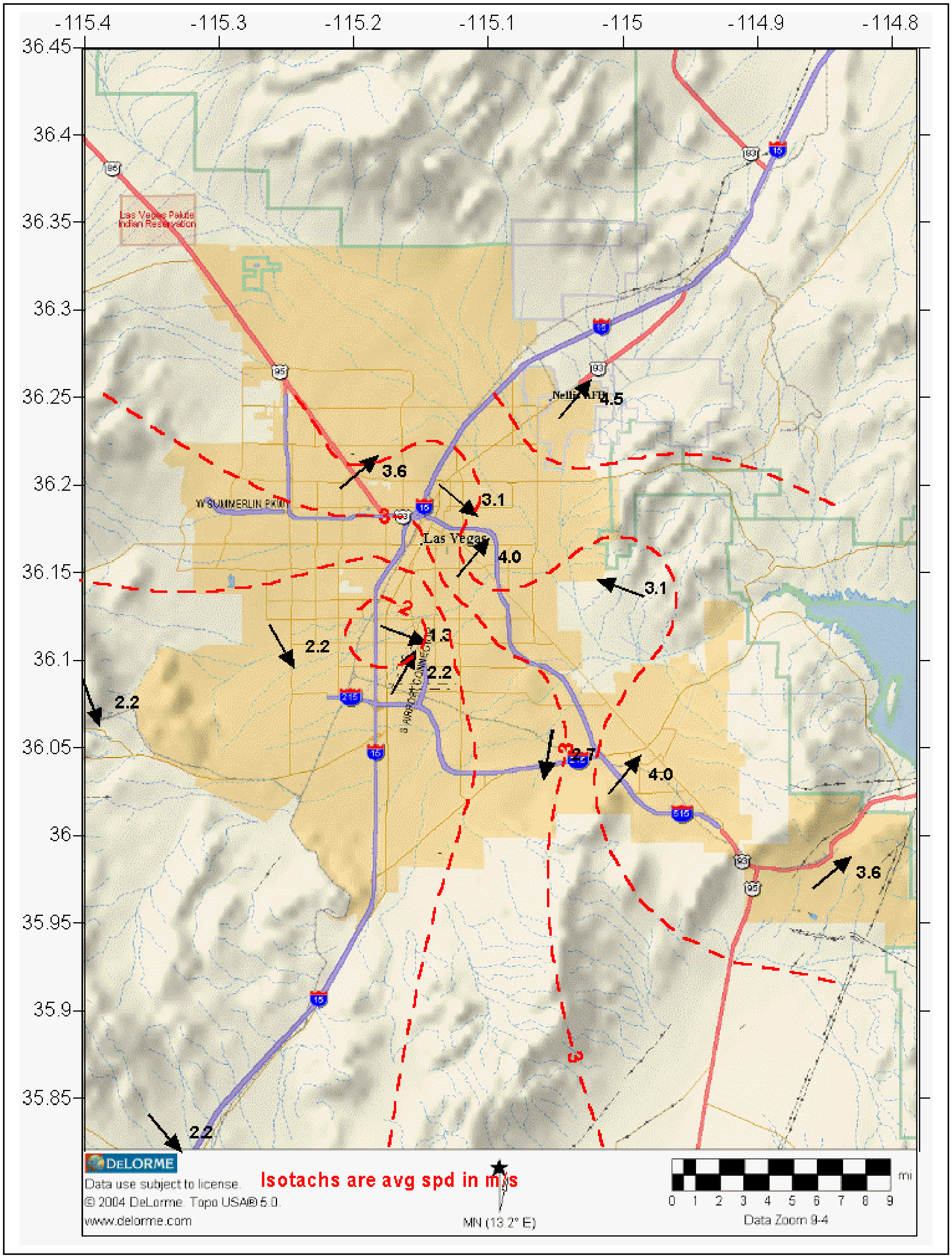


Figure 5-15. Las Vegas Surface Winds at 16 PST on June 16, 2002

5.3 June 27 to 28, 2002 Episode

Ozone Levels

Exceedances of the Federal Ozone Standard for 8-hour running average were experienced on both the June 27th and the 28th. **Table 5-7** shows the daily maximum ozone within the network of Clark County sites for the day leading up to the episode, the two exceedance days, and the following day. Ozone concentrations began building on the 26th, and after two days of exceedances the air quality improved substantially. Five exceedances occurred on the 27th and three on the 28th but in general ozone levels on the two days were remarkably similar. Peak 8 hour ozone concentrations were measured at Jean (93.3 ppb), Joe Neal (93.1 ppb), and Lone Mt (92.9 ppb) on the 27th, and at Jean (92.4 ppb) on the 28th. The similarities in Clark County ozone concentrations are graphically evident in the contour charts shown on **Figures 5-16** and **5-17** for June 27 and June 28, respectively. Gradients, maximum areas and minimum areas are nearly identical on both days for both for the 1-hour and 8-hour charts. On both days, the highest ozone levels were experienced on the west side of the Valley and at Jean. Minimum ozone levels are in the Las Vegas urban core.

The diurnal ozone trend on both days suggests significant contribution from layers aloft by fumigation. This is illustrated on the time-series charts shown on **Figure 5-18**. Hourly ozone readings for six select sites are given for the 48-hour period beginning at 01 PST on the 27th. Of particular interest are the two ozone peaks that occur on the 27th; one occurring 10 to 12 PST and a second in the late afternoon-early evening (18 to 20 PST). At some sites, the earlier peak is the maximum for the day (Craig Rd, JD Smith, Winterwood, Joe Neal for example). This bimodal feature is widespread, occurring from Jean to Apex (although not at the southern sites). Noteworthy is that neither peak occurred in the afternoon when ozone production is most active. At night and in the early morning of the 28th, ozone levels decrease to near zero at the sites in the urban core. Jean's ozone levels remained at 60 ppb or higher; similar to the previous morning. Early (pre-noon) ozone peaks of similar magnitude occurred again on the 28th in Clark County. Thereafter, ozone levels decreased for the remainder of the day. It is hypothesized that the early ozone peaks on both days were the result of layers aloft mixing down to the ground as the new boundary layer developed. Due to the absence of any air quality or meteorological measurements aloft, this cannot be confirmed. The source of the ozone is discussed below.

Table 5-7. Maximum 8-Hour Ozone (ppb) – Case Study 3

Site Name	Site ID	6/26/02	6/27/02	6/28/02	6/29/02
Apex	AP	66.9	77.5	79.5	70
Boulder City	BC	64.3	84.6	76.1	67.75
E Craig Rd	BS	57.8	82.6	79.3	70.63
City Center	CC	42.8	77.0	68.6	64.13
JD Smith	JD	57.6	83.8	80.4	68.13
Jean	JN	71.9	93.3	92.4	74.75
Joe Neal	JO	58.5	93.1	87.2	71.63
Lone Mt	LO	56.4	92.9	86.4	71.38
Mesquite	MQ	55.1	60.3	71.5	61.5
SE Valley	PL	64.3	87.5	75.9	67.88
Paul Myer	PM	56.3	90.0	83.0	67.75
Palo Verde	PV	84.5	70.4	84.5	missing
Searchlight	ST	70.3	64.5	missing	missing
Walter Johnson	WJ	80.0	66.8	83.0	missing
Winterwood	WW	76.1	67.1	76.1	missing
Network Max		84.5	93.3	92.4	74.8
# Sites Exceeded		0	5	3	0

Meteorology

The predominant synoptic weather feature operating during the ozone episode of June 27 and 28, 2002 was a broad, fairly flat high-pressure ridge covering most of the Western U.S. The ridge configuration is best illustrated by the 500 mb level (~18,000 ft). **Figures 5-19(a&b) and 5-20(a&b)** show the NWS 500 mb constant pressure maps for the afternoons of June 26 through June 29. Although the ridge was very broad and flattened, it did have a definitive long-wave ridge configuration with a definable axis, and it was confined to the interior west, east of the Sierra Nevada and Cascade Mountain ranges. As a result, the weather type for the entire period was classified as an Interior Ridge (IR). However, a weak Pacific trough, stretching the length of California, was another synoptic scale feature that became important on the 27th and 28th. This feature never crossed the Sierra into the interior, but it did influence the conditions over the Southwest by producing southerly flow aloft west of the axis of the IR ridge line. By the 29th, the trough disappeared from the maps, and the synoptic configuration had become flat.

Below the 500 mb level, general interior ridging in the West was the predominant feature, but the California trough was also quite distinctive. **Figure 5-21(a&b)** provides the constant pressure maps showing the 700 mb analyses for the mornings of June 27th and 28th. At that level, the trough appears to have entrained a bit further east than at 500 mb. The result was light southerly flow and probably some erosion of the thermodynamic stability associated with the interior ridge to the east. The 700 mb temperature over the Desert Rock rawinsonde site dropped about 1.0° C by the 27th from what it was on the 26th, indicating some destablization of the atmosphere.

Just above the surface at 850 mb, the California trough was also apparent. **Figure 5-22(a&b)** shows the constant pressure 850 mb maps for the mornings of the 27th and 28th. The maps show moderate southwesterly flow over southern Nevada on both mornings as the trough moved just east of the Sierra. Temperatures aloft dropped somewhat, but the 850 mb readings in the area were still high enough to maintain subsidence in the lower boundary layer and the capping stable layers in the interior valleys. The upper-air soundings at Desert Rock on both mornings showed 1000 m deep stable layers with southwesterly winds at 10 to 20 knots starting at several hundred meters above the ground.

Surface air mass trajectory analyses support interbasin transport, most likely from the San Joaquin Valley. Back-trajectories constructed using the HYSPLIT Model are shown on **Figures 5-23** and **5-24** for June 27th and 28th, respectively. Shown are trajectories ending at the surface in downtown Las Vegas at 13 PST and 12 PST, respectively, starting 24 hours earlier at 13 PST. As can be seen from the figures, the 12 PST trajectories are nearly identical on the two days. The trajectories originate 24 hours earlier near Boron, California, approximately 40 miles east of Tehachapi Pass.

Mojave peak ozone levels were 93 and 90 ppb, respectively for the 26th and 27th; Barstow 89 and 104 ppb; and Trona 88 and 93 ppb (see **Table 5-8**). These sites lie roughly along the estimated trajectory, and generally agree with the concentrations experienced at Jean. Mojave is situated on the lee side of Tehachapi Pass, a major transport route out of the San Joaquin Valley (Lehrman et al.,1999). Earlier studies of transport of pollutants from the South Coast and San Joaquin Valley to the desert (e.g., Smith et al., 1997) describe the regular convergence of flows from the two basins just south of Boron near Edwards Air Force Base. Thus, it is also possible that pollutants from the South Coast air basin— transported via Tejon Pass and Soledad Canyon through the Antelope Valley—contributed in part or in total to the high desert background levels. Note that Death Valley experienced ozone levels comparable to Jean.

Table 5-8. Maximum 1-Hour Ozone and Time of Maximum at California Desert Sites and Jean

Date	**06/26/02** (ppb/PST)	**06/27/02** (ppb/PST)	**06/28/02** (ppb/PST)
Jean	82/24	96/11	94/10
Mojave	93/18	90/16	83/15
Barstow	89/16	104/17	105/17
Trona	88/12	93/12	100/13
Death Valley	78/20	86/12	96/13
Twentynine Palms	70/9	94/17	91/16
Victorville	83/15	116/12	98/12
Joshua Tree	103/17	100/15	104/17

(Note: On June 27, ozone shown for JN was secondary max. At 16 PST ozone reached 99 ppb.

The regional winds shifted from the morning to afternoon on the 28th, corresponding to the end of the episode. The afternoon (16 PST) backward trajectory also shown on Figure 5-24 is characterized by a southerly fetch over the previous 12 hours as opposed to the southwesterly fetch during the episode.

Mixing heights, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures ranged from 4,700 m-agl on the 27th to 5,000 m-agl on the 28th.

Summary

- This was a 2-day episode occurring on June 27 to 28. Exceedances of the 8-hour ozone standard were experienced at five sites on June 27 and at three sites on June 28. Maximum ozone levels in the 92 to 93 ppb range were measured at Jean and Joe Neal sites on both days.

- The spatial ozone patterns on the two episode days were nearly identical both in terms of major features and absolute levels.

- A major feature of the diurnal ozone levels was the bimodal peaks at Jean and sites in the northern half of the network. At many sites, the early peak, occurring prior to noon, was the daily maximum. This early peak may be indicative of high ozone concentrations aloft contributing to the high surface concentrations.

- Although this episode took place during a period categorized as IR (Interior Ridge), a weak trough to the west in California apparently influenced the flow aloft and the stability characteristics in southern Nevada on the 27th and 28th. The resultant moderate southwesterly flow just above the ground during both mornings provided for a transport mechanism from west of the area. At the same time, the influence of the trough may have weakened valley stability somewhat, but not enough to trigger significant thermodynamic mixing in the lower atmosphere.

- The HYSPLIT Model trajectory indicates transport again from the San Joaquin Valley to Clark County on both days. The timing of the peaks and regional winds suggest interbasin transport was a major contributor to the ozone burden in Clark County during this episode, although there are no upper-air measurements to support this.

- Both days fell into CART class Terminal Node 7. This terminal node is consistent with ozone transport to the Las Vegas Valley.

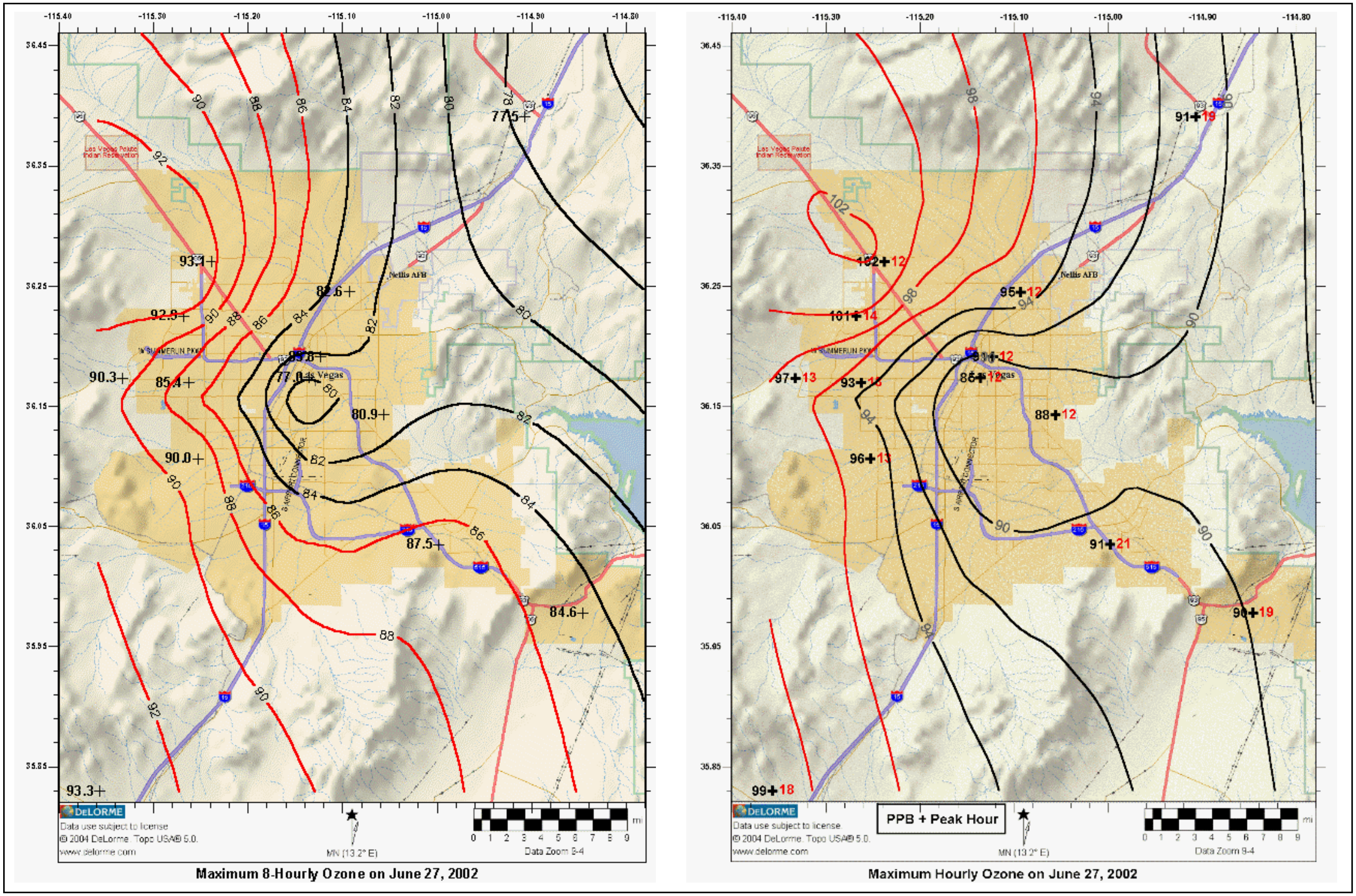


Figure 5-16. Peak Ozone for June 27, 2002

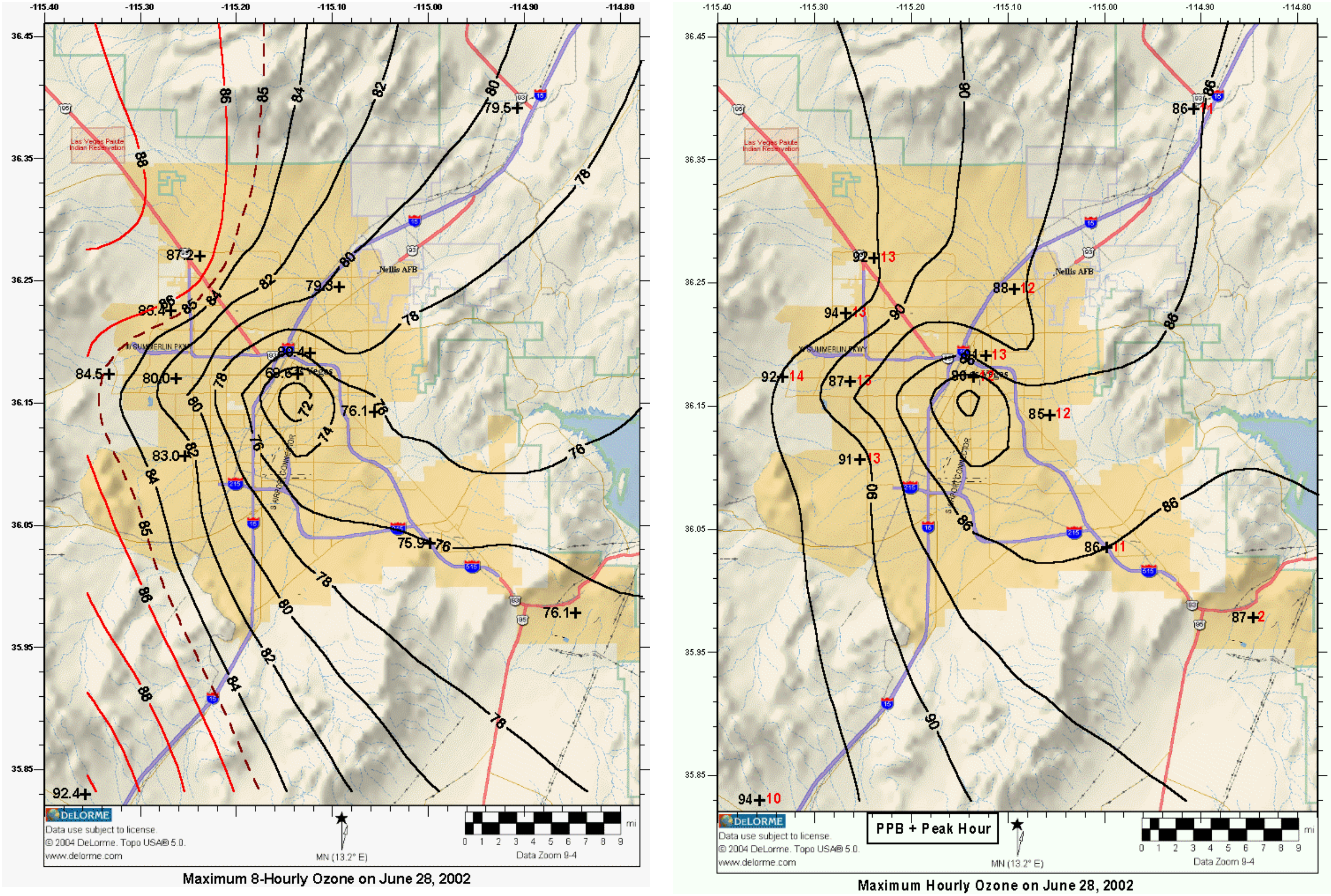


Figure 5-17. Maximum 8-Hour and Hourly on June 28, 2002

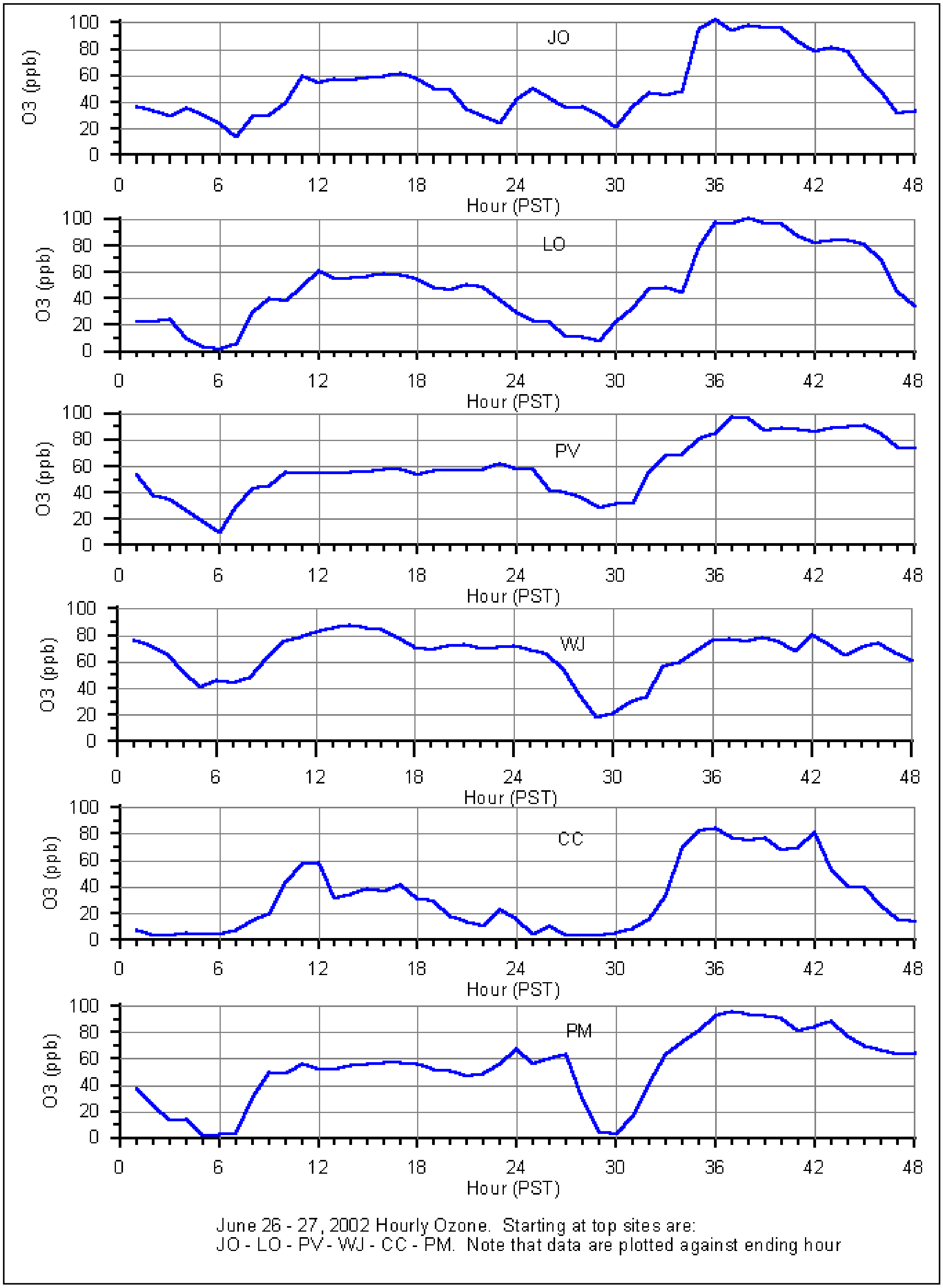


Figure 5-18. Hourly Ozone for June 26-27, 2002

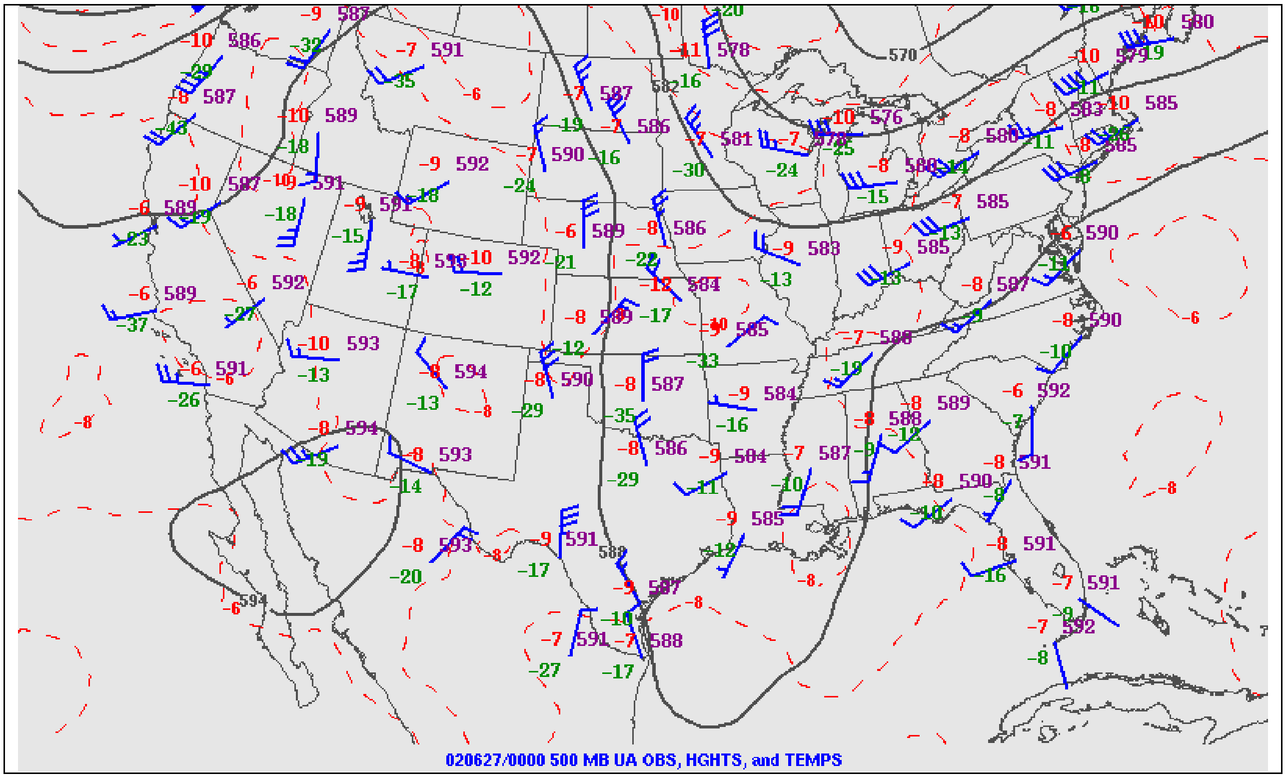


Figure 5-19(a). NWS 500 mb Constant Pressure Map for Afternoon of June 26, 2002

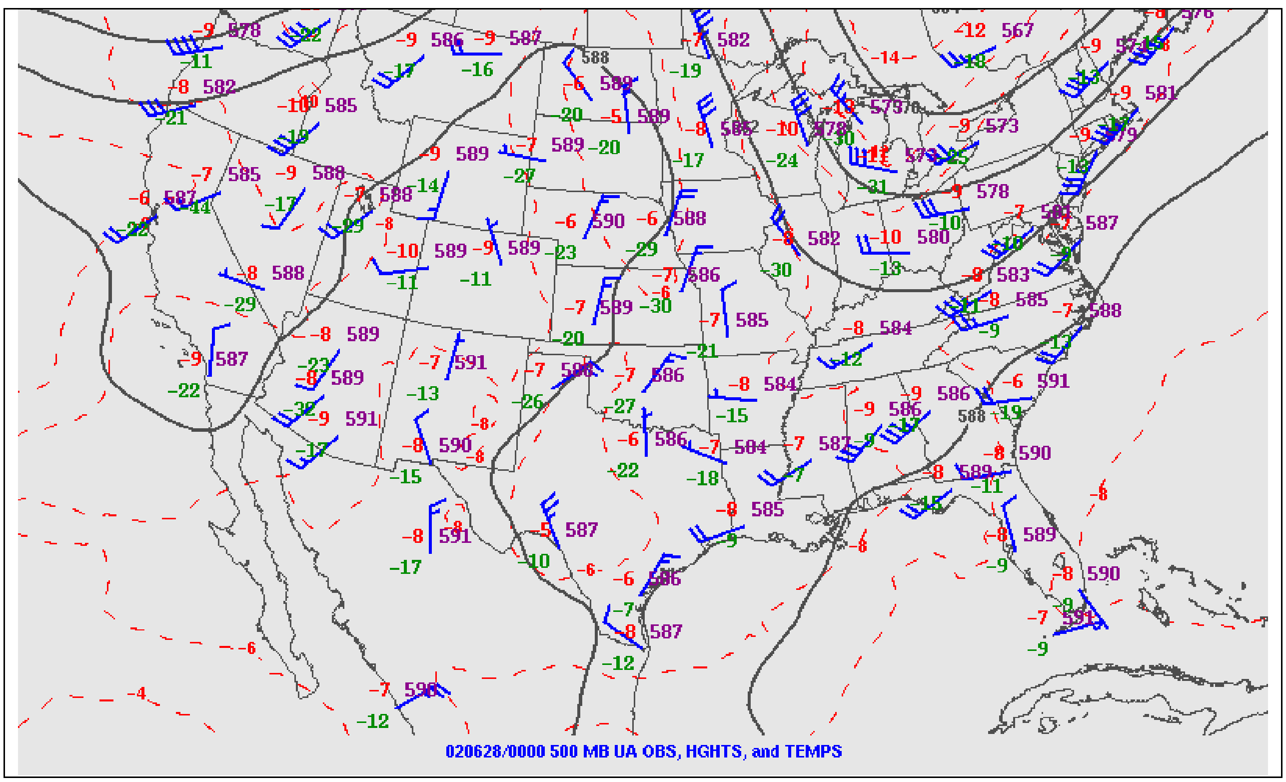


Figure 5-19(b). NWS 500 mb Constant Pressure Map for Afternoon of June 27, 2002

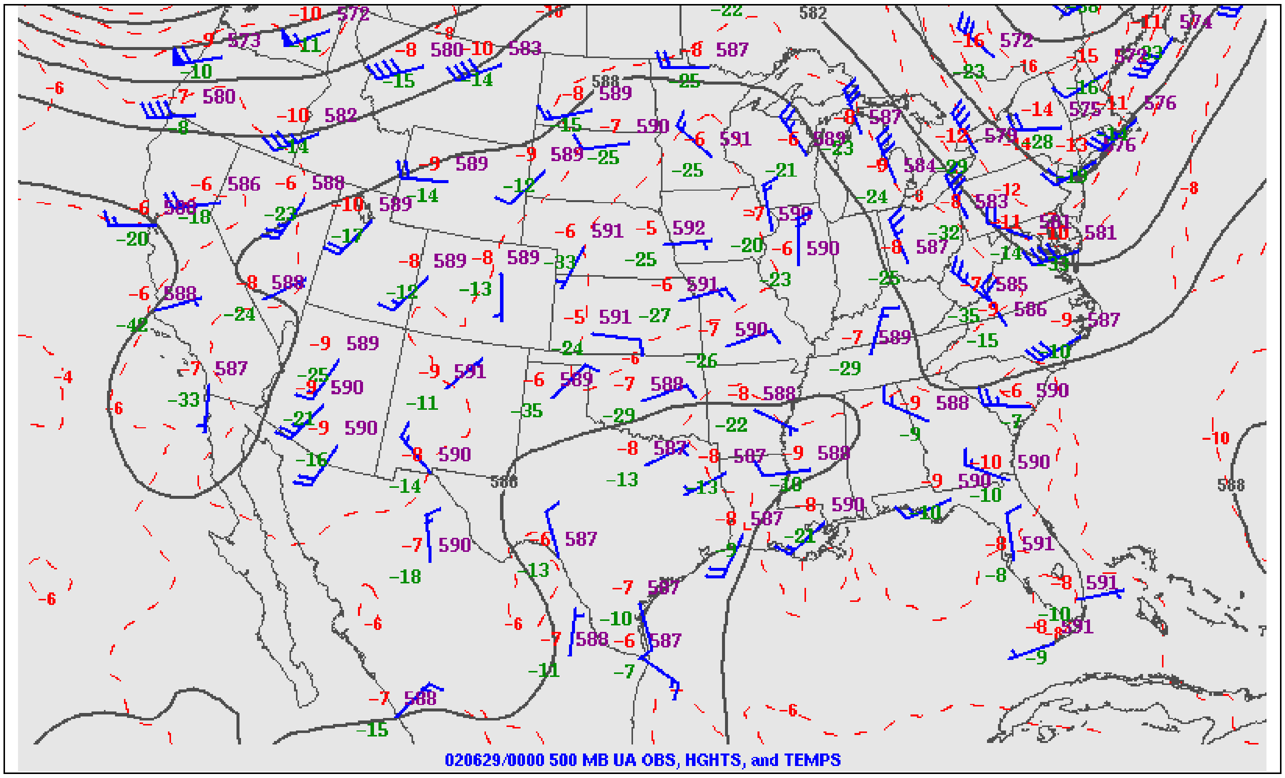


Figure 5-20(a). NWS 500 mb Constant Pressure Map for Afternoon of June 28, 2002

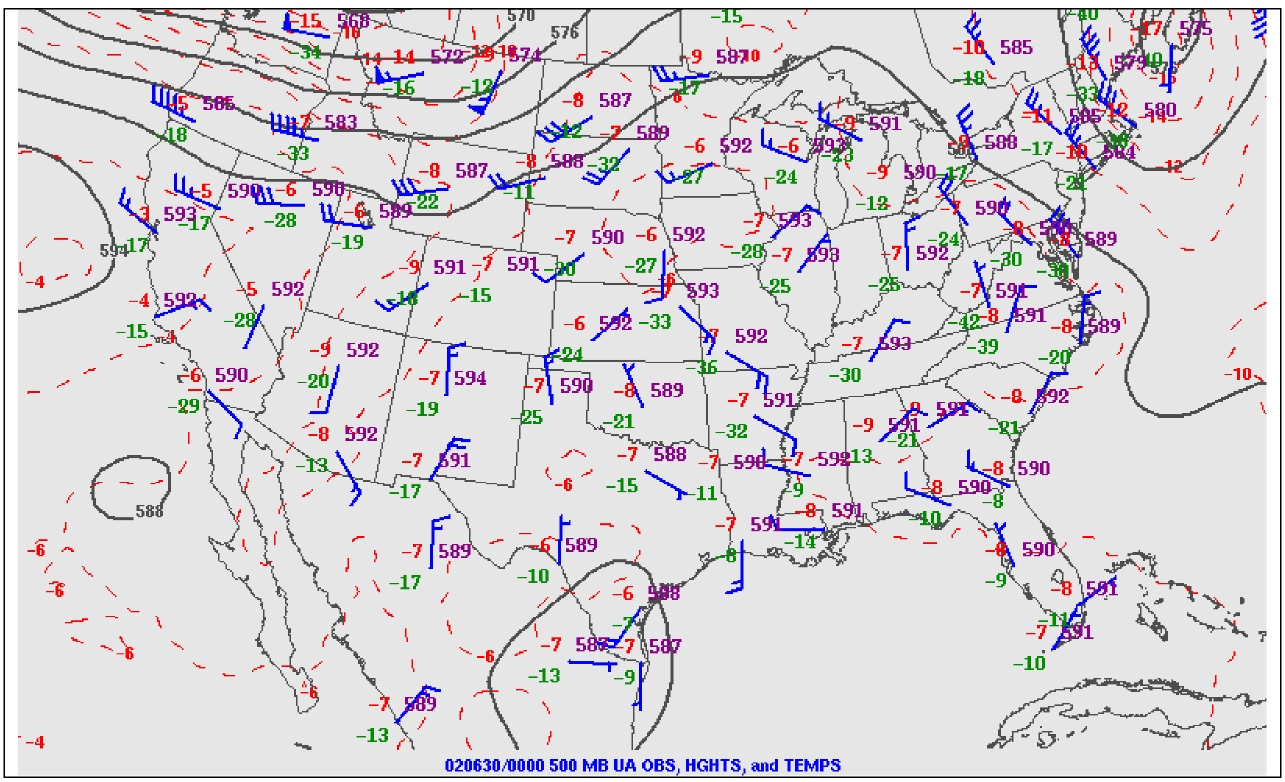


Figure 5-20(b). NWS 500 mb Constant Pressure Map for Afternoon of June 29, 2002

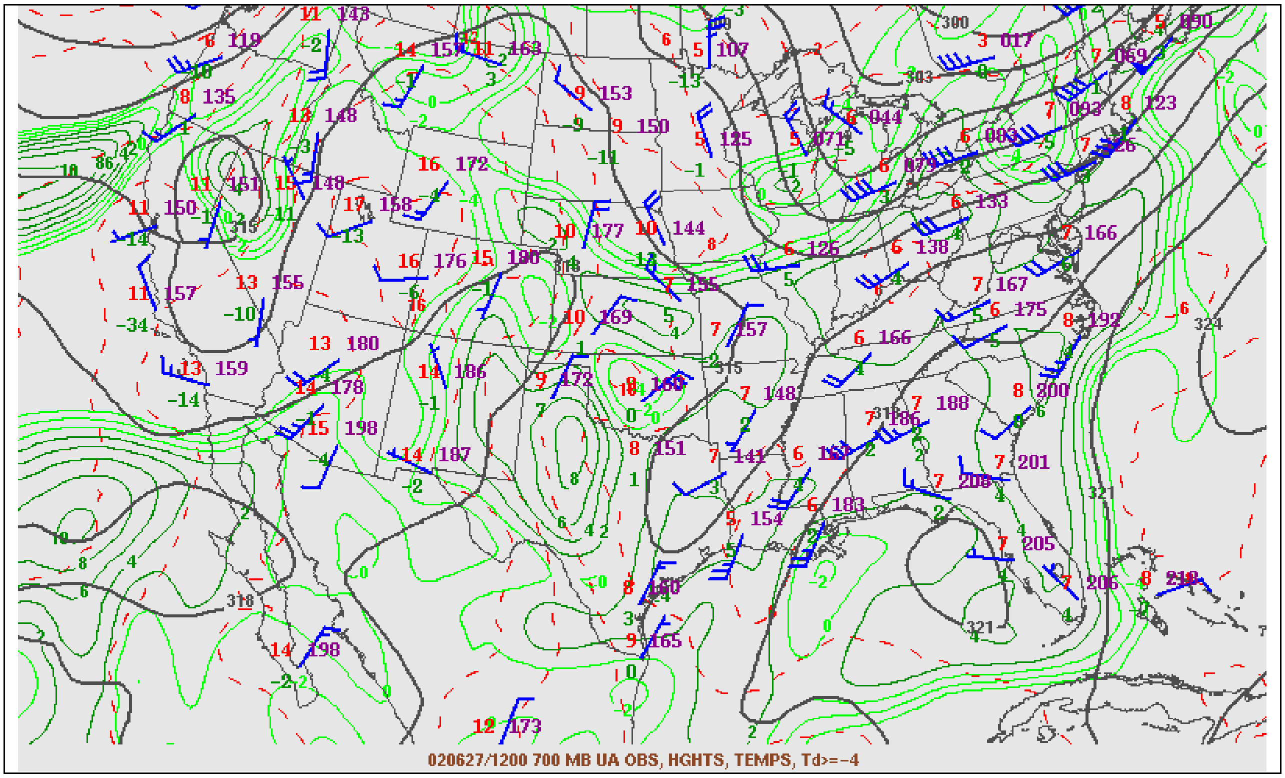


Figure 5-21(a). NWS 700 mb Constant Pressure Map for Morning of June 27, 2002

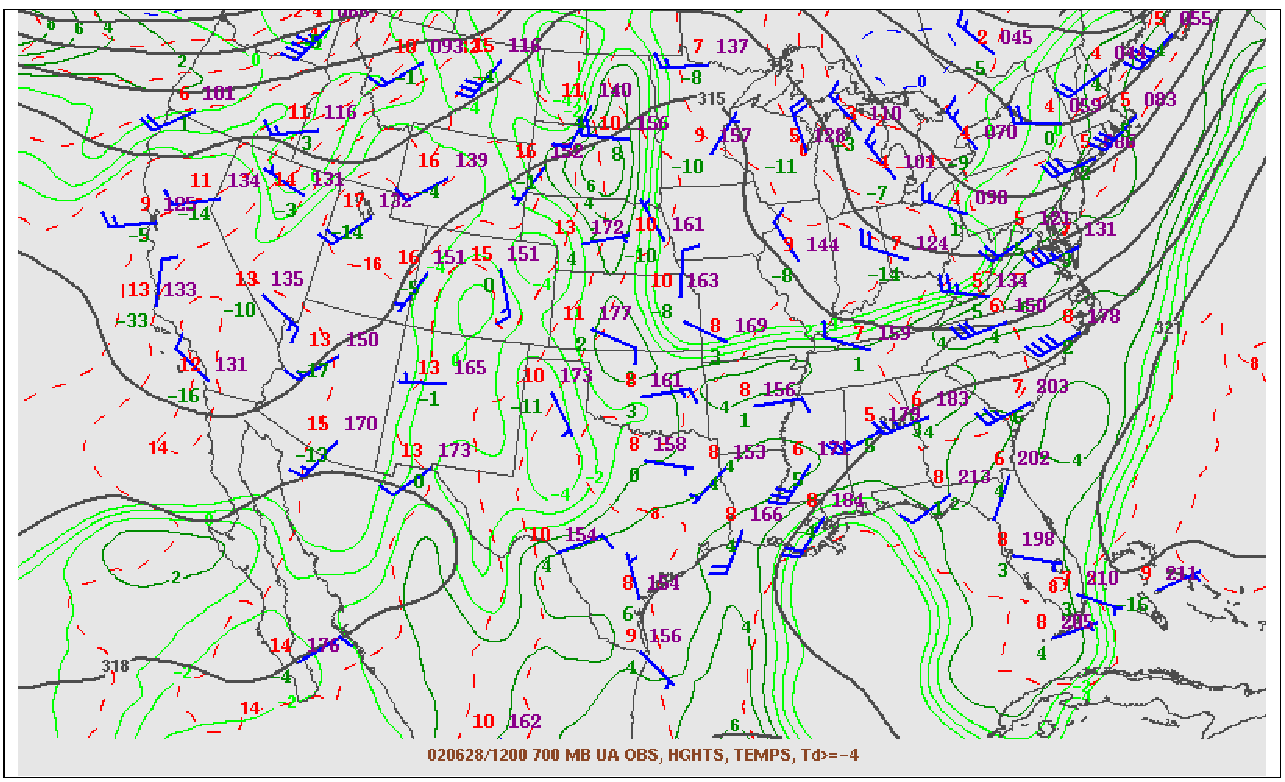


Figure 5-21(b). NWS 700 mb Constant Pressure Map for Morning of June 28, 2002

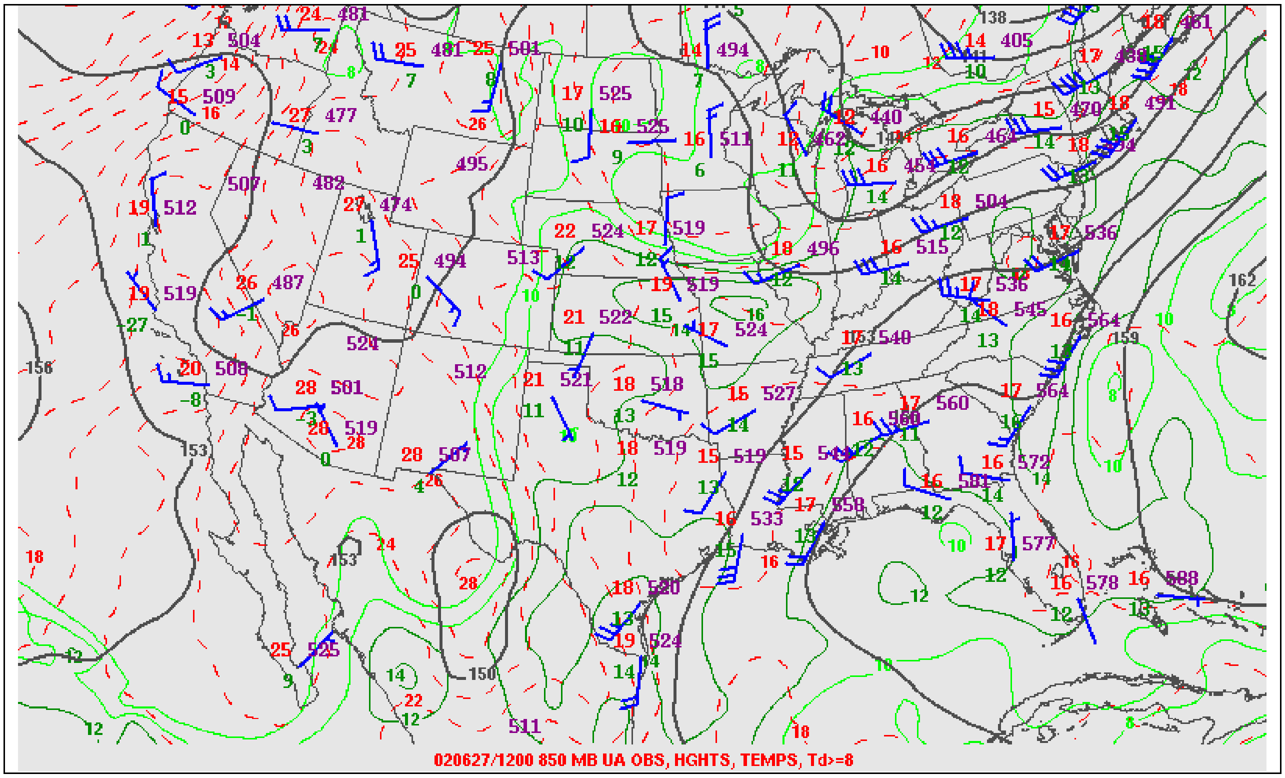


Figure 5-22(a). NWS 850 mb Constant Pressure Map for Morning of June 27, 2002

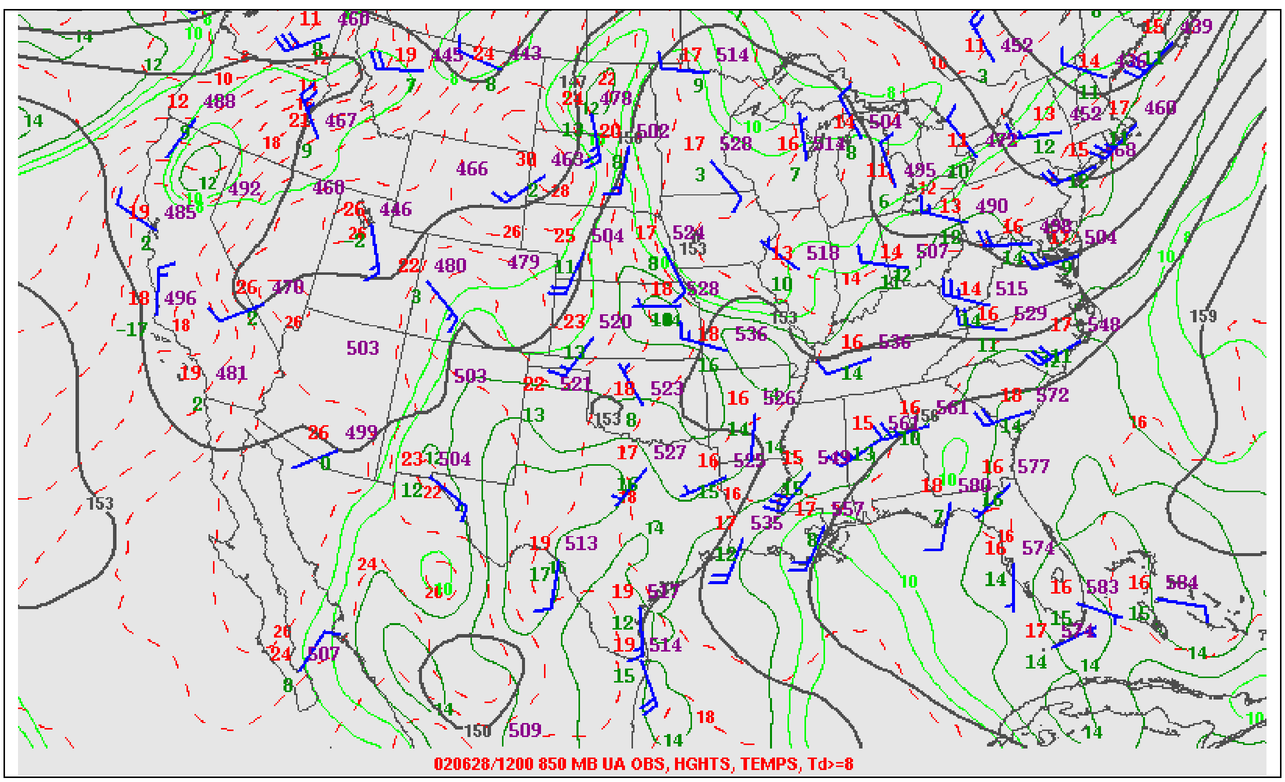


Figure 5-22(b). NWS 850 mb Constant Pressure Map for Morning of June 28, 2002

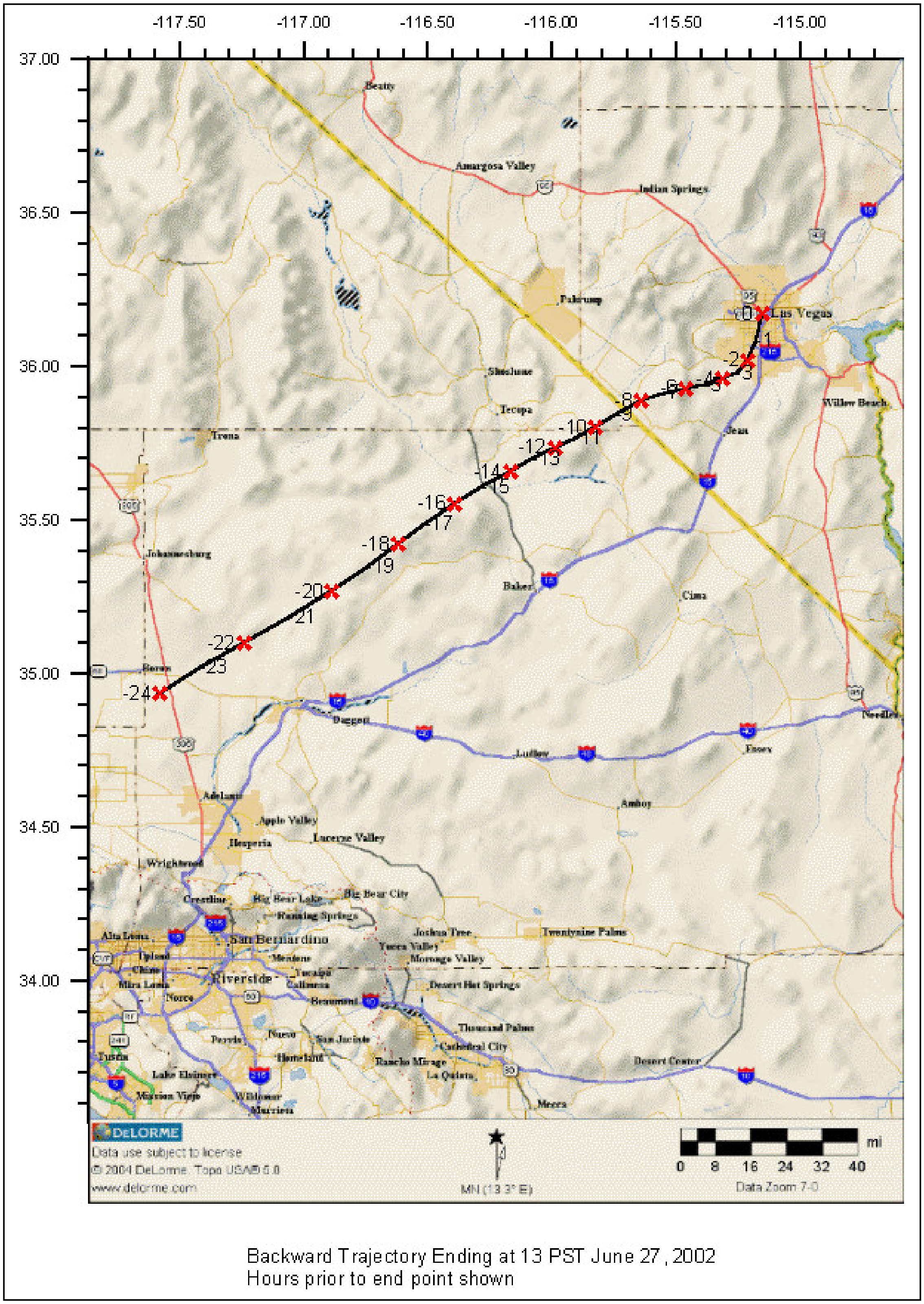
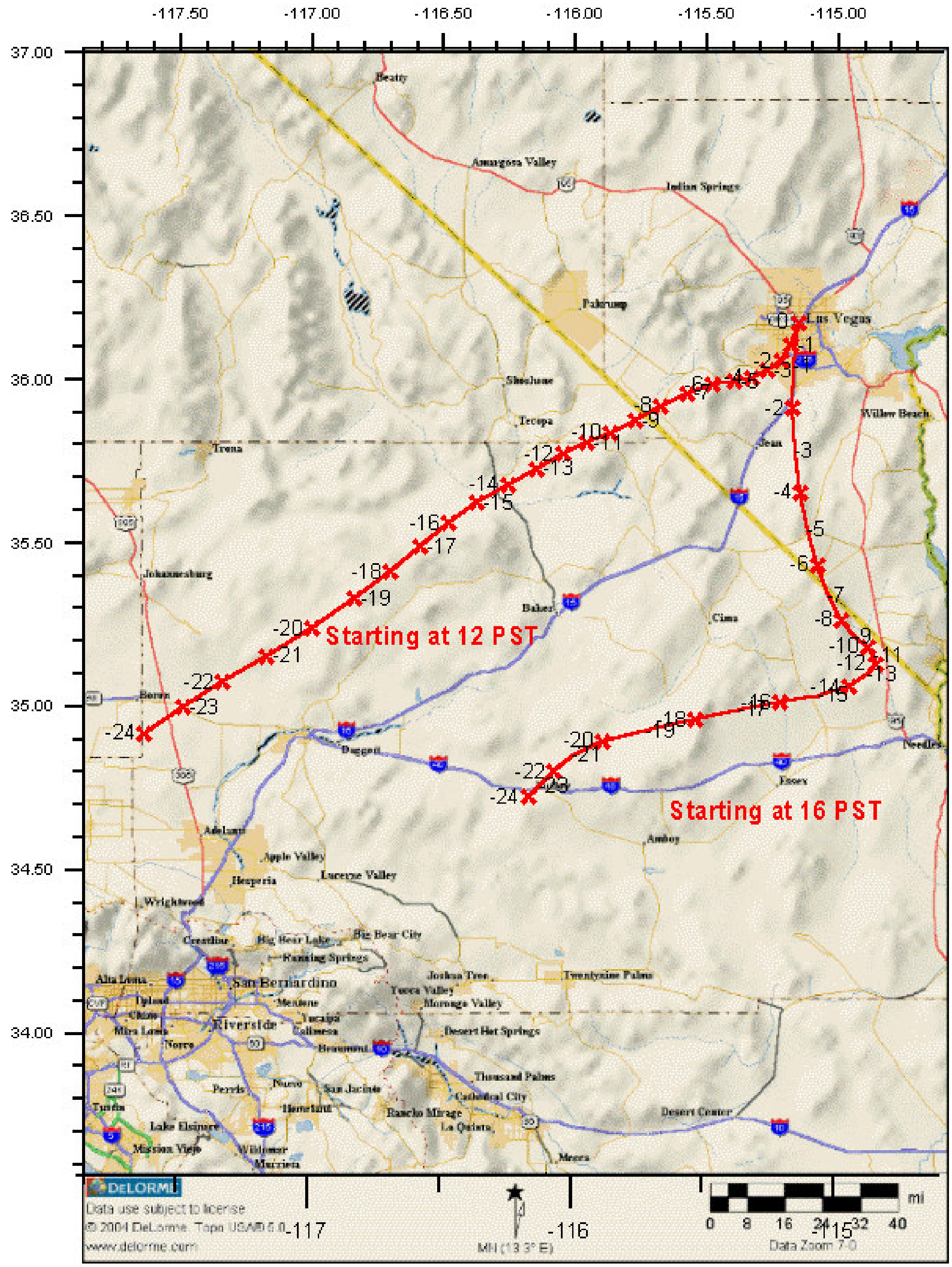


Figure 5-23. Backward Trajectory Ending at 13 PST, June 27, 2002



Backward Trajectories Ending at 12 PST and 16 PST June 28, 2002
Hours prior to end point shown

Figure 5-24. Backward Trajectory Ending at 12 PST and 16 PST, June 28, 2002

5.4. August 11, 2002 Episode

This was a 1-day episode during which three Clark County monitoring sites exceeded the 8-hour Federal Ozone Standard. **Table 5-9** gives the maximum 8-hour measurement by site for the day leading up to the episode, the episode day, and the following day. As can be seen from the table, the ozone standard was narrowly exceeded at Joe Neal, Lone Mt, and Walter Johnson. The maximum reading in the network was 87.1 ppb at Lone Mt. The spatial distribution of the peak readings can be seen on **Figure 5-25**. The ozone gradient was northwest-southeast for both 1-hour and 8-hour maximums, and, with the exception of Winterwood, the spatial patterns are similar. Whereas peak 8-hour ozone at Winterwood forces a closed minimum contour, the peak 1-hour reading is consistent with adjacent sites. There is a 15 ppb difference in 1-hour ozone from Lone Mt/Joe Neal to Boulder City and/or Jean inferring the contribution of the urban plume to downwind ambient levels of at least that amount. From Figure 5-25, it can be observed that peak 1-hour ozone levels were measured at 14 to 16 PST throughout the Las Vegas Valley.

Table 5-9. Maximum 8-Hour Ozone (ppb) – Case Study 4

Site Name	Site ID	8/10/02	8/11/02	8/12/02
Apex	AP	65.1	74.8	76.8
Boulder City	BC	66.1	78.1	67.3
E Craig Rd	BS	68.9	77.1	69.6
City Center	CC	62.5	73.8	57.7
JD Smith	JD	65.6	75.9	71.6
Jean	JN	59.4	83.6	68.8
Joe Neal	JO	75.4	86.4	77.4
Lone Mt	LO	78.1	87.1	75.6
Mesquite	MQ	59.3	60.6	67.6
SE Valley	PL	61.1	79.1	69.1
Paul Myer	PM	67.9	77.1	72.1
Palo Verde	PV	71.4	82.6	69.9
Searchlight	ST	63.4	71.5	65.5
Walter Johnson	WJ	73.3	86.1	75.5
Winterwood	WW	64.1	72.6	68.6
Network Max		78.1	87.1	77.4
# Sites Exceeded		0	3	0

Meteorology

The synoptic weather pattern at the 500 mb level on August 10, 2002 was characterized by extremely flat gradients throughout the southwest U.S. from Texas to California. The day was categorized as a Flat Ridge (FR) situation in the weather-typing scheme. **Figure 5-26(a)** shows the NWS 500 mb constant pressure map for the 10^{th}. This configuration continued through the morning of the 11^{th}, but by the afternoon, a lobe of the eastern Pacific high spread across California from the northwest, raising the 500 mb heights enough to the west of Nevada to change the classification to Pacific Ridge (PR). **Figure 5-26(b)** contains the 500 mb analysis for that afternoon. The end result of the influx of this lobe was to raise the 500 mb heights from 5,940 m to 5,950 m over Clark County and turn the light winds more northerly. This probably increased the atmospheric stability slightly during the 11th. The 500 mb configuration remained static through the afternoon of the 12th.

Below the 500 mb level, the Pacific lobe was not as predominant a feature. The 700 mb constant pressure maps for the 10th and 11th indicated a very flat gradient throughout the southwestern U.S.. **Figure 5-27(a)** presents the 700 mb map for the morning of the 11th. Flow over southern Nevada was extremely light and the air temperatures were greater that 15°C.

Just above the surface at 850 mb on the morning of the 11th, the gradient was still relatively flat, and a pocket of higher temperatures that was just barely discernable at 700 mb was more of a predominant feature over southern Nevada, southeastern California and western Arizona. **Figure 5-27(b)** shows the 850 mb chart for the morning of the 11th. Low-level winds aloft over Desert Rock at that time were southwesterly at 8 to 12 knots in a layer extending from about 200 m above the ground to around 1700 m. This flow was associated with the warm portion of the nocturnal inversion layer.

A backward trajectory from the city's center was constructed using the HYSPLIT Model. **Figure 5-28** depicts the trajectory ending at 16 PST on August 11 and beginning approximately 25 km southeast of Trona, California on the previous afternoon. This trajectory was more westerly than the other case study episode, and was relatively short. Trona measured an 85 ppb 8-hour ozone maximum on the 10th, which is consistent with levels the following day in Clark County. The afternoon surface winds in the Las Vegas Valley were somewhat inconsistent but as can be seen from the plotted wind field on **Figure 5-29,** tend to show southwest winds of moderate strength on the west side accompanied by a weaker easterly wind on the east side with the flows converging over the city.

Mixing height, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperature, was 4,300 m-agl.

<u>**Summary**</u>

- This was a one-day episode with peak 8-hour ozone at 87.1 ppb.
- Exceedances were experienced at three Clark County sites in the northwest quadrant of the Las Vegas Valley. Relatively high background levels (low 80s ppb) and locally produced ozone both contributed to the ozone exceedances.
- This episode took place during synoptic conditions initially categorized as a Flat Ridge (FR) that transitioned to a weak Pacific Ridge (PR). The air mass over southern Nevada was thermodynamically stable with warm air aloft prevailing. The appearance of a thermal low in the lower atmosphere on the morning of the 11th induced light southwesterly flow just above ground level in the area. Although light, the flow in southern Nevada was consistent enough, and extended high enough above the terrain to provide a weak mechanism for interbasin transport.
- Trajectory analyses suggest that the high background levels (83.6 ppb 8-hour maximum at Jean) were due to transport along a northern California desert route.
- The CART model classed this episode intoTerminal Node 3, which is characterized by a minimal transport contribution to Clark County ozone. In this instance, it appears that both transport and local emissions played significant roles in causing the exceedances.

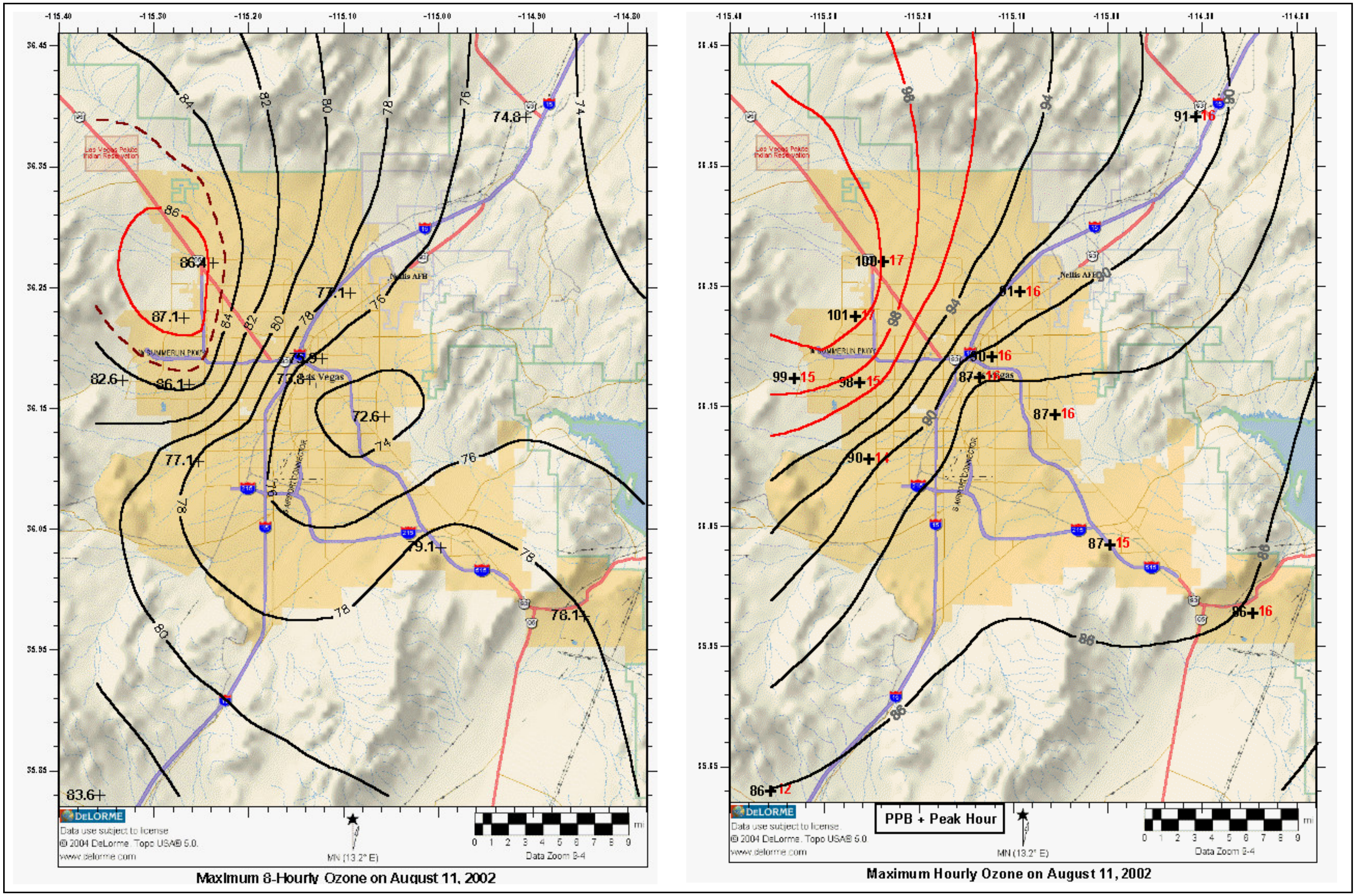


Figure 5-25. Peak Ozone for August 11, 2002

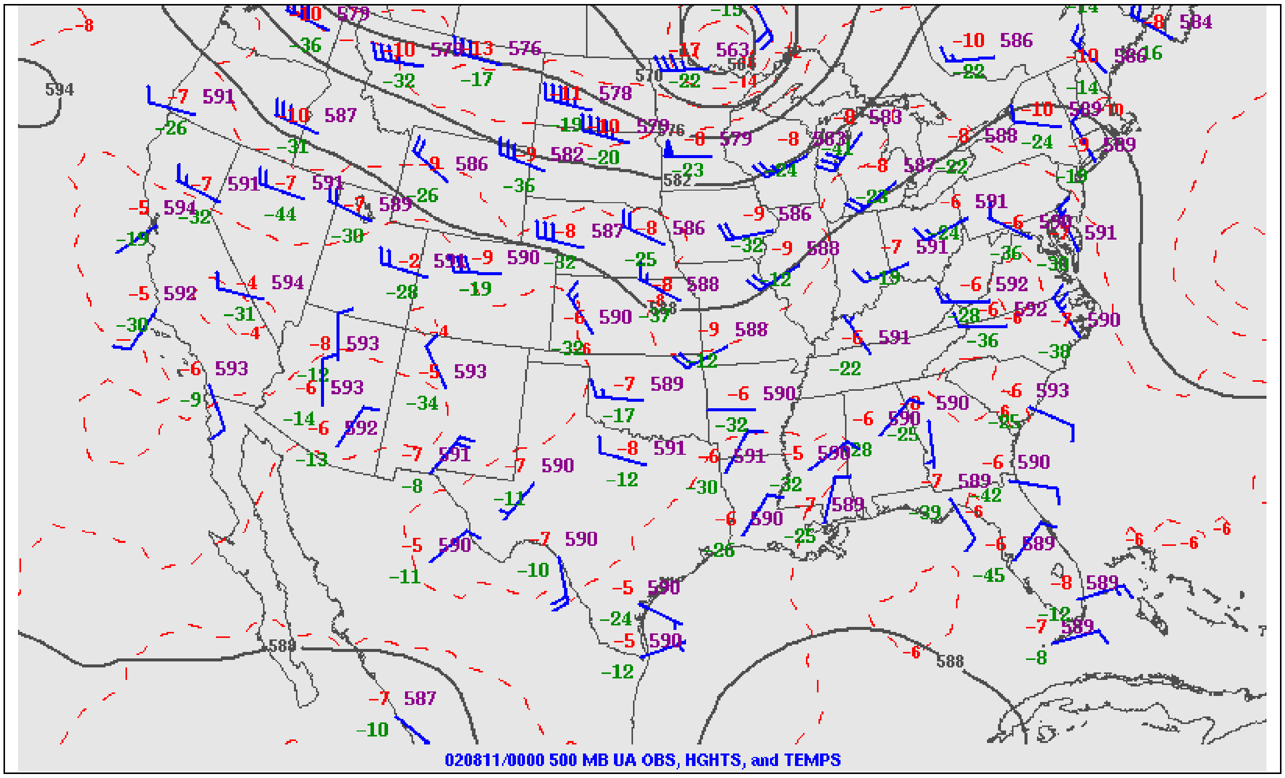


Figure 5-26(a). NWS 500 mb Constant Pressure Map for Afternoon of August 10, 2002

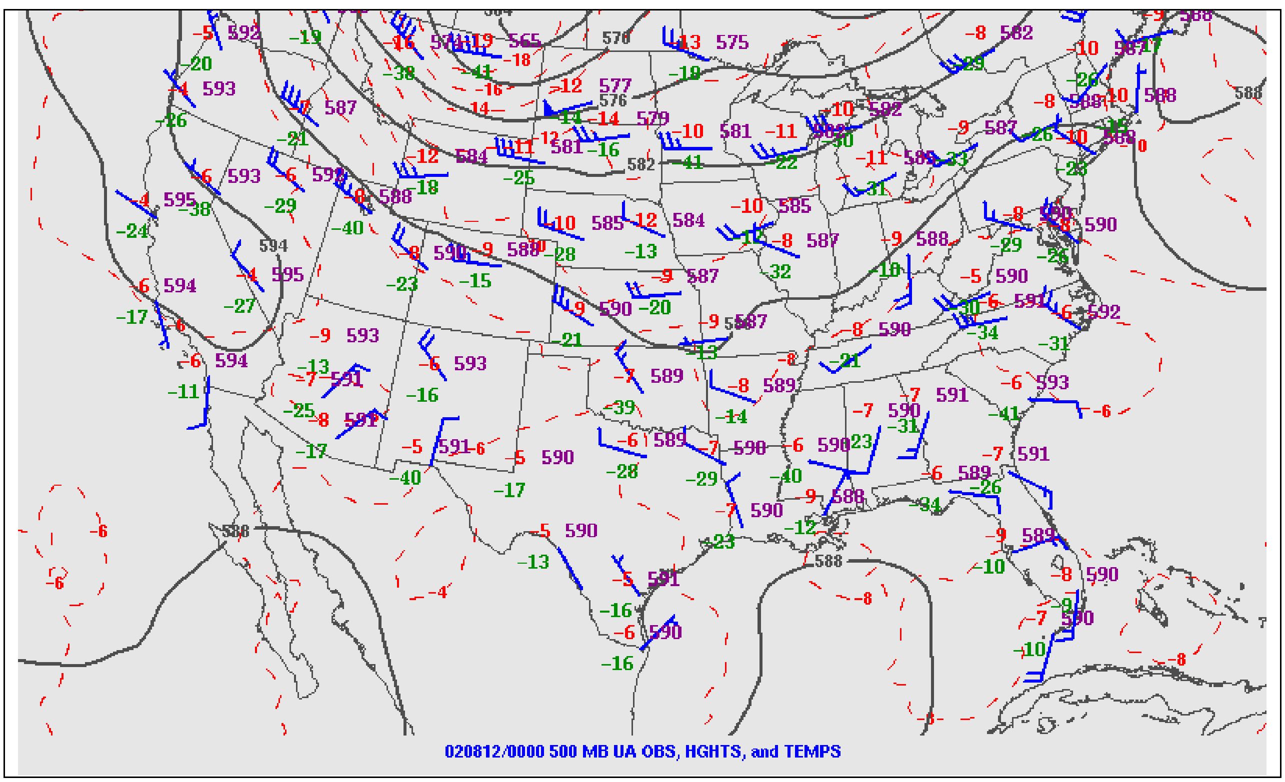


Figure 5-26(b). NWS 500 mb Constant Pressure Map for Afternoon of August 11, 2002

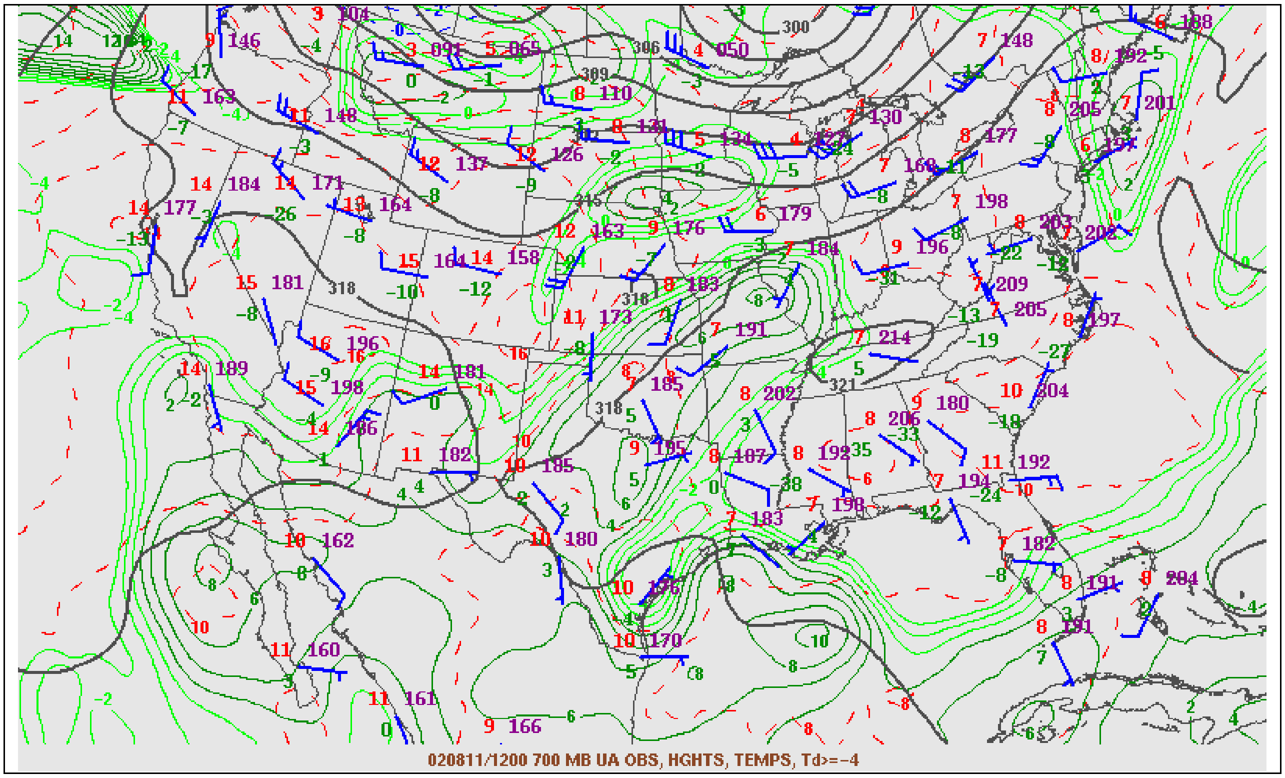


Figure 5-27(a). NWS 700 mb Constant Pressure Map for Morning of August 11, 2002

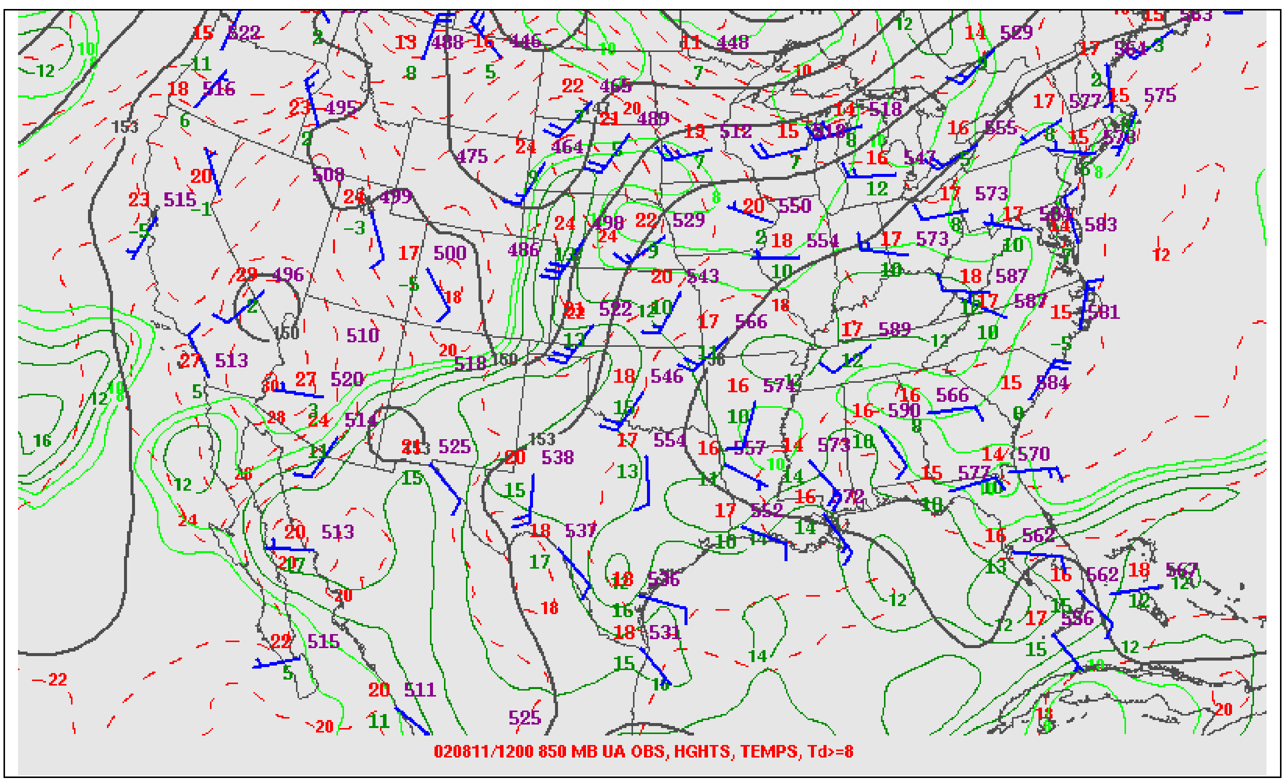


Figure 5-27(b). NWS 850 mb Constant Pressure Map for Morning of August 11, 2002

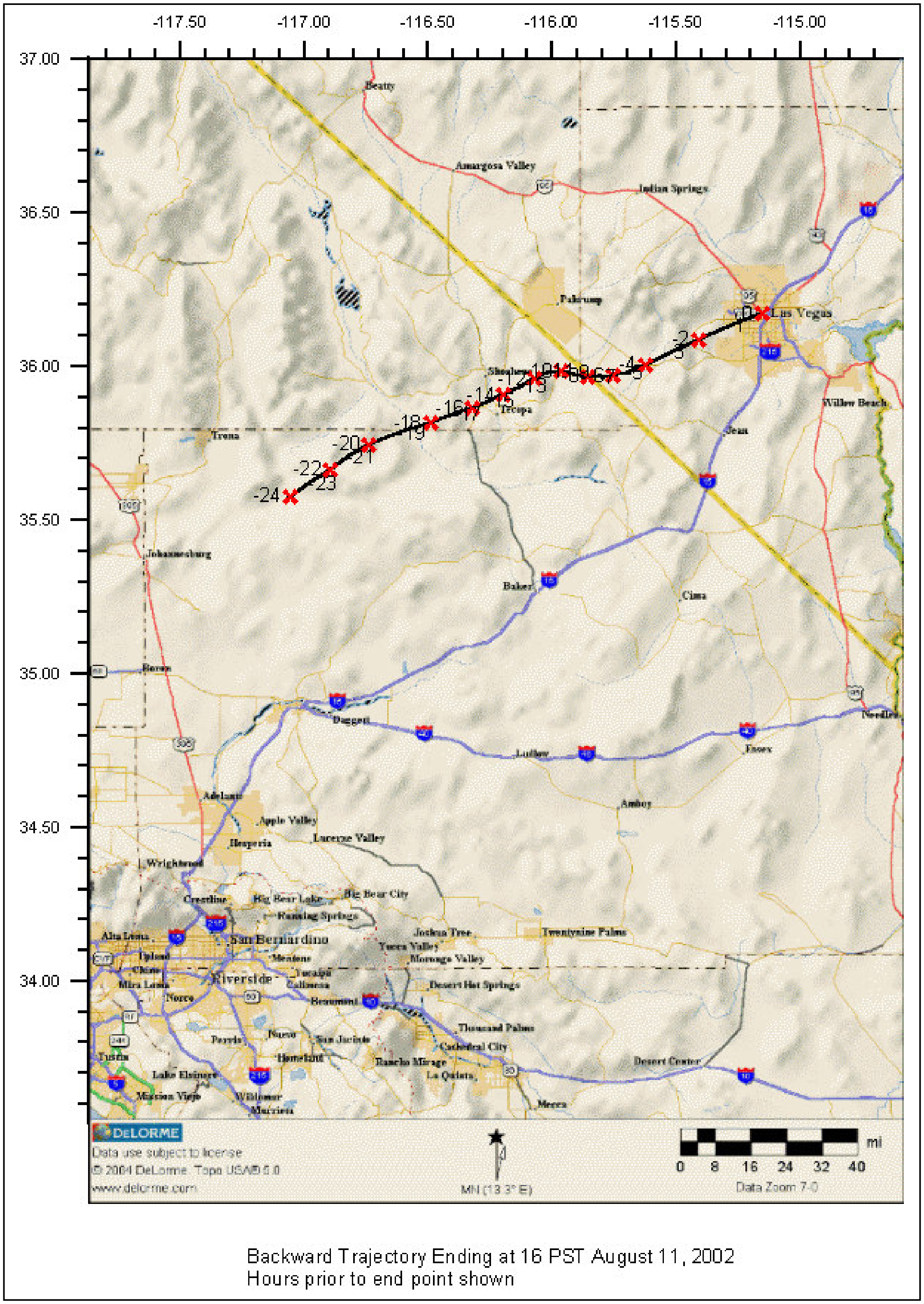


Figure 5-28. Backward Trajectory Ending at 16 PST, August 11, 2002

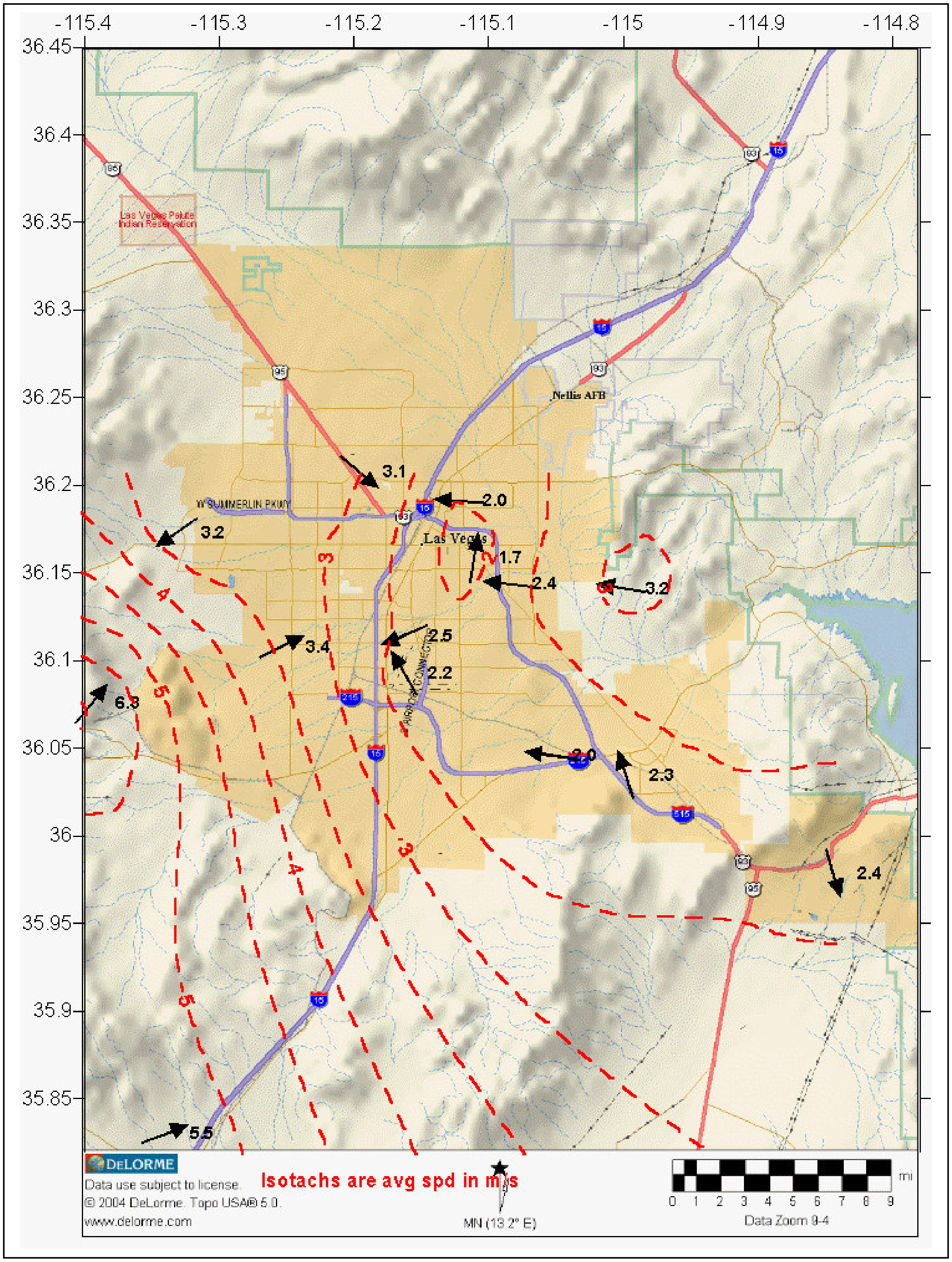


Figure 5-29. Las Vegas Valley Surface Winds at 16 PST on August 11, 2002

5.5 August 18, 2002 Episode

This was another one-day episode with only moderately high ozone levels. **Table 5-10** lists the maximum 8-hour ozone concentrations for all sites in the Clark County monitoring network. The number of sites exceeding and the peak level are also shown. Five exceedances were reported—at Lone Mt, Walter Johnson, Palo Verde, Joe Neal and Jean. The network highest level, 88 ppb, was experienced both at Lone Mt and Walter Johnson School. Charts showing the Las Vegas Valley and adjacent regions peak ozone spatial pattern are shown in **Figure 5-30**. The left panels show daily maximum 8-hour averaged levels and contours of constant ozone. The right panels give daily maximum 1-hour averaged levels, contours of constant ozone, and the time of the peak (PST). The contour patterns for both 1-hour and 8-hour maximums are identical. What is noteworthy is the strong west-east ozone gradient. There is a 30 ppb difference in ozone from Lone Mt/Joe Neal to Boulder City. Jean, located upwind of Las Vegas, experienced near exceedance levels (83.6 ppb) during this period, which agreed well with other rural desert levels to the west. As discussed below, high background levels, augmented by the Las Vegas urban plume, caused exceedances at downwind locations that were the characterizing features of this episode. From Figure 5-30, it can be observed that peak 1-hour ozone levels were measured at 13 to 14 PST throughout the Las Vegas Valley.

Table 5-10. Maximum 8-Hour Ozone (ppb) – Case Study 5

Site Name	Site ID	08/17/2002	08/18/2002	08/19/2002
Apex	AP	68.1	69.0	57.0
Boulder City	BC	61.6	60.5	52.9
E Craig Rd	BS	67.4	66.1	47.5
City Center	CC	55.4	64.5	37.0
JD Smith	JD	63.8	71.0	48.6
Jean	JN	82.1	85.6	62.9
Joe Neal	JO	77.0	85.8	58.0
Lone Mt	LO	79.1	88.0	61.0
Mesquite	MQ	63.6	72.3	57.6
SE Valley	PL	63.9	66.8	53.3
Paul Myer	PM	73.8	84.0	66.0
Palo Verde	PV	77.4	87.1	64.9
Searchlight	ST	58.4	57.4	48.0
Walter Johnson	WJ	77.1	88.0	63.4
Winterwood	WW	64.5	66.6	53.5
Network Max		82.1	88.0	66.0
# Sites Exceeded		0	5	0

Meteorology

The synoptic weather pattern at the 500 mb level on August 17-18, 2002 was distinguished by a flat gradient across the entire southern half of the country from California to the Atlantic coast. Both days were categorized as Flat Ridge (FR) in the weather-typing scheme.
Figure 5-31(a&b) shows the 500 mb constant-pressure charts for the afternoons of the 17th and 18th, respectively. Winds aloft at this level were very light and somewhat variable, with a

tendency to be from the west. High 500 mb heights, around 5,900 m, indicate that the air mass was dynamically stable throughout the region.

Below the 500 mb level, flat gradients were also indicated. **Figure 5-32(a)** shows the 700 mb chart for the morning of the 18th. Tighter gradients were evident to the north where stronger zonal flow began as far south as northern California and Nevada. Flow over southern Nevada was lighter, but speeds were nevertheless greater than at 500 mb. The air temperatures at 700 mb over southern Nevada were around 15.5^{o}C, with the warmest on the map over Clark County. The warm temperatures aloft indicate that substantial stability and capping was occurring during the 18th.

In the lower boundary layer, a broad trough extended from central California, across south central Nevada and into Utah and Wyoming. This feature may have been influencing low-level flow in southern Nevada. **Figure 5-32(b)** presents the 850 mb map for the morning of the 18th. A pocket of very warm air as measured by the Desert Rock sounding, was embedded in the western trough suggesting that the trough may have been induced, at least in part, by heating at the surface. In addition, the afternoon Desert Rock sounding showed a rather deep layer of southwesterly flow extending from about 200 m above the ground to about 3,500 m. Speeds in that layer ranged from 12 to 23 knots.

A backward trajectory from the city center was constructed using the HYSPLIT Model and is shown on **Figure 5-33**. The trajectory path shown ends in Las Vegas at 13 PST and starts 24 hours earlier. In this instance, the backward trajectory originates in the Coachella Valley in Southern California. Two ozone sites are located in that general region--Joshua Tree and Twentynine Palms. Ozone levels at the latter site do not support the levels observed in Clark County, but the Joshua Tree ozone record, although incomplete, reported a 107 ppb daily 8-hour maximum. It should be noted that high ozone was measured throughout most of the California desert network from the Antelope Valley, Mojave, Barstow, and even Trona (**Table 5-11)**. Eight-hour ozone levels of 80 ppb levels were measured in Death Valley. In any case, background levels upwind in the desert were very high and most likely were a major contributor to Clark County's ozone burden.

Table 5-11. Maximum 8-Hour Ozone (ppb) at California Desert Sites

Date	**08/17/2002**	**08/18/2002**
Barstow	91.8	94.6
Death Valley	79.7	79.9
Joshua Tree	107.0	missing
Mojave	102.0	91.5
Trona	84.5	86.8
Twentynine Palms	72.1	78.4
Victorville	108.8	87.4

The afternoon surface winds shown on **Figure 5-34** offer an explanation for the sharp ozone gradient shown on Figure 5-30. As can be seen from both wind speed (isotachs) and direction, significant horizontal shears were present. A uniform southeasterly flow exists east of the axis of the Las Vegas Valley converging with moderate to strong southwesterly flow to the west. Upwind in the southeasterly fetch are ozone levels in the 60 ppb range. Ozone levels are in the high 80 to 90 ppb range upwind in the southwest fetch. The relatively high ventilation rate accounts for the early ozone peaks.

The afternoon mixing height, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, was 5,100 m-agl.

Summary

- This was a one-day episode occurring on August 18 on which exceedances of the 8-hour ozone standard were experienced at 5 sites. The maximum ozone concentration was 88.0 ppb measured at both Lone Mt. and Walter Johnson School. Jean was one of the sites at which the ozone standard was exceeded.

- The areal ozone pattern was characteristic of significant interbasin transport. Peak ozone levels occurred along all of west Clark County, including Jean. Ozone levels decreased sharply to the east.

- The ozone exceedances on August 18, 2002 took place during a period categorized as a Flat Ridge (FR). The air mass over southern Nevada was thermodynamically stable with warm air aloft prevailing. A large-scale shallow trough existed in the lower atmosphere that induced a deep layer of moderate to strong southwesterly winds during the early morning. This strong flow layer extended from just above the surface to above the 700 mb level. With this substantial southwesterly flow, the potential for significant transport appeared to be very good.

- Trajectory analyses pointed to transport from the South Coast air basin. Background levels upwind in the desert were very high and most likely were a major contributor to Clark County's ozone burden.

- The CART model was in good agreement with the other analyses and classed this episode correctly intoTerminal Node 7 that infers interbasin transport played an important role in Clark County ozone levels.

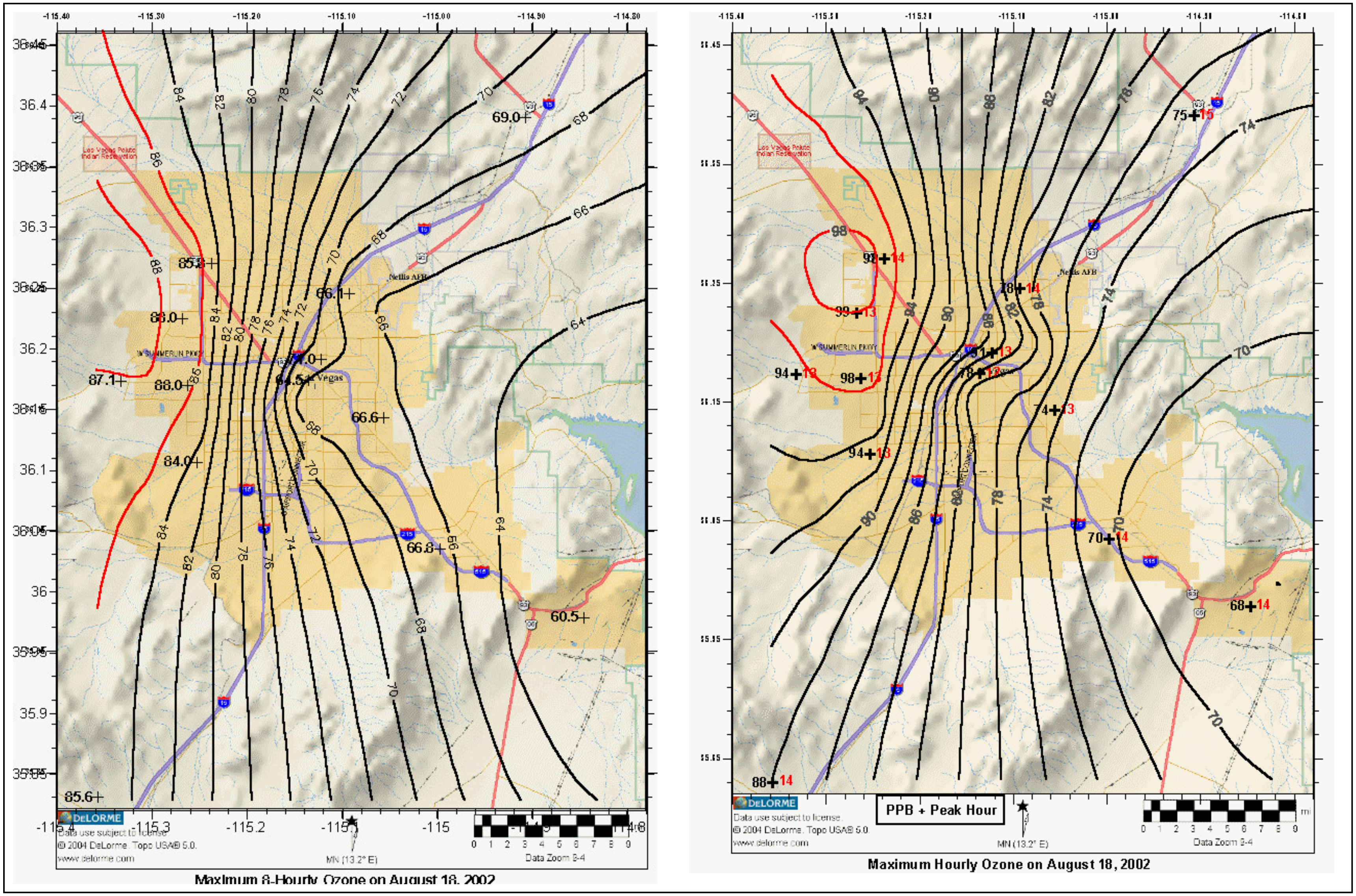


Figure 5-30. Peak Ozone for August 18, 2002

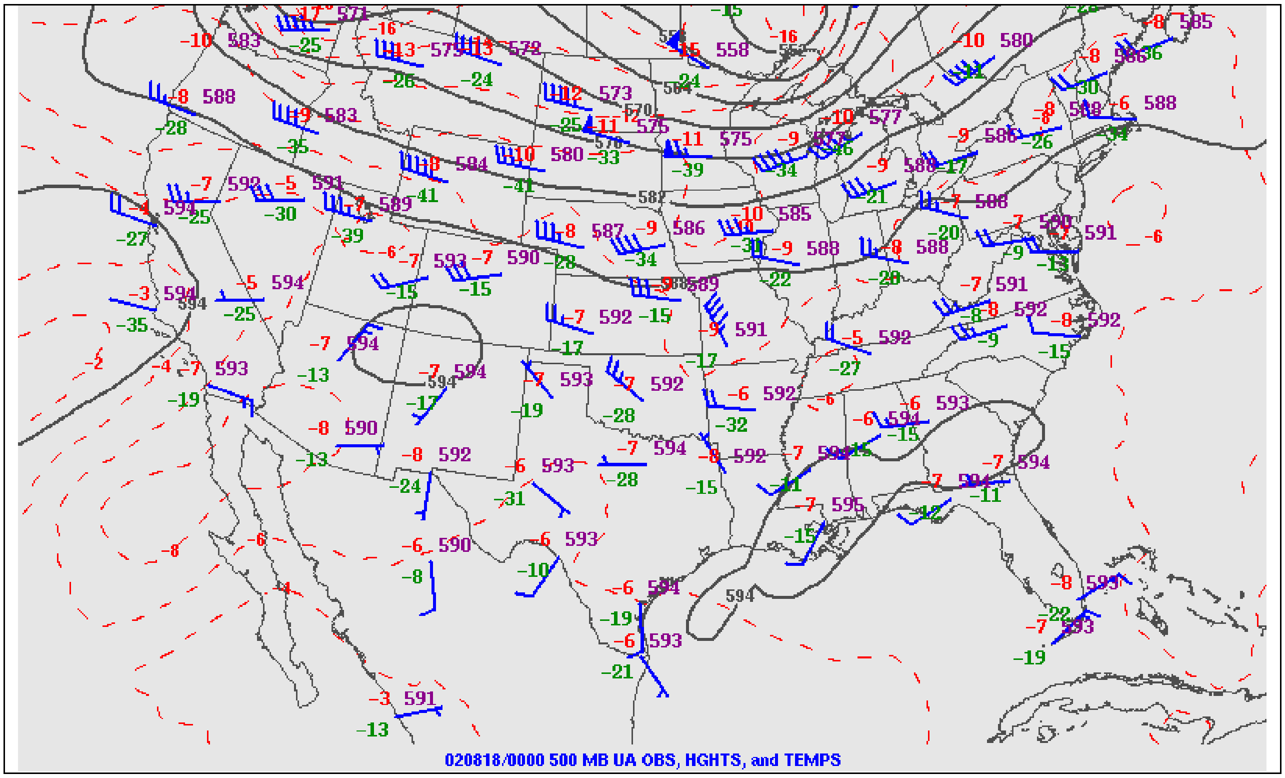


Figure 5-31(a). NWS 500 mb Constant Pressure Map for Afternoon of August 17, 2002

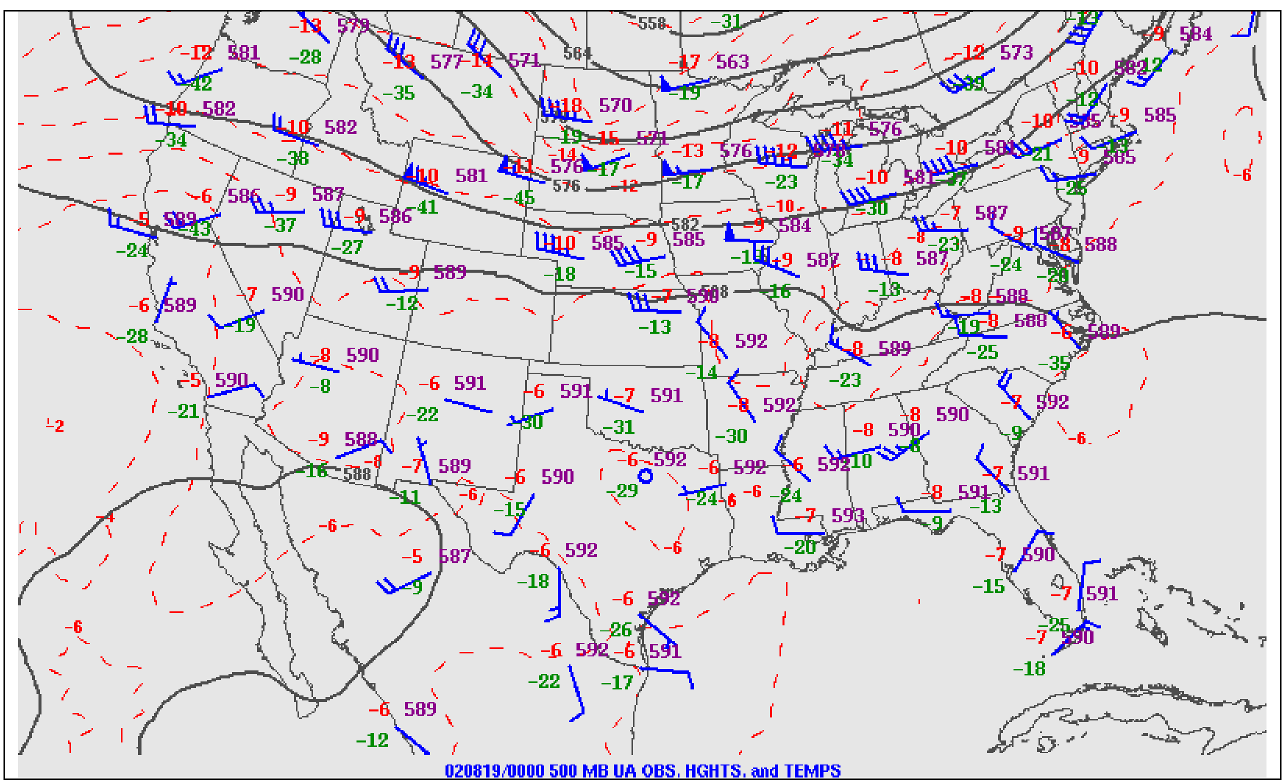


Figure 5-31(b). NWS 500 mb Constant Pressure Map for Afternoon of August 18, 2002

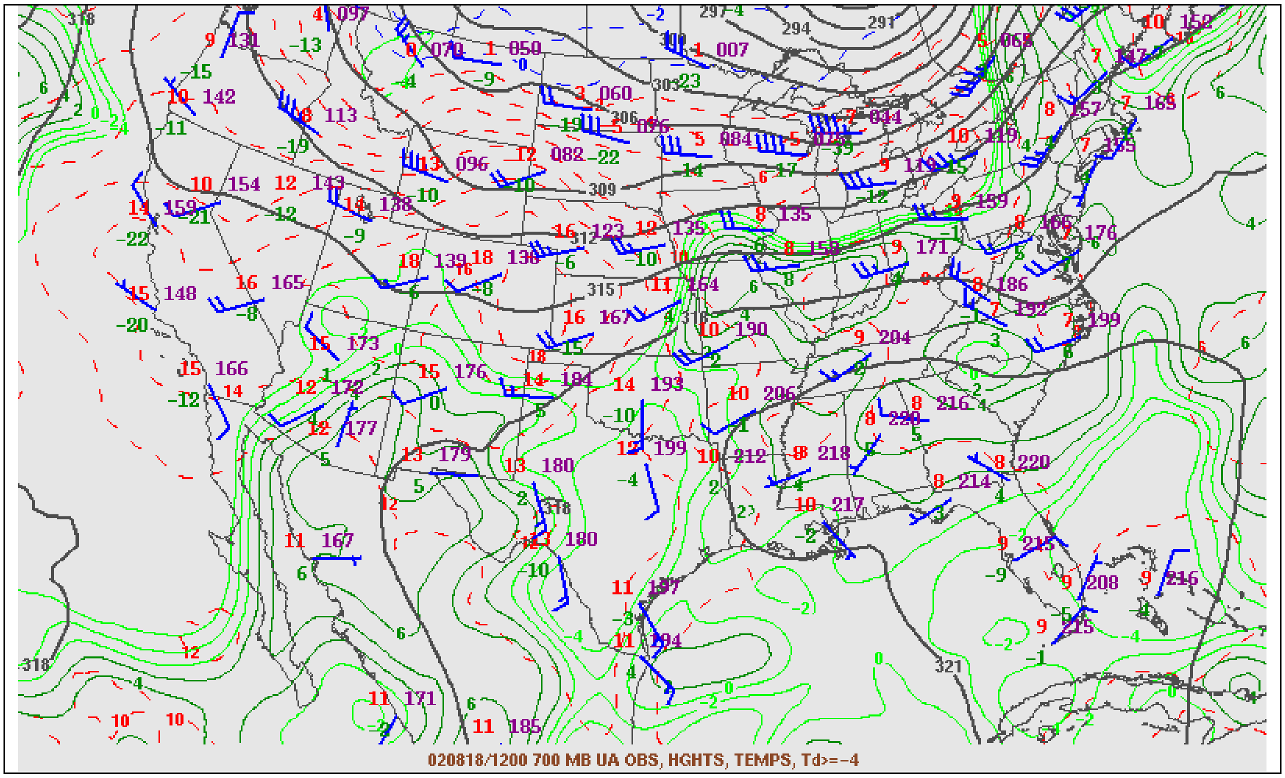


Figure 5-32(a). NWS 700 mb Constant Pressure Map for Morning of August 18, 2002

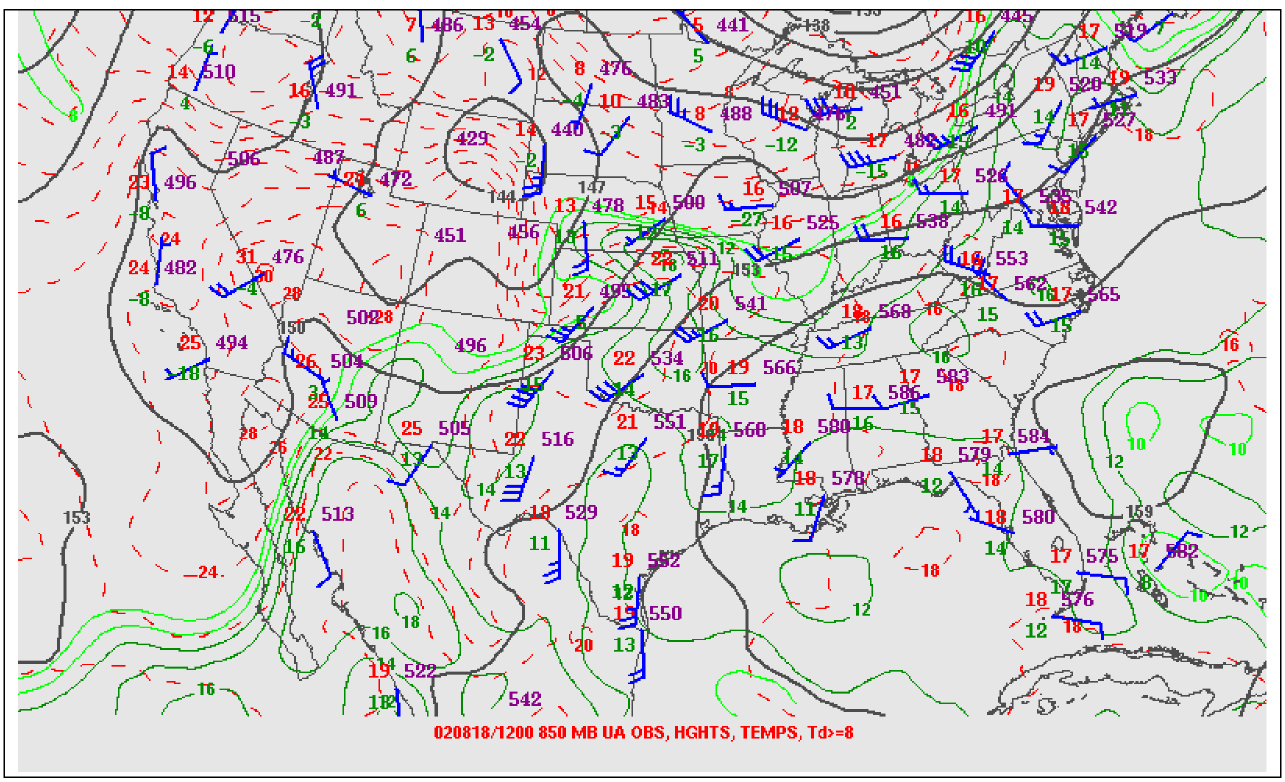


Figure 5-32(b). NWS 850 mb Constant Pressure Map for Morning of August 18, 2002

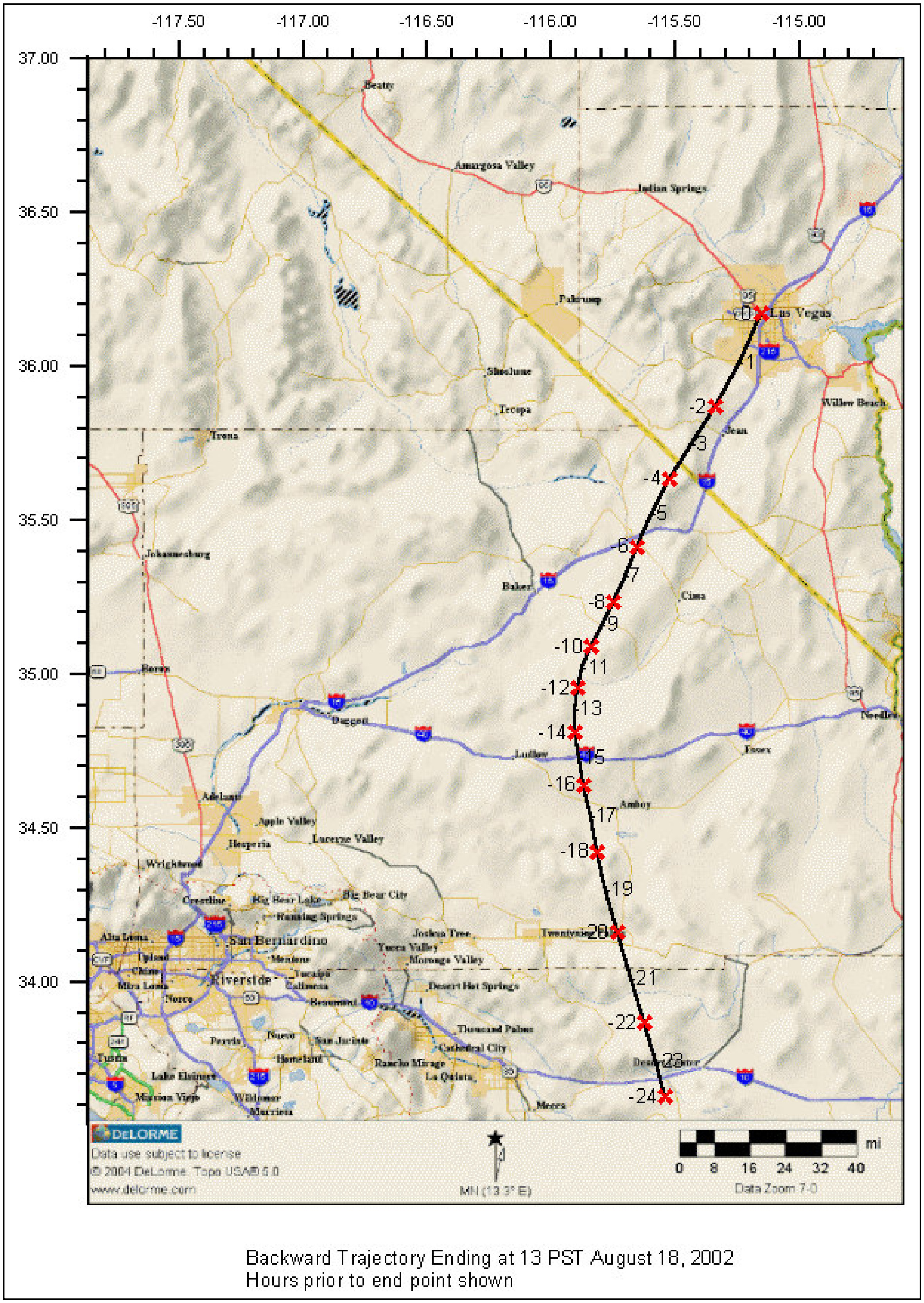


Figure 5-33. Backward Trajectory Ending at 13 PST, August 18, 2002

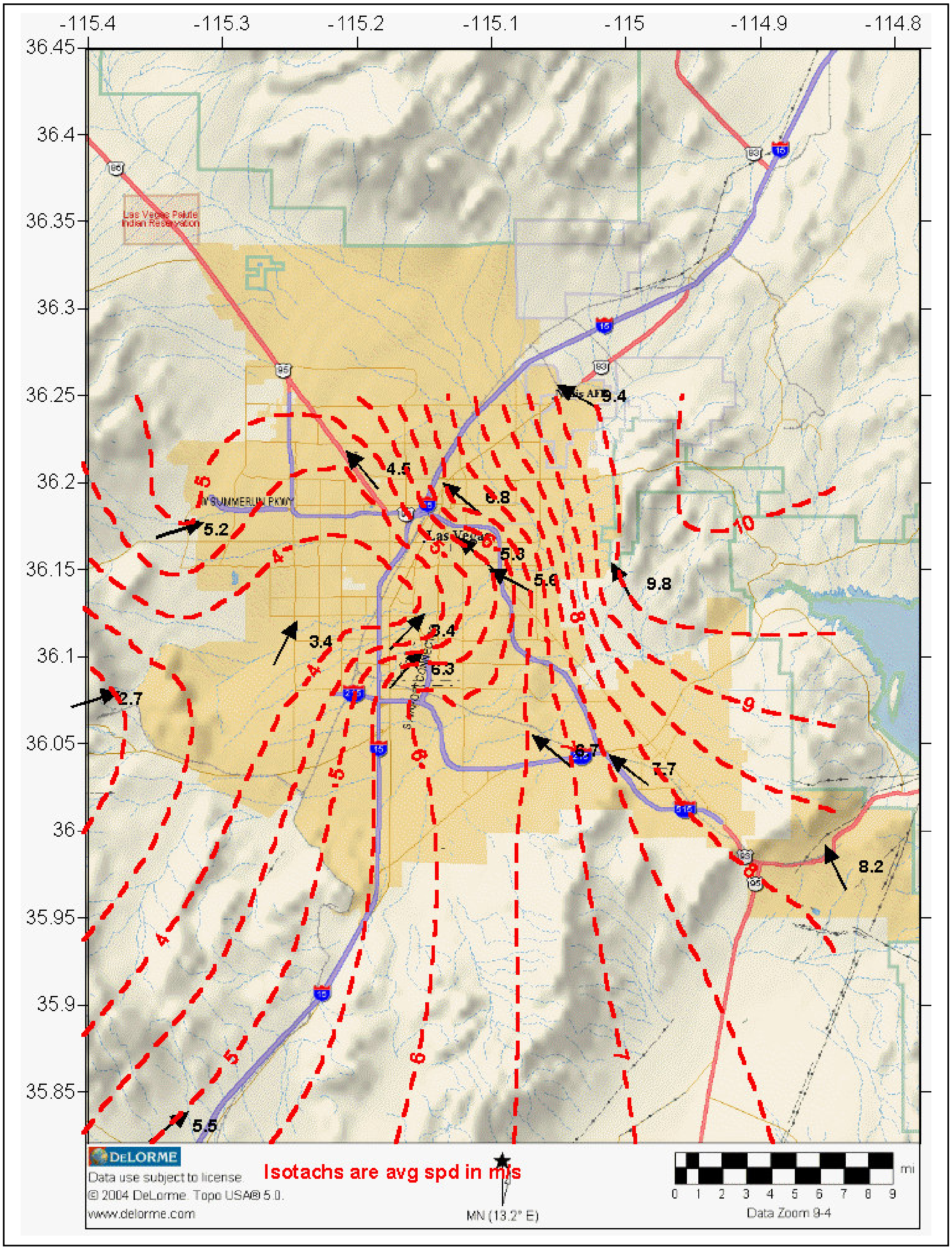


Figure 5-34. Las Vegas Valley Surface Winds at 16 PST on August 18, 2002

5.6 May 26 to 27, 2003 Episode

This was a 2-day episode with only modest exceedances of the 8-hour Federal Ozone Standard (85 ppb) but noteworthy for its occurrence early in the ozone season. Daily maximum ozone levels for the sites that comprise Clark County's monitoring network are listed in **Table 5-12.** The table includes ozone levels for the day prior to episode levels (25th) and for the day following (28th). In the last two rows of the table, the network maximum and number of sites exceeding the standard are provided. As can be seen from the table, ozone exceedances occurred at two sites on the 26th (Joe Neal and Long Mt), and one site (Joe Neal) on the 27th. On the 25th, Jean measured 80.1 ppb 8-hour average, which indicates background levels were particularly high. Jean remained relatively high (>77 ppb) during the two-day episode. It is noteworthy that leading up to this period, California desert ozone levels were not as high as the levels experienced at Jean during this episode. Charts showing the Las Vegas Valley and adjacent regions peak-ozone spatial patterns are shown on **Figures 5-35** and **5-36**. Again, the left panels show daily maximum 8-hour averaged levels and contours of constant ozone. The right panels give daily maximum 1-hour averaged levels, contours of constant ozone, and the time of the peak (PST). With the exception of the center of the city, the ozone spatial pattern did not change appreciably over the two-day episode. Ozone levels at the City Center site were particularly low on the 27th and, as discussed below, are consistent with the light observed winds. On both days and for both the 8-hour and 1-hour averages, peak ozone levels were experienced in the northwestern quadrant of the Valley and the gradient to lower levels was generally to the southeast. (Note that the Henderson 8-hour maximum, although plotted on Figure 5-35, was not included in the isopleth analyses as it was deemed highly suspect relative to the other measurements.)

Table 5-12. Maximum 8-Hour Ozone (ppb) – Case Study 6

Site Name	Site ID	5/25/03	5/26/03	5/27/03	5/28/03
Apex	AP	80.0	76.9	68.5	75.13
Boulder City	BC	72.3	71.3	66.6	70.63
E Craig Rd	BS	79.1	80.1	72.5	70.63
City Center	CC	67.9	81.3	67.4	62.13
JD Smith	JD	75.6	80.5	76.5	70.88
Jean	JN	80.1	77.4	77.5	75.25
Joe Neal	JO	80.5	89.9	86.0	81.5
Lone Mt	LO	74.9	85.5	81.3	76.25
Mesquite	MQ	68.6	65.8	60.6	57.25
SE Valley	PL	73.8	69.8	50.5	47.5
Paul Myer	PM	74.5	80.1	78.4	73.38
Palo Verde	PV	76.4	83.6	78.3	76.75
Shadow Lane	SL				
Searchlight	ST	73.5	68.5	67.9	61.63
Walter Johnson	WJ	74.6	82.9	77.8	72.88
Winterwood	WW	78.1	79.1	75.4	72.75
Network Max		80.5	89.9	86.0	81.5
# Sites Exceeded		0	2	1	0

Although the peaks were similar on both days, the diurnal hourly ozone levels were quite different. Time-series plots of hourly ozone levels for a select set of sites is shown on **Figure 5-37**. On the 26th, the trend is for high ozone throughout the afternoon with some sites showing two ozone peaks—in the early and late afternoon. By contrast, more variability in hourly ozone is evident on the 27th—most notably at City Center (CC). This behavior is characteristic of poor ventilation coupled with limited mixing of fresh emissions.

Meteorology

The synoptic weather pattern that affected the May 26 to 27 ozone episode followed a progression of events starting with a dry Pacific Trough (PT) on the day before the start of the episode, to the onset of a Pacific Ridge (PR) on the 26th, and culminating with the progression of the ridge across the Great Basin to the Four Corners area over the 27th and the 28th. **Figures 5-38(a&b), 5-39(a&b)** present the 500 mb constant-pressure charts for the afternoons of May 25th, 26th, 27th and 28th, respectively. After several days of a late spring trough being the dominant feature, the Pacific ridge spread into southern California on the 26th, causing 500 mb heights to rise rapidly to near 5,900 m over southern Nevada by afternoon. Winds at that time were northwesterly at only about 8 m/s, indicating gradients were weak. The increasing heights on the 26th indicate that the air mass was rapidly stabilizing. By the afternoon of the 27th, the axis of the now Interior Ridge (IR) was directly over southern Nevada, and 500 mb heights had risen to around 5,950 m. Winds at that level had become light and variable. During that evening, the ridge continued to progress eastward into Arizona and Utah, and by the afternoon of the 28th it was centered over the Four Corners. During that time, 500 mb heights remained high (5,940 m) and flow over southern Nevada became light and southerly to southeasterly.

Below the 500 mb level, the ridge progression was not prominent but still apparent. **Figure 5-40(a&b)** provides the constant-pressure charts with the 700 mb analyses for the mornings of May 26th and 27th. Although heights were rising by early on the 26th, the remnants of the old trough could be seen over south-central California into central Nevada. The 700 mb temperature over Clark County was relatively low at 10.4^{o}C, and flow was southerly at about 5 m/s. By the morning of the 27th, the ridge was clearly established as heights increased substantially and the 700 mb temperature rose by almost 4^{o}C from the previous day. Winds became easterly by that time, and remained so through the next day as the ridge moved to the east.

In the lower boundary layer at the 850 mb level, the Pacific ridge remained over the cool waters off the west coast, while flat troughing prevailed in the Great Basin. **Figure 5-41(a&b)** shows the 850 mb pressure-surface charts for the morning of the 26th and 27th. Temperatures at 850 mb were relatively cool over the Desert Rock NWS site early on the 26th, but, as was the case at 700 mb, rapid heating took place during the day and temperatures were 3^{o} C warmer by the morning of the 27th. Despite the relatively cool temperatures, a weak inversion did form during the morning of the 26th, and southerly flow at about 5 m/s prevailed in a layer from 500 m to 3,000 m above the ground. Temperatures warmed the following day, as the Interior Ridge became the dominant weather feature. Wind flow in the lower levels became light and variable. Just above the 850 mb level, at around 1,000 m above ground level, winds became easterly at 5 to 9 m/s, and remained from that direction for the next several days.

The air-mass trajectories on the episode days reflect the changing synoptic weather. Backward trajectories from the city center were constructed using the HYSPLIT Model and are shown on **Figure 5-42** for May 26 and May 27. Shown are two trajectories, both ending at the surface at 16 PST and starting 24 hours earlier. The number of hours back from 16 PST is posted along the trajectories. As can be seen, the fetch on the 25th and 26th was from the south, originating near the California-Arizona border east of the greater Los Angeles area. The air mass then stagnated providing a mechanism for producing the observed high ozone levels. Note that a recirculation of the air in Clark County is suggested by the 24-hour trajectory from the afternoon of the 26th to the 27th. The earlier history of the air mass was not examined. The important feature is that the background ozone burden in Clark County was in the 70 to 80 ppb range when the air mass stagnated. As a consequence, an opportunity is suggested for an already aged, polluted air mass, carried over in the Valley from the prior days, to contribute to the fresh urban plume. The light flows are depicted in different ways on **Figures 5-43 and 5-44**. The 16 PST wind direction and isotachs are shown on the first figure. As can be seen, winds were less than 3 m/s throughout the Valley and ~ 1 m/s at some sites. The trajectory depicted on Figure 5-44 is an estimate of a parcel of air starting downtown on the afternoon of the 26th and ending on the afternoon of the 27th, 24 hours later. The time (PST) is shown in boxes along the trajectory. The parcel moves to the west on the afternoon and early evening of the 26th before reversing direction and traveling back towards the urban core during the night and early morning when the atmosphere is most stable. After emissions from the morning commute add to the mature urban plume, the parcel is slowly transported northwest towards the area of peak-measured ozone.

Afternoon mixing heights, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, were 2,900 m-agl and 3,800 m-agl for the 27th and 28th, respectively.

Summary

- Exceedances of the 8-hour ozone standard were experienced on both May 26 and 27, 2003. Two sites exceeded on the 26th and one site on the 27th. Peak 8-hour ozone experienced was 89.8 ppb (Joe Neal), and the peak 1-hour concentration was 96 ppb (Lone Mt on the 27th).

- The spatial ozone pattern on both days was characterized by the highest ozone levels in the northwest at Joe Neal and Lone Mt with a general southeast gradient to lower concentrations. On the second day of the episode, a distinct minimum was evident in the urban core.

- Owing to light winds beginning on the afternoon of the 26th, generally meandering flows persisted during the night and morning of the 27th. There was suggestion of an air mass recirculation during this period.

- The synoptic scale weather pattern progressed from PT (Pacific Trough) prior to the ozone episode to PR (Pacific Ridge) on the first day to IR (Interior Ridge) by the second day and beyond. Despite fairly cool temperatures initially, there was enough stability early on the 26th to limit mixing somewhat, and allow the transport of pollutants entrained in the moderate southerly flow. As the ridge axis passed through on the 27th, stability increased substantially and flow became light and variable, producing a stagnant pollution trapping situation. By late on the 27th, the ridge had moved far enough to the east to produce easterly flow throughout the boundary layer, bringing in cleaner air and reducing ozone levels.

- There is evidence of interbasin transport leading to high background ozone on the 26th but its origin is unknown. Ozone levels at the California desert sites leading up to the episode were not as high as those at Jean during the episode.

- The CART model classified May 26 into Terminal Node 7 and May 27 into Terminal Node 3. This is consistent with an initial influx of transported ozone into the basin, followed by a stagnant day during which local emissions and meteorological conditions contributed to the observed exceedances.

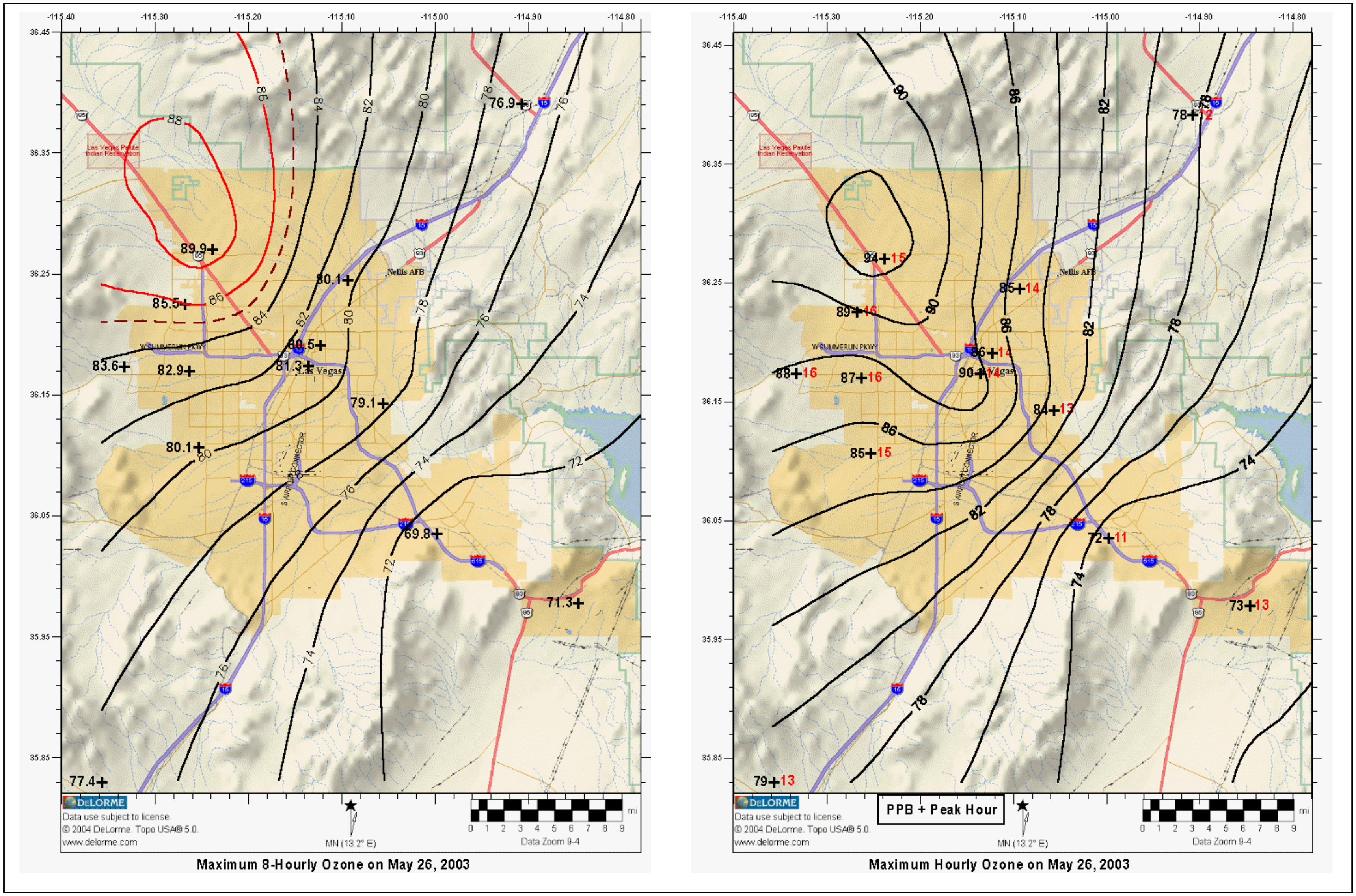


Figure 5-35. Peak Ozone for May 26, 2003

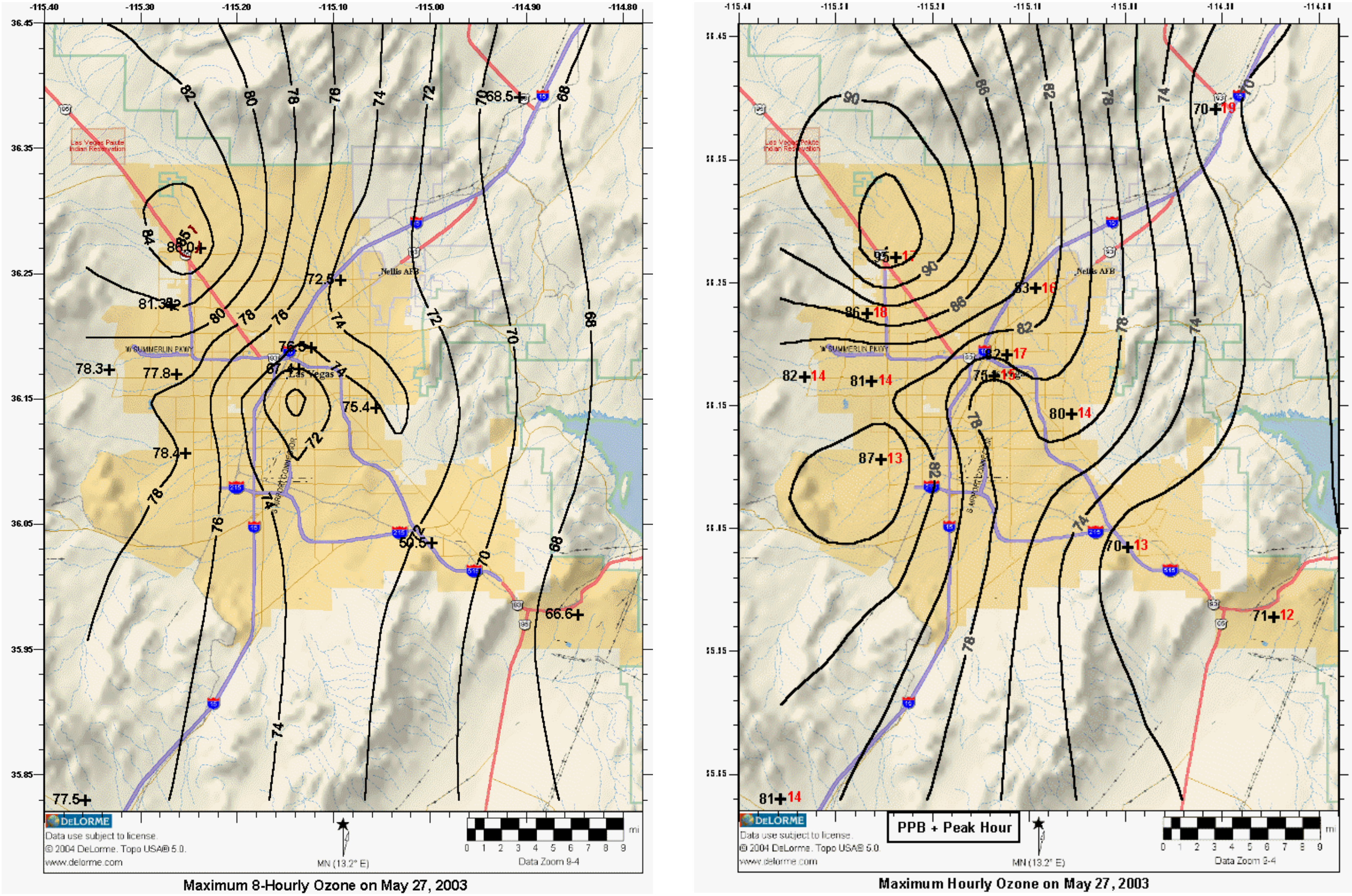


Figure 5-36. Peak Ozone for May 27, 2003

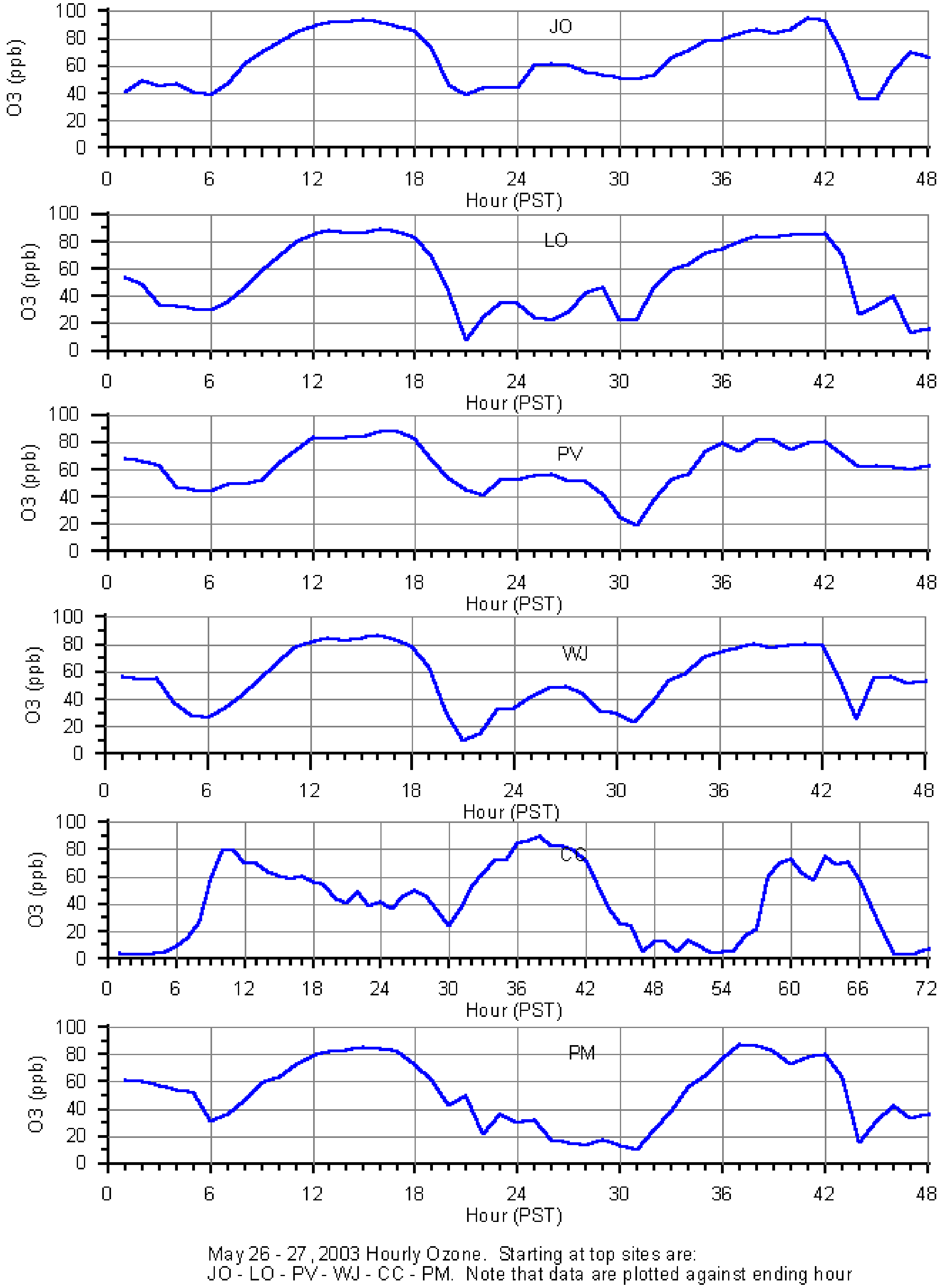


Figure 5-37. Hourly Ozone on May 26-27, 2003

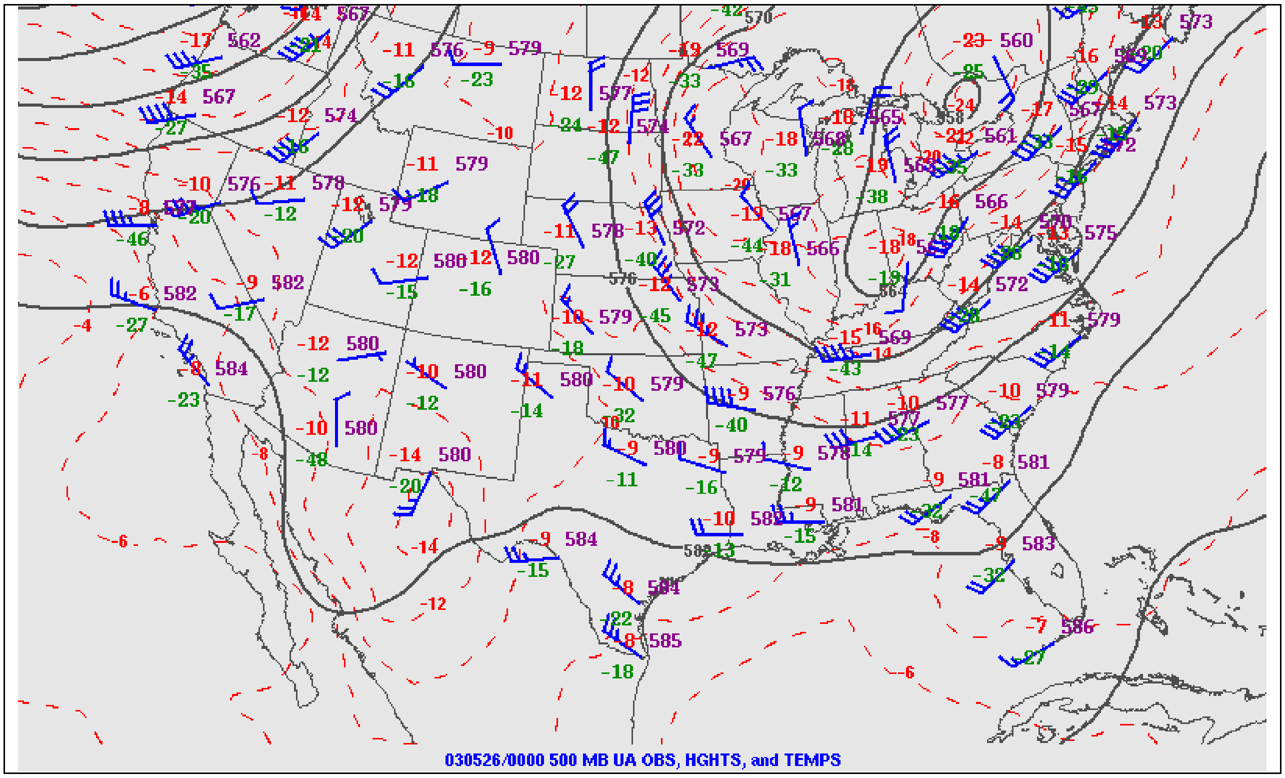


Figure 5-38(a). NWS 500 mb Constant Pressure Map for Afternoon of May 25, 2003

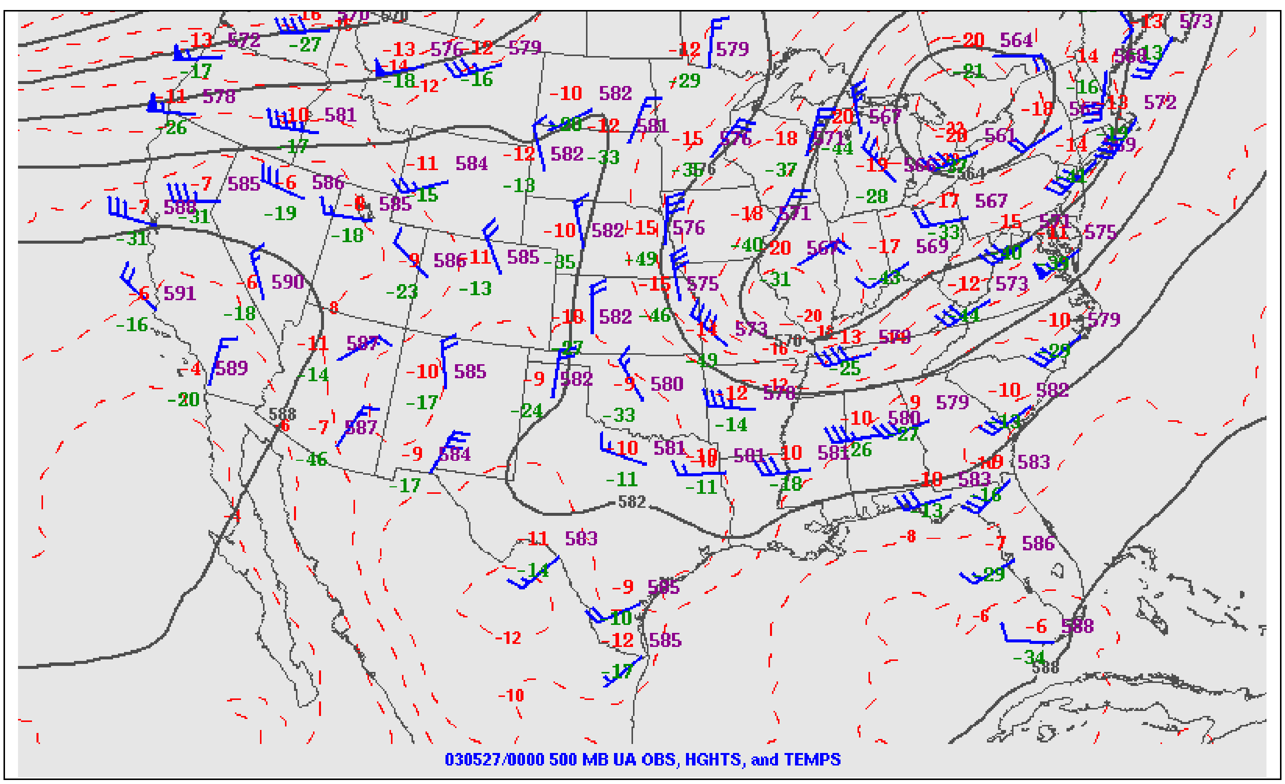


Figure 5-38(b). NWS 500 mb Constant Pressure Map for Afternoon of May 26, 2003

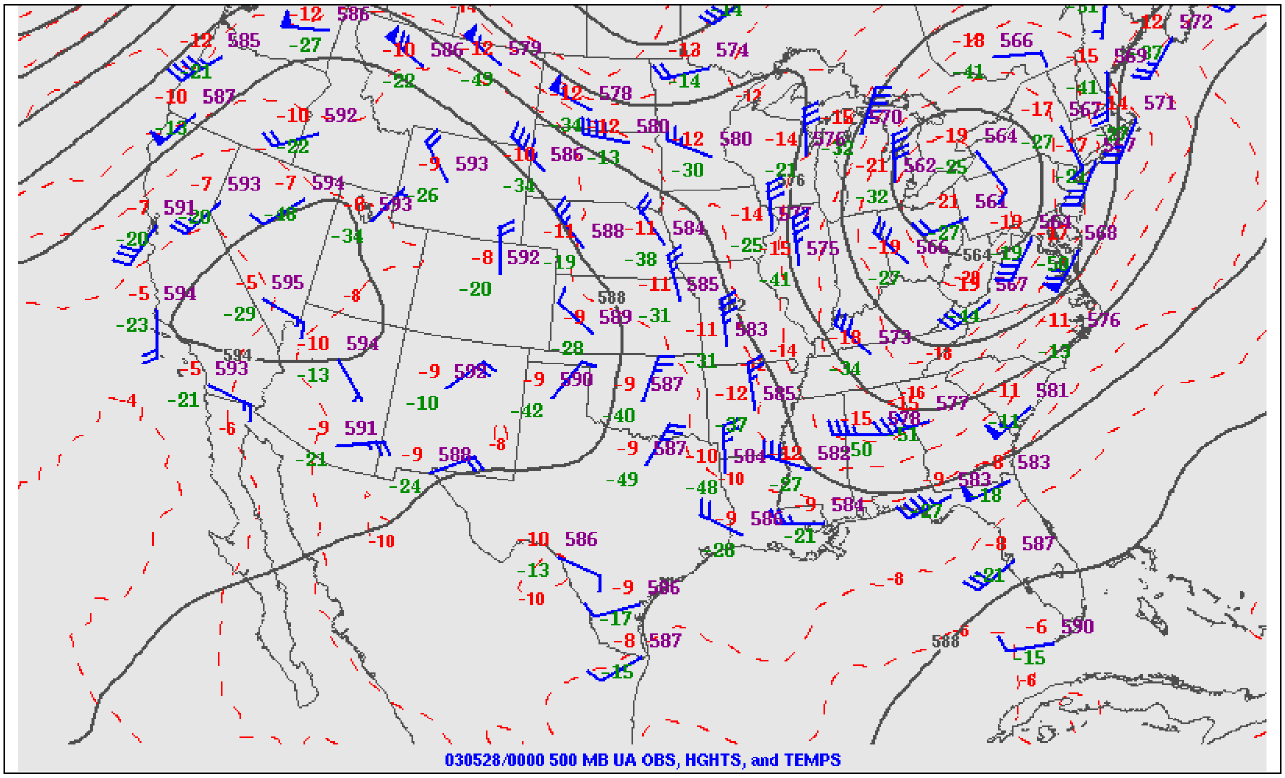


Figure 5-39(a). NWS 500 mb Constant Pressure Map for Afternoon of May 27, 2003

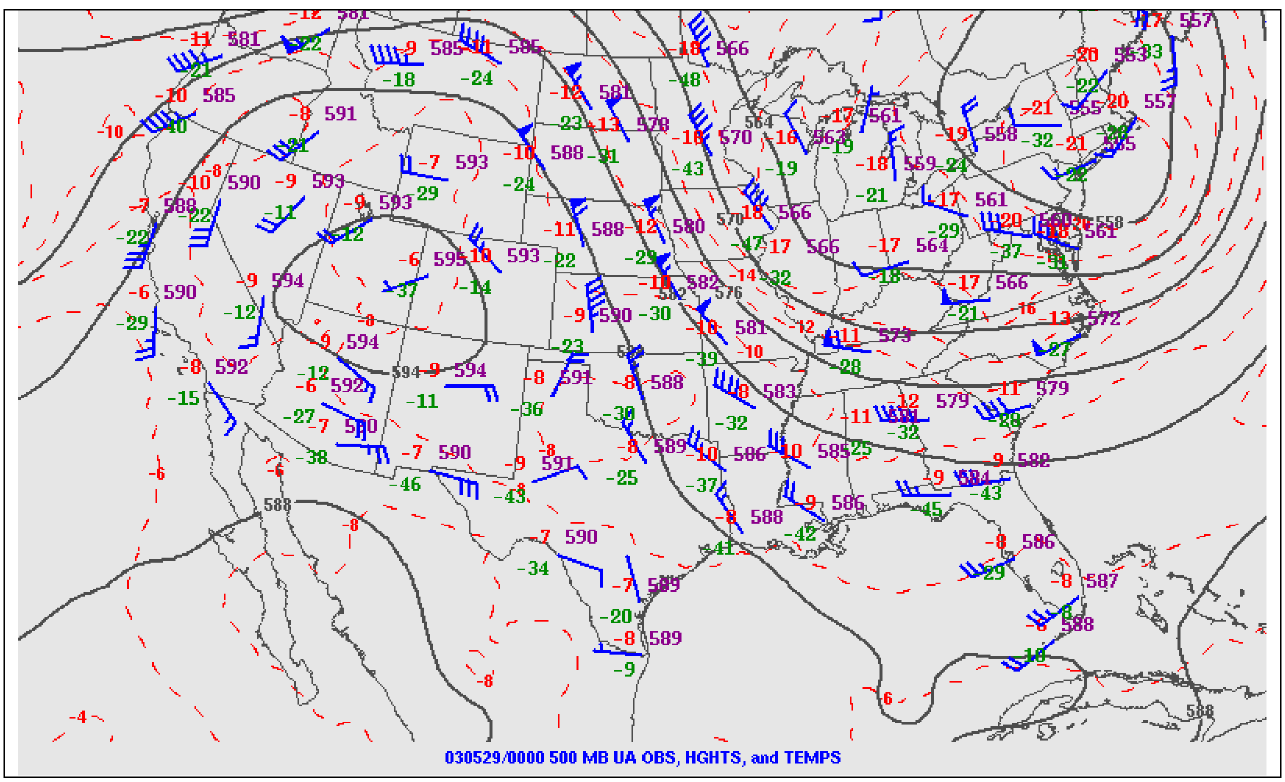


Figure 5-39(b). NWS 500 mb Constant Pressure Map for Afternoon of May 28, 2003

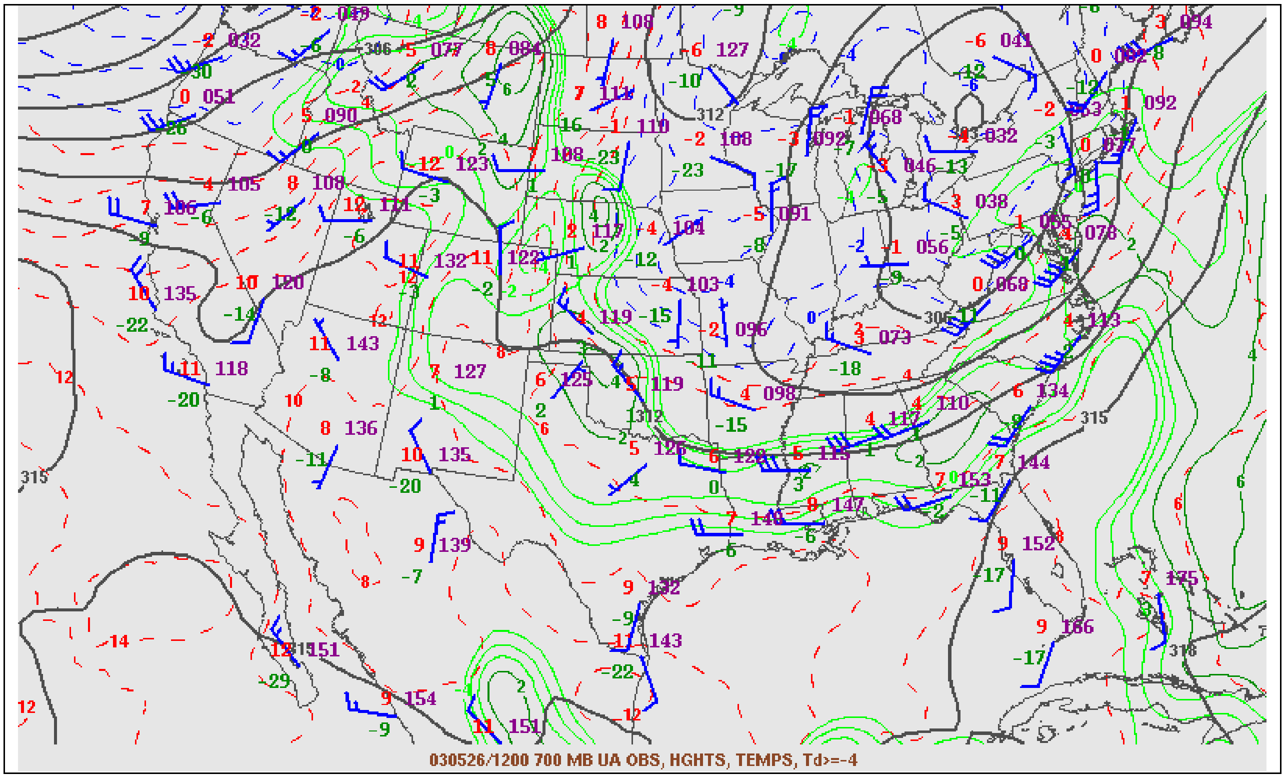


Figure 5-40(a). NWS 700 mb Constant Pressure Map for Morning of May 26, 2003

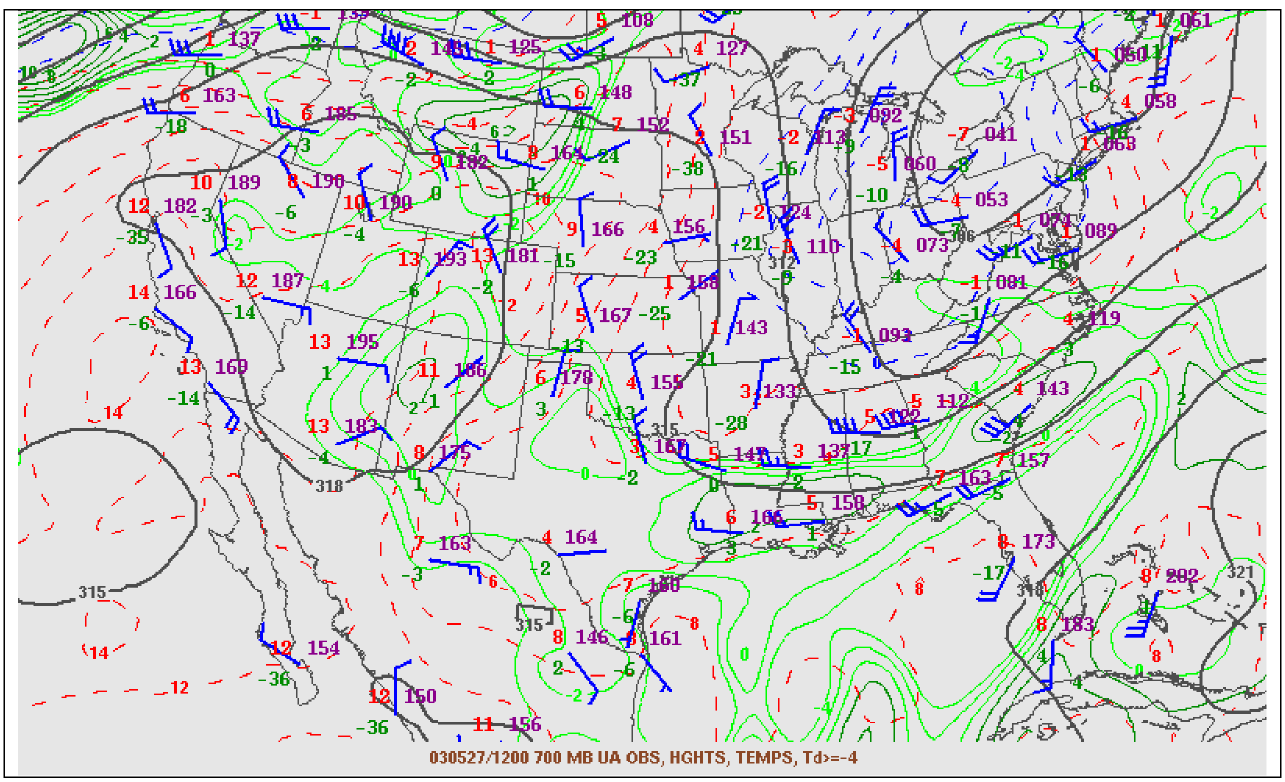


Figure 5-40(b). NWS 700 mb Constant Pressure Map for Morning of May 27, 2003

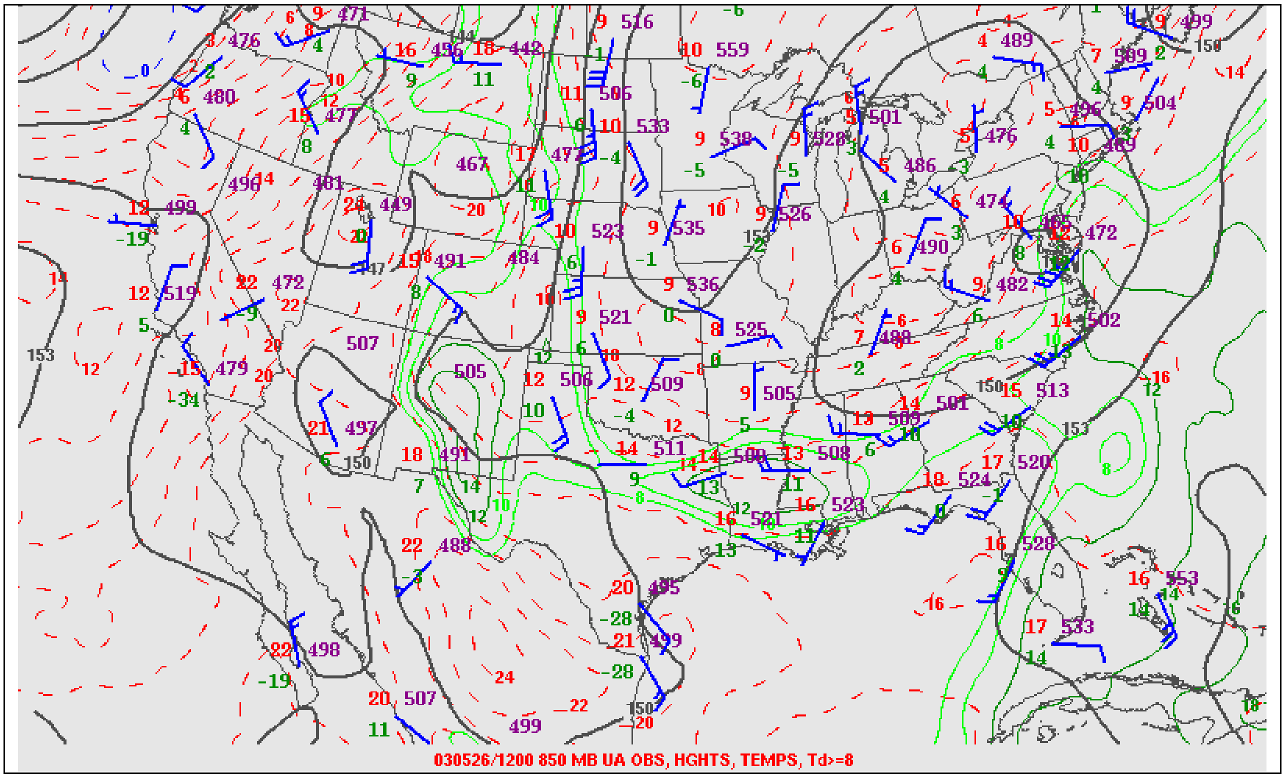


Figure 5-41(a). NWS 850 mb Constant Pressure Map for Morning of May 26, 2003

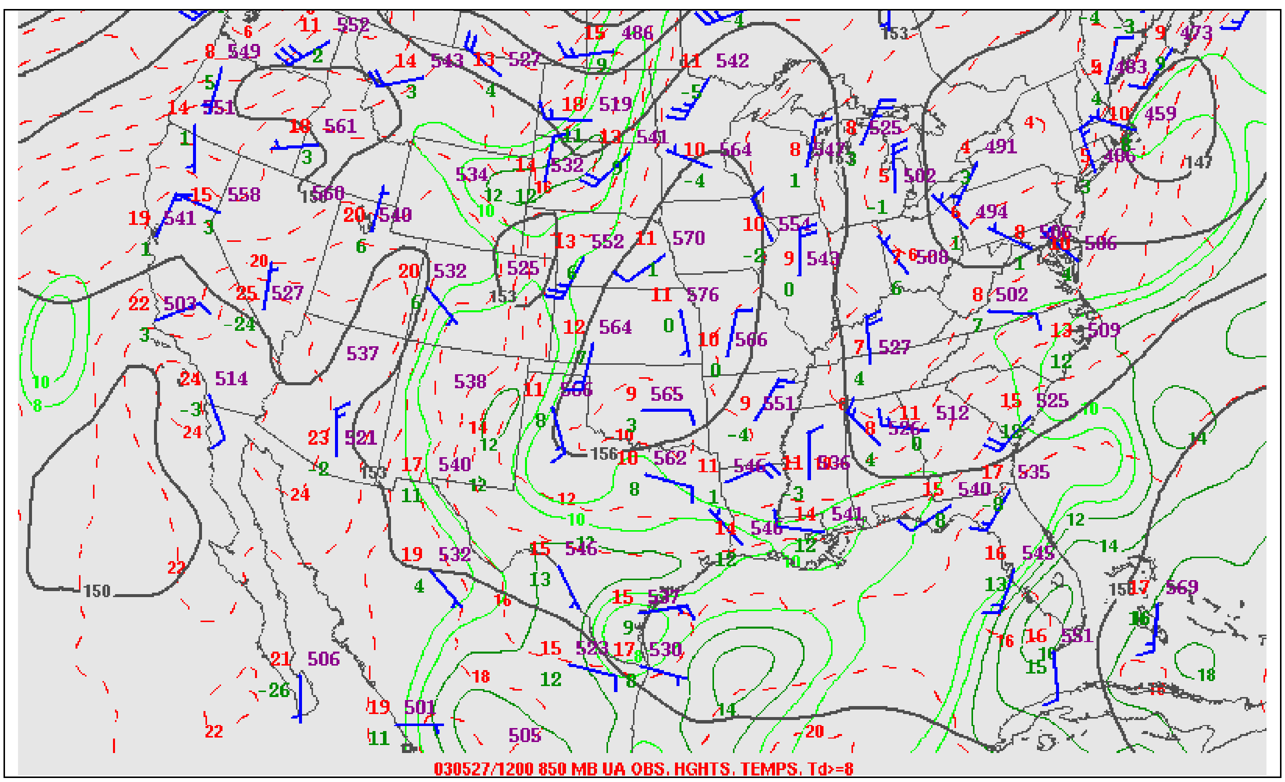


Figure 5-41(b). NWS 850 mb Constant Pressure Map for Morning of May 27, 2003

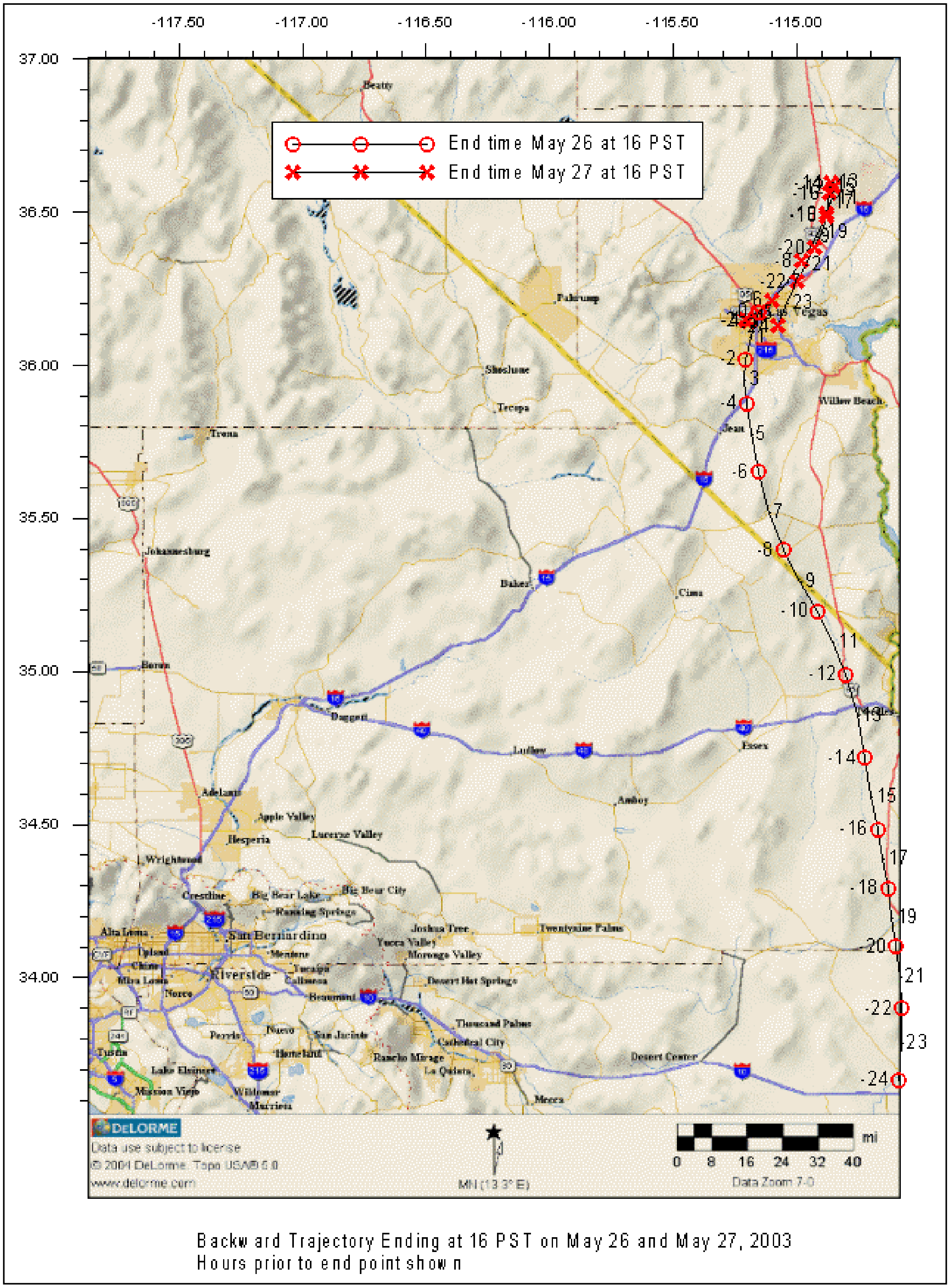


Figure 5-42. Backward Trajectory Ending at 16 PST on May 26 and 27, 2003

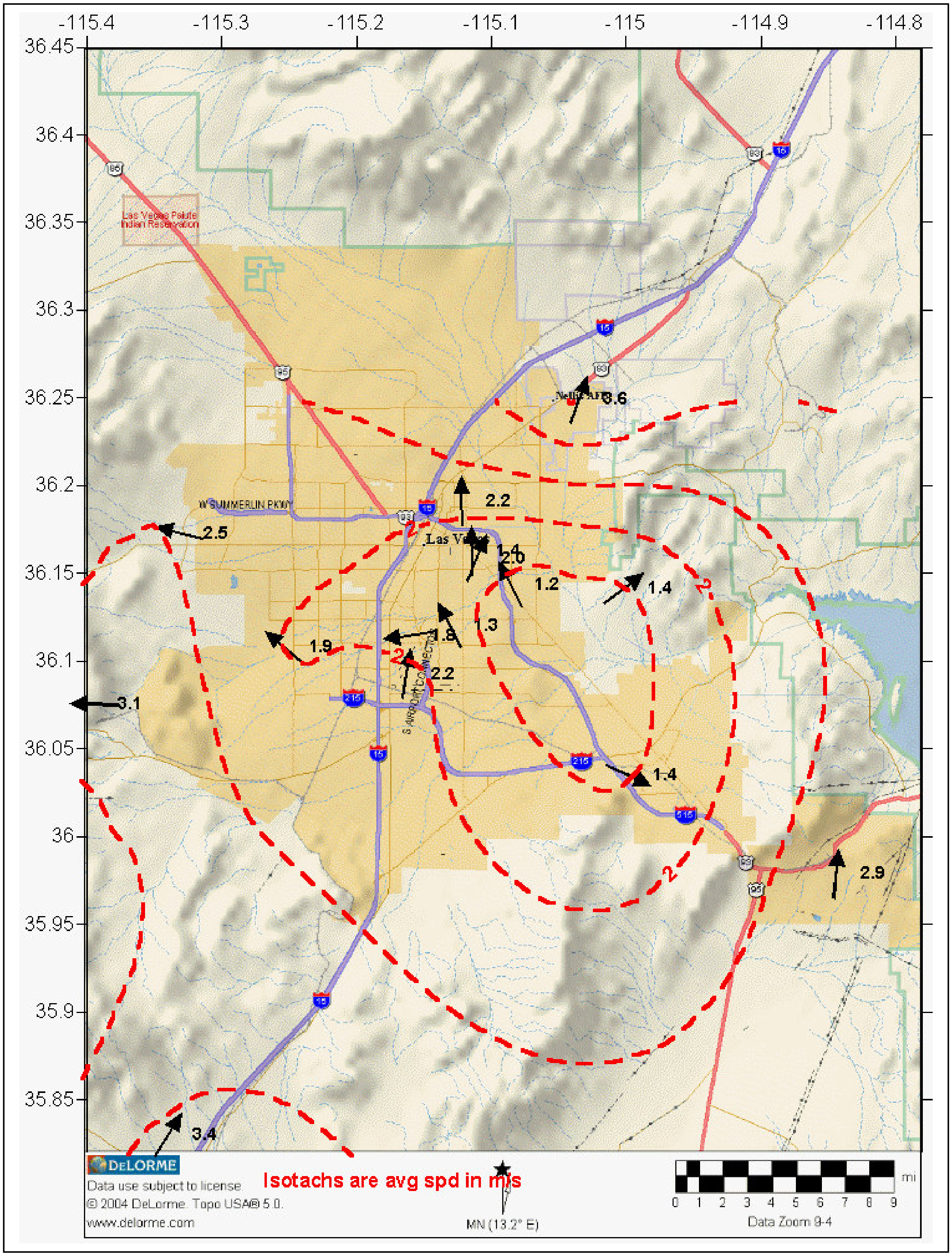


Figure 5-43. Las Vegas Valley Prevailing Winds at 16 PST on May 27, 2003

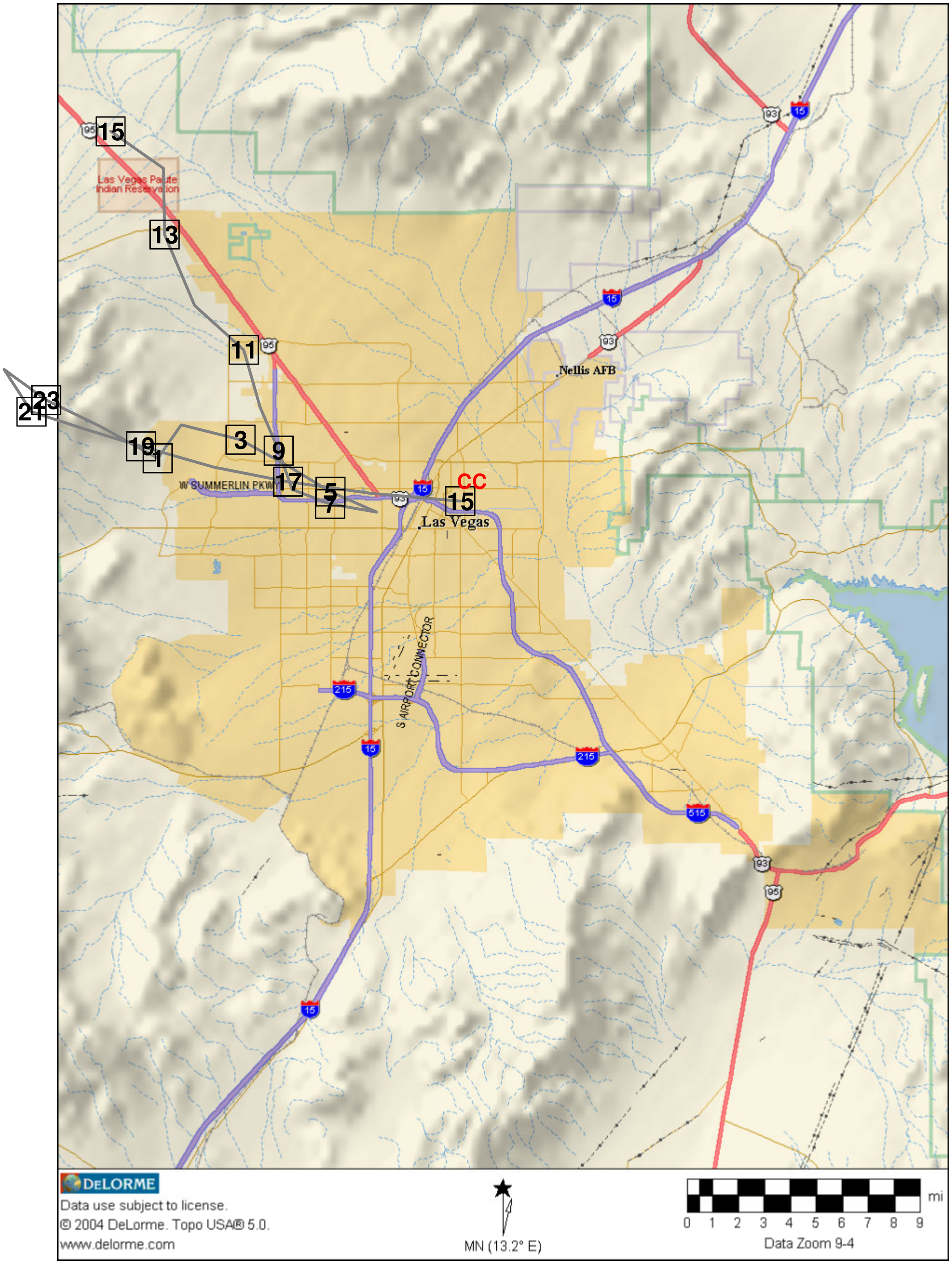


Figure 5-44. Depicting 24-hour Air Parcel Trajectory Starting from Las Vegas Downtown at 15 PST on May 26, Ending at 15 PST on May 27, 2003. Time along trajectory is noted in boxes.

5.7 June 1 to 4, 2003 Episode

This 4-day period was characterized by marginal ozone levels during which exceedances of the 8-hour Federal Ozone Standard occurred at only one site in Clark County on 3 days with one non-exceedance day sandwiched between. In spite of one non-exceedance day, the four days were considered as one episode. Maximum 8-hour ozone levels are listed in **Table 5-13.** In the last row of the table, the number of sites exceeding the 8-hour ozone standard is given. On June 1, Joe Neal experienced the only exceedance (86.4 ppb). There were no exceedances on the 2nd. The only exceedances on June 3rd and 4th were at Jean (86 and 85.3). On May 31 and June 5, although not exceedance days, Jean again recorded the network highest ozone levels. Charts showing the Las Vegas Valley and adjacent regions peak-ozone spatial patterns are shown on **Figures 5-45 to 5-48** for the four-day period beginning June 1. Again, both the daily maximum 8-hour averaged levels and 1-hour levels are shown on separate panels. Contours of constant ozone and the time of the peak (1-hour charts only) are included. There are a number of interesting features on the sequence of charts. On each of the four days, the areal distribution of 8-hour and 1-hour ozone peaks and minimums are in good agreement. The episode began on the 1st with the "typical" ozone pattern shown on Figure 5-45. The highest ozone occurred in the northwest and there was a southeast gradient to lower levels. The 8-hour peak spatial pattern over the next 3 days showed a shifting to higher ozone levels in the southwest as exemplified by Jean experiencing the network maximum each day. Peak 1-hour ozone on June 1 to 3 occurred at Joe Neal and the other sites in the northwest quadrant of the Las Vegas Valley. On June 4, the spatial distribution of peak ozone levels was not uniform, with Jean, Joe Neal, and Paul Myer sites all high.

Table 5-13. Maximum 8-Hour Ozone (ppb) – Case Study 7

Site Name	Site ID	05/31/2003	06/01/2003	06/02/2003	06/03/2003	06/04/2003	06/05/2003
Apex	AP	68.0	78.0	70.6	76.0	74.9	66.5
Boulder City	BC	60.4	69.1	60.1	63.1	73.5	64.38
E Craig Rd	BS	65.5	81.3	67.8	70.8	68.1	63.38
City Center	CC	51.8	78.3	60.0	67.0	66.0	70.25
JD Smith	JD	62.9	81.0	67.3	75.3	75.6	68.5
Jean	JN	70.3	72.4	74.6	86.0	85.3	80.88
Joe Neal	JO	68.3	86.4	78.4	84.0	80.0	74.38
Lone Mt	LO	63.3	83.5	76.1	79.1	76.6	72.88
Mesquite	MQ	56.0	64.8	65.3	70.6	63.9	70.14
SE Valley	PL	61.0	72.3	60.5	66.8	74.0	59
Paul Myer	PM	60.9	77.4	68.4	81.3	79.4	75.13
Palo Verde	PV	65.1	79.5	73.1	82.4	76.9	78.75
Searchlight	ST	61.1	65.3	56.0	54.9	72.5	59.5
Walter Johnson	WJ	61.6	80.4	69.8	78.6	77.1	73.75
Winterwood	WW	65.5	77.9	68.6	71.5	76.5	70.38
Network Max		70.3	86.4	78.4	86.0	85.3	80.9
# Sites Exceeded		0	1	0	1	1	0

Over the period June 1 to 3, the ozone peaks occurred for the most part between 12 and 15 PST. On the 4th, ozone peaked later in the afternoon between 15 and 17 PST.

Meteorology

The synoptic weather pattern at the 500 mb constant-pressure surface prior to the high ozone episode was categorized as a Flat Ridge (FR). Conditions over the southwest U.S. on May 31st were not particularly conducive to producing high ozone levels. There was enough subsidence in the lower atmosphere to limit mixing and enable a build up of pollutants, but not enough to raise concentrations to exceedance levels. By the afternoon of June 1st, an extension of the eastern Pacific ridge was bulging onshore over central California, and flow at 500 mb over southern Nevada became northwesterly at 8 to 10 m/s. The height of the 500 mb surface had risen to close to 5,900 m, although the highest levels were along the California coast. These characteristics are typical of a Pacific Ridge (PR) situation. The PR category persisted through the remainder of the episodic period. **Figure 5-49(a&b)** gives the 500 mb constant-pressure maps for the afternoons of June 1st and 2nd, respectively. Throughout the entire period, flow at 500 mb over the Desert Rock NWS site remained northwesterly at around 8 m/s, and heights stayed between 5,860 m and 5,890 m.

Below the 500 mb level, a flat ridge on May 31st was present but was somewhat more dynamic than is typical during FR conditions. The 700 mb temperature was warm at 10°C but not indicative of substantial air mass subsidence. Wind flow at and below 700 mb was moderately strong southwesterly as high as 9 m/s. **Figure 5-50(a)** shows the 700 mb constant-level map for the morning of June 1st, 2002. By that time, the temperature had increased by about 2° C. The wind flow at and below that level remained southwesterly. The increased stability combined with continued transport winds may have contributed to the higher ozone concentrations later that day in Clark County. On the 2nd, the effect of the Pacific Ridge at the west coast was a bit stronger at the 700 mb level, and the winds at that level became more northwesterly. Even though the temperature had increased to 13.6°C, the shift in wind fetch may have resulted in lower ozone concentrations on that day. On the 3rd, the 700 mb temperature had risen to 14.0°C, and flow had become west-southwesterly again down to the 850 mb level **Figure 5-50(b)**. Temperatures aloft continued to increase on the 4th. At 700 mb, the temperature over Desert Rock was 14.4°C indicating continued air mass stability. Winds aloft on the 4th and 5th showed a significant reduction in speed and a shift back to west-northwesterly during the early morning period.

These conditions were reflected in the lower boundary layer. On the morning of June 1st, temperatures aloft had warmed slightly. The wind flow at 850 mb became southwesterly at 11 to 8 m/s. Moderate wind speeds were in a layer from almost ground level to about 2,000 m-agl. **Figure 5-51(a)** shows the 850 mb constant pressure map for the morning of June 1st. On the morning of June 2nd, moderately strong southwesterly flow was again evident from about 200 m above ground level to around 1,000 m agl. Winds were light and variable below that layer. The opportunity for interbasin transport from the South Coast air basin and/or San Joaquin Valley appeared to be as good as on the 1st, but no exceedances were reported. **Figure 5-51(b)** presents the 850 mb constant level map for the morning of June 3rd. The 850 mb temperature over Desert Rock continued to increase. A thermal low was detectable at that level over southern Nevada. The Desert Rock sounding showed winds at 850 mb and below from the north to northeasterly with a strong southwesterly flow above. By the early hours of June 4th, the only major change in the low levels was the cessation of the southwesterly flow layer. Winds at and below 850 mb had become variable from north-northeasterly to west-northwesterly at 5 m/s or less.

The trajectories that the HYSPLIT Model produced over this episode for the most part agreed well with the flow characteristics described by the constant-pressure level charts. Hysplit trajectories are depicted on **Figure 5-52**. Each backward trajectory shown ended at 15 PST and began 24 hours earlier. The trajectories suggest interbasin transport from the southwest near Tehachapi Pass on the 1st, from the south (Twentynine Palms) on the 2nd, and from the south-southwest (near Apple Valley) on the 3rd. The descriptive analyses of the synoptic weather maps suggest transport from the southwest on the 1st and 2nd, but below ~ 2,000 ft-agl from the northwest on the 3rd. This was based on the Desert Rock morning sounding and may be due to local terrain. The synoptic charts implied a significant reduction in the interbasin transport potential on the 4th. The trajectory on Figure 5-52 shows good agreement. Ozone levels in the desert of California leading up to and during the episode are given in **Table 5-14**. As can be seen exceedance levels did not occur on May 31 and June 1. Ozone increased at the northern California desert sites (Mojave, Barstow, and Trona) beginning on the 2nd. Mojave recorded an 8-hour peak of 101.6 ppb on the 3rd. Exceedances were measured at Barstow and Trona on the 3rd as well.

Table 5-14. Maximum 8-Hour Ozone at California Desert Sites

Date	05/31/2003	06/01/2003	06/02/2003	06/03/2003	06/04/2003
Barstow	63.6	71.6	76.9	86.6	90.0
Death Valley	58.9	62.1	71.3	78.8	80.0
Joshua Tree	missing	missing	missing	missing	missing
Mojave	81.3	85.0	92.6	101.6	98.8
Trona	60.5	70.9	76.0	87.5	83.8
Twentynine Palms	65.5	62.4	70.9	71.9	83.8
Victorville	57.5	78.6	66.5	81.5	88.4

Surface winds within the Las Vegas Valley and adjacent areas were characteristically like those shown for 16 PST on June 3 (**Figure 5-53**). Within the Valley the flow was generally east to southeast, while southwest at the western boundary sites. On the 3rd, wind speeds are seen to be generally stronger than during (most) of the other episodes. However, wind speeds were generally lower on the other episode days.

Mixing heights, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures ranged from 3,900 to 4,000 m-agl on the 1st and 2nd, to 4,900 m-agl on both the 3rd and 4th.

<u>Summary</u>

- The 4-day period was characterized by marginal ozone levels during which exceedances of the 8-hour Federal Ozone Standard occurred at only one site in Clark County on three days with one non-exceedance day sandwiched between.

- The only exceedance on June 3rd and 4th occurred at Jean. On June 1, the exceedance occurred at Joe Neal. There were no exceedances of the ozone standard on the 2nd but, interestingly, Jean again had the highest reading in the network.

- The spatial distribution of the daily 8-hour peaks began on the 1st with the highest ozone in the northwest quadrant with a southeast gradient to lower levels. Each day thereafter, the peaks shifted to the sites in the southwest portion of the network.

- The Pacific Ridge (PR) synoptic scale weather pattern prevailed during the 4-day period of this ozone episode. From the synoptic charts, layers of moderately strong southwesterly flow were evident in the lower boundary layer during the 1st through the 3rd. The height above the ground of these potential transport layers varied from day to day, and it is difficult to postulate with any accuracy what the low-level wind pattern just above the surface was in the Las Vegas Valley. Low level transport winds were not apparent on the morning of the 4th.

- The descriptive analyses of the winds from the synoptic charts were consistent with the Hysplit trajectory model results. HYSPLIT-constructed Backward trajectories originated in the California desert on June 1 to 3. A more local trajectory was predicted by Hysplit on the 4th.

- Owing to missing data from a key transport indicator (Joshua Tree), the CART model results cannot be considered conclusive. However, with the 1st falling in Terminal Node 7, and the 3rd and 4th falling in Terminal Node 3, they generally support the conclusions of transport being a factor more at the beginning than at the end of the 4-day episode.

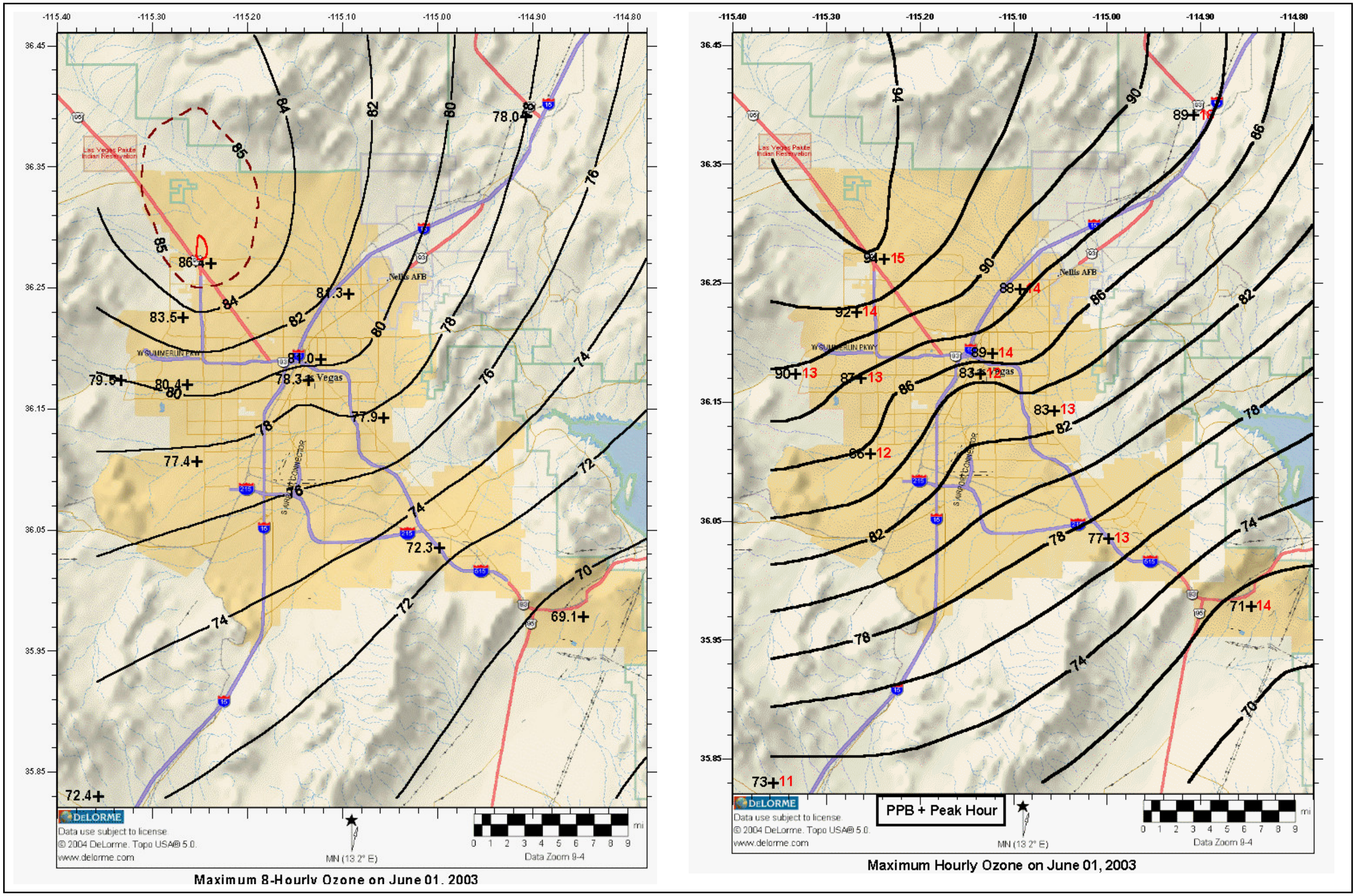


Figure 5-45. Peak Ozone for June 1, 2003

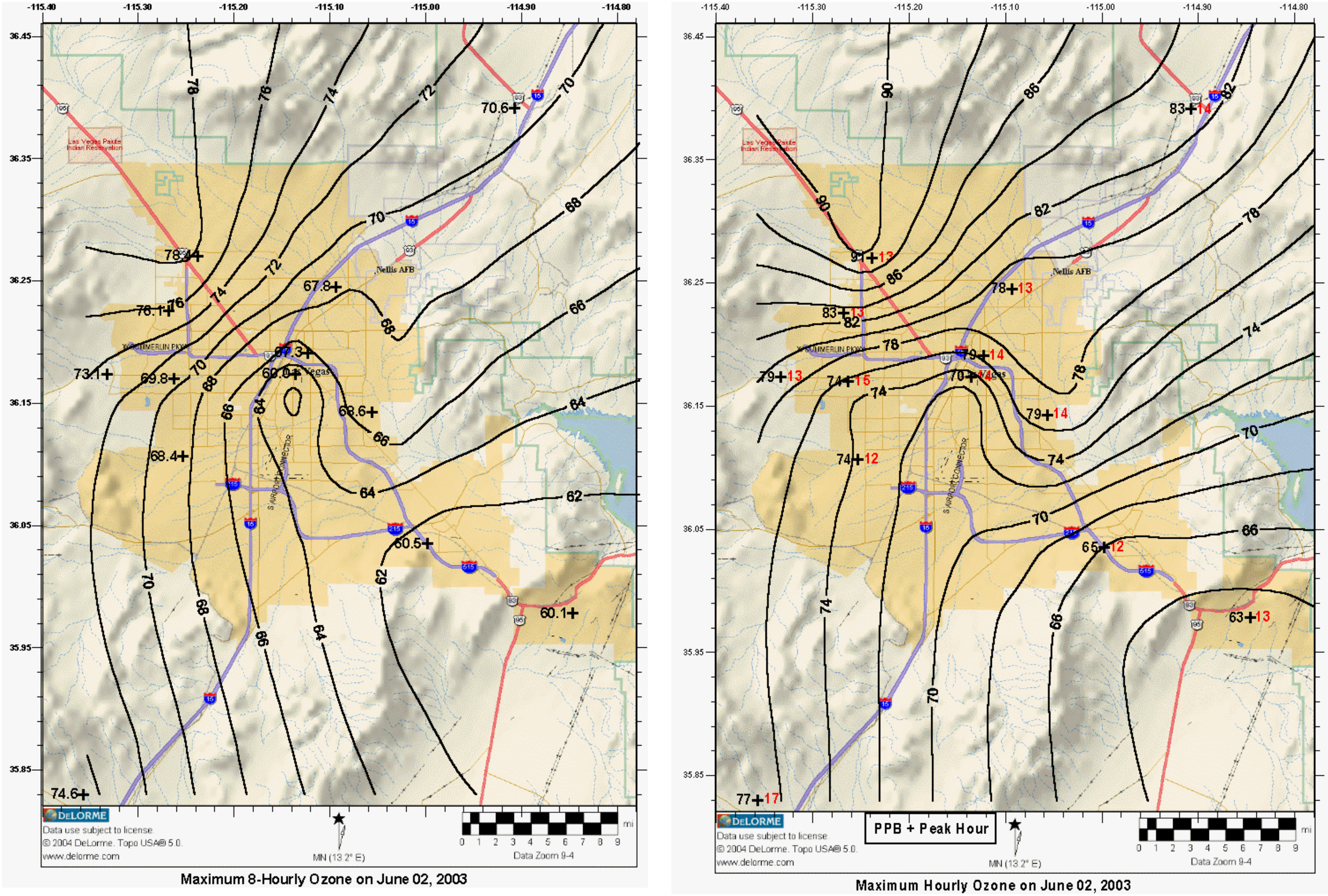


Figure 5-46. Peak Ozone for June 2, 2003

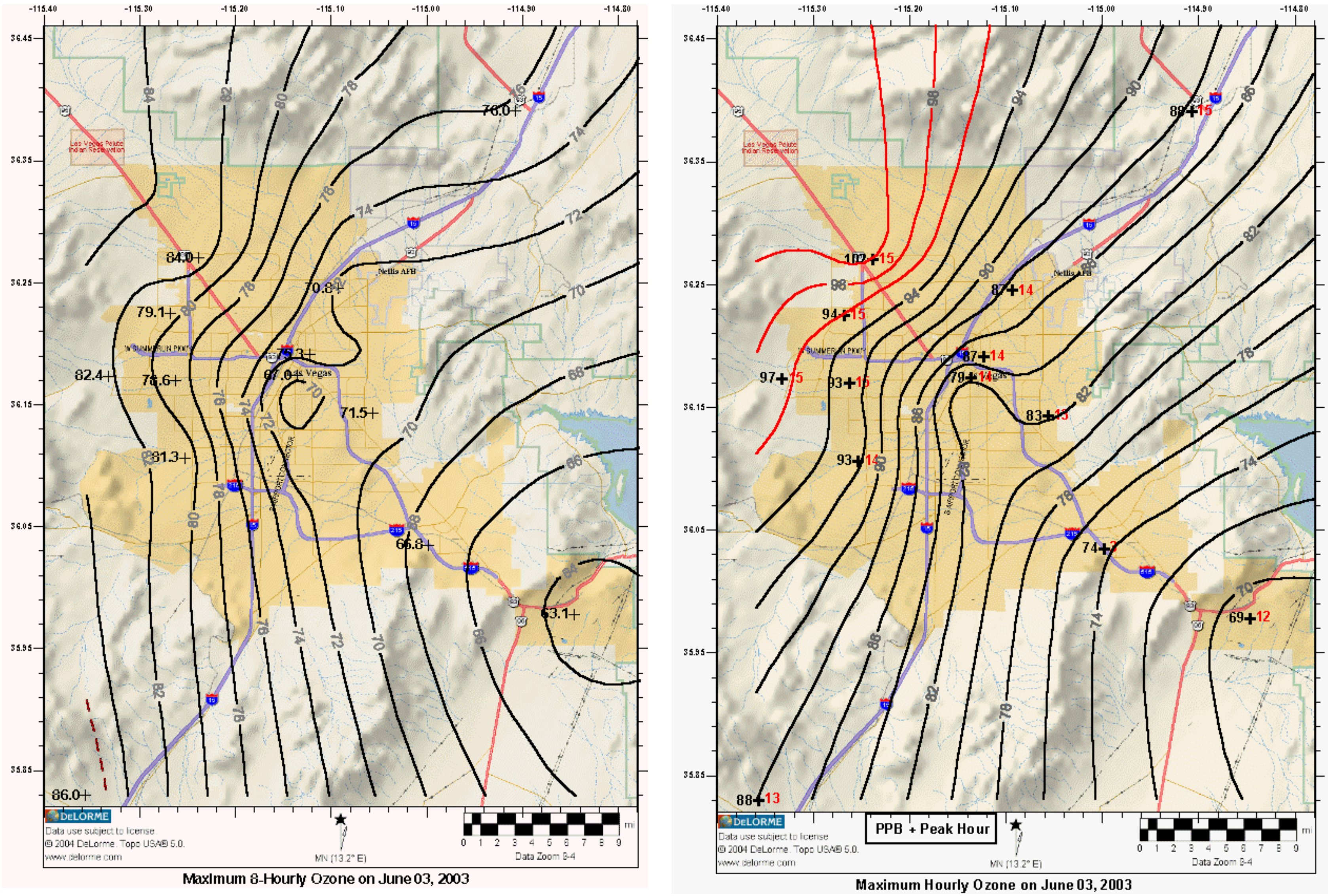
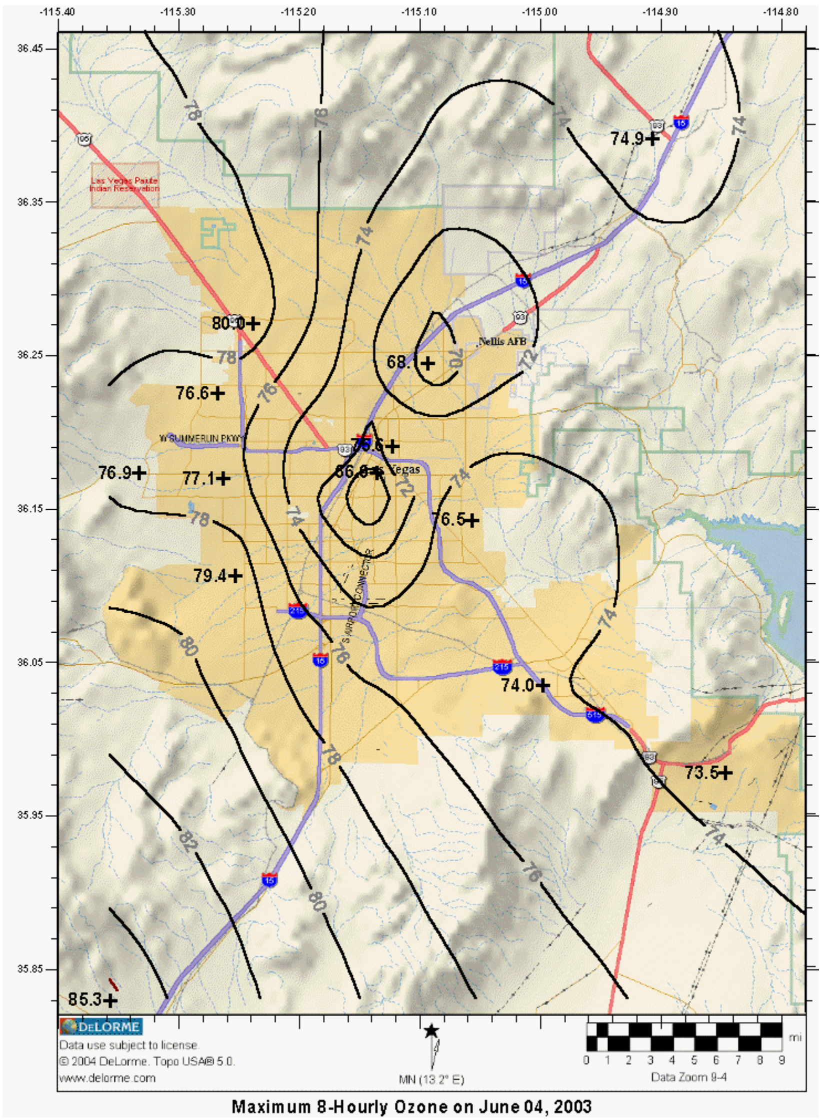


Figure 5-47. Peak Ozone for June 3, 2003



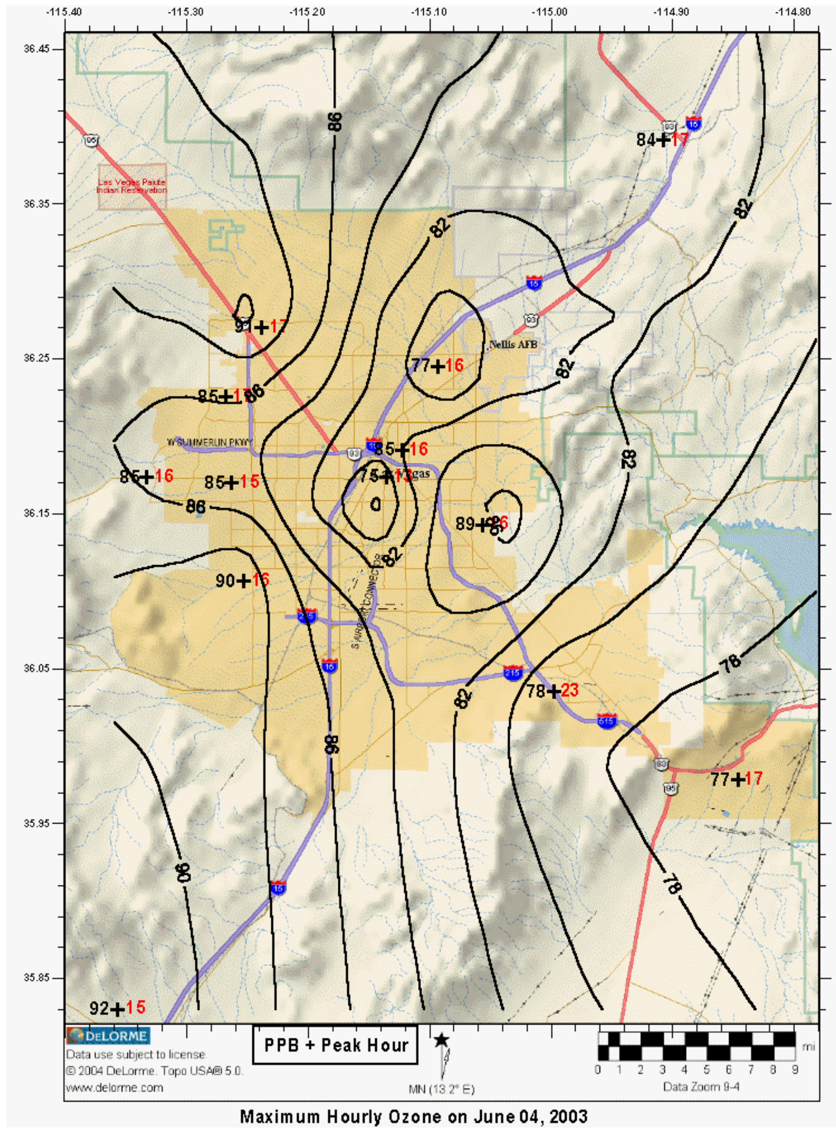


Figure 5-48. Peak Ozone for June 4, 2003

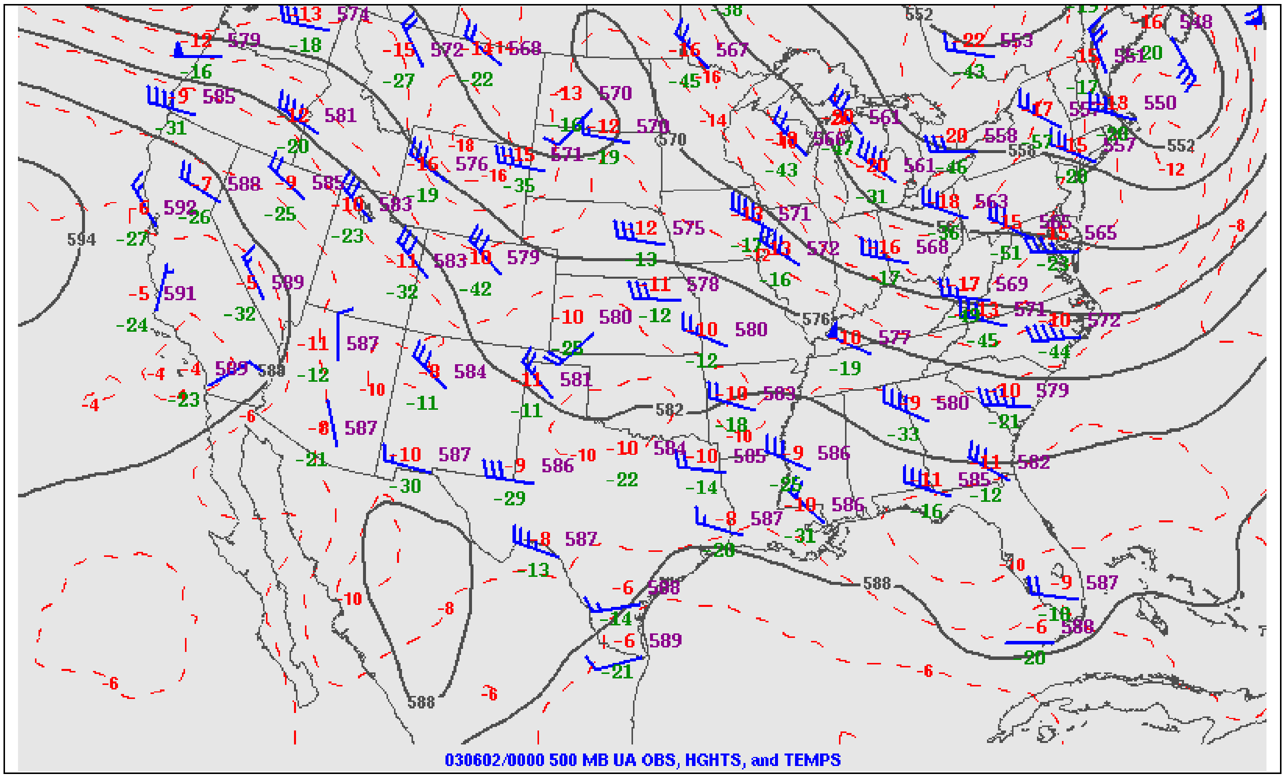


Figure 5-49(a). NWS 500 mb Constant Pressure Map for Afternoon of June 1, 2003

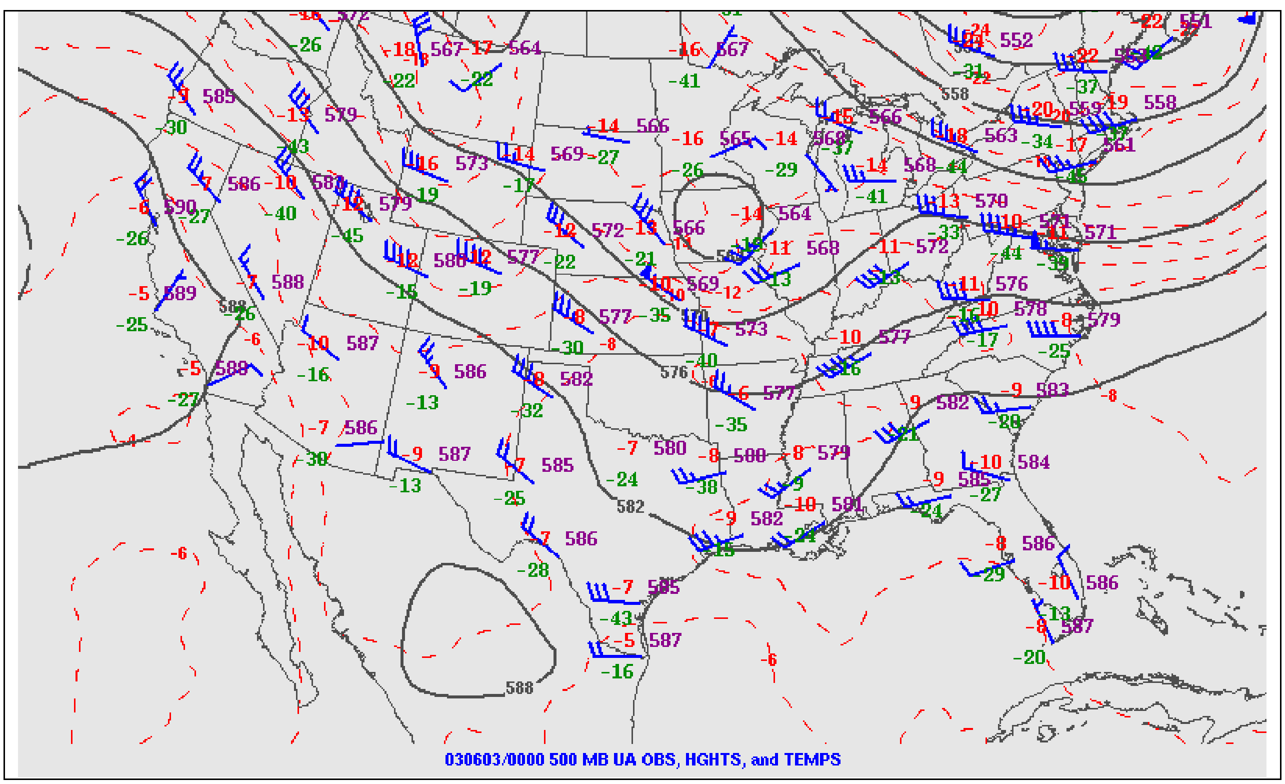


Figure 5-49(b). NWS 500 mb Constant Pressure Map for Afternoon of June 2, 2003

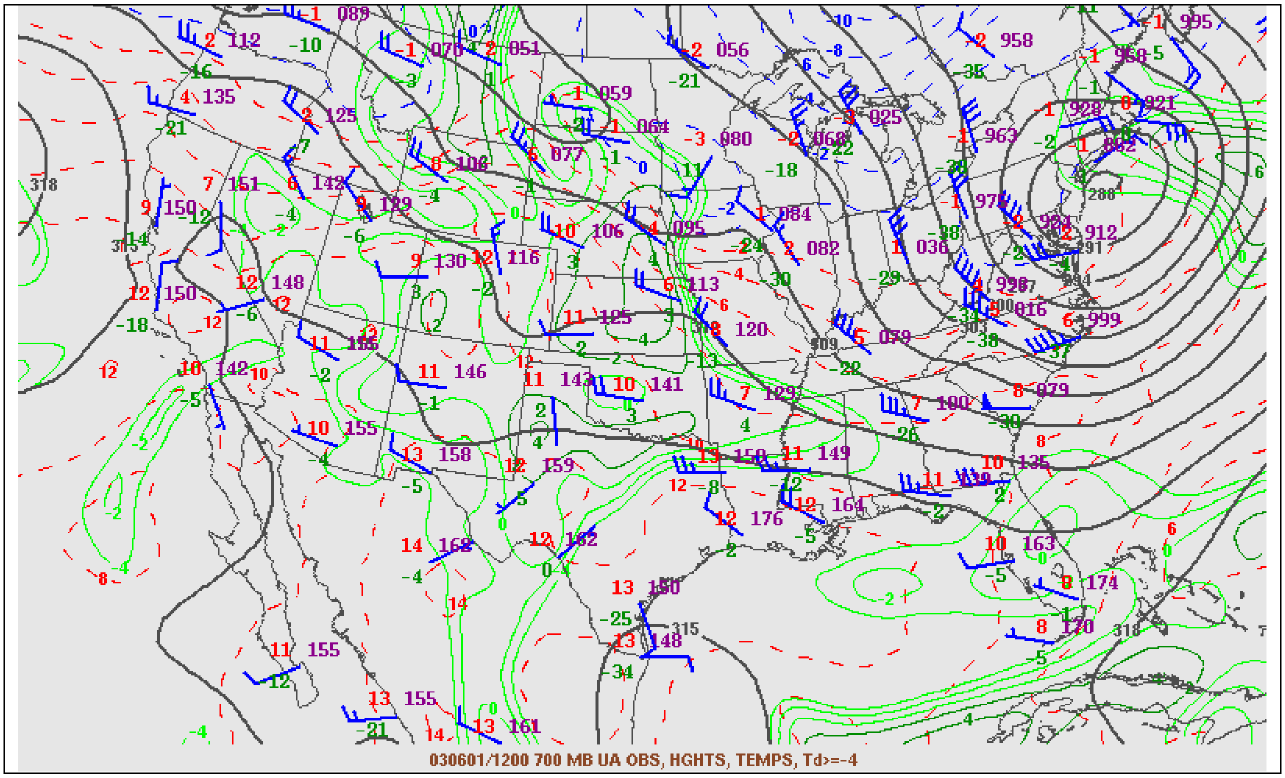


Figure 5-50(a). NWS 700 mb Constant Pressure Map for Morning of June 1, 2003

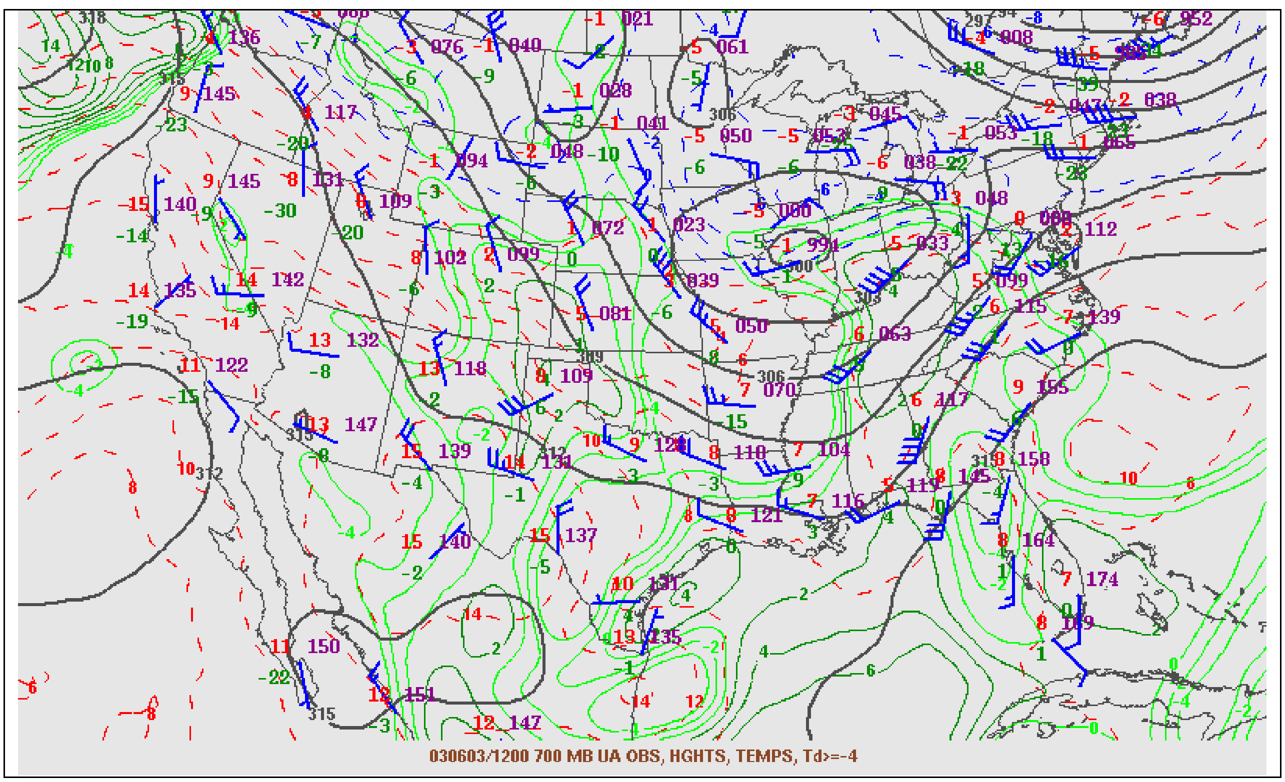


Figure 5-50(b). NWS 700 mb Constant Pressure Map for Morning of June 3, 2003

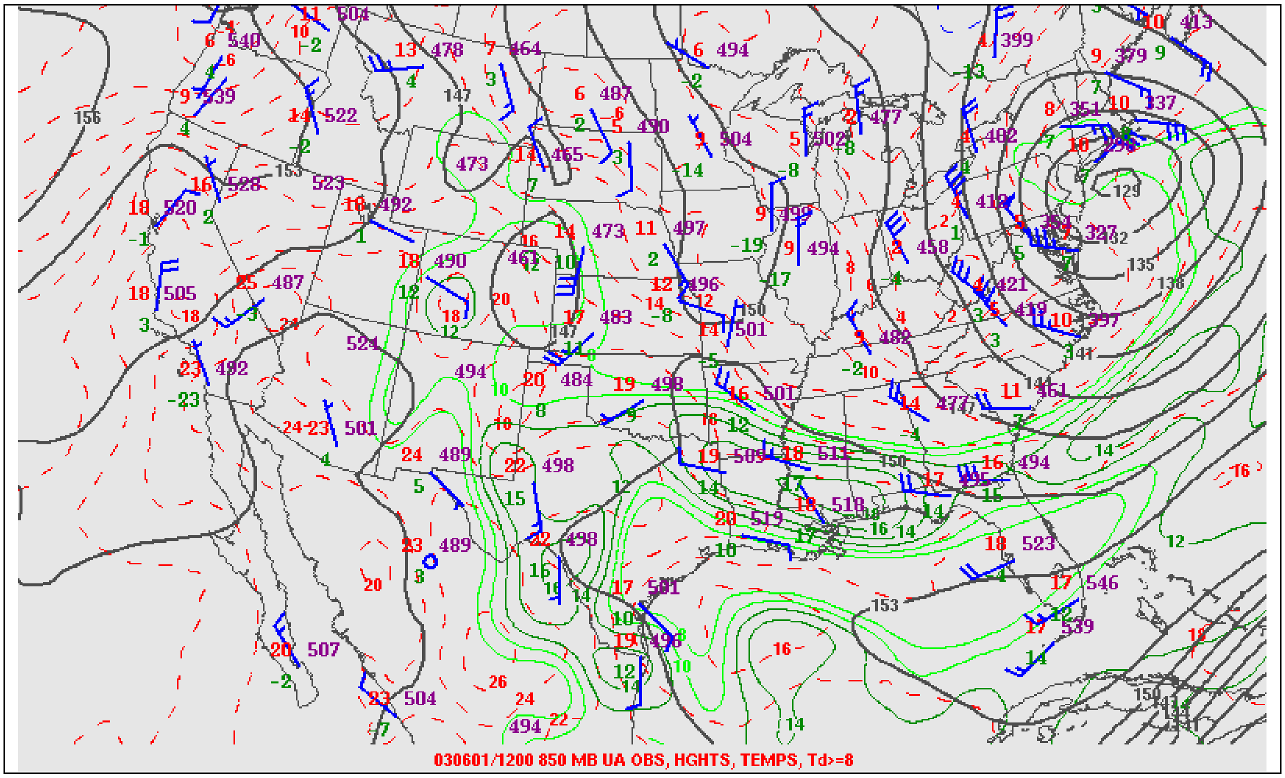


Figure 5-51(a). NWS 850 mb Constant Pressure Map for Morning of June 1, 2003

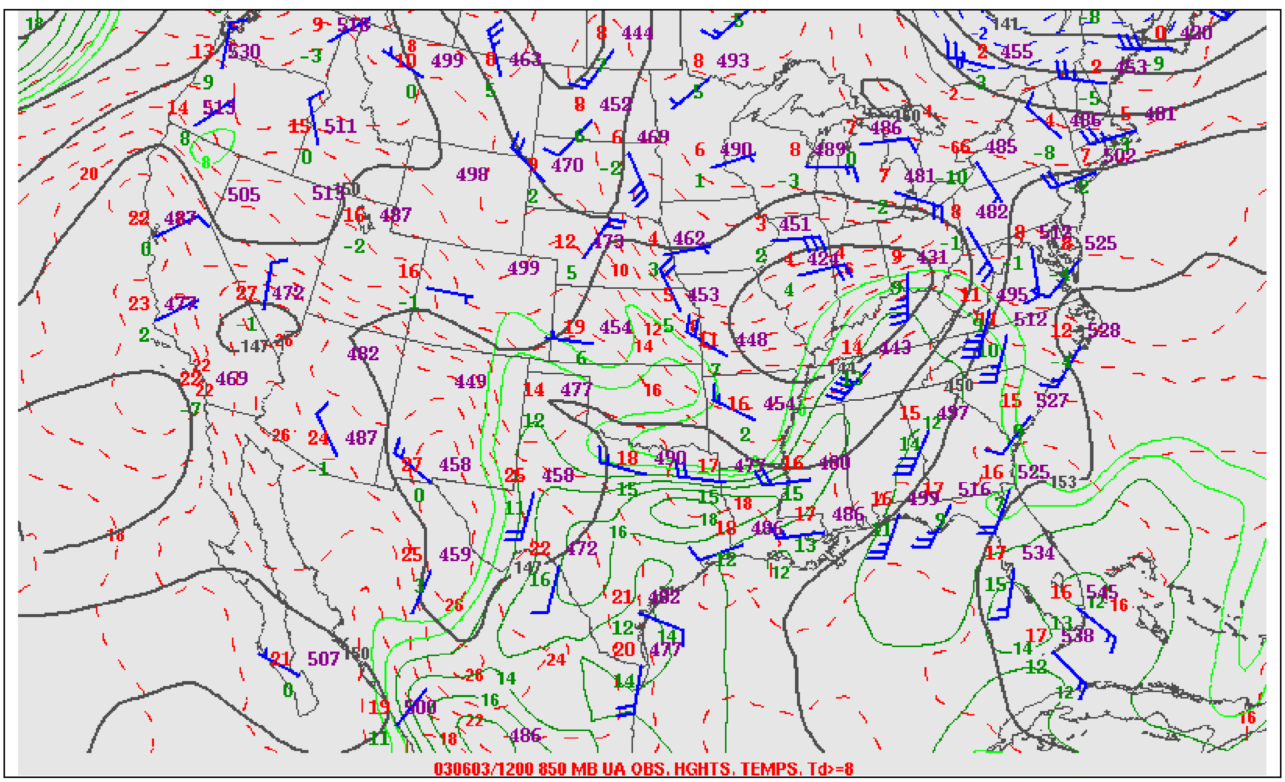


Figure 5-51(b). NWS 850 mb Constant Pressure Map for Morning of June 3, 2003

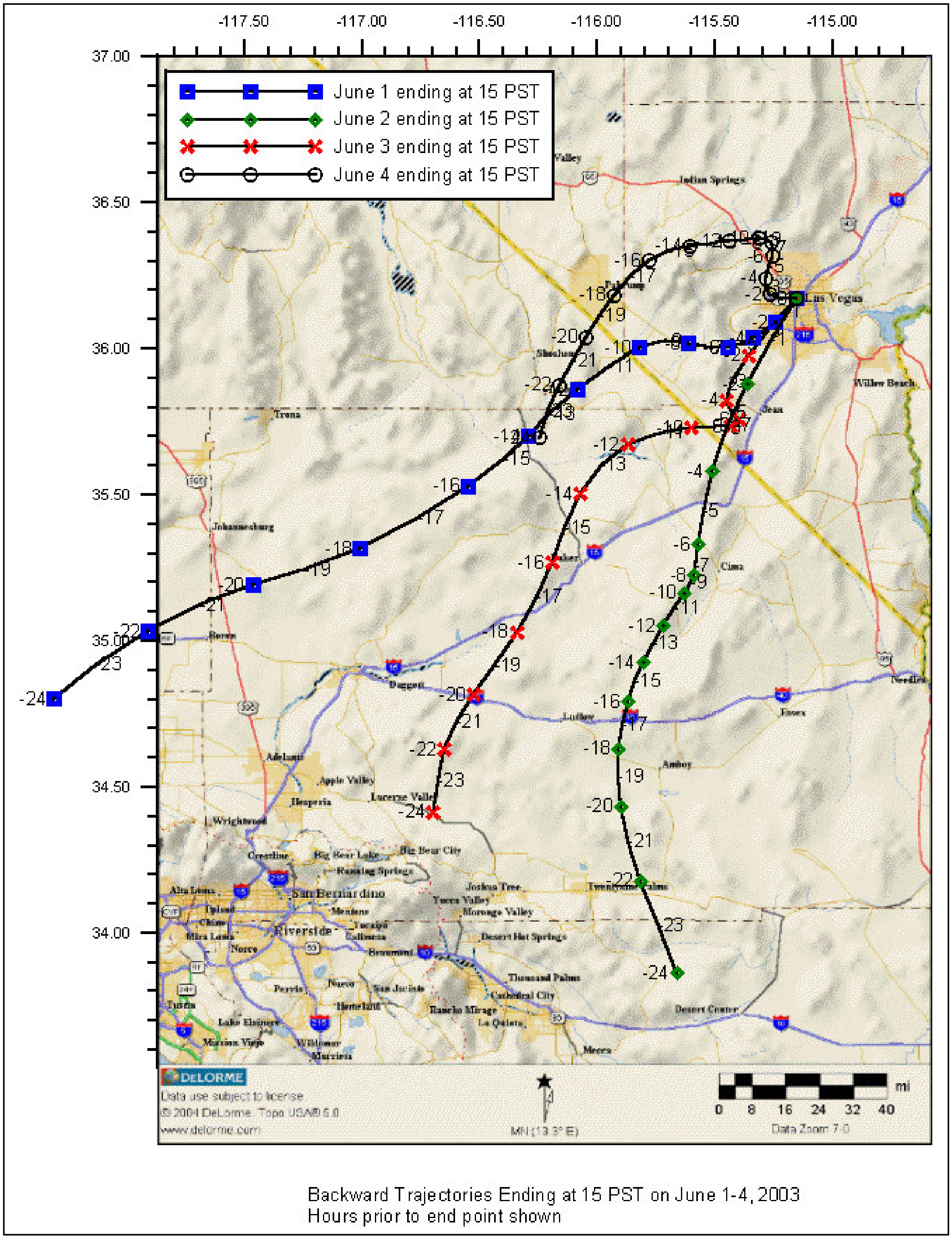


Figure 5-52. Backward Trajectories Ending at 15 PST on June 1-4, 2003

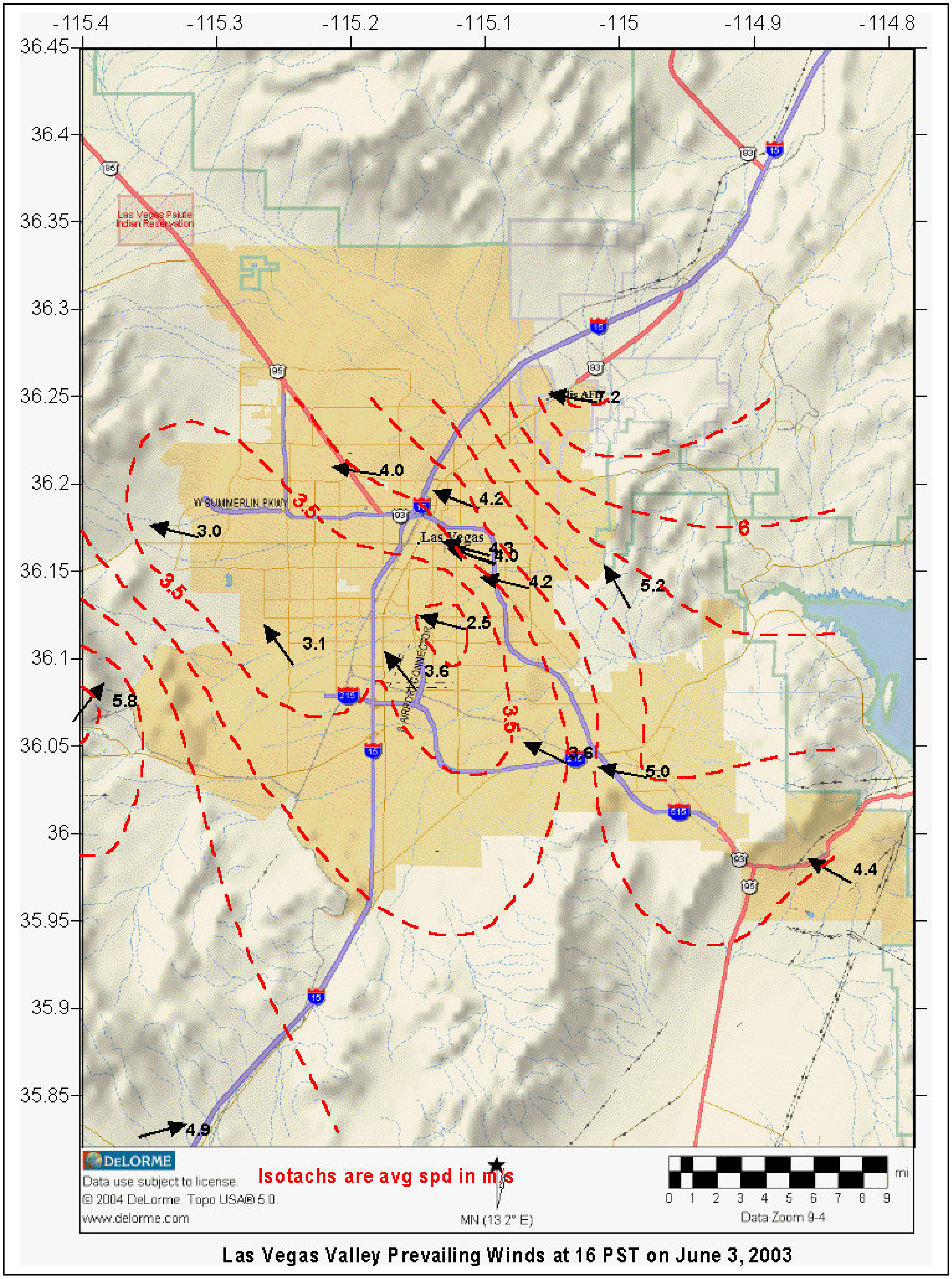


Figure 5-53. Las Vegas Valley Prevailing Winds at 16 PST on June 3, 2003

5.8 June 29, 2003 Episode

June 29, 2003 was a one-day episode characterized by the greatest number of sites that exceeded the 8-hour Federal Ozone Standard, and, of the periods examined, the highest levels measured. Maximum ozone levels are listed in **Table 5-15**, ordered by site ID. In the last row of the table, the number of sites exceeding the 8-hour ozone standard is given. Charts showing the Las Vegas Valley and adjacent regions peak ozone spatial pattern are shown on **Figure 5-54.** The left panel shows daily maximum 8-hour averaged levels and contours of constant ozone. The right panel gives daily maximum 1-hour averaged levels, contours of constant ozone, and the time of the peak (PST). The maximum levels were again experienced at Joe Neal although exceedances of the 8-hour standard were experienced at eight locations including Jean and Apex. Near-exceedances (84.9 ppb) were measured at Craig Road and Paul Myer School. The second highest 1-hour ozone level of the episodes studied was experienced at Joe Neal (114 ppb). (Both Joe Neal and Lone Mt measured 115 ppb on July 21, 2003.)

Table 5-15. Maximum 8-Hour Ozone (ppb) – Case Study 8

Site Name	Site ID	6/28/03	6/29/03	6/30/03
Apex	AP	77.9	92.1	75.1
Boulder City	BC	77.6	79.5	62.6
E Craig Rd	BS	79.1	84.9	64.0
City Center	CC	82.4	81.0	51.8
JD Smith	JD	80.0	85.6	64.4
Jean	JN	83.6	89.4	71.5
Joe Neal	JO	84.6	94.4	76.1
Lone Mt	LO	82.5	88.4	70.6
Mesquite	MQ	69.5	80.3	63.5
SE Valley	PL			32.5
Paul Myer	PM	83.1	84.9	69.1
Palo Verde	PV	81.8	87.1	70.8
Shadow Lane	SL			
Searchlight	ST	74.1	82.3	59.1
Walter Johnson	WJ	80.9	86.8	70.1
Winterwood	WW	76.6	88.3	70.1
Network Max		84.6	94.4	76.1
# Sites Exceeded		0	8	0

Noteworthy is the timing of the peak ozone. From the right chart on Figure 5-54, it can be seen that the exceedances occurred almost simultaneously between 11 and 13 PST. The time-series of hourly ozone at the select set of sites included on **Figure 5-55** show ozone concentrations dropping very rapidly after the early peaks. This is very much in contrast to the usual behavior of ozone in Clark County. As discussed below, this was a prime example of long-range transport from the South Coast air basin.

Meteorology

The synoptic weather pattern at the 500 mb level over the southwest U.S. during June 27th and 28th was categorized as a Flat Ridge (FR) in the weather typing scheme. Heights at the 500 mb levels during that period were around 5,900 m, indicating a very stable air mass. Because of the flat gradient, wind flow was very light and directionally inconsistent, with a tendency to be northerly. **Figure 5-56(a)** shows the NWS 500 mb constant pressure map for the afternoon of the 28th. The pattern on the afternoon of the 29th is presented in **Figure 5-56(b)**. A short-wave trough most noticeable in northern California induced a transition to an Interior Ridge (IR). Winds speed increased and shifted to southwesterly although the air mass continued to be very stable (500 mb heights persisted at around 5,900 m). On June 30th, the pattern began to change back into a FR with the ridgeline having migrated well east into New Mexico. At the same time, the troughing near the west coast became more pronounced, and by July 1st a Pacific Trough (PT) situation had evolved. Reduced air mass stability and increased southwesterly flow associated with the approaching trough were already evident by the afternoon of June 30th.

Below the 500 mb level, flat gradients were also recorded during the period from June 27th through the 29th. **Figure 5-57(a&b)** presents the 700 mb constant pressure maps for the mornings of June 28th and 29th. Temperatures aloft over southern Nevada steadily increased from 11.4°C on the 27th to 15.0°C on the 29th. This was indicative of increasing atmospheric stability that peaked on June 29th. By the 30th, the 700 mb temperature over the Desert Rock NWS site had dropped back down to 12.6°C. Wind flow at and above that level was light northeasterly on the 27th, becoming light and variable on the 28th, and then southeasterly at around 5 m/s on the 29th. The southeast flow continued on the 30th, with speeds increasing dramatically to 15 m/s.

Just above the surface at the 850 mb level, the synoptic pattern was also rather flat. During June 27th, a hint of a thermal low associated with increasing temperatures could be seen over southern Nevada. On the 28th, weak troughing was evident along the California coast. By the morning of the 29th, a broad thermally induced trough occupied the entire Great Basin from Idaho to the mouth of the Colorado River. **Figure 5-58(a&b)** shows the NWS 850 mb maps for the mornings of the 28th and 29th. (Please note that an erroneous temperature report at Boise, Idaho caused extreme packing of isotherms on the June 29th map). As was the case at 700 mb, temperatures at the 850 mb level increased at Desert Rock each day from the 27th through the 29th. On the 30th, temperatures dropped substantially. Wind flow in the lower boundary layer over southern Nevada was light northeasterly on the 27th, but then became southwesterly on the 28th and 29th. The southwest winds were recorded in a layer starting at about 200 m above ground level and extending up to 1,100 m agl the morning of the 28th and 1,400 m agl on the 29th. Wind speeds in the layers were around 5 m/s on the 28th, but increased to a strong 10 m/s by the morning of the 29th. By the 30th, the southwest winds had all but disappeared and were replaced by light southeasterly flow.

Of particular significance was that during the relative stagnation due to the flat pressure-height gradients and stable air mass that persisted over southern California, ozone levels became quite high in the South Coast air basin. Time-series graphs of hourly ozone levels at some California desert sites (and Jean) for June 28th and 29th are shown in **Figure 5-59**. As can be seen, by late afternoon on the 28th, ozone levels from Barstow to Joshua Tree were 100 ppb or greater.

A backward trajectory from the city center ending at 12 PST on the 29th when the peak ozone in Clark County was experienced is shown on **Figure 5-60.** The estimated air-parcel trajectory shown originates 24 hours earlier near the Antelope Valley in the South Coast air basin. Local Clark County surface winds support strong transport winds on the 29th. The 16 PST wind direction and speed contours are shown on **Figure 5-61** and depict a uniform southwesterly flow at moderate speed throughout the county, as opposed to the light southeast flow typically observed on high ozone days.

The afternoon mixing height, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, was 4,400 m-agl.

The CART model classified June 29th into Terminal Node 7, which is characterized by conditions conducive to interbasin transport to Clark County. This is consistent with the rest of the analysis.

Summary

- Exceedances of the 8-hour ozone standard were widespread in Clark County occurring at sites both upwind and downwind of the Las Vegas Valley. Eight sites recorded exceedances, more than in any other episode studied. Ozone levels experienced during this case study were exceeded on only one other instance during the episodes examined.

- The typical spatial ozone pattern (i.e., highest levels in the northwest at Joe Neal and Lone Mt with the lowest levels to the southeast) was observed again, suggesting that the Las Vegas urban plume had at least some impact on peak ozone.

- The ozone exceedances on June 29, 2003 took place during a period that had transitioned from a Flat Ridge (FR) to an Interior Ridge (IR). The air mass over southern Nevada was thermodynamically stable with warm air aloft prevailing. A large-scale shallow trough existed in the lower atmosphere that induced a deep layer of moderate to strong southwesterly winds by the morning of the 28th, and particularly on the 29th. This provided the mechanism to transport pollutants from the South Coast air basin to southern Nevada. This southwesterly flow layer extended from just above the surface to 1,100 m above the ground level. Wind speeds in the layer reached 10 m/s during the morning of the 29th. By the 30th, this transport mechanism had disappeared, along with the strong stability of the previous days.

- Trajectory analysis, local winds, and regional air quality data indicates that the exceedances were due to overwhelming interbasin transport.

- This day fell into CART class 7, which correctly points to interbasin transport as a significant factor.

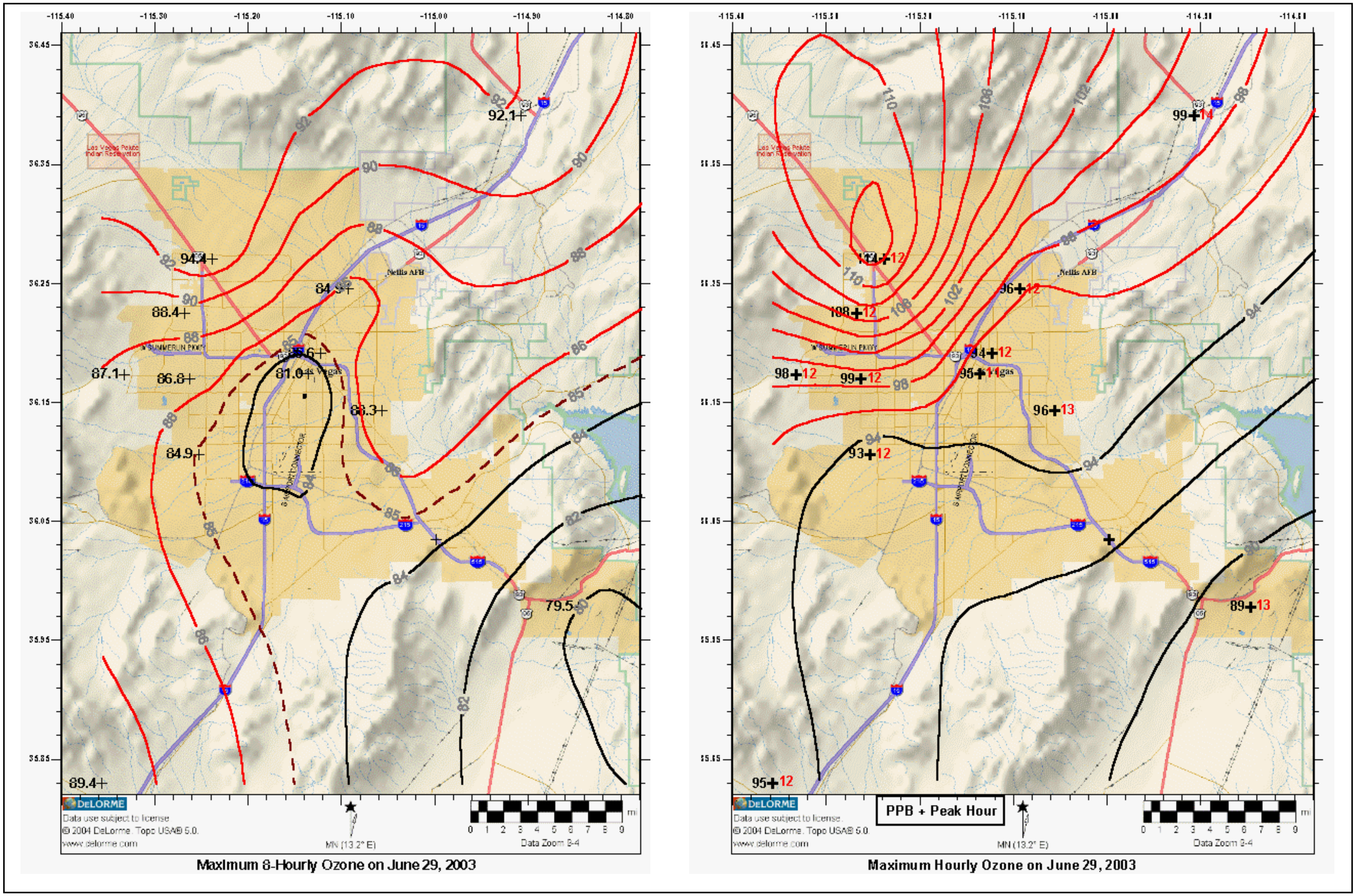


Figure 5-54. Peak Ozone for June 29, 2003

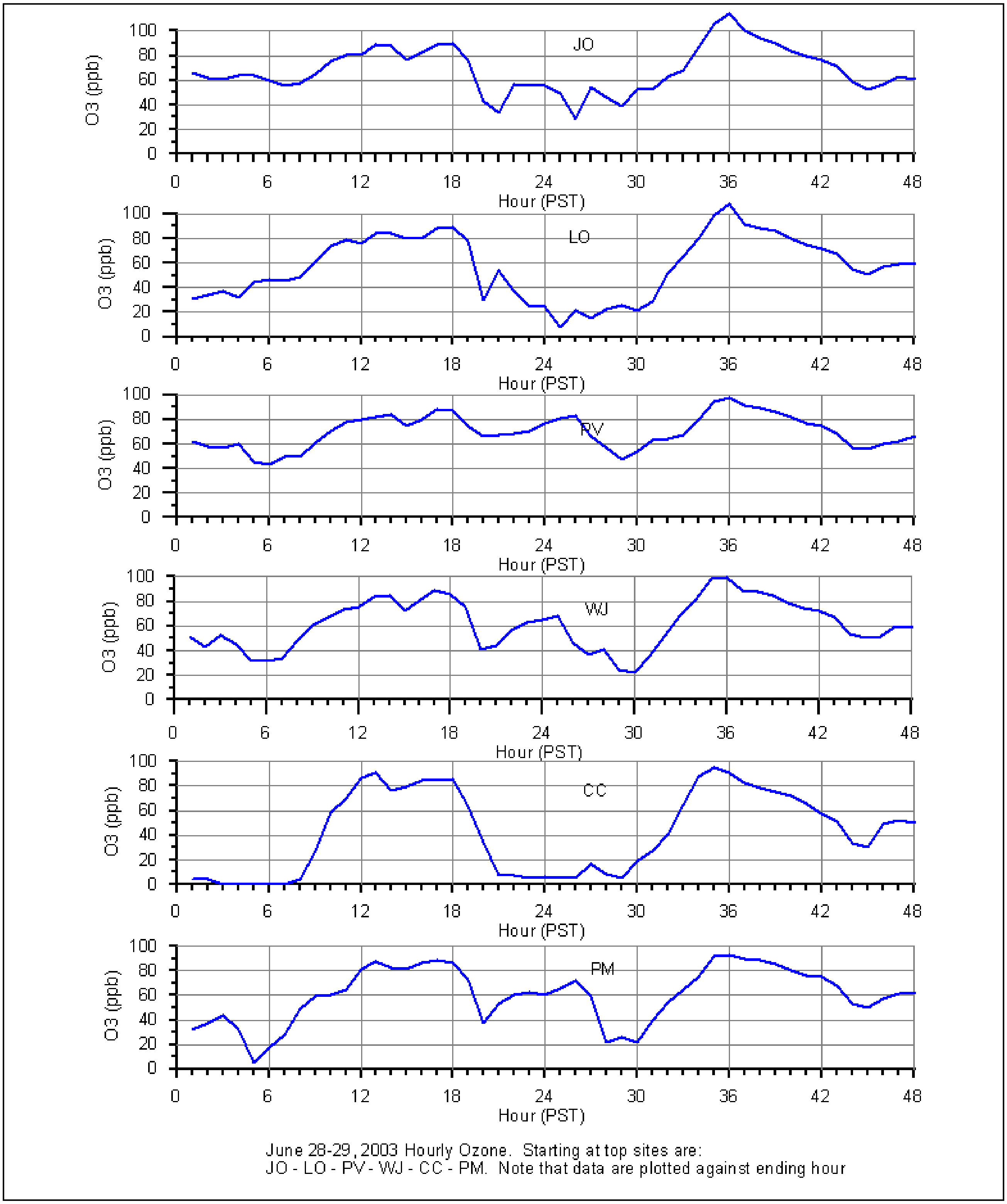


Figure 5-55. Hourly Ozone on June 28-29, 2003

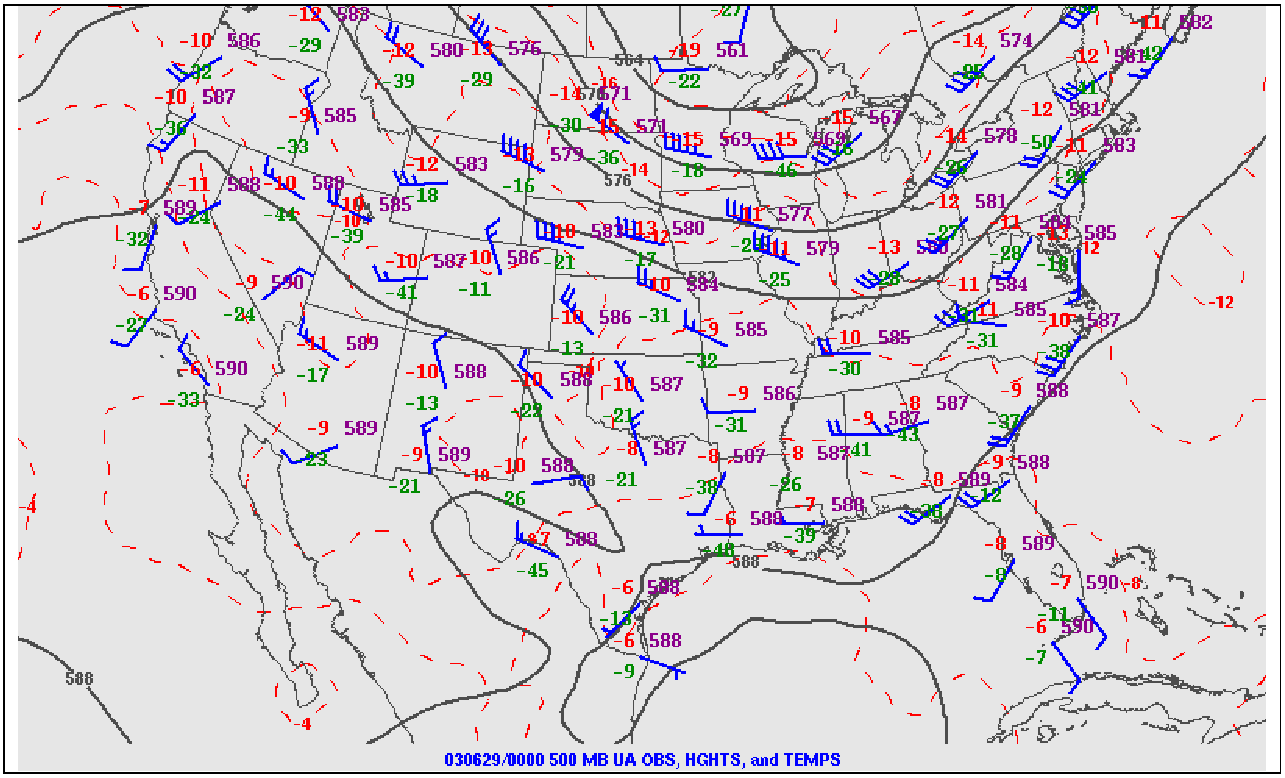


Figure 5-56(a). NWS 500 mb Constant Pressure Map for Afternoon of June 28, 2003

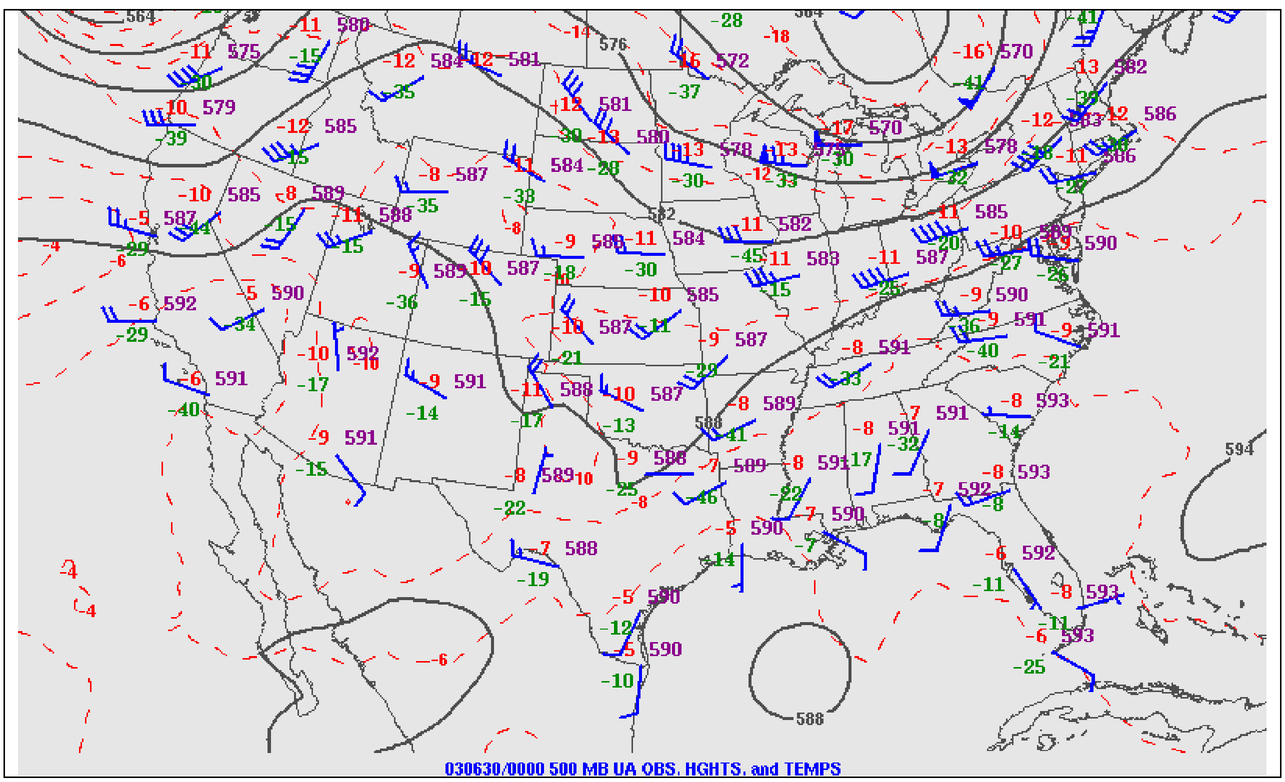


Figure 5-56(b). NWS 500 mb Constant Pressure Map for Afternoon of June 29, 2003

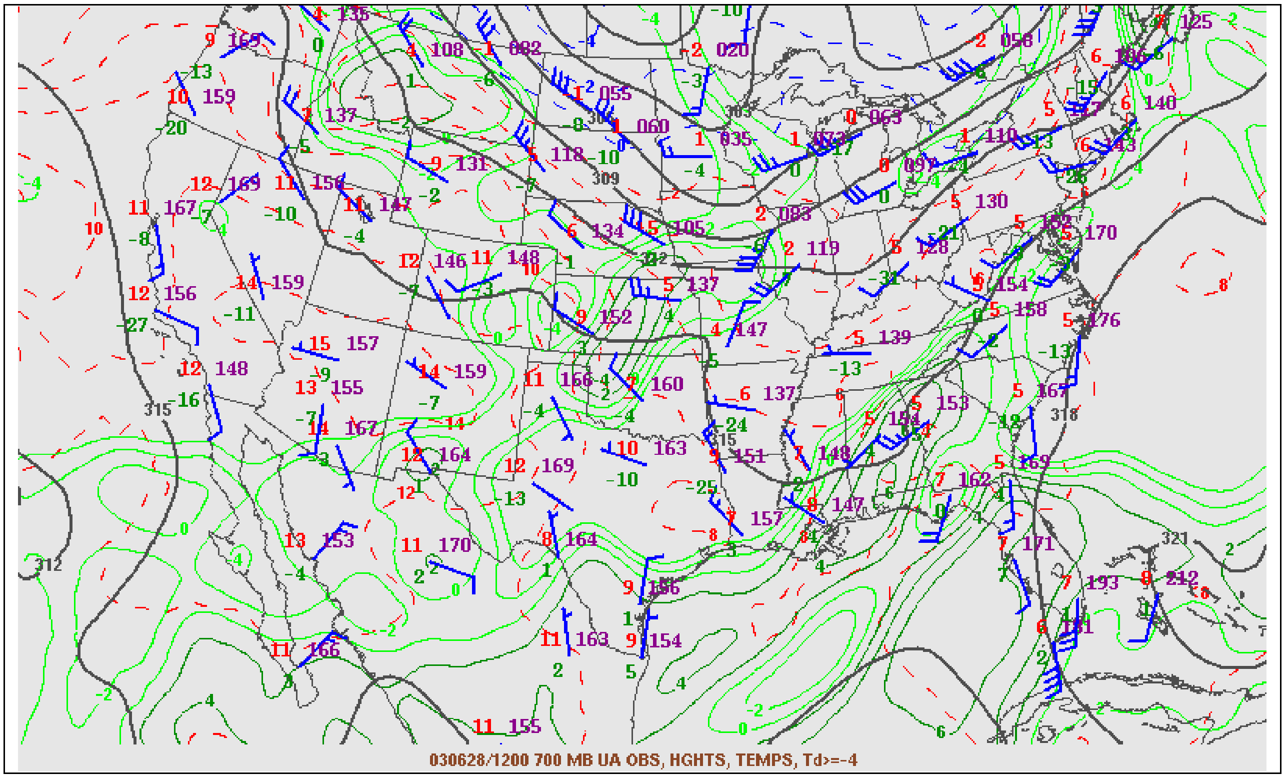


Figure 5-57(a). NWS 700 mb Constant Pressure Map for Morning of June 28, 2003

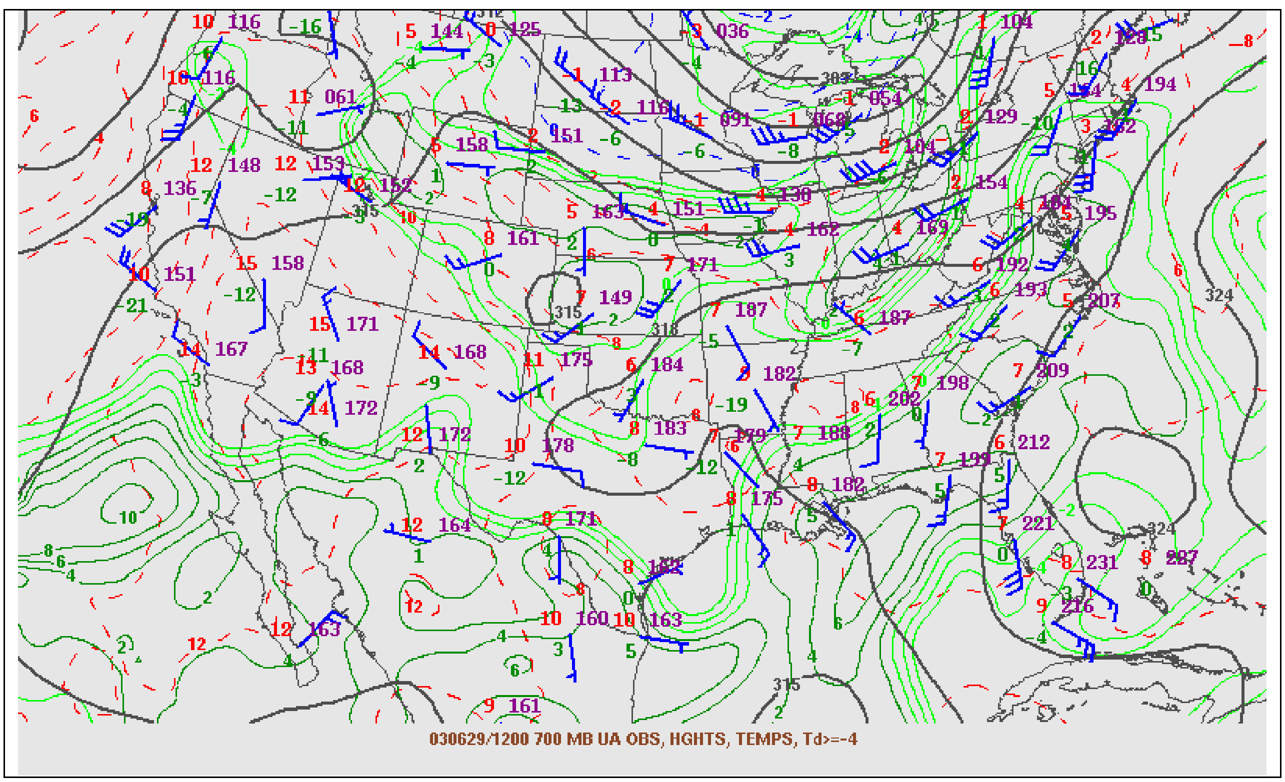


Figure 5-57(b). NWS 700 mb Constant Pressure Map for Morning of June 29, 2003

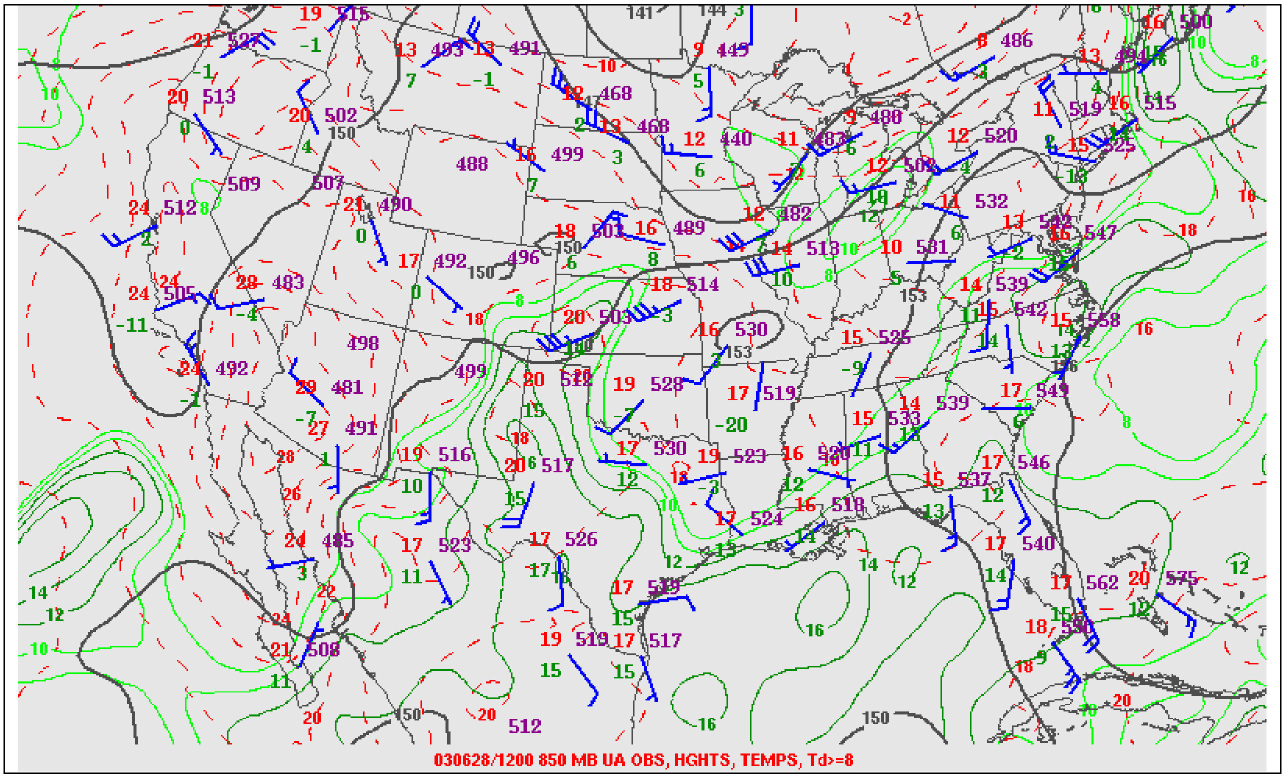


Figure 5-58(a). NWS 850 mb Constant Pressure Map for Morning of June 28, 2003

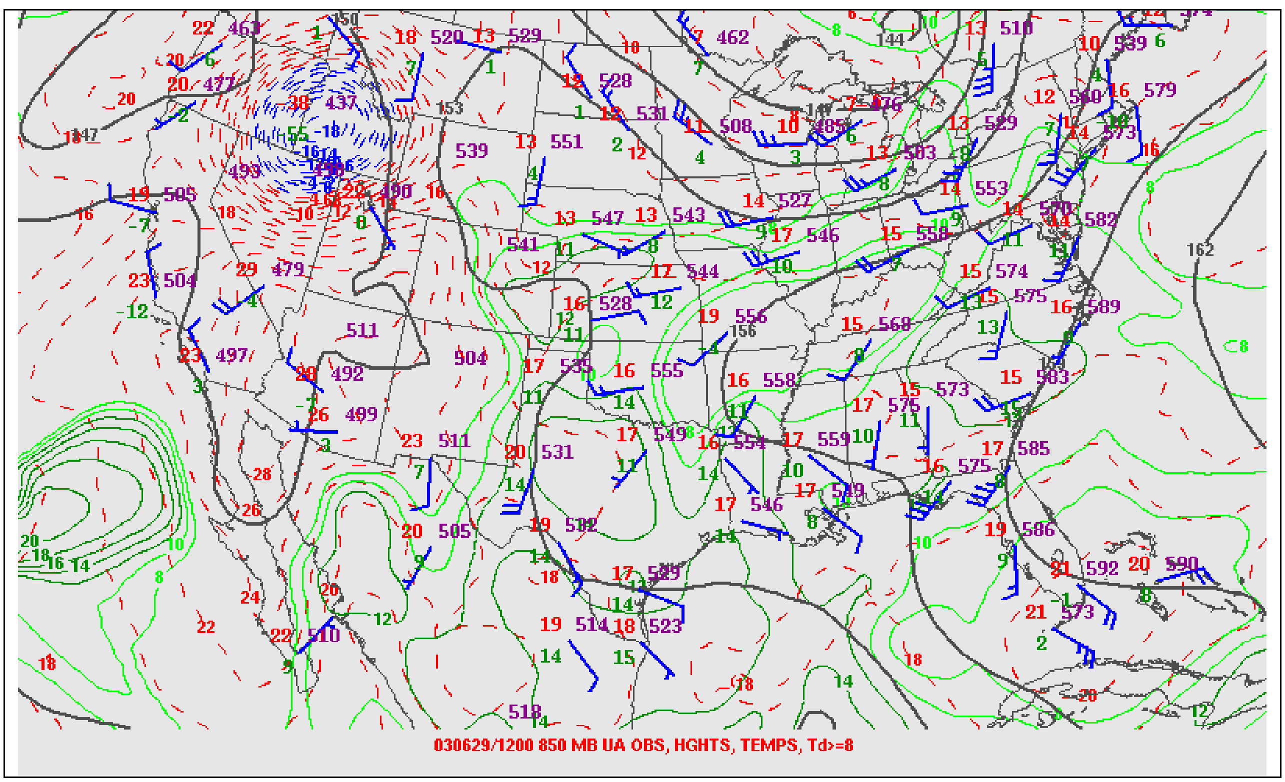


Figure 5-58(b). NWS 850 mb Constant Pressure Map for Morning of June 29, 2003

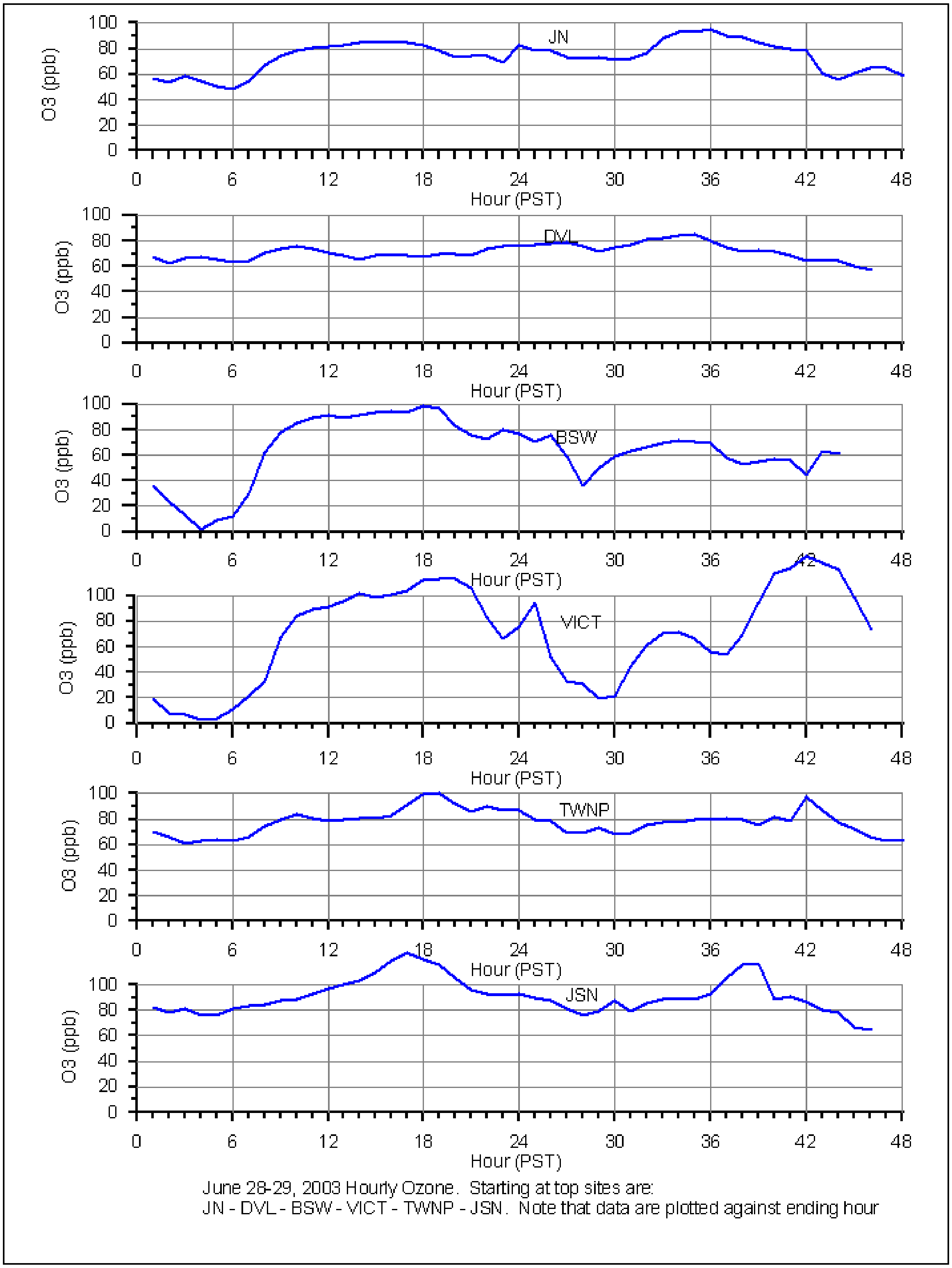


Figure 5-59. Hourly Ozone for June 28 to 29, 2003

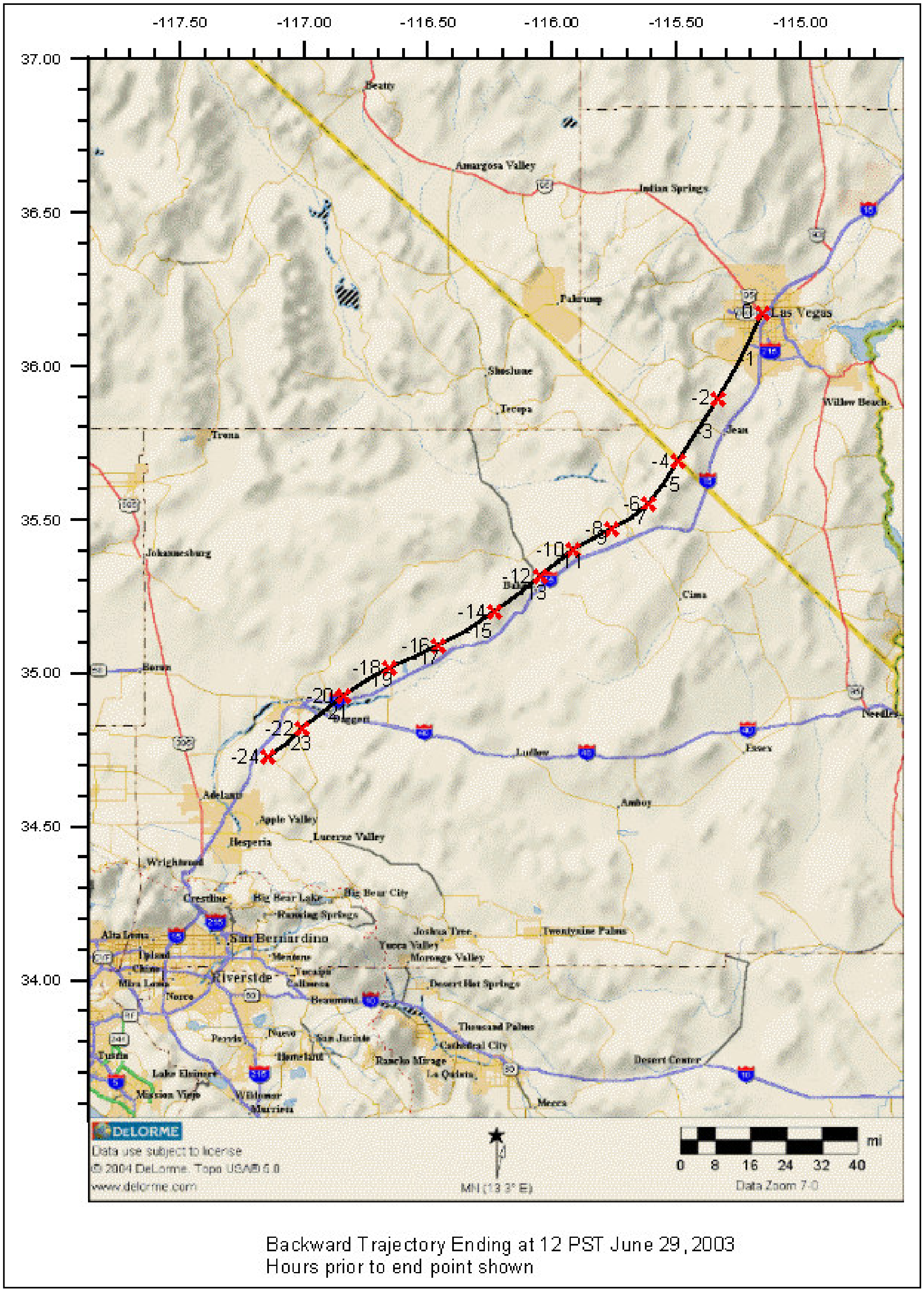


Figure 5-60. Backward Trajectory Ending at 12 PST, June 29, 2003

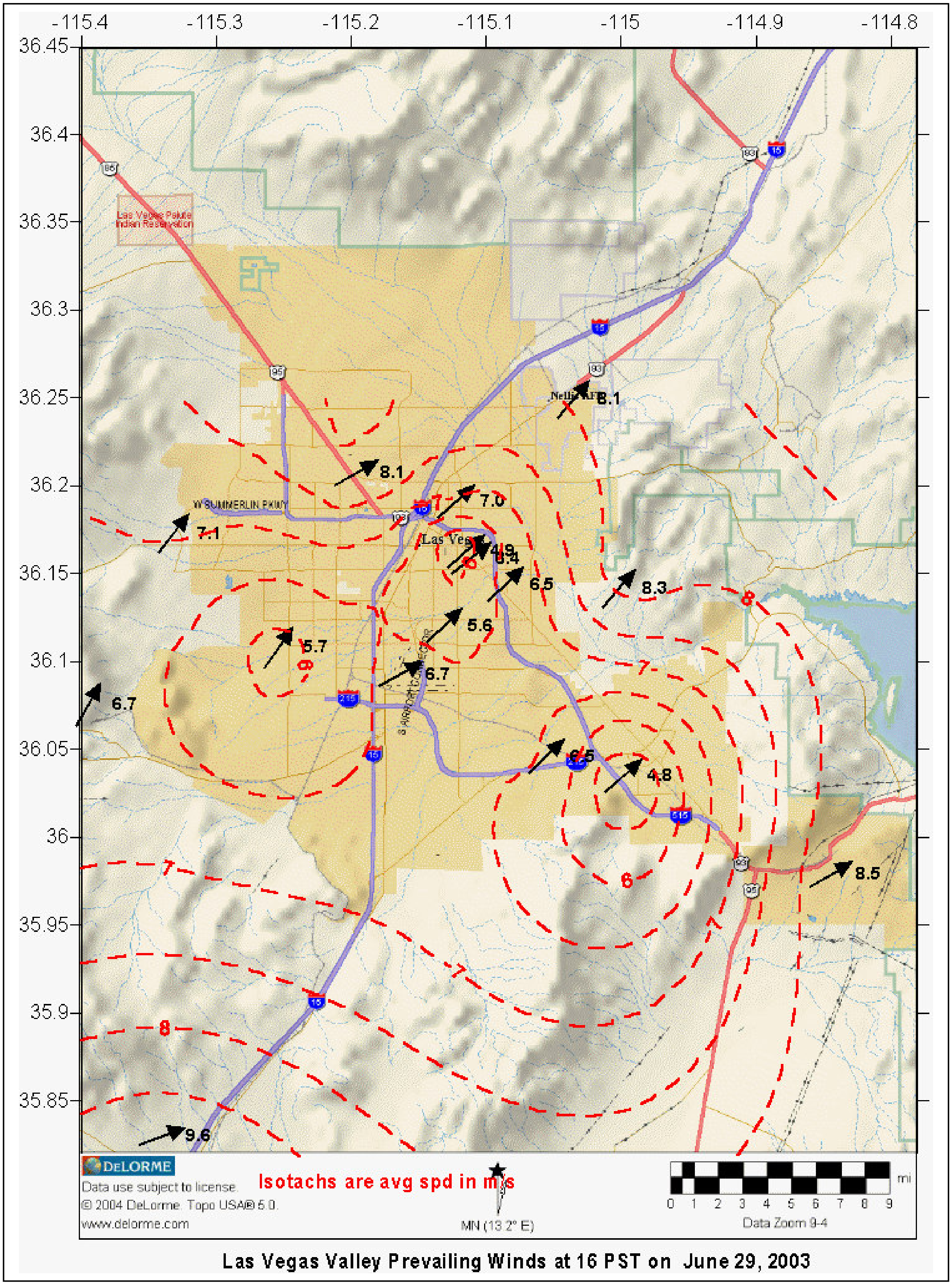


Figure 5-61. Las Vegas Prevailing Winds at 16 PST on June 29, 2003

5.9 July 9, 2003 Episode

This was 1-day episode on which the 8-hour Federal Ozone Standard of 85 ppb was exceeded at two sites. **Table 5-16** gives the daily maximum 8-hour ozone at the Clark County monitoring network sites on the day prior, the exceedance day, and the day after. The usual suspects, Joe Neal and Lone Mt, were the two sites that experienced exceedances. The peak ozone at Jean, considered a background site, was ~ 75 ppb on both the 8th and 9th. By contrast, Joe Neal experienced ozone concentrations of 75.4 ppb, 90.4 ppb, and 75.3 ppb on the 8th, 9th, and 10th, respectively. Likewise, Lone Mt ozone concentrations were comparable to background concentrations on the 8th and 10th, and exceeded the standard on the 9th. The spatial pattern of the ozone peaks can be observed from the charts on **Figure 5-62**. Here we see a pattern both in the hourly and 8-hour charts almost identical to the May 27, 2003 episode. Peak ozone was experienced in the northwest quadrant of the Las Vegas Valley with the southeast gradient to lower levels interrupted by a network minimum at City Center. The meteorology during the earlier episode suggested the exceedances were in a large part due to local ozone production and poor ventilation in the Valley.

Table 5-16. Maximum 8-Hour Ozone (ppb) – Case Study 9

Site Name	Site ID	7/8/03	7/9/03	7/10/03
Apex	AP	70.9	76.4	71.3
Boulder City	BC	58.6	67.3	67.6
E Craig Rd	BS	69.3	79.5	63.6
City Center	CC	58.5	68.0	64.7
JD Smith	JD	72.1	81.1	72.1
Jean	JN	74.1	75.8	64.6
Joe Neal	JO	75.4	90.4	75.3
Lone Mt	LO	72.0	85.6	72.9
Mesquite	MQ	56.1	64.1	59.6
SE Valley	PL	63.5	72.6	64.1
Paul Myer	PM	70.9	78.4	66.7
Palo Verde	PV	74.0	81.9	68.8
Searchlight	ST	60.0	58.5	63.1
Walter Johnson	WJ	69.6	81.3	73.7
Winterwood	WW	68.6	76.0	68.8
Network Max		75.4	90.4	75.3
# Sites Exceeded		0	2	0

Peak ozone occurred in the afternoon (16 to 17 PST) at sites seemingly impacted by Las Vegas emissions. Jean, Henderson, and Boulder City experienced earlier peaks at 12 to 14 PST. Time-series plots of hourly ozone for the 2-day period July 8 and 9, 2003 for selected sites are shown on **Figure 5-63**, and should be compared with May 26 and 27, 2003 (Figure 5-37). The similarities between May 27 and July 9 are striking. On both days, peak ozone occurred late in the afternoon followed by a rapid decrease at Joe Neal, Lone Mt, Walter Johnson, and Paul Meyer. The City Center site hourly ozone exhibits a series of peaks and troughs most likely due to little air movement coupled with fresh emissions, hence ozone reduction. As discussed below, the two episodes share many of the same meteorological features as well.

Meteorology

The synoptic weather pattern at the 500 mb level during the period surrounding July 9, 2003 was consistently the Interior Ridge (IR) type. **Figure 5-64(a&b)** shows the NWS 500 mb constant pressure charts for the afternoons of the 8th and 9th, respectively. The ridge had moved onshore over southern California on the 7th, and was building into southern Nevada, Arizona and Utah by the afternoon of the 8th. By that time, 500 mb heights were around 5,950 m and winds over southern Nevada were west-southwesterly with speeds in excess of 10 m/s. Air mass subsidence was clearly strong in the region. By the afternoon of the 9th, the ridge had built into the entire western interior of the U.S., and the axis was located just east of the Colorado River. The 500 mb heights near the axis approached 6,000 m that afternoon, and were measured to be 5,980 m over the Desert Rock NWS site. Because of the close proximity of the ridge center, wind speeds aloft were lower during the morning than 24 hours previous, and had swung around to the south-southeast by the afternoon. By the following day, the ridge had slid further east, and winds at 500 mb increased to south-southwesterly at well over 15 m/s.

The Interior Ridge configuration was also apparent at lower levels of the atmosphere. **Figure 5-65(a)** shows the 700 mb map for the morning of the 9th. The 700 mb temperature above Desert Rock was 15.6^{o} C, indicating a very stable air mass, and the winds were very light. Winds at Desert Rock were east-southeast below 500 mb.

Just above the surface at the 850 mb level, the ridge configuration was still apparent. **Figure 5-65(b)** shows the 850 mb map for the morning of the 9th. Temperatures at that level were quite warm, but unlike during many other ridging situations examined in this analysis, a well-defined thermal low was not apparent. The warm temperatures were more evenly distributed spatially, and therefore a heating induced pressure gradient was not apparent. As a result, wind speeds in the lower boundary layer were quite light. At the Desert Rock site on the morning of the 9th, a layer of southwesterly flow started at about 200 m above the ground, and extended up to around 1100 m agl. Wind speeds in that layer were just 2 to 4 m/s. Above that layer, light easterly flow prevailed, at 3 to 5 m/s.

The backward trajectory from the city center, constructed using the HYSPLIT Model, is shown on **Figure 5-66**. The trajectory shown estimates an air-parcel trajectory ending at the surface at 16 PST on July 9 near to the time of maximum ozone, and starting 24 hours earlier. The number of hours back from the end time (16 PST) is posted along the trajectory. As can be seen from the figure, over the last 12 hours (04 to 16 PST) there was very little air movement and a strong indication of a "sloshing" of the air within the Valley. This is precisely the scenario describe on May 27, 2003.

The plotted wind field for 16 PST (**Figure 5-67**) shows winds 2 m/s or less in the Las Vegas Valley. Wind direction shows a tendency for transport of the urban plume north and east.

The afternoon mixing height, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, was 3,700 m-agl. The mixing height was the same on May 27, 2003 (3,800 m-agl).

The CART model classified July 9th into Terminal Node 3. Terminal Node 3 parameters are normally indicative of a non-transport scenario. This agrees with the other analysis elements.

Summary

- The meteorology and air quality features of July 9, 2003 were remarkably similar to May 27, 2003.
- Exceedances of the 8-hour ozone standard were experienced at two sites. The highest reading occurred at Joe Neal (90.4 ppb). Lone Mt ozone, the only other exceedance, lagged far behind at 85.6 ppb.
- The spatial ozone pattern was characterized again by the highest ozone levels in the northwest at Joe Neal and Lone Mt, with a general southeast gradient to lower concentrations. As on May 27th, a distinct minimum was evident in the urban core.
- This episode occurred during a period categorized as an Interior Ridge (IR). The air mass over southern Nevada was thermodynamically stable with warm air aloft prevailing. Synoptic-scale transport winds on the morning of the 9th were very light. Thus, ventilation in the Las Vegas Valley will likely dominated by local wind-forcing mechanisms.
- Local winds were very light in the morning and afternoon of the 9th, and trajectory estimates indicated a meandering flow with possible air mass recirculation.
- The CART model correctly classified this day as an exceedance owing primarily to local conditions.

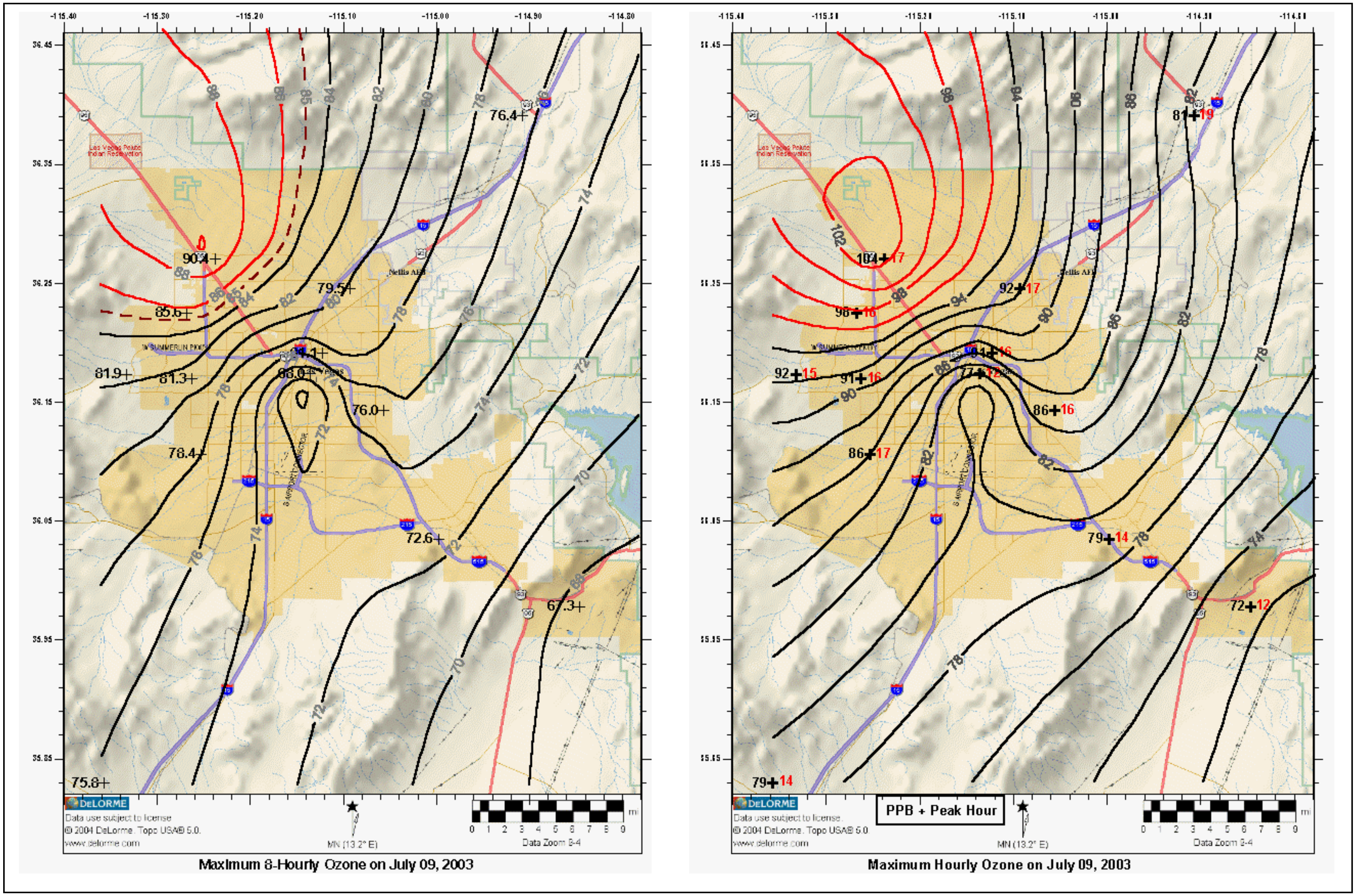


Figure 5-62. Peak Ozone for July 9, 2003

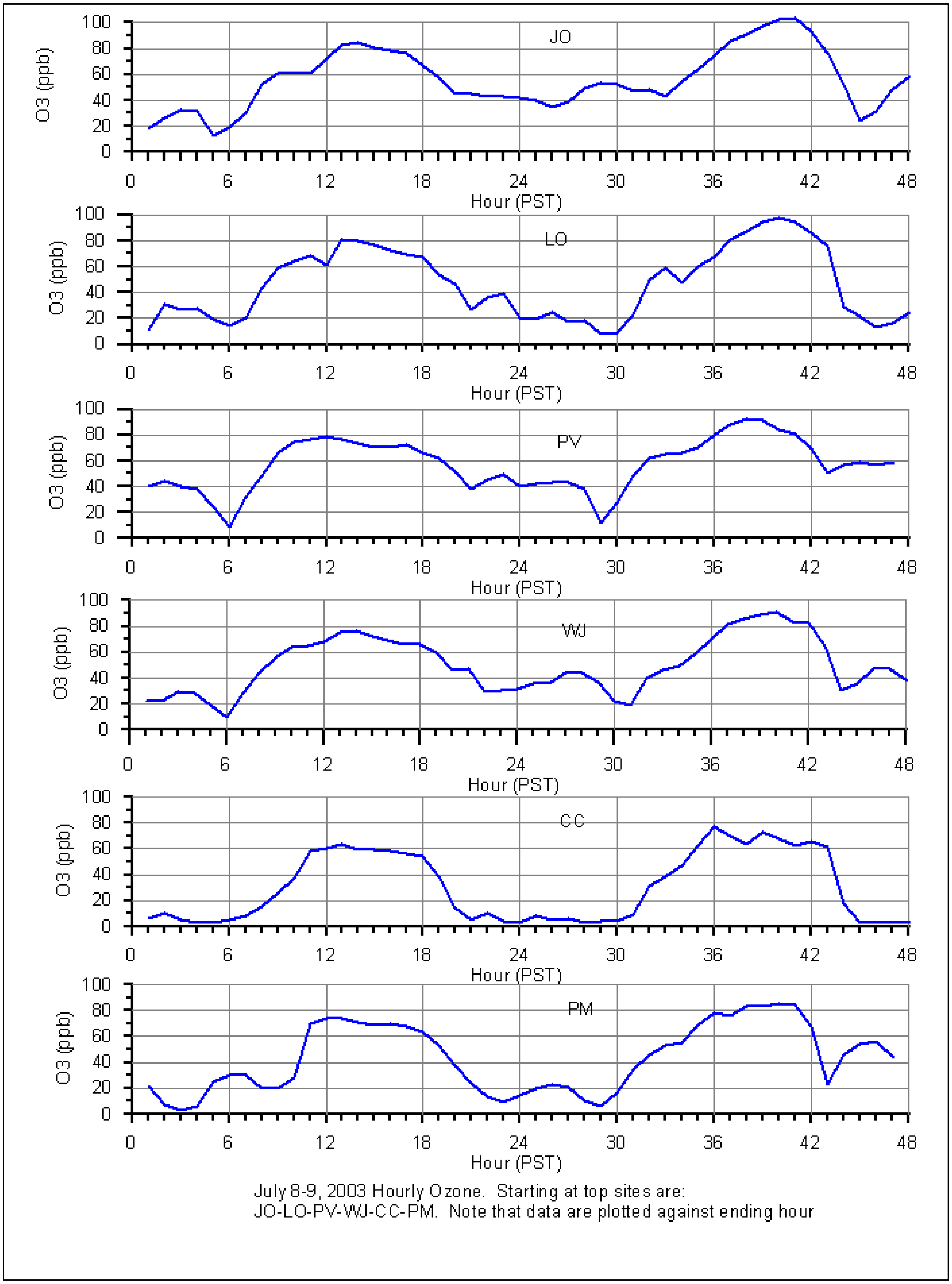


Figure 5-63. Hourly Ozone on July 8-9, 2003

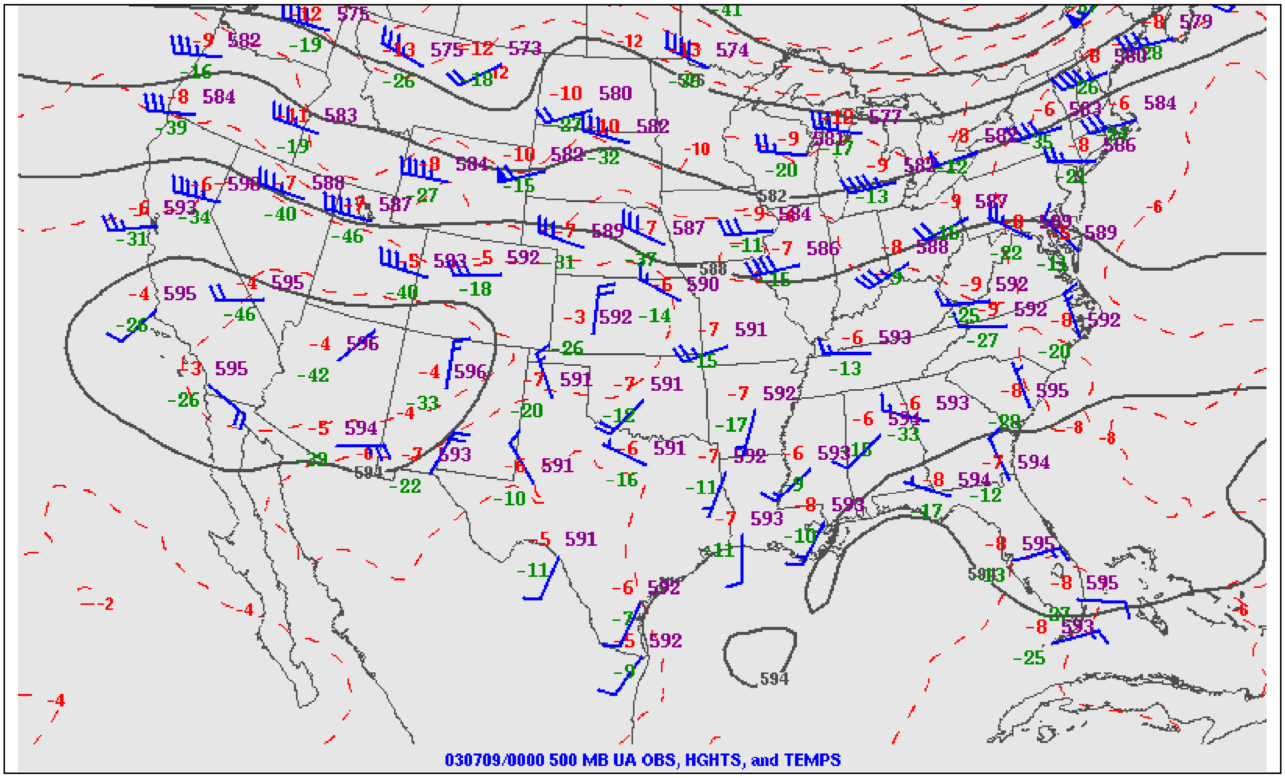


Figure 5-64(a). NWS 500 mb Constant Pressure Map for Afternoon of July 8, 2003

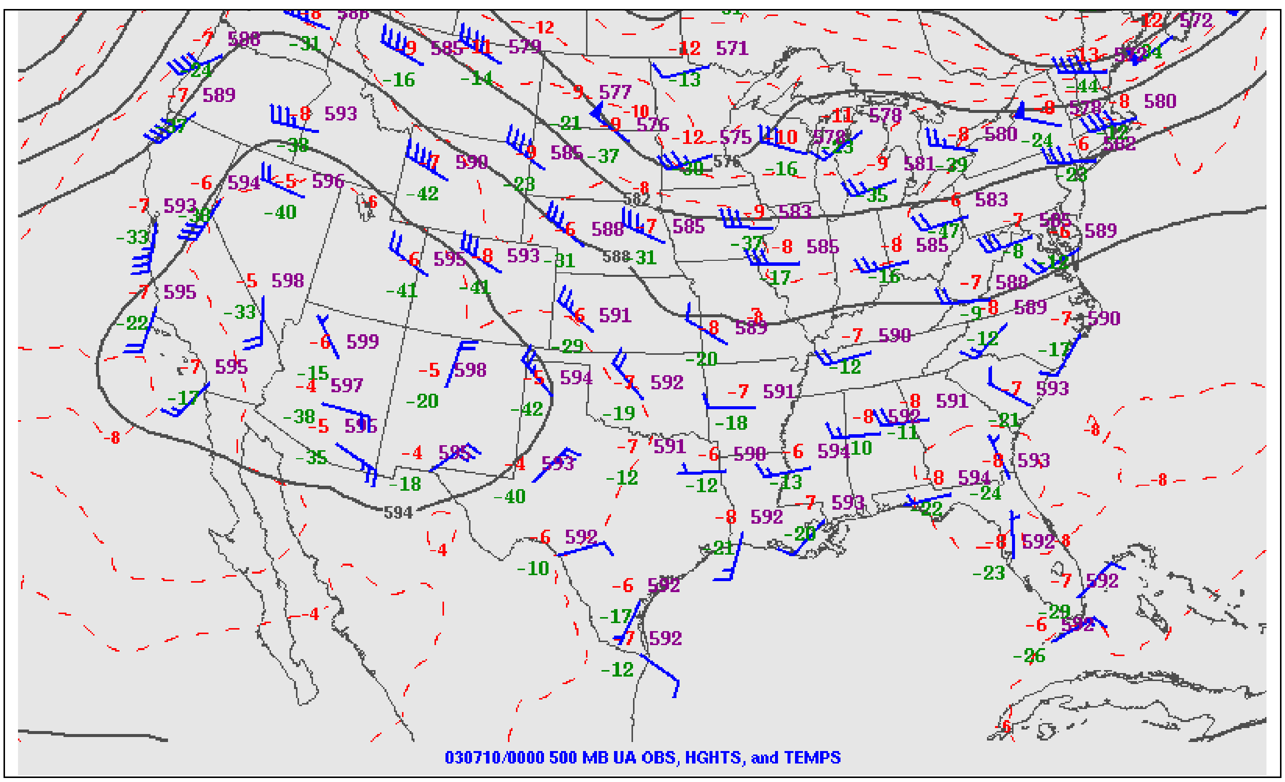


Figure 5-64(b). NWS 500 mb Constant Pressure Map for Afternoon of July 9, 2003

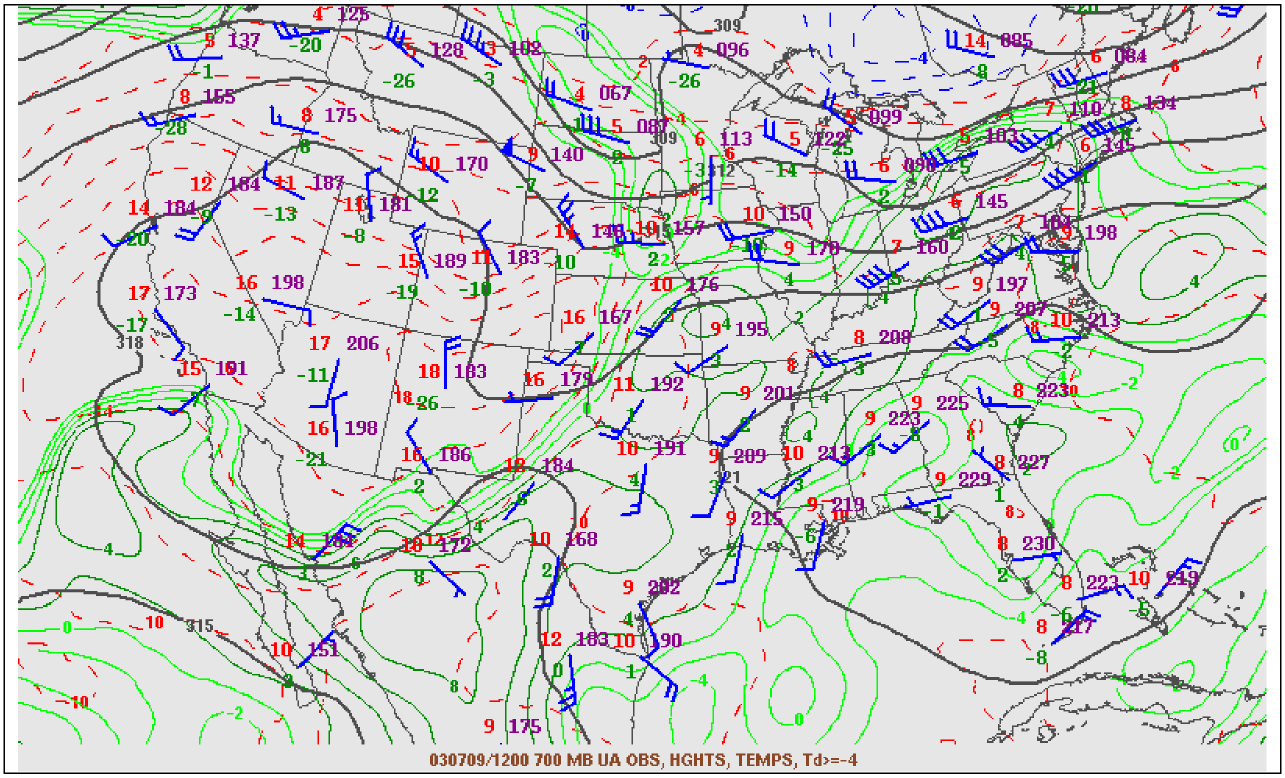


Figure 5-65(a). NWS 700 mb Constant Pressure Map for Morning of July 9, 2003

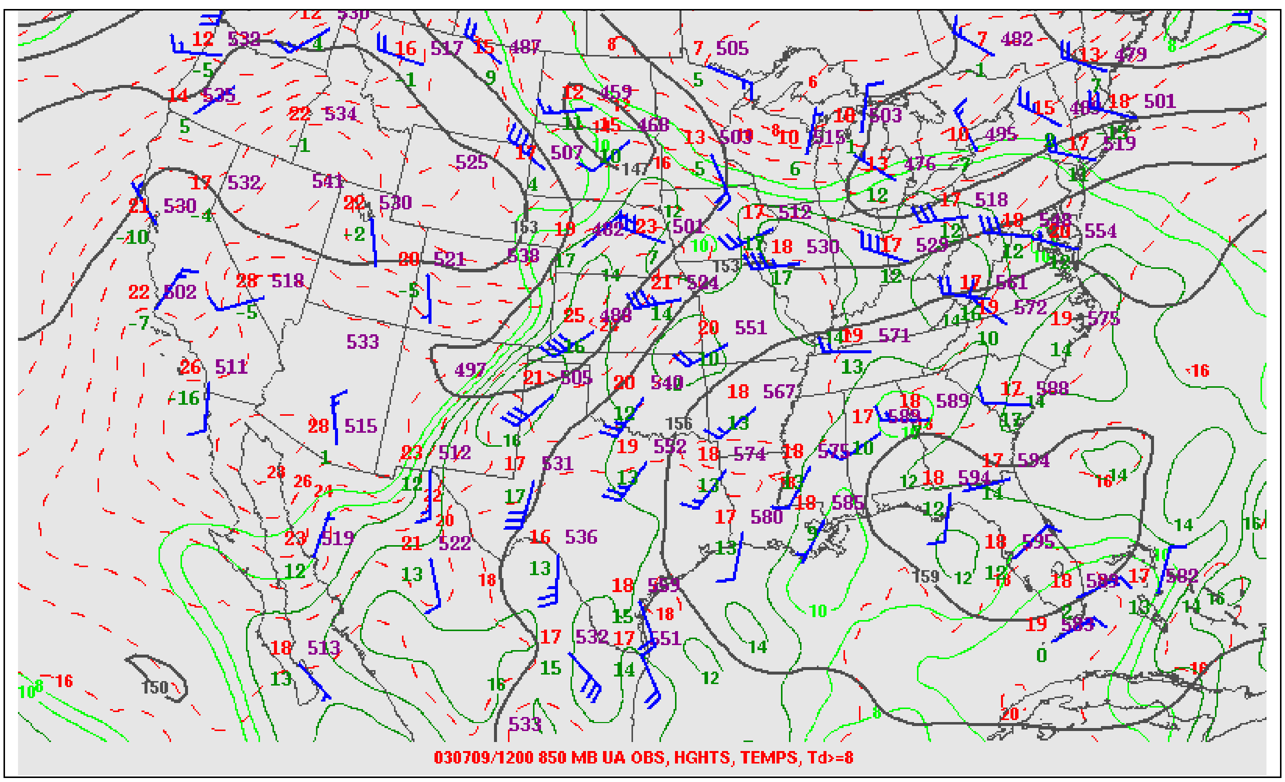


Figure 5-65(b). NWS 850 mb Constant Pressure Map for Morning of July 9, 2003

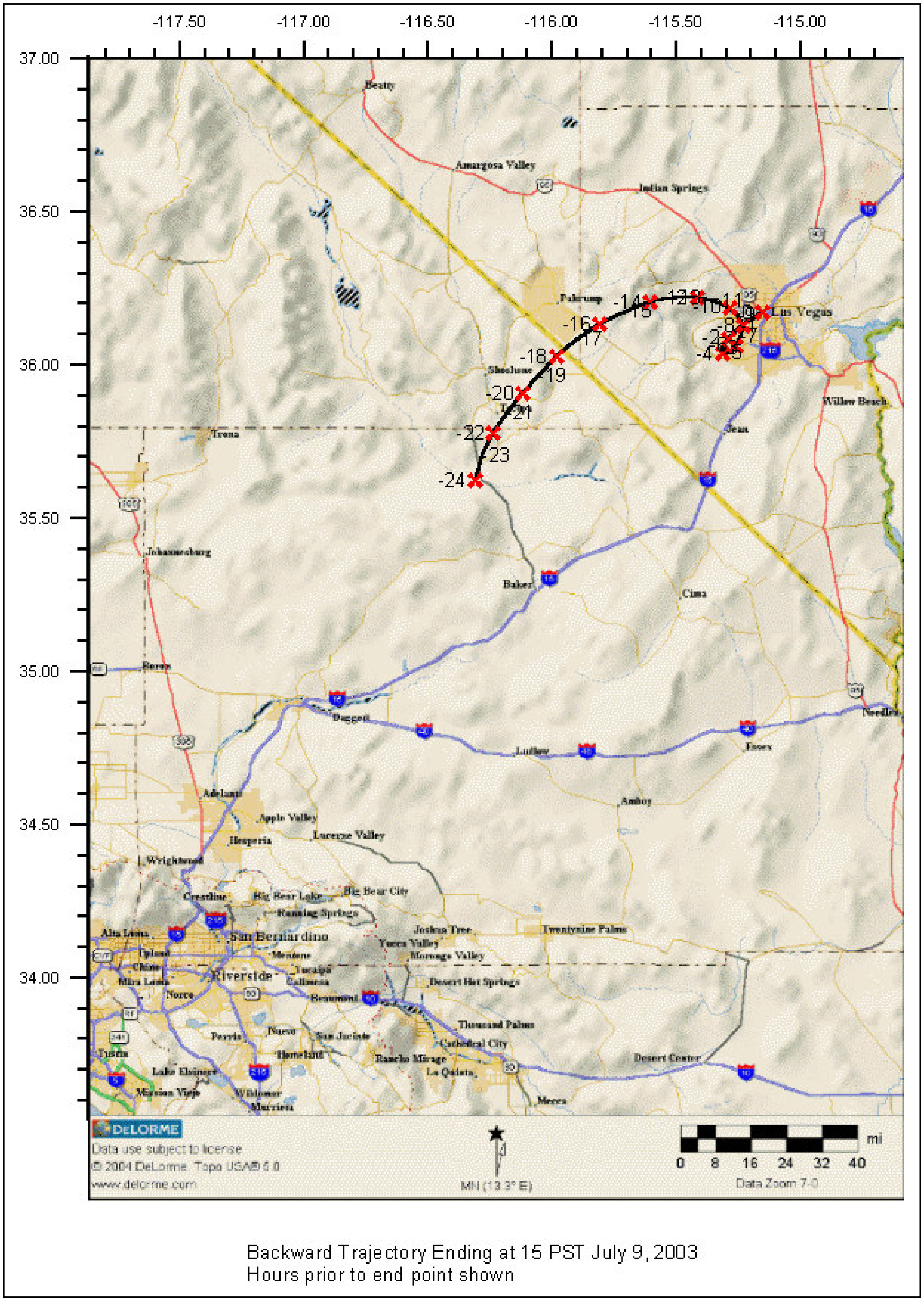


Figure 5-66. Backward Trajectory Ending at 15 PST, July 9, 2003

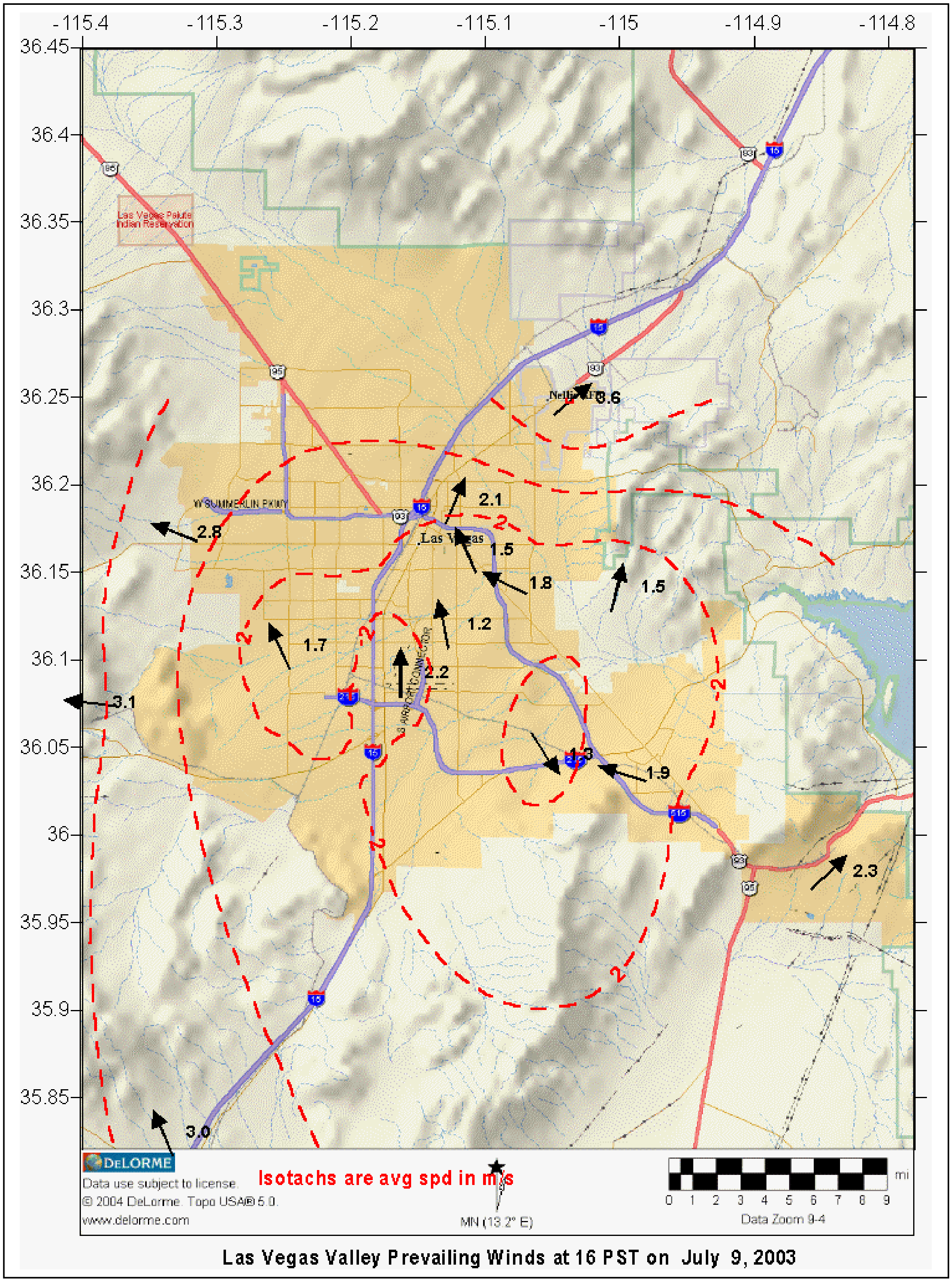


Figure 5-67. Las Vegas Valley Prevailing Winds at 16 PST on July 9, 2003

5.10 July 21, 2003 Episode

Of the 10 episodes studied, the second highest peak ozone levels occurred during this one-day episode. Noteworthy is that this episode is associated with some of the lightest low-level winds as well. **Table 5-17** lists the peak daily 8-hour ozone concentrations for each site within Clark County's monitoring network for day preceding the episode, during the episode, and on the day following. The network maximum ozone is given as well as the number of sites exceeding the standard. The spatial pattern of the ozone peaks are depicted by the contours on **Figure 5-68**. As standard, charts showing the Las Vegas Valley and adjacent regions peak 8-hour and 1-hour ozone spatial pattern are shown on separate panels. Exceedances occurred at seven sites, all within the Las Vegas Valley. The peak 8-hour ozone was measured at the Walter Johnson School (93.1 ppb) followed closely by JD Smith and Joe Neal (92.1 ppb). Jean and Boulder City, representative of upwind conditions given the prevailing winds, experienced peak levels in the high 60's and lower 70's. The spatial distribution of peak hourly levels were similar to the 8-hour values. Lone Mt reached 115 ppb. Within the Valley, ozone peaks were reached from 14 to 16 PST.

Table 5-17. Maximum 8-Hour Ozone (ppb) – Case Study 10

Site Name	Site ID	7/20/03	7/21/03	7/22/03
Apex	AP	61.9	78.9	73.9
Boulder City	BC	60.6	74.1	71.3
E Craig Rd	BS	65.4	89.8	70.6
City Center	CC	63.0	70.9	62.6
JD Smith	JD	65.9	92.1	74.0
Jean	JN	65.9	68.6	77.6
Joe Neal	JO	63.6	92.1	79.3
Lone Mt	LO	71.0	89.4	74.6
Mesquite	MQ	55.5	63.0	59.8
SE Valley	PL	57.6	73.0	70.8
Paul Myer	PM	65.6	86.6	75.3
Palo Verde	PV	66.4	88.8	73.4
Searchlight	ST	61.4	66.1	66.6
Walter Johnson	WJ	71.8	93.1	76.0
Winterwood	WW	61.0	78.1	72.1
Network Max		71.8	93.1	79.3
# Sites Exceeded		0	7	0

Ozone levels in the California desert on the prior day were well below the levels experienced in Clark County. **Table 5-18** lists the maximum 1-hour levels at the California desert sites.

Table 5-18. Maximum 1-Hour Levels at California Desert Sites

Site	Ozone (ppb)
Barstow	102
Death Valley	63
Joshua Tree	93
Mojave	77
Trona	72
Twentynine Palms	77
Victorville	96

Meteorology

The synoptic weather pattern at the 500 mb level during the period around July 21, 2003 was a persistent Interior Ridge (IR) type. **Figure 5-69(a&b)** shows the NWS 500 mb constant pressure maps for the afternoons of the 20th and 21st respectively. A large-scale ridge dominated the weather throughout the western U.S. for most of the month of July. The central axis of the ridge ran from south to north along the eastern portion of the Great Basin from the Arizona/Mexico border to Idaho. In the southwestern U.S., the ridgeline ran right across southeastern Nevada, and then southward just over or slightly east of the Colorado River. The 500 mb heights recorded at the Desert Rock NWS upper-air site during the 20th and 21st were the highest in the region, at around 5,970 to 5,980 m. Wind flow at 500 mb during the period was east-southeasterly at around 10 m/s on the 20th, and 5 m/s on the 21st. The peak 500 mb height dropped slightly to around 5,960 m by the 22nd, and the flow became east-northeasterly at around 8 m/s. During this persistent ridging event, a stable, warm air mass was the dominant synoptic-scale feature.

The Interior Ridge configuration was reflected at lower levels of the atmosphere. **Figure 5-70(a)** shows the 700 mb map for the morning of the 21st. The 700 mb temperature above Desert Rock was 15.2^{o} C, indicating strong air mass subsidence and atmospheric stability. The wind flow at that level was southeasterly at around 6 m/s, almost exactly the same as at 500 mb. The general east to west flow pattern throughout the middle and upper boundary layer indicated that the ridgeline was located east of the Desert Rock site.

In the lower boundary layer, just above the surface at the 850 mb level, the ridge configuration was still detectable, especially to the north over northern Nevada. **Figure 5-70(b)** shows the 850 mb map for the morning of the 21st. Temperatures at that level were quite warm, a reflection of a thermal trough in that area, but unlike other periods studied, it did not seem to have a noticeable influence on the flow patterns. The 850 mb winds at Desert Rock on the morning of the 20th, were east-northeast to east-southeast and less than 3 m/s from the surface to the 700 mb level. On the morning of the 21st, lower boundary layer flow below the 700 mb level could only be described as light and variable. A more consistent west-southerly flow at 2 to 3 m/s was measured in the lower levels at Desert Rock by the morning of the 22nd.

As with the other cases, a backward trajectory from the city's center was constructed using the HYSPLIT Model. The 24-hour backward trajectory, beginning at 16 PST on July 21, is depicted on **Figure 5-71.** The short trajectory, especially for the 15 hours preceding 16 PST, is contrary to long-range transport being a significant factor during this episode. This is particularly important since, of the 10 episodes examined, these were some of the highest ozone levels that occurred.

The surface winds within Clark County were very light, as might be expected. The 16 PST plotted winds and isotachs are shown on **Figure 5-72**. Focusing on the isotachs, it can be seen that the 2 m/s contour encloses most of the Las Vegas Valley. The 2.5 m/s contour encompasses the entire Valley.

The afternoon mixing height, estimated from the Desert Rock rawinsonde and maximum Las Vegas surface temperatures, was 4,600 m-agl. Thus, from this estimate, limited vertical mixing was not a factor that contributed to the particularly high ozone concentrations.

Consistent with the other analysis results, July 21 was classified in the CART model Terminal Node 3, which is characteristically locally induced high ozone rather than interbasin transport.

Summary

- Of the 10 episodes studied, the second highest peak ozone levels occurred during this one-day episode. Exceedances occurred at 7 sites within the Clark County network. Ozone at the Walter Johnson School reached an 8-hour average of 93.1 ppb. JD Smith and Joe Neal readings were nearly as high (92.1 ppb).

- Of particular significance, all the measurements and meteorological products examined, including local winds, adjacent basin ozone levels, synoptic charts, the Desert Rock soundings, and trajectory analyses, discount interbasin transport contributing to the local ozone burden.

- The exceedance episode on July 21, 2003 took place during a long period categorized as an Interior Ridge (IR). The air mass over southern Nevada was thermodynamically stable with warm air aloft prevailing. East to west flow in the middle and upper boundary layer extended down to the surface most of the time. This tended to inhibit or completely shut off the low level southwesterly flow needed for transport from background source areas to the west. Lower boundary layer flows in southern Nevada on the 21^{st}, were light and variable.

- The CART model correctly classified this day as an exceedance owing primarily to local conditions.

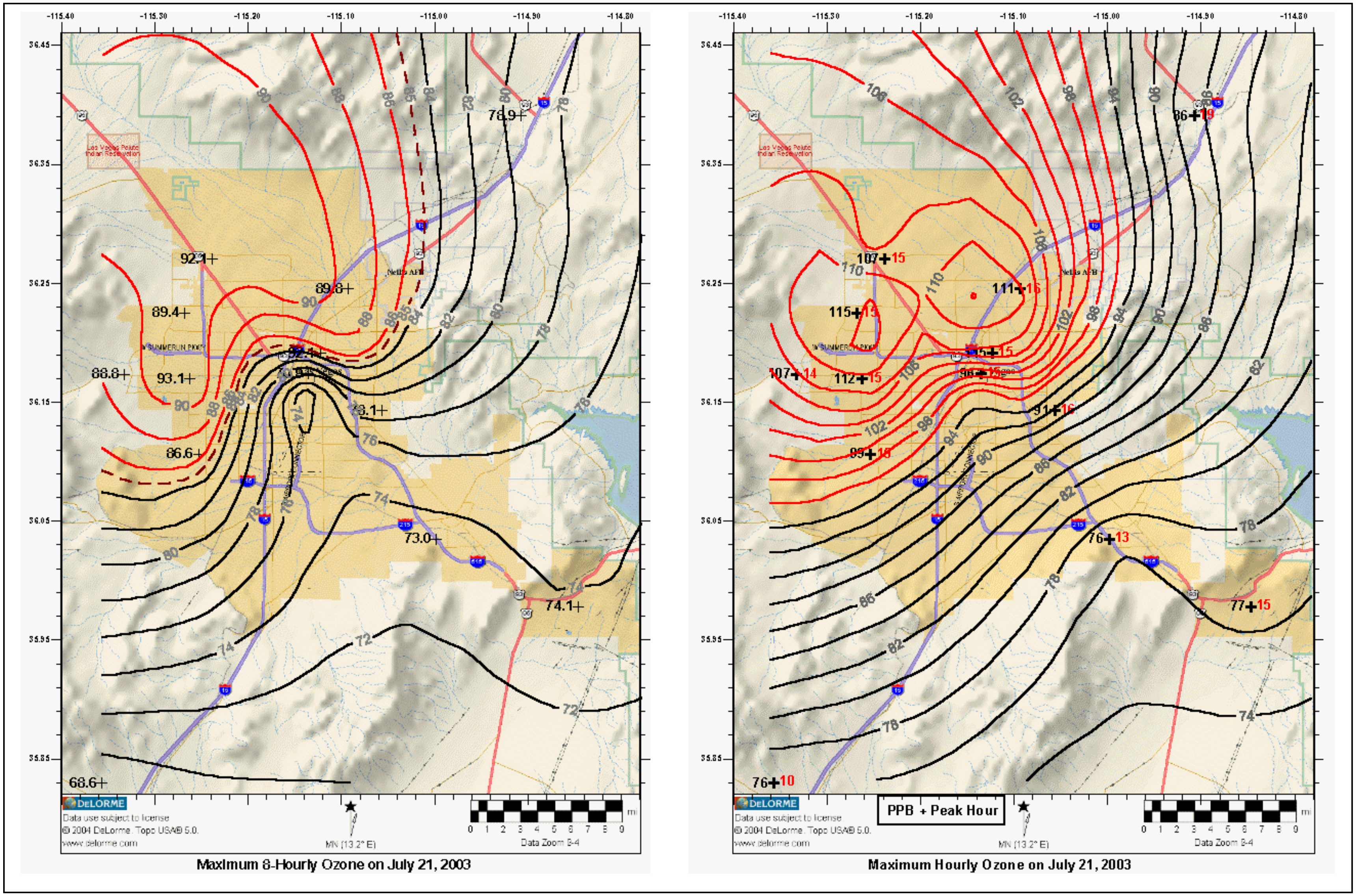


Figure 5-68. Peak Ozone for July 21, 2003

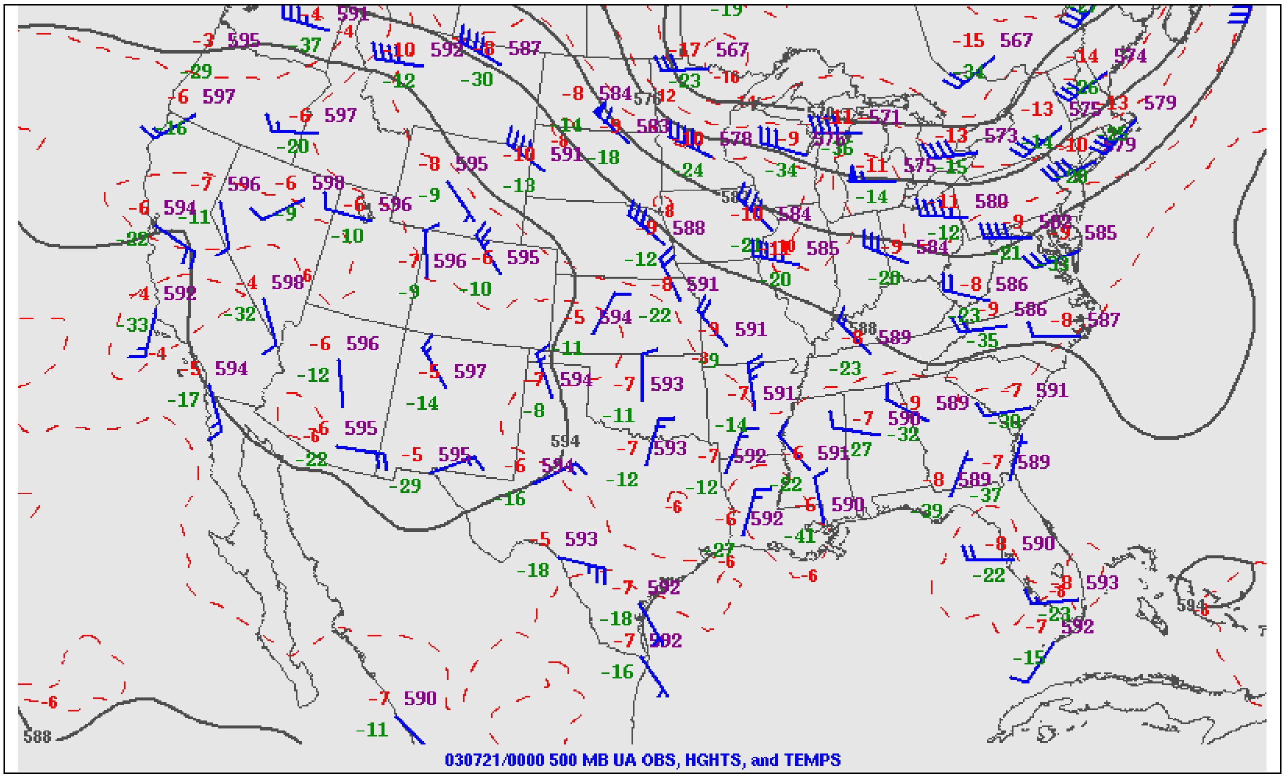


Figure 5-69(a). NWS 500 mb Constant Pressure Map for Afternoon of July 20, 2003

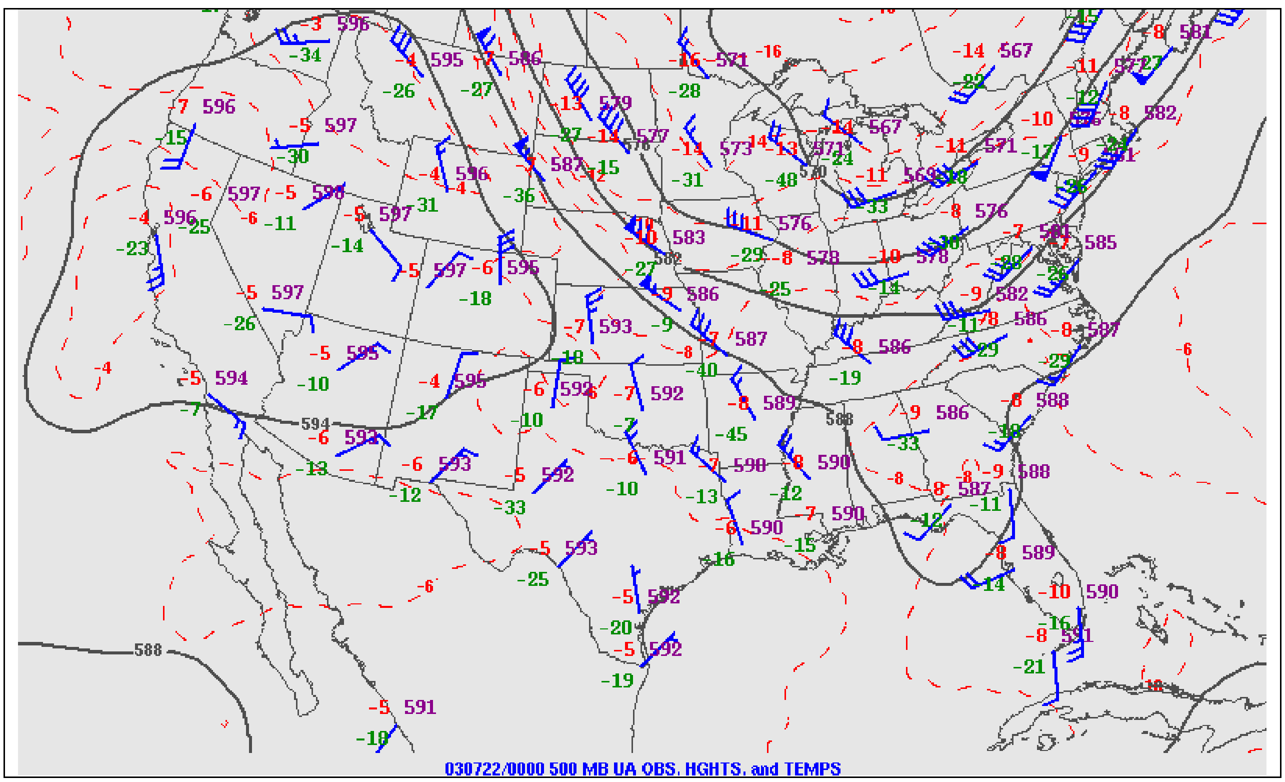


Figure 5-69(b). NWS 500 mb Constant Pressure Map for Afternoon of July 21, 2003

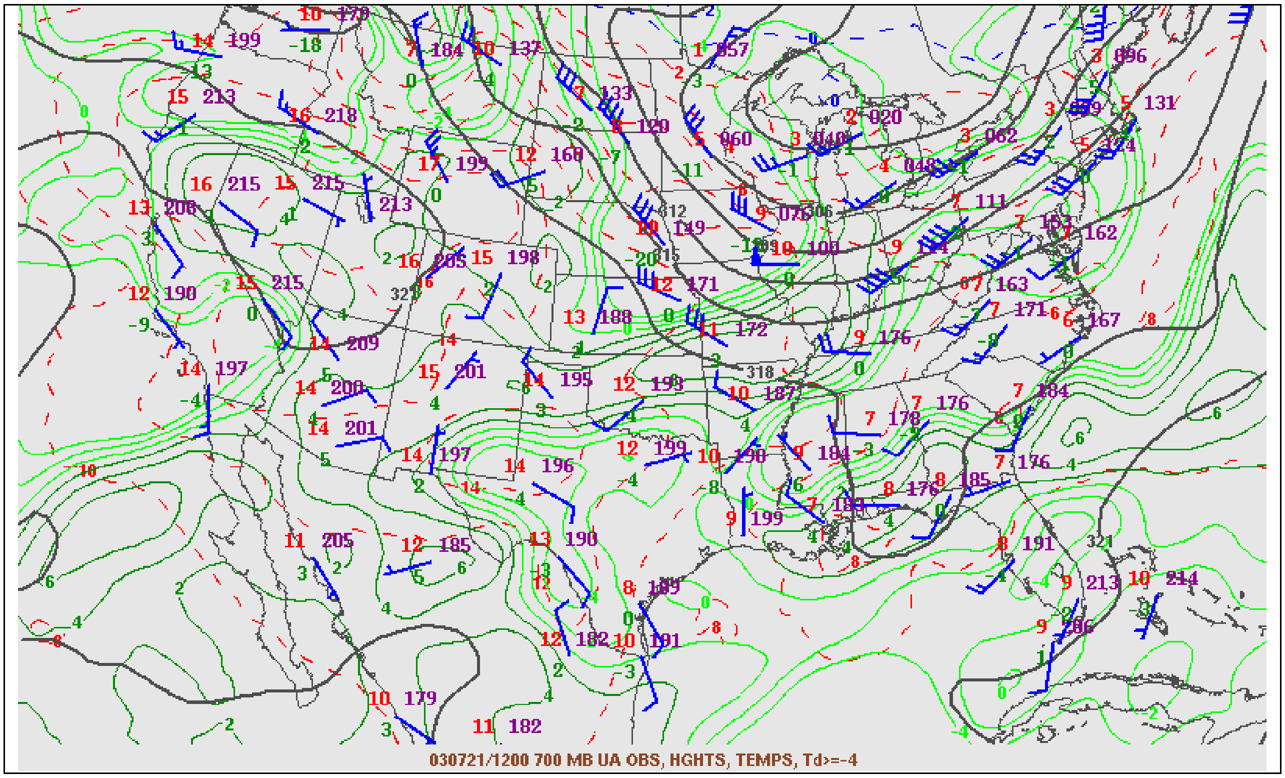


Figure 5-70(a). NWS 700 mb Constant Pressure Map for Morning of July 21, 2003

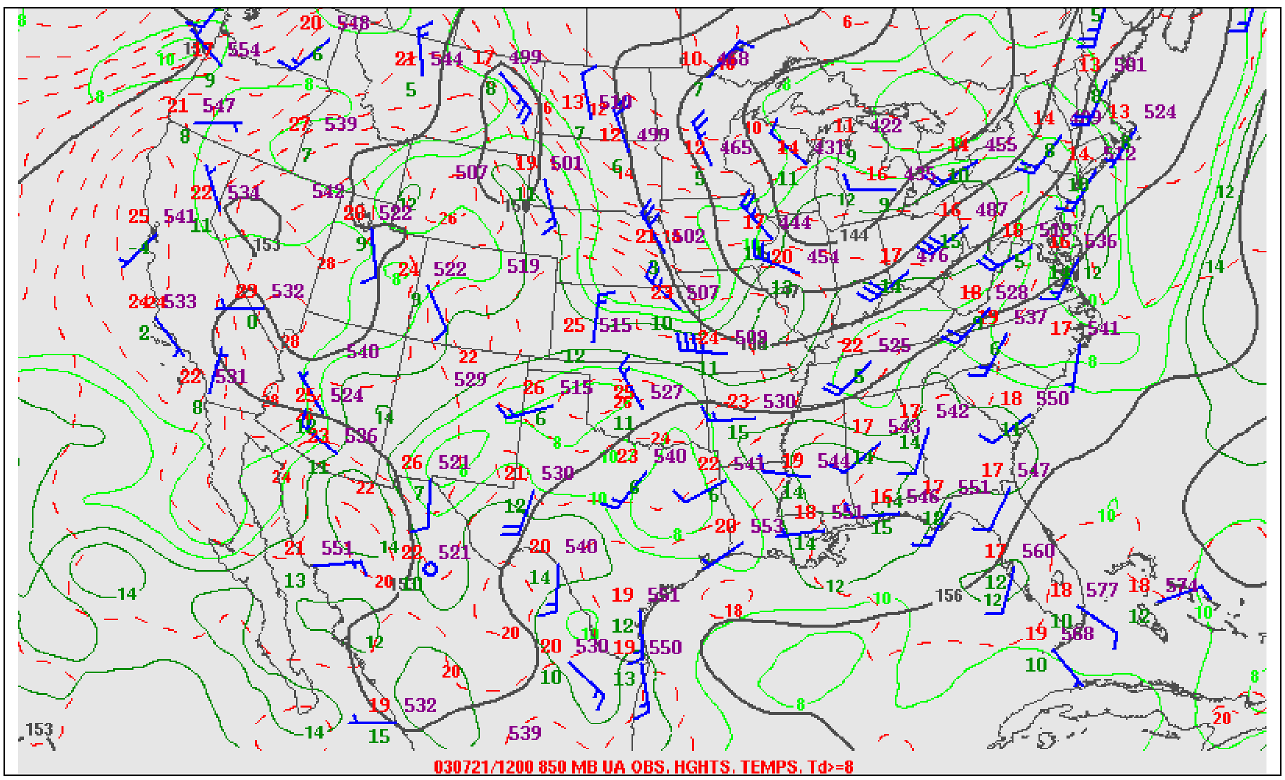


Figure 5-70(b). NWS 850 mb Constant Pressure Map for Morning of July 21, 2003

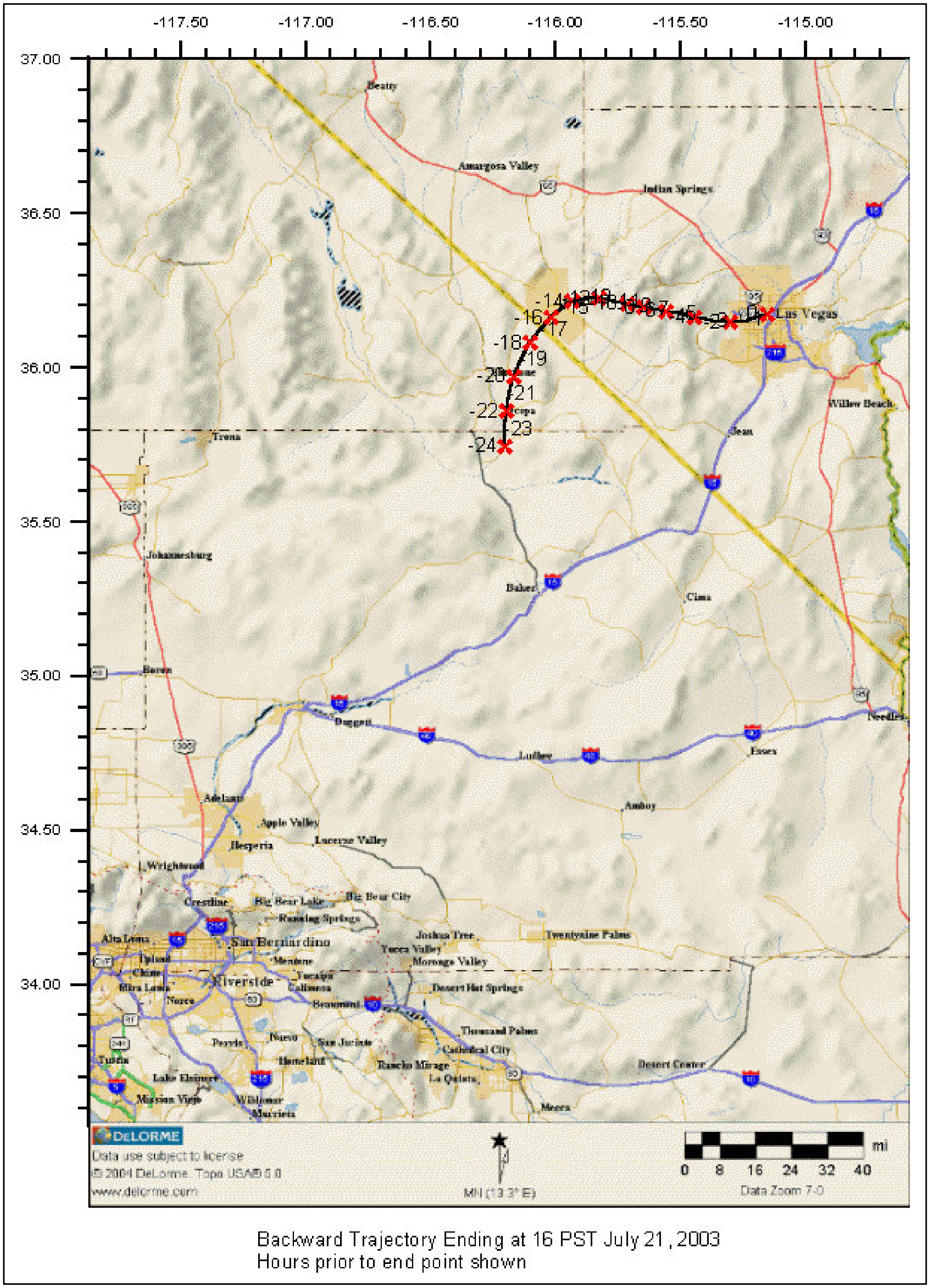


Figure 5-71. Backward Trajectory Ending at 16 PST, July 21, 2003

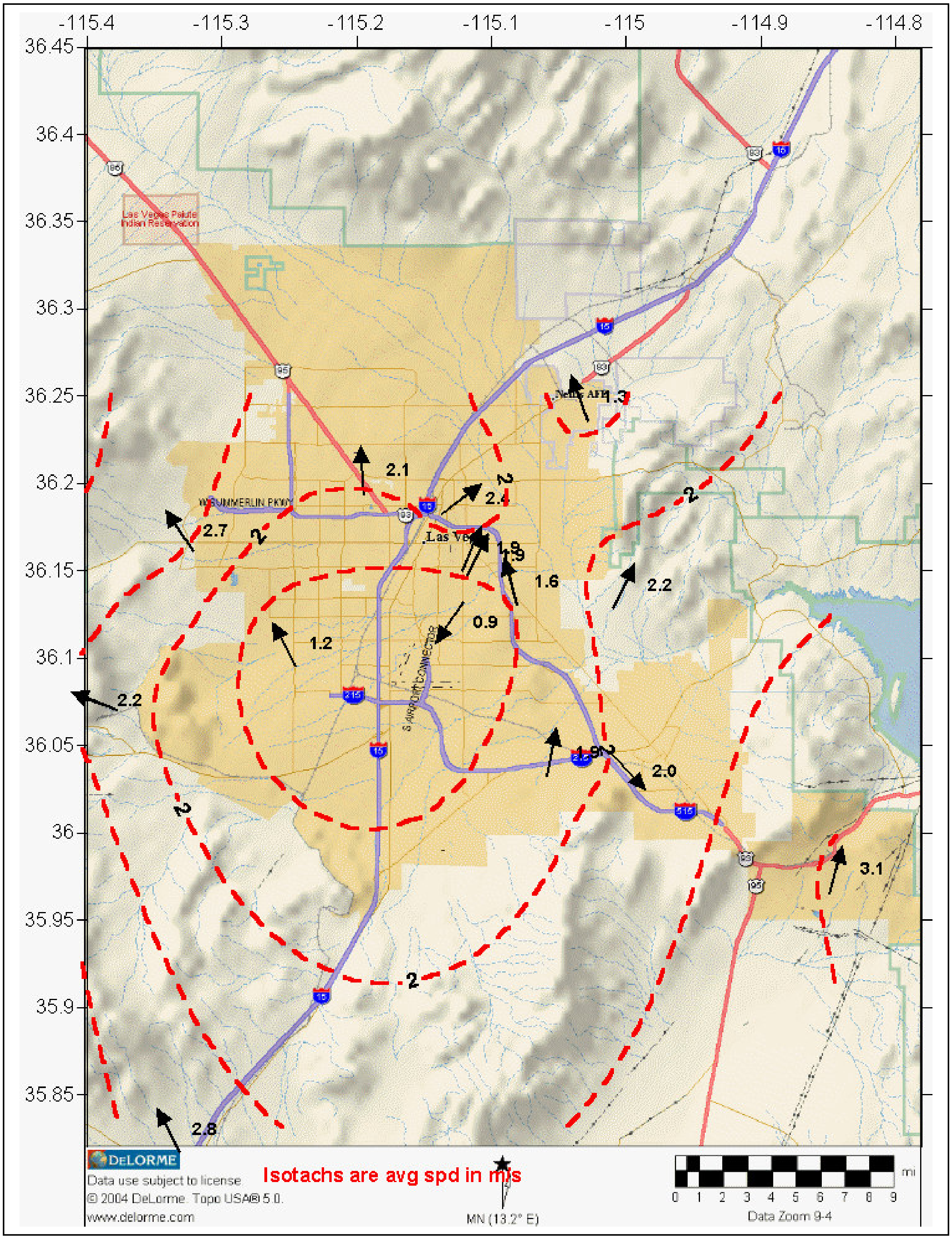


Figure 5-72. Las Vegas Valley Prevailing Winds at 16 PST on July 21, 2003

6. SUMMARY AND RECOMMENDATIONS

6.1 Summary of Findings

Based on the historical record, June experiences the greatest number of exceedances followed closely by July. There were no exceedances noted in September or October during the 8-year period examined. Most episodes persisted for only 1 to 2 days but multi-day episodes were not uncommon.

Significant characteristics of the exceedance case study days are summarized in **Table 6-1**. The number of Clark County sites that exceeded the 8-hr Federal Ozone Standard, the weather type, the CART terminal nodes and our best estimate as to the relative contribution from local sources and interbasin transport to the ozone burden in Clark County are included. Interbasin transport was considered to have been a significant contributor to Clark County ozone on 9 of the 15 days examined. On 6 days there was no evidence in the meteorology or California desert ozone levels to suggest direct interbasin transport contributed in a significant manner.

It should be noted that without upper-air measurements it was difficult to know with any certainty the relative contributions to the local ozone from interbasin transport. Winds aloft measurements would provide information on the potential for boundary layer transport. The Desert Rock sounding appeared (in a sample of one) to reasonably represent upper-air conditions in Clark County at heights above the terrain. However, the sounding as it is reported lacks the required detail within the boundary layer, specifically the Las Vegas Valley. The Desert Rock sounding location is about 400 meters higher than the elevation in downtown Las Vegas and thusly does not accurately characterize the low-level meteorology. This demonstrates the need for continuous measurements in order to understand and better predict high ozone days.

Measurement of ozone levels aloft would identify the existence of an ozone reservoir that is not identifiable on the surface. Case study results seem to imply that mixing of ozone layers aloft may be an important mechanism for creating high ozone days. However, the existence and strength of such layers will only be known if routine monitoring at an elevated site (the Stratosphere for example) is conducted. In addition, boundary layer measurements of the thermal structure would provide information on the mechanisms that are required to mix ozone aloft to the surface.

CART decisions may provide a reasonably simple approach to predicting high ozone days. Results from the CART analysis appear to be in relatively good agreement with observations made during the case studies. In all cases when there was considerable evidence of interbasin transport, the day fell into terminal node 7 of the final CART model (Figure 4-12). The decision branches for this terminal node are parameters that imply transport from the California desert to Clark County. Similarly, days when local sources most likely contributed to the exceedances fell into terminal node 3 of the CART model. This node is characterized by light winds, which was also a feature noted during the case study analysis. Looking beyond the case studies, the CART analysis similarly implies 17 exceedance days resulting from predominantly local conditions and 10 exceedance days resulting more from transport for the 1999 to 2003 period (**Table 6-2**).

Table 6-1. Summary of Ozone Exceedance Case Studies

Date	# Sites >85ppb	Wx Type	CART Node	Transport/Local Scenario
8/10/01	6	FR	3	Significant local contribution
8/11/01	3	FR	3	Significant local contribution
6/16/02	5	IR	7	Interbasin transport significant contribution
6/27/02	5	IR	7	Interbasin transport significant contribution
6/28/02	3	IR	7	Interbasin transport significant contribution
8/11/02	3	FR	3	Significant contribution from both interbasin transport and local sources
8/18/02	5	FR	7	Interbasin transport significant contribution
5/26/03	3	PR	7	Interbasin transport may be significant contribution
5/27/03	1	IR	3	Significant local contribution
6/1/03	1	PR	7	Interbasin transport significant contribution
6/3/03	1	PR	7	Interbasin transport may be significant contribution
6/4/03	1	PR	3	Significant local contribution
6/29/03	8	FR to IR	7	Overwhelming interbasin transport
7/9/03	2	IR	3	Significant local contribution
7/21/03	7	IR	3	Significant local contribution

Table 6-2. Summary of Exceedance Days and CART-Implied Source

Year	Local	Transport	Total
1999	4	1	5
2000	2	1	3
2001	2	0	2
2002	2	4	6
2003	7	4	13

It does not appear that weather typing alone can reasonably identify high ozone periods. In all cases, synoptic-scale high-pressure patterns were established during the episodes, indicating some sort of ridging. However, of the three ridge types investigated, no type stood out as being particularly more conducive for exceedances than the others. It is likely that further classifying the ridge types into several sub-types would provide a better relationship between high ozone days and weather types. For example, the case studies revealed that a thermal low was frequently positioned near Las Vegas on exceedance days. The position of the ridge, the strengths of the pressure gradients, and the speed of the synoptic changes may all similarly play a role in defining the best conditions for high ozone concentrations, leading to further sub-classification of weather types.

Area of Impact of Urban Plume

One of the most interesting features of the meteorology on high ozone days was the prevailing southeasterly winds in the Las Vegas Valley in the morning and afternoons when ozone production is active. The prevailing winds discussed in Section 3 are generally from the southeast beginning at 8 to 9 PST but by 15 PST have shifted to southwesterly accompanied by increased speeds. However, on most of the high ozone days examined in this section, southeasterly flow continued until late in the afternoon. Air parcel trajectories were computed using downtown Las Vegas surface winds for case study days. The resulting trajectory end-points are plotted on the graph in **Figure 6-1**. Admittedly crude, as they assume a uniform wind field in the Valley, this exercise still provides useful information on the most frequent area impacted by the Las Vegas urban plume on high ozone days. The trajectories depicted start near the city center at 06 PST, at the start of the commute, and end at 17 PST after the peak ozone is measured.

The trajectory based on the downtown prevailing winds is drawn on the figure in red for comparison with the individual episode days, which are indicated by the blue X's. Note the trajectory constructed from the prevailing wind initially meanders in the downtown area before traveling upvalley. Other significant features of the figure are that most of the trajectories end upvalley (or to the northwest), where and when maximum ozone levels usually occur, and that those trajectories are not that much different from the prevailing flow. Three outliers are apparent: June 3, 2003, August 18, 2002, and June 29, 2003.

Interbasin transport played a major role in each of these three outlier episodes. All three days were classed by the CART model in the same terminal node, which represented the interbasin transport scenario. (Note that some critical data were missing during these episodes, which lead to a greater uncertainty in CART.) Perhaps the most interesting of the outliers is June 29, 2003. As discussed in Section 5-10, the meteorology and air quality was very different from the other episodes. In addition to having the most widespread ozone exceedances, the timing of the peaks was noteworthy. Peak ozone was measured almost simultaneously unusually earlier, between 11 to 13 PST. Ozone levels dropped rapidly in the afternoon. Afternoon winds were exceptionally strong compared to the other episodes. The August 18, 2002 episode was noteworthy for the afternoon strong wind shears that occurred in the Valley (see Section 5.5). Relatively strong southwest flow converged with a southeast flow along the Valley's longitudinal axis. Also, the peak ozone areal distribution was unique for the strong west to east gradient, and early timing. The June 3, 2003 episode was unique in that Jean experienced the only exceedance. June 3 was part of a multi-day episode. What characterized the 3rd from the other days in that episode were the strong afternoon winds.

Given the above considerations, it seems reasonable to conclude that the conceptual model for Clark County includes peak ozone levels in the northwest quadrant of the Valley supported by light southwest flows. During interbasin transport episodes, peak ozone levels may occur in other locations as well. Timing of ozone peaks typically occur in mid-afternoon but again may vary considerably during interbasin transport scenarios.

6.2 Recommendations

- The origin and fate of pollutants in Clark County cannot be adequately understood without boundary layer measurements of temperature, winds, and ozone, at a minimum. The planned 2005 field monitoring study should include wind profiler/RASS and/or sodar/RASS or rawinsonde measurements for at least one site in the Las Vegas Valley and for one upwind location. Ozone monitoring sites should be placed at elevated platforms of opportunity (i.e., isolated hill tops or tall towers). Ozone aloft measurements using aircraft or ozonesondes is strongly recommended.

- Additional surface ozone monitoring should occur at locations at the extreme northwest and northeast of the Valley, and along the western foothills of the Valley to determine if the existing ozone network adequately characterizes peak levels.

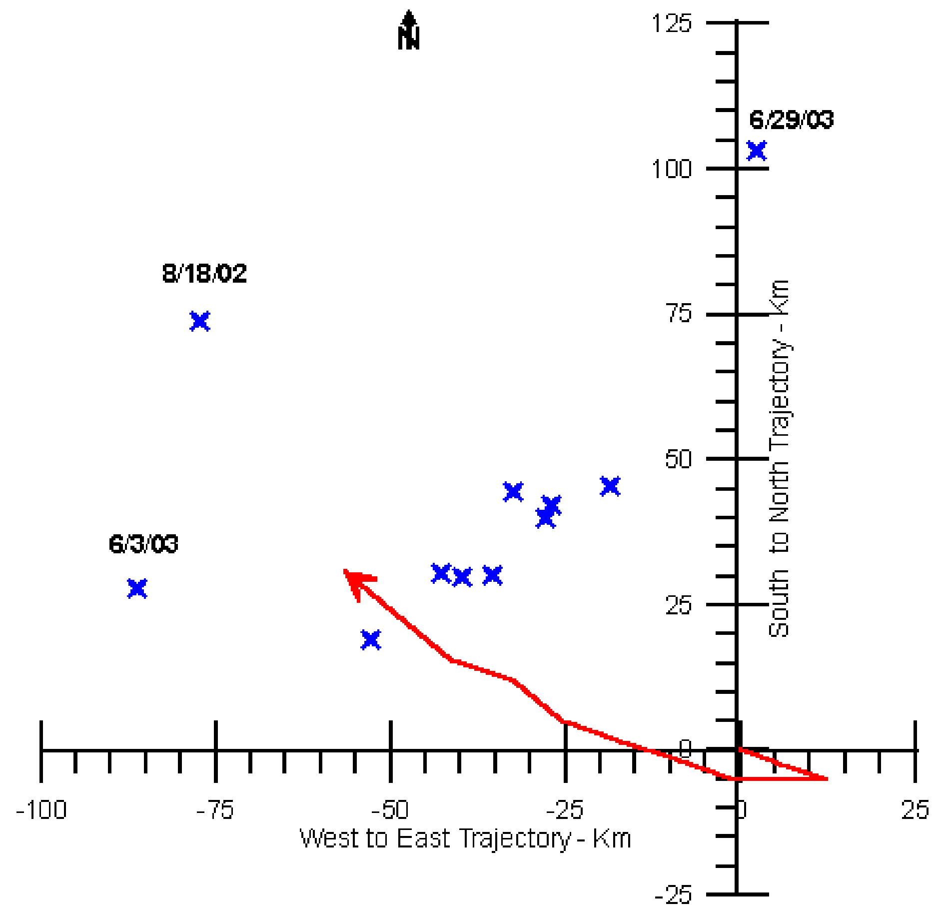


Figure 6-1. Showing the Trajectory of the Prevailing Wind at CC Between 06 to 17 PST (red line) and the Trajectory End Points for the Corresponding Winds on Episode Days (blue X's)

- It is recommended that wind measurements be obtained from a site along the Las Vegas Wash, between Lake Mead and Las Vegas. The temperature gradients between Lake Mead and the Las Vegas basin is the likely mechanism for the southeasterly winds that dominate the meteorology during ozone exceedances, and the additional meteorological measurements will assist in confirming this mechanism and the role it plays on ozone concentrations.

- The possibility of using the CART model as a forecasting tool should be further evaluated using 2004 data. Assuming it shows promise, the CART model should be utilized as an integral part in the 2005 field campaign. In addition, it is recommended that further CART analysis be conducted for future seasons using additional predictor parameters that may be collected during the 2005 field study and future years, including upper-air meteorological data, temperature profiles, mixing heights, ozone concentrations aloft, VOC concentrations, and NO_y concentrations.

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