ALPINE GEOPHYSICS

REGIONAL AIR QUALITY COUNCIL

Colorado Department of Public Health and Environment

ENVIRON

Denver Metropolitan Area and North Front Range 8-Hour Ozone State Implementation Plan

Weight of Evidence to Support the Modeled Attainment Demonstration

DRAFT FINAL

October 29, 2008

Preface

This Weight-of-Evidence report was completed in October 2008 prior to the Colorado Air Quality Control Commission's (AQCC) December 12, 2008 approval of the Ozone Action Plan, including revisions to the State Implementation Plan. After the hearing and as directed by the AQCC, the photochemical modeling was revised in the late December 2008 to early January 2009 timeframe to incorporate the final SIP control measures approved by the AQCC, which are based on a slight modification of the original Ozone Action Plan's Alternative Proposal #2.

The emission control scenarios (2010 base case, 2010 control 1, and 2010 control 2) referenced in this Weight-of Evidence document are summarized in Table ES-2 in the following September 2008 report:

> Morris R., T. Sakulyanontvittaya, E. Tai, D. McNally and C. Loomis. 2008. *2010 Ozone Attainment Demonstration Modeling for the Denver 8-Hour Ozone State Implementation Plan Control Strategy*. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. September 22, 2008. (http://www.colorado.gov/airquality/documents/deno308/Denver_2010ControlStrat_Draft_Sep22_2008.pdf)

The final SIP control measures (referred to as the "Final 2010 Control Strategy") are summarized in the following January 2009 report:

> Morris R., E. Tai, T. Sakulyanontvittaya, D. McNally and C. Loomis. 2009. *Final 2010 Ozone Attainment Demonstration Modeling for the Denver 8-Hour Ozone State Implementation Plan*. ENVIRON International Corporation, Novato, California. Prepared for Denver Regional Air Quality Council (RAQC), Denver, Colorado. January 12, 2009. (http://www.colorado.gov/airquality/documents/deno308/2010_Denver_Final_Control_Jan12_2009.pdf)

Section 3.2 ('Alternative 2010 Ozone Projection Procedures') of the January 2009 report (Morris, et al, 2009) supplements section 4.3 ('Alternative 2010 Ozone Projections') of this Weight-of-Evidence document by including metrics for the "Final 2010 Control Strategy." Similarly, section 3.3 ('Additional Modeling Metrics') of the January 2009 report (Morris, et al, 2009) supplements section 4.1 ('Additional Modeling Metrics') of this Weight-of-Evidence document.

The final ozone modeling and analysis (Morris, et al, 2009) do not contain any results that alter the conclusions in this Weight-of-Evidence Report.

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Executive Summary

The United States Environmental Protection Agency's (EPA) 8-hour ozone modeling guidance (EPA, 2007) recommends a weight of evidence analysis (WOE) (a set of supplemental analyses) to support the attainment determination if the maximum-modeled 8-hour ozone design value is between 0.082 ppm and 0.087 ppm at more than one monitor. Although all monitoring locations in the Denver/North Front Range SIP attainment demonstration indicate modeled attainment of the 8-hour ozone standard, four monitors (Rocky Flats North, Fort Collins West, Chatfield and National Renewable Energy Laboratory) have modeled concentrations that fall into the 0.082-0.087 ppm range. Therefore, a set of supplemental analyses are required to determine if these monitors are expected to demonstrate compliance with the ozone standard.

Overview of Supplemental Analysis and Weight of Evidence

Supplemental analyses used in a weight of evidence will help determine whether attainment is likely where modeled attainment test results indicate future air quality levels are near the National Ambient Air Quality Standards (NAAQS). A weight of evidence determination includes the modeled attainment and screening test results, plus results of additional model outputs plus other analyses of air quality, meteorological and emissions data. A weight of evidence analysis may be used either to increase or decrease emission reductions identified as sufficient to meet the NAAQS by a modeled attainment test.

The final WOE combines and weighs the various supplemental analyses with the results of the attainment test resulting in an aggregated, qualitative, and quantitative conclusion as to whether the proposed set of control strategies will result in the Denver Metro Area/North Front Range reaching attainment in 2010.

The supplemental analyses used in the weight of evidence for the Denver Ozone SIP include:

- Monitoring and emission inventory trend analysis
- Review of the conceptual model for ozone formation along the northern Front Range
- Additional modeling metrics

- Alternative attainment test methods
- Assessment of the efficacy of SIP, state-only, and voluntary control measures

Monitoring and Emission Inventory Trend Analysis

Trend analyses for ambient measurement of ozone and emission inventory trends are presented as one of the supplemental analysis for this weight of evidence. The trends analyses indicate several important points:

- The aggregate trend in weather-corrected 4th maximum time series suggests that ozone levels have been flat from 2004 through 2008, although individual concentrations have been highly variable. This suggests that without additional emission reductions the region will remain at or near the level of the standard.
- Trends in emissions correlate well with surrogate indicators such as fleet turnover.
- If the emissions trends are correct, then the Relative Response Factors (RRFs) are likely to be directionally correct.
- Meteorological variability is a key component for ozone formation and is reflected in the year-to-year variability of peak ozone levels. A key metric for upper level high pressure strength has remained steady or trended downward in recent years, suggesting a reasonable likelihood for moderate high pressure strength in the next few years, which would favor attainment.
- Analysis of the weekend-weekday effect for the Front Range shows a strong effect in Central Denver and weaker effects in outlying areas. This points to the possibility for NOx control disbenefits in central Denver due to the role of NOx quenching here. The spatial pattern of the weekend effect is consistent with the localized NOx disbenefit identified in the photochemical modeling.
- Reductions in VOC emissions are expected to reduce ozone.
- Reductions in NOx emissions are expected to reduce ozone, possibly with greater efficiency than VOC reductions, at troublesome monitors outside of the urban core of metro Denver. Increases in ozone concentrations in the urban core of metro Denver due to NOx emissions reductions do not appear to be significant.

Conceptual Model

A review of the conceptual model for the Front-Range reveals the complexity of the meteorological, emission inventory, and photochemical modeling challenges that exist in the formation and subsequent control of ozone formation along the northern Front Range. Several diagnostic tests with subsequent changes to the science options and other input were made to the meteorological model to achieve the best performing meteorological model for the Front Range. Trajectory analyses indicate that the base case modeling of the June-July 2006 timeframe encompasses various local meteorological regimes under which elevated ozone levels have and are expected to occur. This assures that the modeled ozone impacts from various 2010 emissions scenarios have been examined under a range of meteorological regimes that are favorable for ozone formation.

Additional Modeling Metrics

Additional modeling metrics, such as the reduction in Total Ozone[1], the number of grid-cells with elevated ozone (Grid Cells[2]), and the number of hours of elevated ozone (Grid Cell-Hours[3]), are used to demonstrate that the existing controls along with potential SIP and state-only emissions controls are effective in reducing ozone along the Front Range. Additional modeling metrics indicate that:

- The emission reductions between 2006 and 2010 are effective at reducing elevated 8-hour ozone concentrations.
- The changes in Total Ozone and Grid Cells greater than 85 ppb" modeling metrics between the 2006 and 2010 base cases are -21% and -14%, respectively. This suggests that changes in emissions between 2006 and 2010 base case emission scenarios reduce ozone levels.
- The changes in Total Ozone and Grid Cells are greater for the 2010 Control 1 case (-28% and -17%, respectively) and for the 2010 Control 2 case.
- Other modeled metrics indicate that there are reductions in Total Ozone, Grid Cells, and Grid Cell-Hours of 15% to 30% for thresholds of 85 ppb and 80 ppb

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[1] "Total Ozone" is defined as the difference between the modeled daily maximum 8-hour ozone concentrations and the threshold concentration, for modeled values above the threshold, summed across all grid cells in the Denver NAA and modeling days during June-July 2006.

[2] "Grid Cells" is the number of grid cell-days with modeled daily maximum 8-hour ozone concentrations greater than a given threshold (e.g., 85 ppb) for all grid cells in the NAA and days from the June-July 2006 episode.

[3] "Grid Cell-Hours" is the number of grid cell-hours with modeled running 8-hour ozone concentrations greater than the threshold for all grid cells in the NAA and hours during the June-July 2006 episode.

from the 2006 base case through the 2010 base case, the 2010 Control 1 case, and the 2010 Control 2 case.

Alternative Attainment Test Methods

EPA's modeling guidance for ozone offers several potential approaches for establishing base year design values. The guidance recommends the preferred methodology for establishing a base year design value as follows:

> "For the modeled attainment tests we recommend using the average of the three design value periods which include the baseline inventory year. Based on the attributes listed above (in the guidance), the average of the three design value periods best represents the baseline concentrations, while taking into account the variability of the meteorology and emissions (over a five year period)."

At the start of the work on the SIP in 2007 and throughout development of the proposed plan, the modeling analysis has used the 2005-2007 three-year design value as representative of the ozone situation facing the region at the time. In the SIP, modeled attainment of the 8-hour ozone standard was demonstrated at all of the monitored locations by 2010 as a result of the reductions in ozone precursors expected from existing programs and regulations. The use of the three-year design value from 2005-2007 is a conservative approach with higher base year and future year design values when compared to using the EPA preferred method.

Since the start of the Denver ozone SIP project, additional data from the 2008 ozone season (though currently not formally quality assured by the State or EPA) has become available. The additional data from 2008 provides the necessary data to estimate the average of the three Design Values in the 2004-2008 time period as prescribed in the the EPA recommended method. The importance of using 2008 monitoring data in the design value estimation is that year 2008 is the first year of the 2008-2010 ambient monitoring period used to demonstrates monitored attainment of the ozone standard.

Using the EPA preferred method of calculating the modeled base year design value using years 2004-2008, the current attainment tests show that the Denver region will attain the ozone standard by 2010. Table ES-1 presents the results of using EPA's recommended methodology for estimating the base year design value with projected 2010-modeled concentrations.

Table ES-1: 2010 Control Case Design Values Utilizing EPA's Recommended DVB Calculation Methodology

Site Name	Current (2004-08*) Base Case Design Value (ppm)	Modeled Control Case Relative Reduction Factors	Calculated 2010 Control Case Design Value (ppm)	Truncated 2010 Control Case Design Value (ppm)
Welby	0.0707	1.0039	0.0709	0.071
Arvada	0.0777	1.0022	0.0779	0.077
NREL	0.0808	1.0027	0.0810	0.081
Rocky Flats North	0.0840	0.9981	0.0838	**0.083**
S. Boulder Creek	0.0791	0.9963	0.0788	0.078
Fort Collins	0.0728	0.9853	0.0717	0.071
Fort Collins West**	0.083	0.9852	0.0818	0.081
Carriage	0.0728	1.0015	0.0729	0.072
Welch	0.0740	1.0002	0.0740	0.074
CAMP	0.0560	1.0009	0.0560	0.056
Weld County Tower	0.0769	0.9925	0.0763	0.076
Highland	0.0760	0.9900	0.0752	0.075
Chatfield Res.	0.0829	0.9921	0.0822	**0.082**
Rocky Mtn. N.P.	0.0759	0.9892	0.0751	0.075

* Thru August 31, 2008. 2008 data have not been fully quality assured at this time;

** FCW only has three years of data and is presented as a Design Value to three places

Alternative 2010 Ozone Projections

Several alternative 2010 ozone projection procedures for the 2010 base case, Control 1 and Control 2 scenarios have been examined to estimate the uncertainties in the projection procedures and provide confidence that passing the modeled attainment demonstration indicates that attainment will likely be achieved in 2010 under the 2010 base case, Control 1 or Control 2 emission scenarios. Six additional ozone projection procedures were analyzed, in addition to the EPA guidance default procedure.

The six additional tests provide a range of future design values for the 2010 base case that is a more robust test than just using the EPA guidance default. In addition, the supplemental attainment tests provide a range of concentrations by which the likelihood of reaching attainment can be assessed. As presented in the technical support documentation, some of the six alternative projection approaches result in ozone concentration increases, whereas others in decreases in the projected 2010 design values (DVFs) at the two key sites, Rocky Flats North (RFNO) and Fort Collins West (FTCW), relative to the default EPA guidance approach. The future 2010 base year design value for the RFNO and the FTCW monitors using the alternative projection approach range from 84.6 ppb to 85.2 ppb with an average of 84.9 ppb. Using the default EPA guidance approach to show modeled attainment of the ozone standard also yielded a 2010 base year design value for RFNO and FTCW of 84.9 ppb, which is comparable to the six alternative projection methods.

When the proposed SIP control strategies are applied, the six alternative projection methods indicate that, at the RFNO monitoring site, the projected DVFs for the 2010 Control 1 scenario range from 84.3 to 85.1 ppb with an average of 84.8 ppb. At the FTCW monitoring site the projected DVFs range from 84.4 to 85.0 ppb with an average of 84.7 ppb. This indicates the SIP control strategies will provide a slightly better 'cushion' than reliance on only those strategies that are currently on the books.

The 2010 projected DVFs at RFNO using the 2010 Control 2 case are similar to the 2010 Control 1 case ranging from 84.3 to 85.1 ppb, with an average of 84.8 ppb. More benefits are seen at FTCW where the 2010 projected DVFs range from 84.3 to 84.8 ppb with an average of 84.5 ppb.

Assessment of the Efficacy of SIP, State-only, and Voluntary Control Measures

Along with the control measures contained in this SIP and proposed State-only measures contained in the Control 2 scenario, there have been and will continue to be a myriad of voluntary measures in the DMA/NFR that are not directly accounted for in the current and projected emissions inventories.

Conclusion

In conclusion, the collective supplemental analyses contained in this weight of evidence document support the current photochemical model attainment demonstration for the 0.08 ppm 8-hour ozone NAAQS using the EPA default approaches for the 2010 base case, 2010 Control 1, and the 2010 Control 2 scenarios. In addition, at this time, the photochemical modeling is considered to be the best predictor of future ozone levels. The collective supplemental analyses in this weight of evidence analysis support the findings using the EPA methods, as specified in the EPA modeling guidance, that the 2010 base case will likely achieve attainment of the 0.08 ppm 8-hour ozone NAAQS in the Denver Metro Area and North Front Range. As demonstrated using alternative attainment test methodologies, the same WOE indicators demonstrate that there will be more certainty that the Denver region will achieve 8-hour ozone attainment in 2010 under the 2010 Control 1, and Control 2 emissions scenario. The preponderance of evidence suggests that the region will attain the standard in 2010 under the base case, Control 1, and Control 2 scenarios, but the safety margin is small.

1 Introduction to the Weight of Evidence (WOE) Analysis

EPA's 8-hour ozone modeling guidance (EPA, 2007) suggests development of a weight of evidence analysis (a set of supplemental analyses) to support the attainment determination if the maximum-modeled 8-hour ozone design value is between 0.082 ppm and 0.087 ppm at more than one monitor. Although all monitoring locations in this SIP attainment demonstration indicate modeled attainment of the 8-hour ozone standard, four monitors (Rocky Flats North, Fort Collins West, Chatfield and National Renewable Energy Laboratory) have modeled concentrations that fall into the 0.082-0.087 ppm range. Therefore, a set of supplemental analyses are required to determine if these monitors are expected to demonstrate compliance with the ozone standard.

Supplemental analyses used in a weight of evidence will help determine whether attainment is likely where modeled attainment test results indicate future air quality levels are near the NAAQS. A weight of evidence determination includes the modeled attainment and screening test results, plus results of additional model outputs plus other analyses of air quality, meteorological and emissions data. A weight of evidence analysis may be used either to increase or decrease emission reductions identified as sufficient to meet the NAAQS by a modeled attainment test.

2 Air Quality Related Trends

2.1 Emission Trends

Impacts of federal tailpipe regulations have continued to reduce mobile source emissions of VOC and NOx over time. The downward emissions trend in On-Road Mobile source emissions between 2006 and 2010 are consistent with the expected changes in emissions due to mobile source fleet turnover and federal tailpipe regulations. Similarly, downward trends in Non-Road Mobile source emissions are consistent with expected changes in emissions from the Tier 2 and Tier 3 non-road regulations. The correlation between the expected emission reductions from existing regulatory programs and the calculated emissions reductions from the emissions modeling systems suggest that the emissions reductions are providing directionally correct emissions projections for 2010.

Reformulation of paints and consumer products are reducing emissions in the area source category. Point source growth has been modest. Therefore despite continued growth in vehicle miles traveled, population and housing in the Denver/North Front Range area, the region has seen declining emissions of VOC and NOx in mobile, non-road and area sources.

The one area of significant emissions growth in the region since 2002 has been in the oil and gas industry. Controls were first applied to the industry prior to the 2005 peak ozone season and tightened prior to the 2007 peak ozone season to regulate previously uncontrolled facilities (condensate tanks). Due to continued growth, controls applied barely managed to keep pace with the growth in emissions. Additional recommended controls in this SIP and currently proposed state-only controls will continue to reduce emissions in the oil and gas industry and mobile sources beyond 2010.

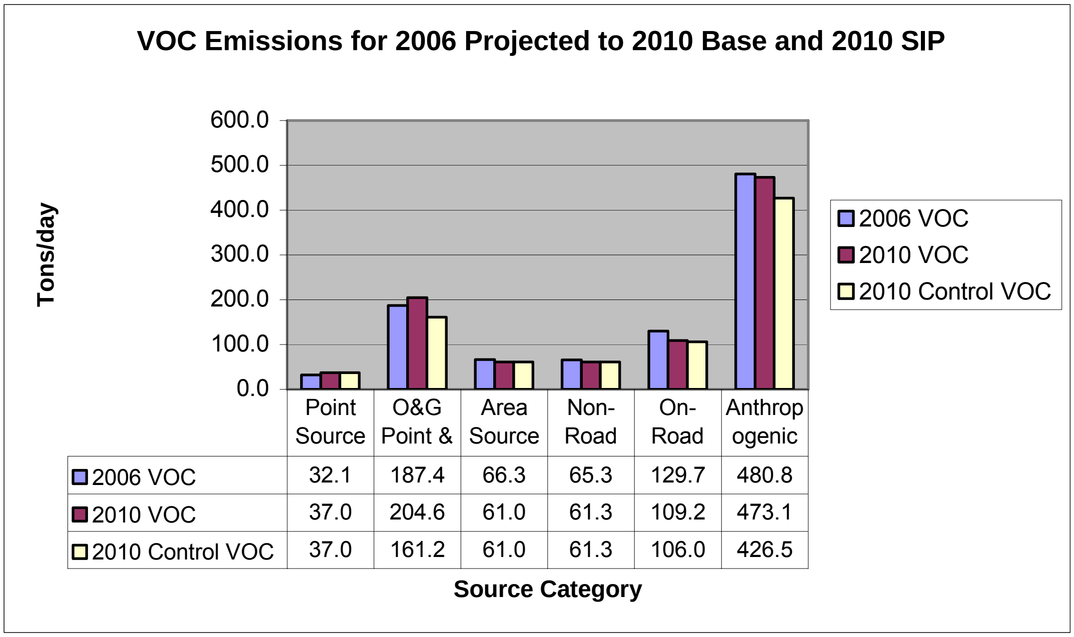

Figure 2-1: Emissions for 2006 Projected to 2010 Base and 2010 SIP

The total estimate of VOC and NOx emissions from all sources in Figure 2-1 and Figure 2-2, respectively, demonstrate an overall reduction in emissions between the 2006 base case and the 2010 base and control case. In Figure 2-1, the reduction in total anthropogenic VOC from 2006 base case to 2010 base case is about 8 tpd. The 2010 control case will net an additional 46 tpd. The total VOC reduction from 2006 base case to 2010 Control Case is around 54 tpd, which is about an 11% reduction.

In Figure 2-2, the reduction in total anthropogenic NOx from 2006 base case to 2010 base case is about 36 tpd. The 2010 control case will net an additional 4 tpd. The total NOx reduction from 2006 base case to 2010 control case is around 40 tpd, which is about a 12% reduction.

The decrease in emission inventory trends presented in Figure 2-1 and Figure 2-2 are directionally consistent with the photochemical modeling results and the sensitivity analysis that indicate that a decrease in both VOC and NOx are beneficial for reduction in ozone.

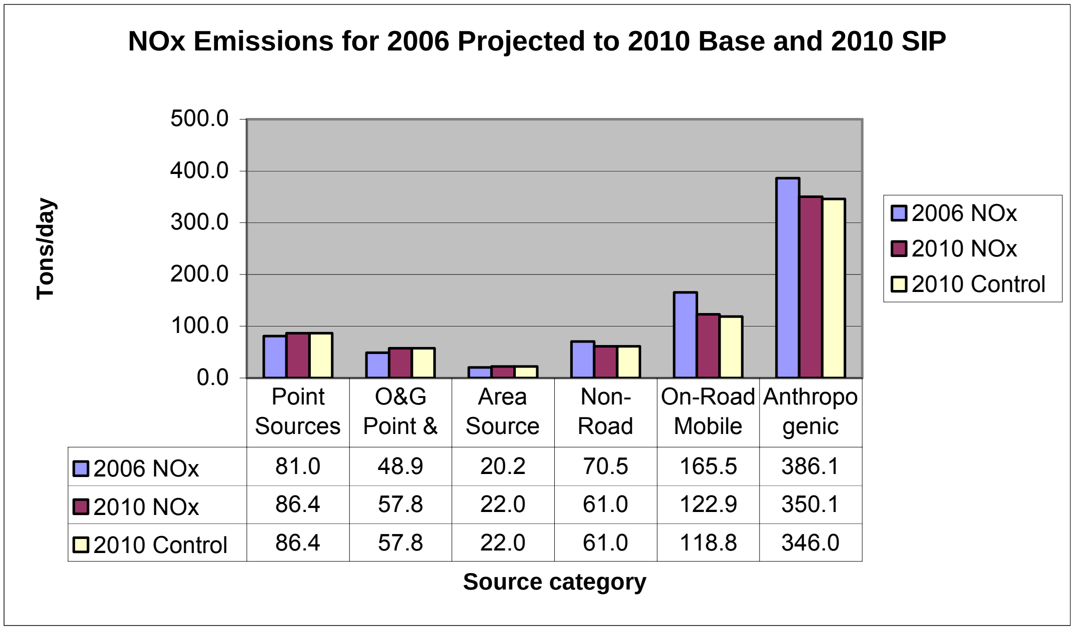

Figure 2-2: Emissions for 2006 Projected to 2010 Base and 2010 SIP

Figure 2-3 presents projected trends from on-road mobile sources out to 2035 using the current conformity network. The trend indicates that both NOx and VOC emissions will continue to decrease through 2025. After 2025, the effectiveness of technology will be overtaken by the increase in VMT and VOC emissions will trend upward at that point. The reductions in NOx and VOC from on-road mobile sources will likely help reduce ozone concentrations into the future.

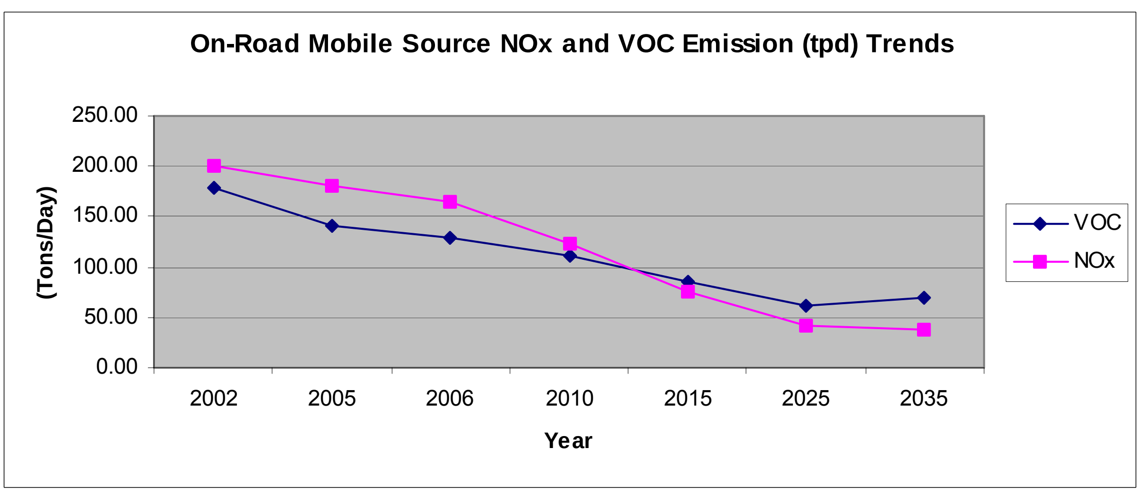

Figure 2-3: Trends in Mobile Source Emissions

2.2 Ozone Monitoring Trends

2.2.1 Time Series of Monitored 4th maximum ozone values

The EAC Ozone Action Plan (OAP) required controls on oil and gas industry condensate VOC emissions prior to the 2005 peak ozone season. Due to recorded growth in condensate flash emissions, Regulation No. 7 was amended in late 2006 to preserve the EAC OAP and additional controls were applied to condensate tanks prior to the 2007 peak ozone season. The EPA required 7.8 RVP fuel in the DMA 1-hour ozone attainment maintenance area prior to the 2004 ozone season.

Figure 2-4 presents data from 2002 prior to application of controls by the region through the end of August 2008. The 4th maximum 8-hour ozone value time series at monitors still projecting values between 82 and 87 ppb in the modeling exercise (i.e., NREL, Rocky Flats-N, Chatfield and Fort Collins West) are shown in Figure 2-4.

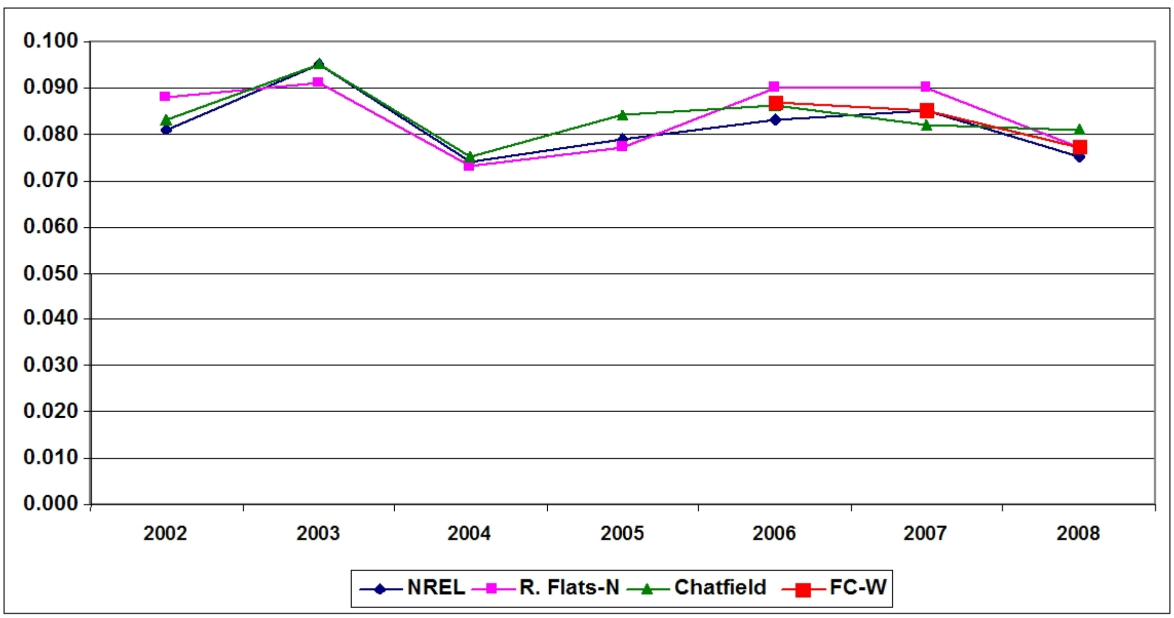

Figure 2-4: Time Series of Monitored 4th Maximum 8-Hour Ozone Values (ppm)

2.2.2 Linear Regression of Monitored 4th maximum ozone values

A linear regression analysis of the 4th high ozone concentration values between 2002 and 2008 for the Rocky Flats North monitor shown in Figure 2-5 shows what appears to be a downward trend. However, the coefficient of determination (R^2) value of the line is extremely small, and additional analysis shows that this trend does not pass a standard t-test for statistical significance. Therefore, there is not a statistically significant linear trend at Rocky Flats North during this period for 4th high values. There is too much inter-annual variation in the 4th high values at Rocky Flats North to conclude from the trend line alone that the 4th high value in future years will be above or below current levels. In addition, analyses for the monitors at Chatfield, NREL, and Fort Collins West show that there are no statistically significant trends in 4th high values at these sites. Similarly, an analysis of all four sites together does not show significant or discernable trends during this period.

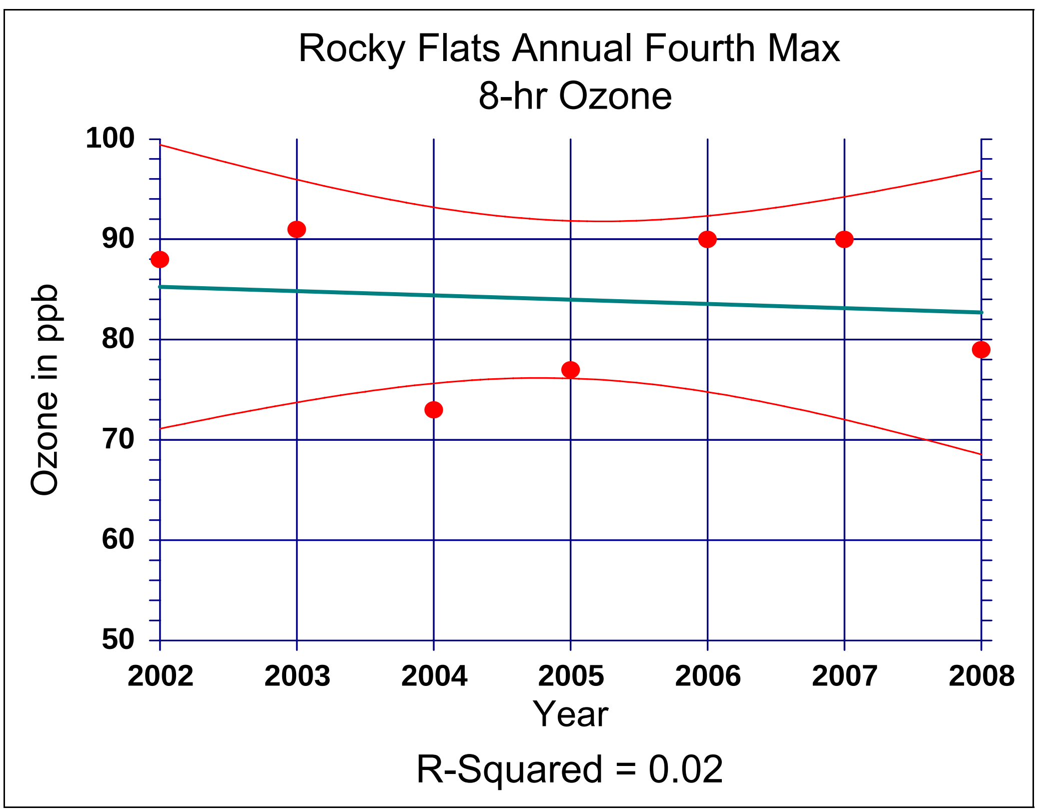

Figure 2-5: Linear Regression of Monitored 4th maximum ozone values

2.2.3 Time Series of Monitored Highest Maximum Ozone Concentrations

Figure 2-6 presents a time series of first maximum ozone concentrations at Rocky Flats-N, Chatfield, National Renewable Energy Laboratory, and Fort Collins West from 2002 through 2008. As shown in Figure 2-6, there is no discernable trend in the first maximum ozone concentration values at these monitoring sites. There is too much inter-annual variation in the 1st high values to conclude that the 1st high values in future years will be above or below current levels.

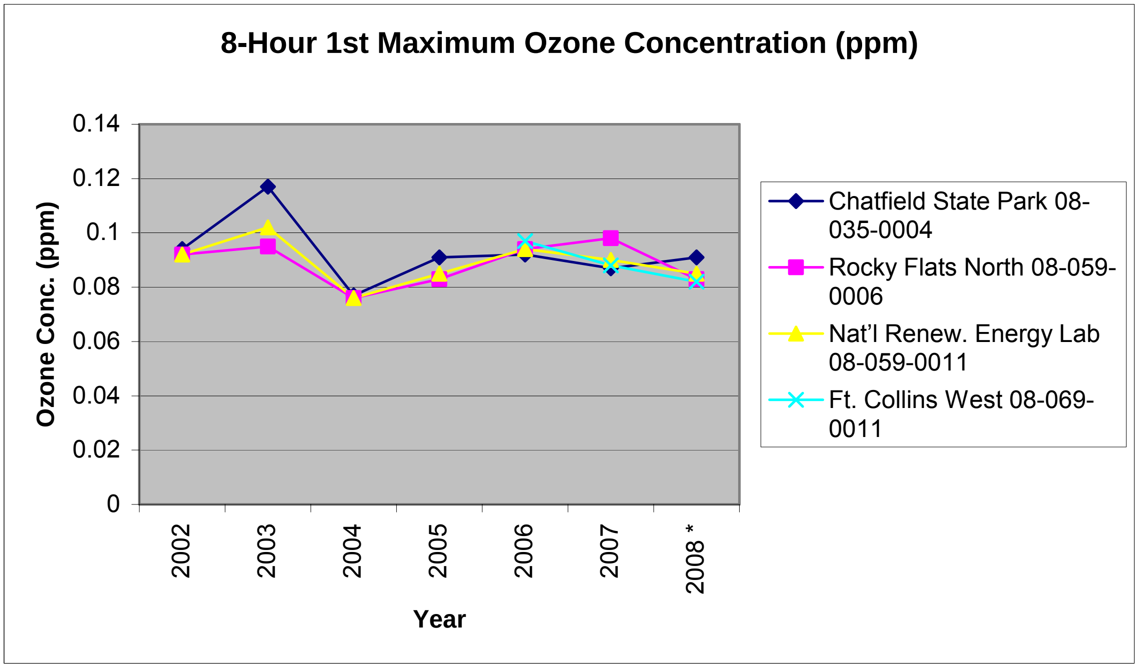

Figure 2-6: First Maximum Ozone Concentrations at Rocky Flats-N (RFN), Chatfield (CHAT), National Renewable Energy Laboratory (NREL) and Fort Collins West (FTCW) [Note: Data for 2008 are preliminary.]

2.2.4 Trend in Days greater than 75 ppb and 84 ppb

Figure 2-7 presents data from the 2000 ozone season through August 31 of the current 2008 peak ozone season. The data presents days during the ozone seasons when there was a reading at any monitor in the region greater than 75 ppb and greater than or equal to 85 ppb. Excluding the year, 2004, the years 2005 through 2008 show a reduction in the number of total days of elevated ozone when compared with the years 2000 through 2003.

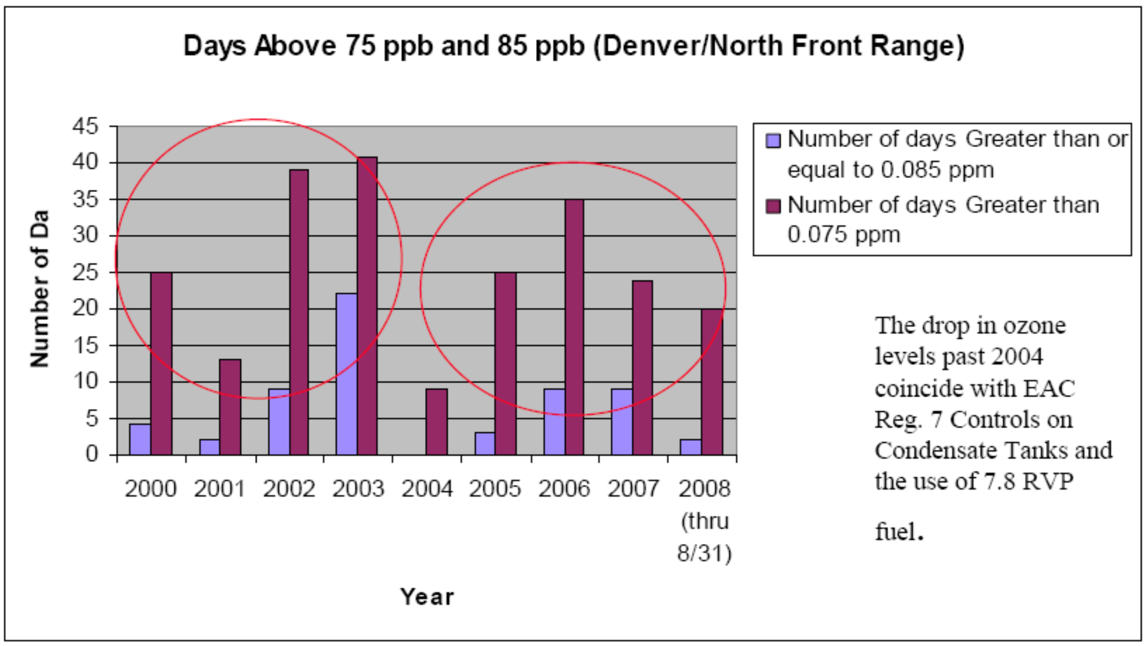

Figure 2-7: Days with 8-hour ozone greater than 75 ppb and greater than or equal to 85 ppb

2.2.5 Trends in Three Year Design Values

Figure 2-8 presents a plot of the design value days, which are defined as the 3-year average of the fourth high concentration at each monitor. Similar to the analysis of fourth high concentrations, there is not a statistically significant linear trend at Rocky Flats North, NREL, or Chatfield. There is too much inter-annual variation in the design values at the sensitive monitoring sites to conclude from this graph alone that the design values in future years will be above or below current levels.

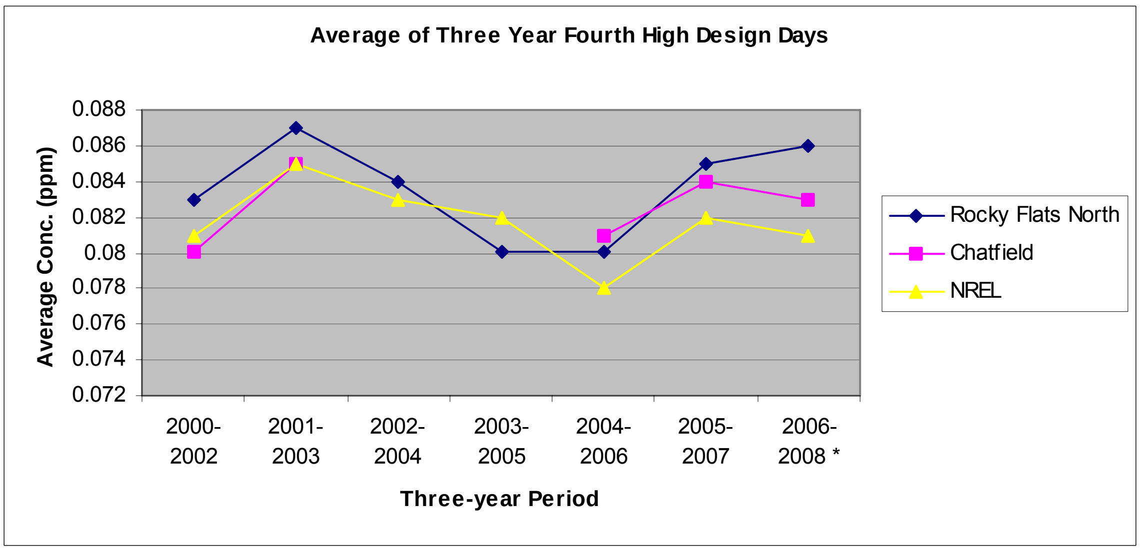

Figure 2-8: Design Value Days (Three Year Average of the Fourth High Concentration)

2.3 Weather-Corrected Ozone Time Series

A variety of ozone trend-decomposition or filtering methods can be used to remove the effects of meteorology from an ozone time series. This filtering or decomposition can make it possible to see the effects of changes in emissions in relative isolation from many of the meteorological factors that also affect ozone concentrations. For the Early Action Compact of 2004 (Colorado Department of Public Health and Environment, 2004), the Zurbenko-Rao method (Porter et al., 1996; Eskridge et al., 1997; Rao et al., 1997) was used to cleanly separate ozone time series into distinct short and long-term components. Since 2004, the Division has developed a new method of correcting ozone time series for weather for monitoring sites along the Front Range.

For summer months, monthly mean 500-millibar heights are a measure of the mean strength of upper level high pressure systems that strongly affect weather in Colorado. Monthly mean 500-millibar heights are an excellent predictor of monthly mean daily maximum 8-hour ozone concentrations. July monthly mean daily maximum 8-hour ozone is more strongly correlated with 500-millibar heights than a host of other logical choices for significant predictors of ozone, including mean surface temperatures, mean temperatures aloft, winds aloft, cloud cover, solar radiation, and number of days with temperatures above 90 degrees. While annual fourth maximum 8-hour ozone concentrations can occur in any of the months of summer, it turns out that the mean July 500-millibar height over Denver is one of the single best predictors for this value at sites along the Front Range Urban Corridor. The predictive power of mean August and June meteorological variables and meteorological data for shorter averaging times (e.g., daily, weekly, etc.) is substantially lower.

Figure 2-9 through Figure 2-11 show the relationship between July monthly mean daily maximum 8-hour ozone concentrations and July monthly mean 500-millibar heights at Rocky Flats North, NREL, and Chatfield Reservoir, three of the four key ozone monitors identified in the SIP modeling (there are not enough years of data for a similar analysis for the fourth key site, Fort Collins West.) The 500-millibar height data are from the National Center for Environmental Prediction (NCEP) Reanalysis data set (Kalnay et al., 1996; and NOAA/OAR/ESRL PSD, 2008). These data are calculated for grid cells with dimensions of 2.5 degrees latitude by 2.5 degrees longitude. The grid cell with data having the highest predictive power for the Front Range extends from near Colorado Springs, north to near Cheyenne Wyoming, and from Denver west to near Glenwood Springs (essentially the northern Front Range and north central mountains of Colorado). Data from the grid cell immediately to the east, which covers much of the urban corridor and the northeast plains, had slightly weaker correlations with mean ozone concentrations.

Figure 2-9 through Figure 2-11 also show the linear regression between July mean daily maximum 8-hour ozone and July mean 500-millibar heights, the confidence intervals for the regression line, and the coefficient of determination or R-squared value for the regression. The R-squared describes the fraction of the variance, or fraction of the year-to-year variation, that can be explained by mean 500-millibar heights. This coefficient ranges from 0.66 to 0.88 for these three sites, suggesting that 66% to 88% of the year-to-year variation in July mean daily maximum ozone at these sites can be explained by changes in July mean 500-millibar heights.

Table 2-1 lists regression statistics for 9 Front Range ozone monitors. The trend for increasing ozone with increasing high-pressure strength is statistically significant for all sites but Welby, which may be disconnected from the influence of heights because of the effects of local NOx sources and/or local flow regimes. R-squared values for sites with statistical significance range from 0.46 to 0.88. Welch was not included because of an apparent local anomaly that may have been caused by facility activities at the Colorado Department of Transportation workstation where it is located. Highlands Ranch was not included because it was shut down in June of 2008.

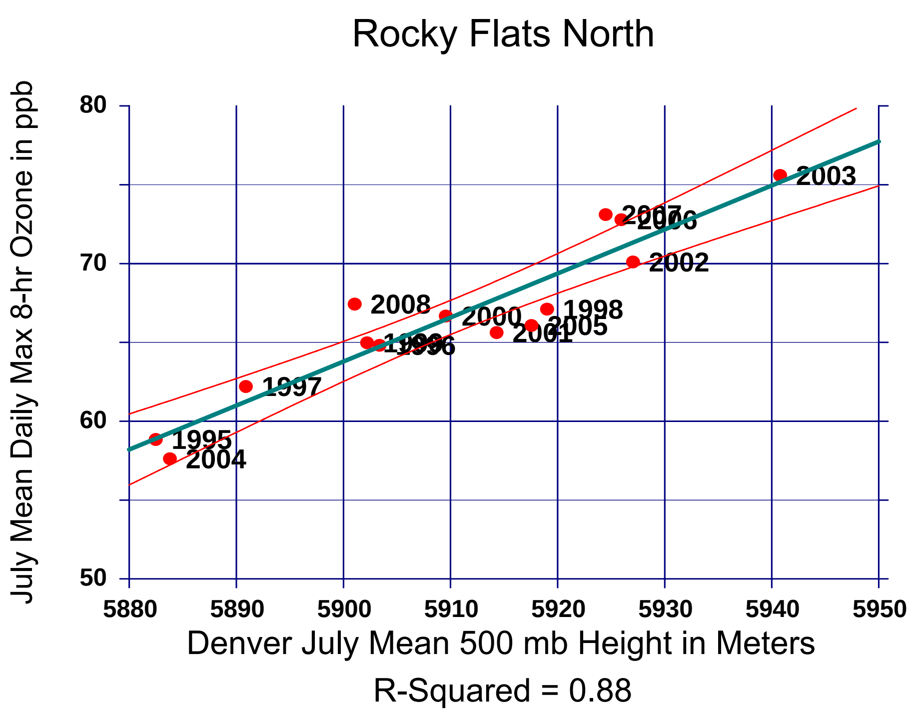

Figure 2-9: Linear regression between July monthly mean daily maximum 8-hour ozone and July monthly mean 500-millibar heights at Rocky Flats North.

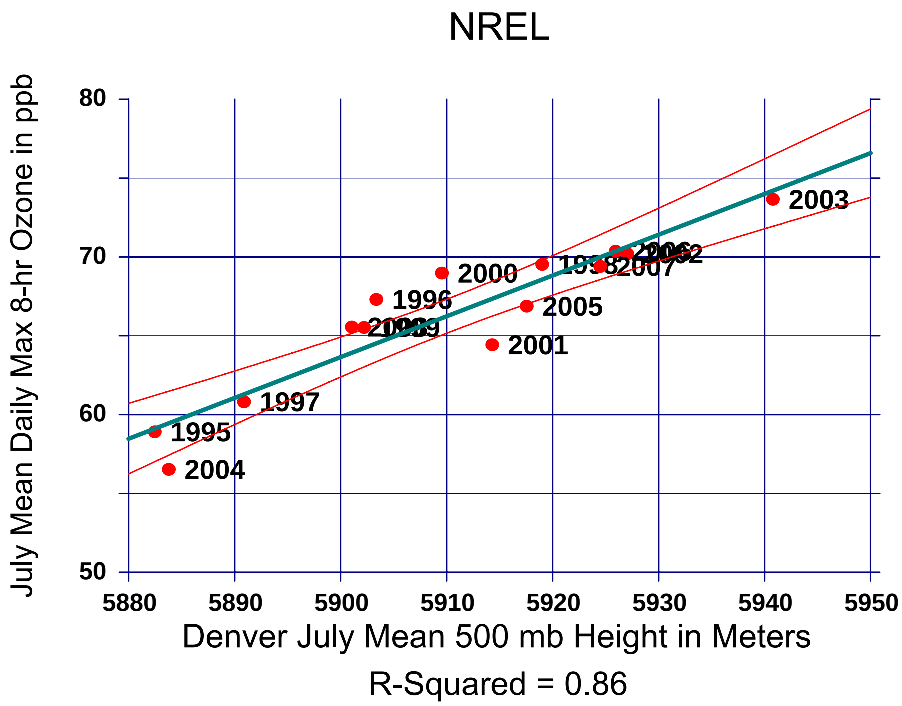

Figure 2-10: Linear regression between July monthly mean daily maximum 8-hour ozone and July monthly mean 500-millibar heights at NREL.

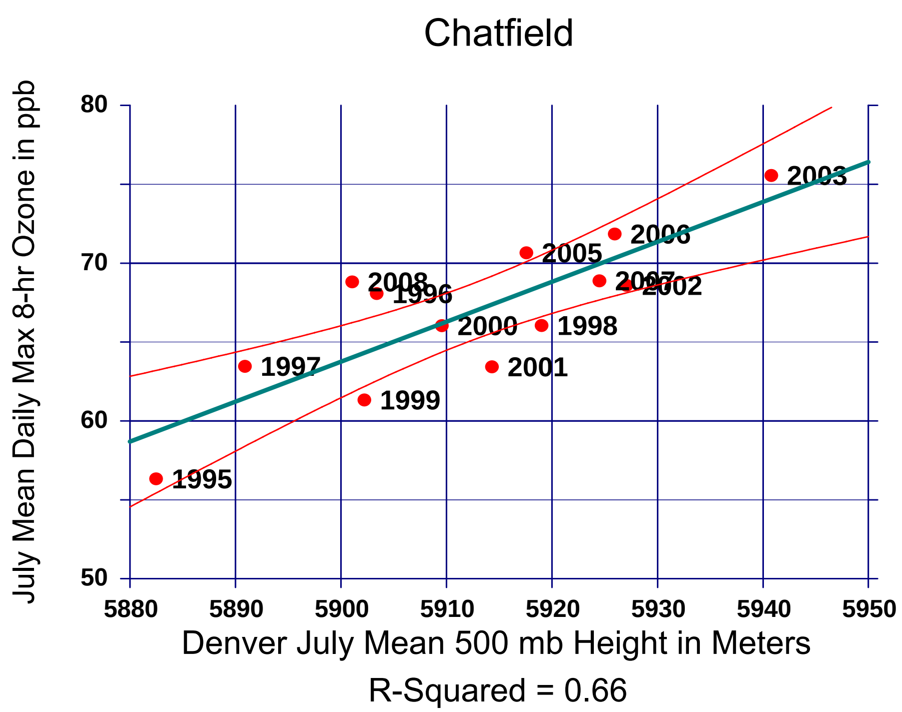

Figure 2-11: Linear regression between July monthly mean daily maximum 8-hour ozone and July monthly mean 500-millibar heights at Chatfield Reservoir.

Table 2-1: Linear Regression Statistics for the Relationship between July Mean Daily Maximum 8-hour Ozone Concentrations and July Mean 500-millibar Heights

Monitoring Site	Slope	R-Squared Value	Passed t-test for Statistical Significance	Period Used in Regression
Arvada	0.278	0.62	Yes	1995-2008
Chatfield	0.351	0.66	Yes	1995-2008
Carriage	0.271	0.84	Yes	1995-2008
Fort Collins	0.188	0.46	Yes	1988-2008
Greeley/Weld County Tower	0.227	0.65	Yes	1988-2008
NREL	0.259	0.86	Yes	1995-2008
Rocky Flats North	0.279	0.88	Yes	1995-2008
South Boulder Creek	0.277	0.67	Yes	1995-2008
Welby	0.049	0.02	No	1995-2008

Figure 2-12 through Figure 2-14 show the relationship between annual 4th maximum 8-hour ozone concentrations and July monthly mean 500-millibar heights at Rocky Flats North, NREL, and Chatfield Reservoir. R-squared values for these monitors range from 0.52 to 0.77. This suggests that 52% to 77% of the year-to-year variation in annual 4th maximum values can be explained by changes in July mean 500-millibar heights. Table 2-2 shows the linear regression statistics for the same 9 Front Range monitors described above. Regression lines show significance for all sites but Welby. Welch and Highlands Ranch were excluded from the analysis for reasons already discussed. R-squared values for sites with statistical significance range from 0.47 to 0.77.

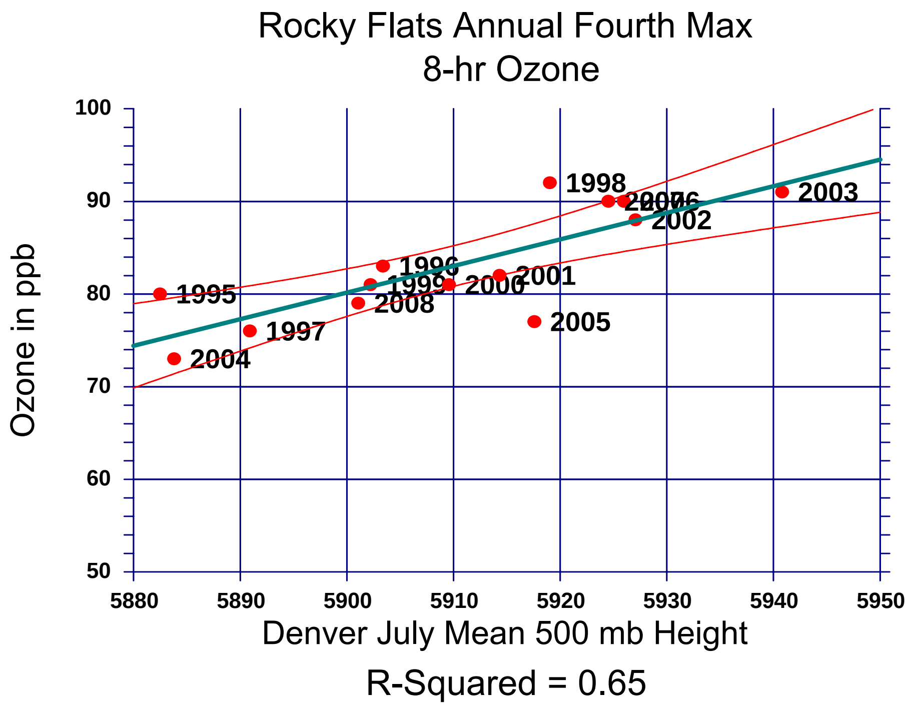

Figure 2-12: Linear regression between annual 4th maximum 8-hour ozone and July monthly mean 500-millibar heights at Rocky Flats North.

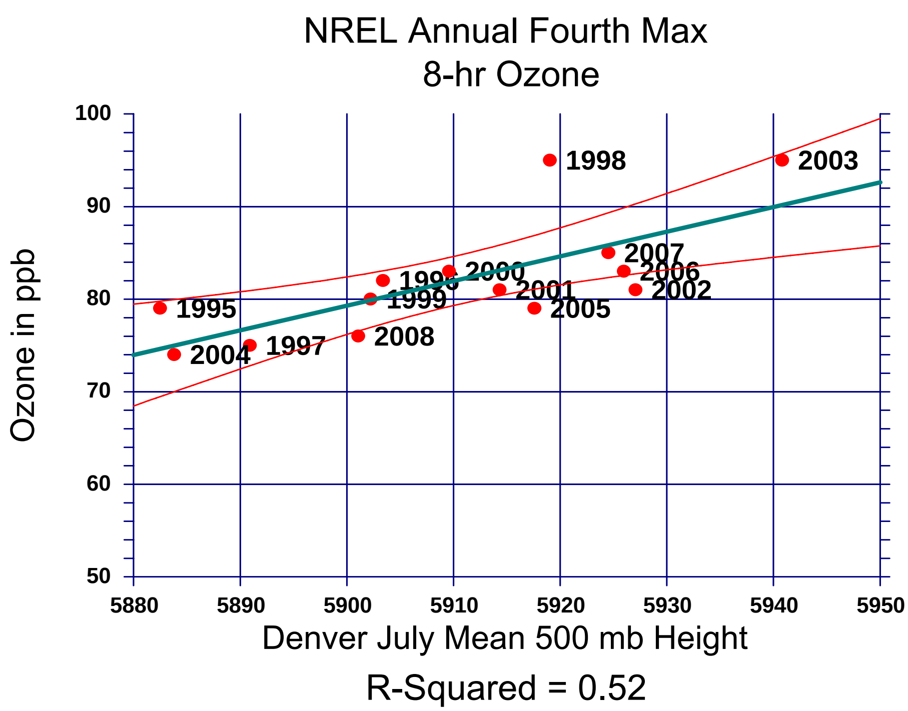

Figure 2-13: Linear regression between annual 4th maximum 8-hour ozone and July monthly mean 500-millibar heights at NREL.

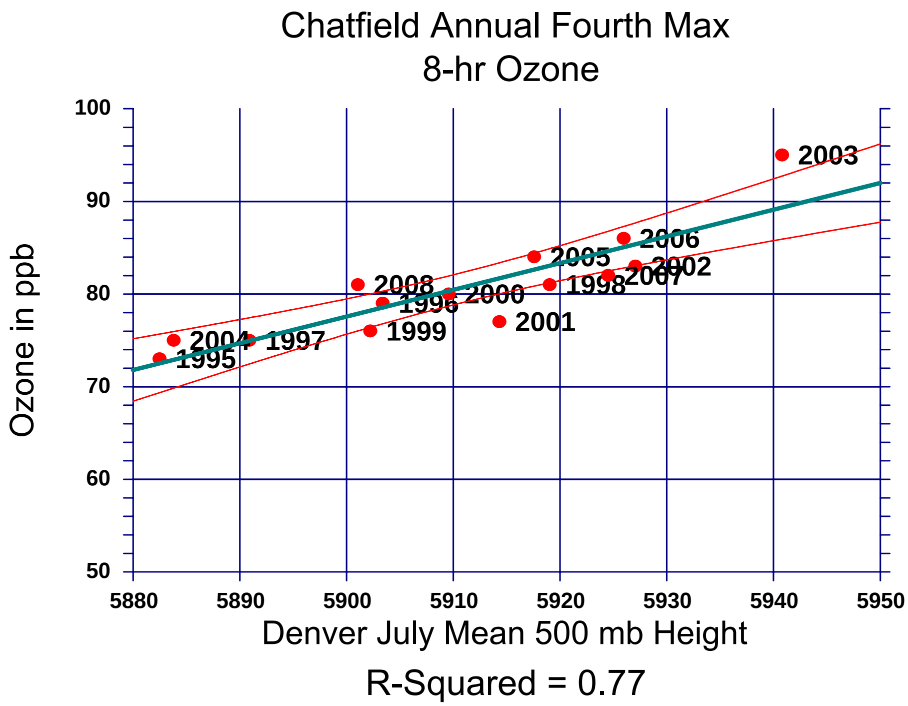

Figure 2-14:Linear regression between annual 4th maximum 8-hour ozone and July monthly mean 500-millibar heights at Chatfield Reservoir.

Table 2-2: Linear Regression Statistics for the Relationship between Annual 4th Maximum 8-hour Ozone Concentrations and July Mean 500-millibar Heights

Monitoring Site	Slope	R-Squared Value	Passed t-test for Statistical Significance	Period Used in Regression
Arvada	0.269	0.57	Yes	1995-2008
Chatfield	0.288	0.77	Yes	1995-2008
Carriage	0.269	0.59	Yes	1995-2008
Fort Collins	0.212	0.60	Yes	1995-2008
Greeley/Weld County Tower	0.235	0.67	Yes	1995-2008
NREL	0.267	0.52	Yes	1995-2008
Rocky Flats North	0.287	0.65	Yes	1995-2008
South Boulder Creek	0.232	0.47	Yes	1995-2008
Welby	-0.025	0.01	No	1995-2008

The correspondence between 500-millibar heights and ozone can be used to correct ozone time series for the effects of weather. The differences between the linear regression concentrations and the actual concentrations (the differences are the residuals) can be plotted by year to show weather-corrected trends in ozone. These corrected trends or time series are much more likely to show the effects of changes in emissions than the uncorrected time series.

The trend in weather-corrected July mean daily max 8-hour ozone for Fort Collins and Greeley is shown in Figure 2-15 (with a simple cubic spline smoother applied). A continuous increase in ozone from the late 1990s through 2005 may be the result of local growth and increases in oil and gas emissions. A sudden drop from 2005 through 2007 may be the result of reductions in area oil and gas emissions. The increase in 2008 will be discussed below.

A similar analysis for Rocky Flats, NREL, Chatfield, Carriage, South Boulder Creek, and Arvada is shown in Figure 2-16. Gradual decreases through 2004 are replaced by apparent step increases in 2005 and 2008. The increases in 2008 in both plots suggest that there may have been an increase in background concentrations across all of the Front Range, with a magnitude of about 4 ppb. Many factors may have contributed to this increase, and it is not possible to complete a thorough analysis of the causes within the timeframe of this SIP. It is possible that widespread smoke-enhanced ozone from fires on the West Coast, nation-wide reductions in vehicle miles traveled (VMT, Colorado VMT values declined about 4% in June of 2008 compared with June of 2007, see Federal Highway Administration, 2008) or other factors may have caused this apparent increase. VMT reductions may have resulted in reductions in NOx quenching of surface ozone, changes in photochemistry, or a redistribution of emissions in time and space.

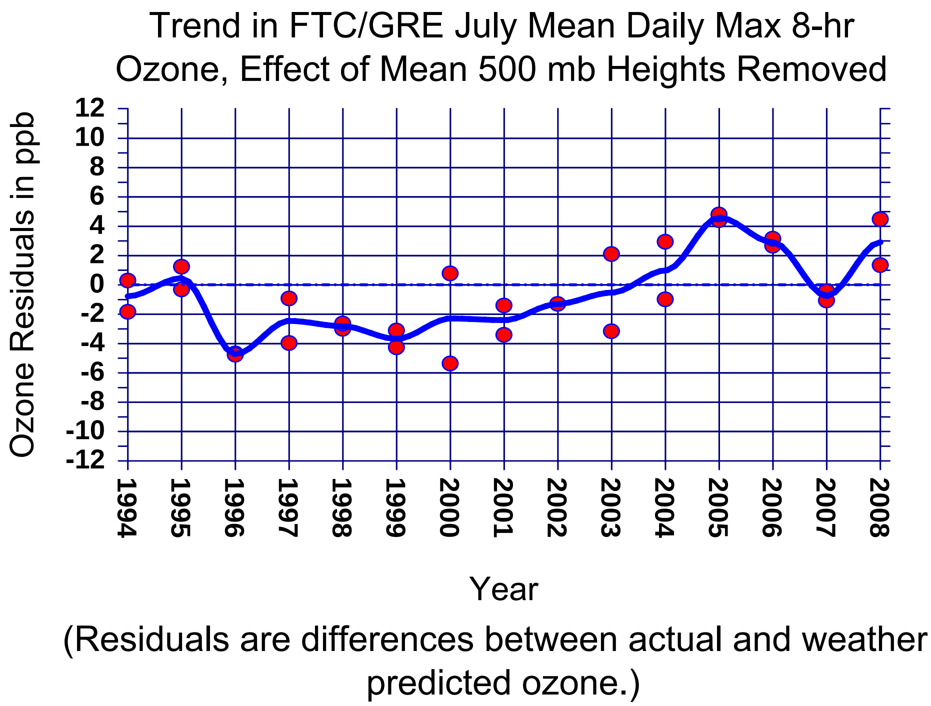

Figure 2-15: The trend in weather-corrected July mean daily max 8-hour ozone for Fort Collins and Greeley.

Correcting all 8 of the Front Range annual fourth max time series for weather leads to the pattern shown in Figure 2-17. Here the smoothing algorithm used is a Lowess curve with 40% weighting. When smoothed in this way, the trend shows a period of decline followed by a rise and ending in a level line from 2004 through 2008. This is consistent with the idea that ozone is difficult to control but increases have ceased since 2004. In addition, the possible increase in regional background in 2008 seen in earlier plots does not appear to have had an impact on these worst-case concentrations.

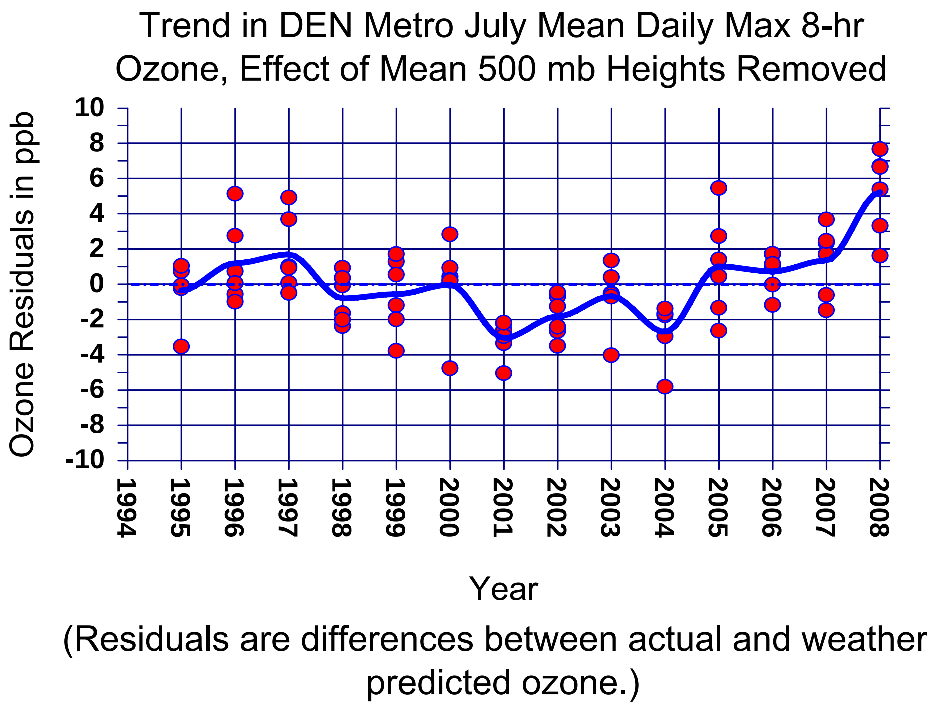

Figure 2-16: The trend in weather-corrected July mean daily max 8-hour ozone for Rocky Flats, NREL, Chatfield, Carriage, South Boulder Creek, and Arvada.

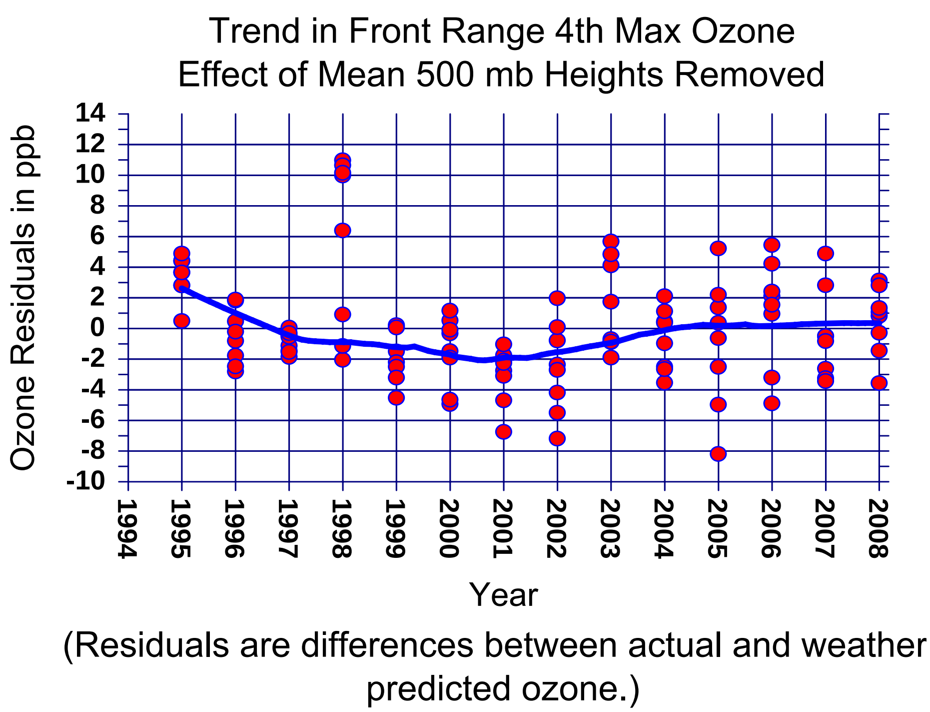

Figure 2-17: The trend in weather-corrected annual 4^{th} maximum 8-hour ozone for Rocky Flats, NREL, Chatfield, Carriage, South Boulder Creek, Arvada, Fort Collins, and Greeley.

Why are ozone concentrations along the Front Range so highly correlated with July mean 500-millibar heights? Increased heights are associated with strong regional upper level high pressure systems. Strong regional upper level high pressure systems lead to light winds at the surface and aloft, decreased cloud cover and storms, increased temperatures at the surface and aloft, an enhancement of the local thermally driven circulations that tend to keep ozone and its precursors in the area, and a greater likelihood that ozone and its precursors will accumulate in regional circulation patterns. Recent research highlights the role of upper level high pressure systems in the accumulation of ozone aloft (Cooper, Owen, et al. 2006, Cooper, Owen, et al. 2007). Because of deep vertical mixing during the afternoon over most of the state, this ozone aloft affects ground level concentrations, and ozone at ground level is ultimately mixed vertically into the upper level high. The Air Pollution Control Division believes that persistent upper level high pressure over Colorado in mid summer increases background concentrations, providing an increase in both mean and worst-case ozone concentrations.

Since upper level high pressure systems have such a strong effect on ozone, it is important to consider recent trends in upper level high pressure strength. Time series for 500-millibar heights presented in Figure 2-18 and Figure 2-19 show that a long period of increases has recently shifted to a leveling off or perhaps a decline since 2004. A Lowess curve with 40% weighting has been applied to the heights data in Figure 2-18 Climate change or “natural” patterns of drought and heat may alter this trend in the future, but there would appear to be a reasonable chance for relatively stable or declining heights through 2010. A continued cessation in rapid increases in heights would help the area reach attainment by 2010.

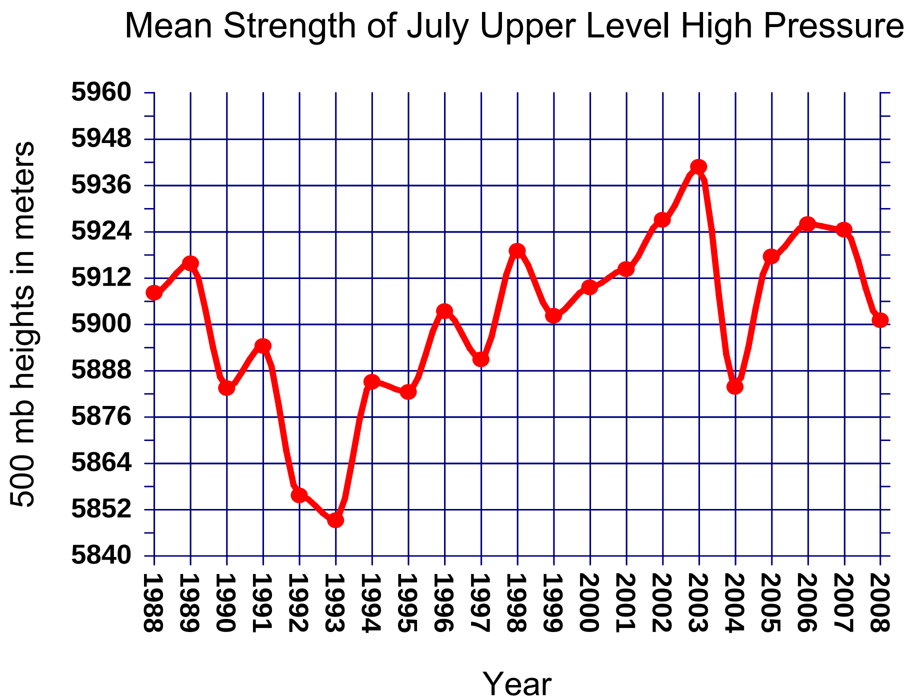

Figure 2-18:Trends in the mean strength of the upper level high pressure or 500-millibar heights for the Denver-area NCEP Reanalysis data.

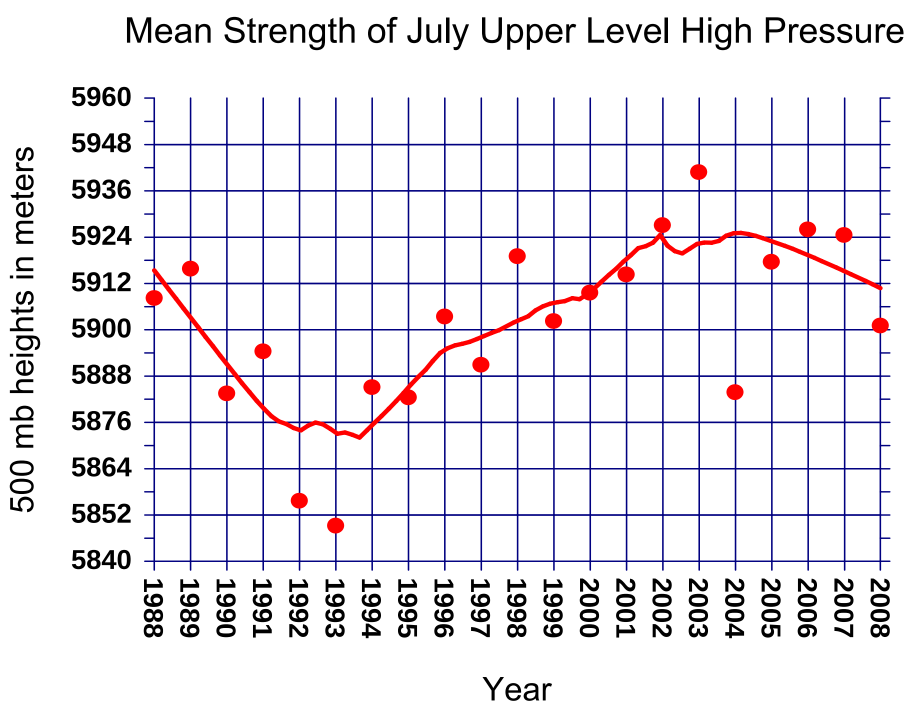

Figure 2-19: Trends in the mean strength of the upper level high pressure or 500-millibar heights for the Denver-area NCEP Reanalysis data, with Lowess trend curve at 40% weighting.

2.4 Trends in the Weekend-Weekday Effect

Lawson (2003) reports that research conducted for the LA Basin and other urban areas shows a significant increase in ozone on weekend days compared with weekdays. This is known as the weekend effect. For the LA Basin study he reports that "Hypothesis testing using empirical observations, data analysis, and different modeling approaches suggested that decreased weekend NOx emissions, resulting mostly from fewer trucks on the roads on weekends, was the largest single contributor to elevated weekend ozone…" Lawson says that the weekend effect offers us a real world analogue of a NOx control strategy experiment. Lawson suggests that the existence of the weekend effect is evidence that an area is VOC limited. Scientists have identified a number of hypotheses for the causes of the weekend effect and what the implications of these are for emissions control strategies (Croes et al., 2003). While these include changes in the timing of NOx emissions on weekends and changes in VOC to NOx ratios on weekends, a recent study suggests that the weekend effect may, in large part, be due a reduction in near surface NOx titration on weekends (Murphy et al., 2006). NOx titration can be described as follows: Nitric Oxide or NO is emitted by mobile sources and other surface sources, and quickly reacts with ozone to reduce concentrations in that portion of the atmosphere near the surface.

The effect of NOx titration and its relative importance in various environments along the Front Range is illustrated in Figure 2-20. Mean hourly ozone concentrations for July 11 through 31, 2008, are plotted for five monitors. Data for four monitor locations have been provided by the NOAA Earth Systems Research Laboratory Global Monitoring Division (NOAA ESRL GMD) (Oltmans and Levy, 1994). Two of these were sited on the NOAA research tower near Erie Colorado, near the surface and at the 300-meter level on the tower (984 feet above ground level or 6,180 feet above sea level). The Erie Tower is located within the broad Platte Valley northwest of Denver at an elevation of about 5,200 feet above sea level. The Erie Tower monitors provide a clear picture of the impacts of near-surface NOx titration on hourly ozone. Similarly, NOAA ESRL GMD data for two locations at Niwot Ridge near the Continental Divide west of Boulder show the temporal behavior of ozone at high altitude locations where the influence of the mid-atmosphere ozone reservoir is strong and NOx titration is weak. The Tundra monitor is above tree line at about 11,500 feet above sea level, and the other Niwot Ridge monitor is within a conifer forest at about 9,900 feet above sea level. Data for NREL, which shows some of the characteristics of a high altitude site and some of the impacts of NOx titration, is included. The NREL monitor is at about 6,000 feet above sea level on top of South Table Mountain, which is largely free of NOx sources, and the populated area to the south is at about 5,800 feet above sea level. The July 11 through 31, 2008, period was chosen because of the availability of data for all five monitors.

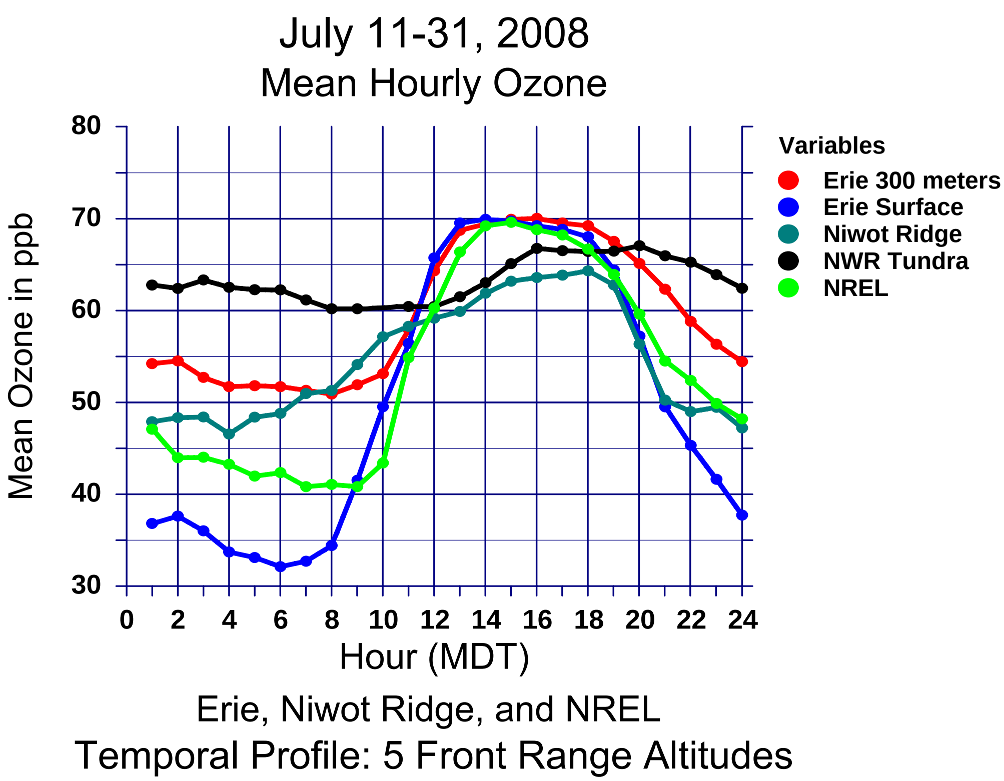

Figure 2-20: Mean hourly ozone concentrations at 5 monitoring sites (the NOAA Erie Tower surface and 300-meter levels, NREL, and NOAA's two Niwot Ridge sites) for July 11-31, 2008, showing variations in ozone by time of day and altitude.

Nighttime and morning surface inversions on the Plains trap NOx from surface sources in the atmosphere near the ground. These inversions greatly increase NOx-based destruction of ozone. Morning rush hour emissions can lead to an ozone minimum within the inversion between 4 AM and 8 AM MDT. This inversion-enhanced NOX titration is visible in the hourly data for the Erie Tower surface monitor. By mid-morning the inversion begins to transform into a deepening surface mixed layer. The surface mixed layer continues to grow until mid afternoon and can reach to 10,000 to 20,000 feet above sea level. As the mixed layer grows, the effects of NOx titration decrease, and the photochemical production of ozone leads to an increase in ozone, with peak hourly concentrations occurring between 1 PM and 7 PM MDT. The hourly ozone trace for the 300-meter level of the Erie Tower shows that NOx titration is much less important at this altitude above ground level sources. Ozone concentrations at the 300-meter level stayed at concentrations of 50 to 60 ppb throughout the nighttime and early morning hours.

Hourly average ozone for the high-altitude Niwot Ridge site within the conifer forest are similar to the values measured at 300 meters on the Erie Tower. NOx titration at this remote site is probably minimal, but ozone deposition within the forest mimics the nighttime decreases seen on the Plains. The Niwot Ridge Tundra site has a narrow diurnal range of ozone concentrations, with levels varying between 60 and 67 ppb throughout the day. The daytime peak is broad and persists through 11 PM MDT. The absence of significant NOx titration or deposition is evident.

Concentrations at the NREL monitor fall somewhere between the Erie surface and 300-meter monitors for much of the morning and evening periods. NREL is only 200 feet above significant local NOx sources, and it may show the effect of a relative lag in photochemical rate increases because of its downwind distance from Denver.

Taken together, the data for these monitors suggests that NOx titration plays a significant role in shaping diurnal patterns for ozone concentrations on the Plains and in areas that are more directly affected by ground level emissions of NOx. A preliminary analysis of weekend-weekday patterns of hourly ozone at the Erie Tower (for July 11 through August 31, 2008) highlights the influence of NOx titration on weekend-weekday differences. Figure 2-21 shows mean hourly ozone concentrations at the surface and 300 meters on weekdays and weekends. At the surface site, morning weekday ozone concentrations are much lower than on weekends because of higher rush hour emissions. Similarly, evening concentrations are higher on weekends, because of the lack of rush hour emissions. While weekend concentrations at this level are generally higher, weekday hourly values are higher during the mid afternoon.

The hourly patterns for the 300-meter level show that differences are smaller with a tendency for higher afternoon and evening concentrations on weekdays and lower morning concentrations on weekdays. Since daytime surface ozone is directly affected by the ozone contained in the large volume of the atmosphere below the afternoon mixing level, the 300-meter level data suggests that there may be no normal weekend effect in this mid-level ozone reservoir. In other words, the effect as calculated here may dampen or perhaps reverse with increased altitude.

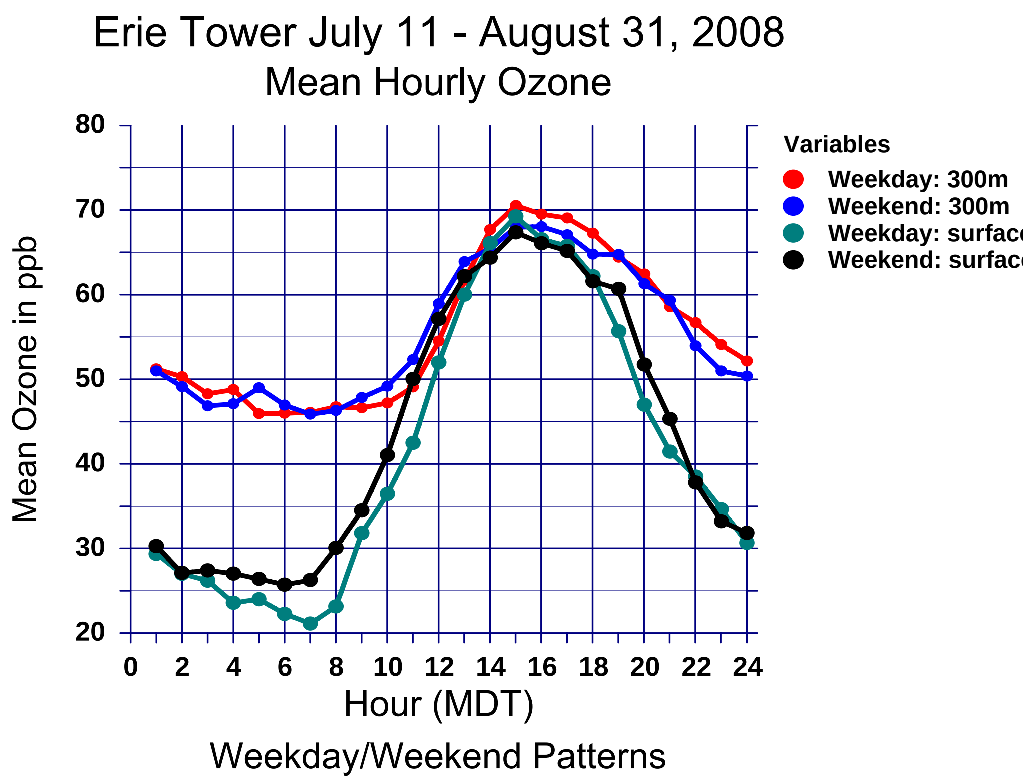

Figure 2-21: Mean hourly ozone concentrations at the NOAA Erie Tower surface and 300-meter levels showing variations by time of day, by altitude, and for weekends and weekdays (for July 1 – August 31, 2008.)

Figure 2-22 shows the differences between hourly weekend and weekday concentrations for the two Erie Tower monitors. Lowess curves with 30% weighting have been applied to the data to highlight the underlying pattern. Positive differences indicate that weekend concentrations are higher. At the surface, the weekend effect is much more pronounced, with higher morning and evening concentrations on weekends. At 300 meters, morning concentrations are generally higher on weekends, but weekday concentrations are typically higher during the afternoon and evening hours.

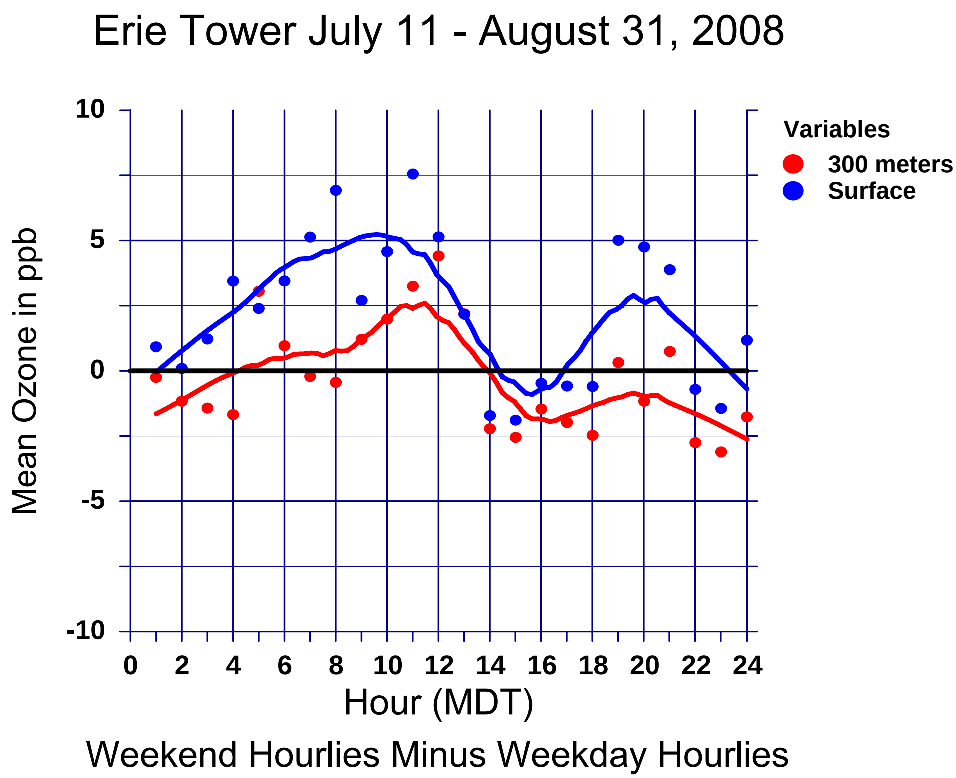

Figure 2-22: Weekend-Weekday differences in mean hourly ozone at the NOAA Erie Tower surface and 300-meter levels for July 1 – August 31, 2008, with a Lowess curves at 30% weighting.

Table 2-3 presents weekend effect data that also shows the influence of NOx titration on the weekend effect. Based on an analysis of daily maximum 8-hour ozone levels from June through August for 2005 through 2007, the mean weekend effect for this three-year period ranges from about 1% to 3% at the highest ozone sites (NREL, Chatfield, Fort Collins West, and Rocky Flats); 5% to 8% at Arvada, Carriage, Fort Collins, and Welby; and 23% at the downtown Denver CAMP monitor. Here the weekend effect is expressed as the percentage change in ozone on weekends compared with weekdays. The weekend effect clearly increases in those areas with higher densities of mobile NOx sources, and peaks in downtown Denver. The spatial distribution of the effect is mapped in Figure 2-23, and this shows that central and downtown Denver as well as downtown Ft. Collins has the strongest weekend effect. In this map, the contoured values represent the ratio of weekend concentrations to weekday concentrations. The color-scale legend is not intended to define a threshold or cutoff for NOx and VOC limitation, but rather to indicate a general tendency towards either state at opposite ends of the scale.

Table 2-3: Percent Increase in Weekend Daily Maximum 8-Hour Ozone for June through August of 2005 through 2007.

Monitoring Site	2005 Percent Weekend Difference	2006 Percent Weekend Difference	2007 Percent Weekend Difference	Mean 2005-2007 Percent Weekend Difference
Welby	2	6	6	**5**
Highlands Ranch	0	2	6	**2**
S. Boulder Creek	-1	2	6	**2**
CAMP	22	22	25	**23**
Carriage	-1	10	7	**5**
Chatfield	-2	2	3	**1**
Academy	1	-1	1	**0**
Manitou	1	-3	1	**0**
Arvada	3	5	7	**5**
Welch	2	6	7	**5**
Rocky Flats N.	0	2	6	**2**
NREL	-2	5	5	**3**
RMNP	-2	-2	-1	**-1**
Ft. Collins West		-1	4	**1**
Ft. Collins	9	4	12	**8**
Mesa Verde	-1	-2	-2	**-1**
Weld County Tower	2	-3	7	**2**
Front Range Mean	**2**	**4**	**6**	**4**

In a recent study of the weekend effect in Southern California, Blanchard et al. (2003) concluded, "Nearly all VOC-limited sites exhibited higher weekend peak O3 concentrations, whereas NOx-limited sites did not show significant differences between mean weekday and weekend peak O3 levels. Thus an interpretation of the site's responses as an indication of spatial patterns of VOC or NOx limitation was supported."

If we were to assume that this finding also applies in the Denver metro area, it follows from the logic presented by Blanchard et al. (2003) that ozone may be VOC-limited at central, urban sites in 2005 through 2007. It may be that the metro area as a whole is transitional between NOx and VOC limitation or that the high-concentration sites are

NOx limited. There is not yet enough information about the relationships between changes in weekend emissions and local photochemistry to draw definitive conclusions about the implications of this effect for NOx or VOC limitation along the Front Range. What is clear, however, is that reductions in NOx are more likely to have a disbenefit in central Denver and perhaps downtown Fort Collins, where NOx titration plays a significant role in net ozone formation during the day. This phenomenon is supported by the photochemical/dispersion modeling for this SIP, which shows a NOx reduction disbenefit in downtown Denver. A reduction in morning rush hour NOx emissions, for example, would allow ozone concentrations to increase sooner and perhaps more rapidly in areas with high densities of mobile source emissions.

Table 2-3 suggests that the weekend effect increased each year from 2005 through 2007, with annual mean Front Range differences rising from 2% to 6%. It is possible that this increase is a response to reductions in VOC emissions from oil and gas fields during the period. Reducing VOC emissions could push the area *in the direction* of VOC-limitation, and in theory this could increase the weekend effect. Other factors might be at work, however, including changes in meteorology from year to year. Since NOx titration has been shown to be a significant factor and since the magnitude of NOx titration is mediated by the strength and duration of the nighttime/morning surface inversion and afternoon mixing height, it may be that year-to-year changes in inversion and mixing depth climatology are responsible for the increases in the weekend effect. A thorough analysis of mixing height and inversion climatology for these summers is beyond the scope of this report.

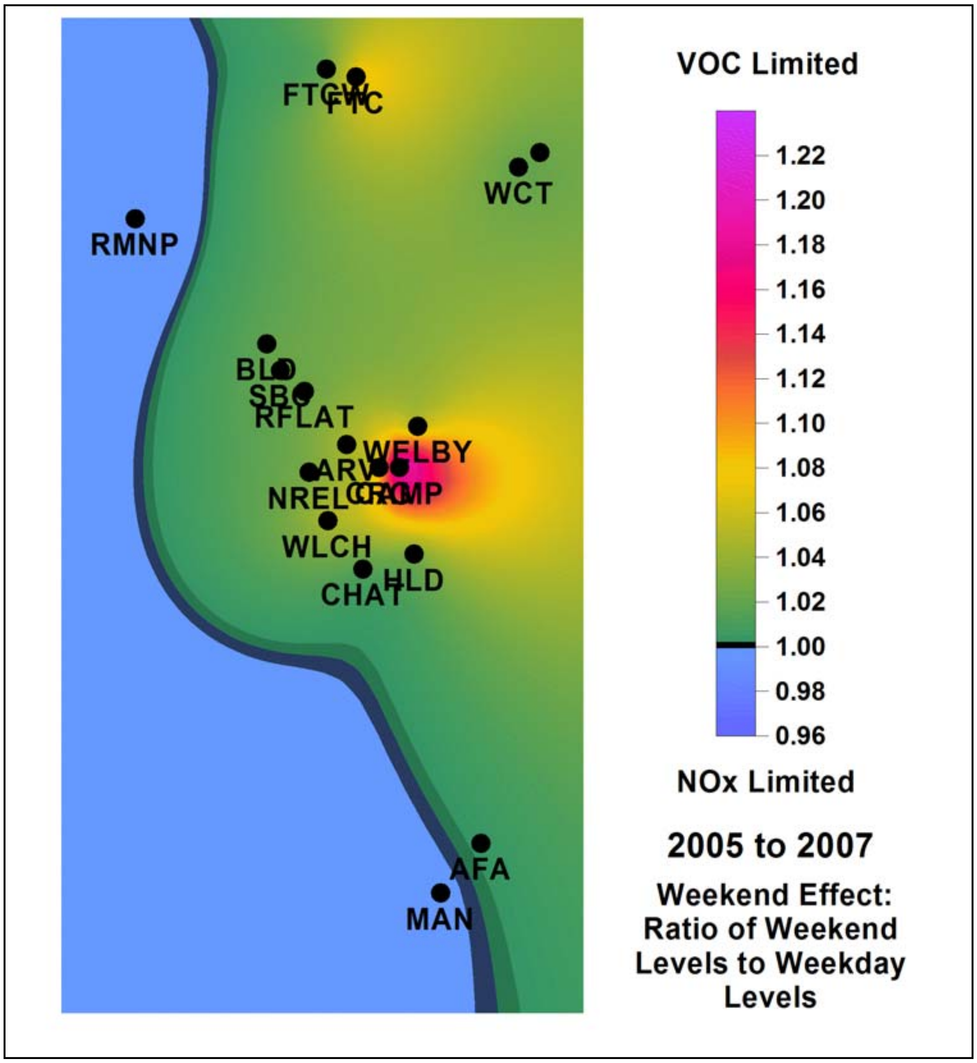

Figure 2-23: Mean ratio of daily maximum 8-hour ozone on weekends to weekdays for June through August of 2005 through 2007. The color-scale legend is not intended to define a threshold or cutoff for NOx and VOC limitation, but rather to indicate a general tendency towards either state at opposite ends of the scale

3 Review of the Ozone Conceptual Model for the 8-hour DMA/NFR NAA

EPA guidance for the development of a conceptual model defines the meteorological conditions associated with high ozone concentrations. A conceptual model of ozone formation includes the current understanding of the local meteorological conditions and associated large-scale weather patterns typically experienced during periods of elevated ozone. Local understanding of ozone formation is not only important for forecasting elevated ozone levels to protect public health, but, also to gain an understanding of the effectiveness of control strategies.

As part of the conceptual model, supporting analysis includes a review of available ambient air quality data, meteorological data, and photochemical modeling efforts. As new meteorological data and emission inventory data becomes available as well as a better understanding of the chemical processes that take place in the nonattainment area, the opportunity to review the current understanding of local ozone formation in the Denver/NFR region presents itself.

Generally, ozone is formed by a complex series of chemical reactions involving photochemical reactive Volatile Organic Compounds (VOCs) and Oxides of Nitrogen (NOx) in the presence of sunlight. In the DMA/NFR, ambient concentrations of these precursor compounds are sufficient to produce ozone as evident by an occasional exceedance of the 8-hour ozone standard of 85 ppb. However, favorable meteorological conditions are also required before high ozone concentrations are measured.

3.1 Local and Synoptic Scale Meteorology

Meteorology is the single most important factor affecting mid-summer ozone in the DMA/NFR. Light winds, a deep layer of thermally-driven upslope flow, local vertical recirculation through the actions of a Front Range Mountain-Valley circulation, cloud-free skies, and warm temperatures are key ingredients for high ozone at the surface. The Mountain Valley circulation consists of thermally-driven surface upslope flow (toward the west) to mountain top level during the afternoon, mixing and transport vertically, and weak transport to the east at higher altitudes. Vertical mixing over Denver closes this loop, keeping ozone in the area. Nighttime surface drainage along valleys allows pooling of morning emissions in lower terrain along the Platte Valley. This phase contributes to the accumulation of emissions that are later processed by the sun and the daytime mountain-valley circulation during the afternoon.

Pollutants emitted during the day mix upwards and accumulate in that portion of the atmosphere that eventually becomes isolated from the nighttime inversion layer. In addition, elevated point sources release pollutants above the inversion layer at night. These pollutants are transported aloft by mid-level winds. In the morning, under strong insolation, surface temperatures rise rapidly, forming a mixed layer that brings pollutants, transported or stored aloft during the night, to the surface.

High ozone levels along the Front Range are significantly affected by upper air transport and the retention of ozone aloft during the nighttime hours. The ozone aloft is subsequently incorporated into the surface boundary layer during the day. Research by National Oceanic and Atmospheric Administration (NOAA) scientists and APCD staff indicate a retention and buildup of ozone in the upper portion of the troposphere (the atmosphere below the stratosphere.) Ozone increases in the atmosphere above the nighttime boundary layer can be as large as 20 – 40 ppb.

A key synoptic factor is the multi-day mean 500-millibar height in the area, which is the mean strength of the synoptic-scale regional upper level high-pressure system. Since the 500-millibar height is directly related to the mean temperature of the column of air below about 18,000 feet, it can have a direct effect on the magnitude of regional background concentrations. Warm temperatures throughout this layer are a typical prerequisite for high ozone concentrations. Higher 500-millibar heights are also associated with weaker westerlies and a lower incidence of thunderstorms and can lead to the stagnation and re-circulating of ozone and its precursors in the Four Corners states. This stagnation and re-circulation, and the retention of ozone in the mid levels from one day to the next, can lead to a regional build up an ozone base or background. Monthly mean 500-millibar heights are an excellent predictor of monthly mean daily maximum 8-hour ozone concentrations. July monthly mean daily maximum 8-hour ozone is more strongly correlated with 500-millibar heights than a host of other logical choices for significant predictors of ozone, including mean surface temperatures, mean temperatures aloft, winds aloft, cloud cover, solar radiation, and number of days with temperatures above 90 degrees. While annual fourth maximum 8-hour ozone concentrations can occur in any of the months of summer, it turns out the mean July 500-millibar height over Denver is one of the single best predictor for this value at sites along the Front Range urban corridor.

3.2 Back Trajectory Analyses for the 2006 Ozone Episodes and Ozone Season

Back trajectory calculations for 8-hour ozone exceedance events at worst-case monitors are recommended as part of the WOE attainment demonstration and to support the understanding of an area's conceptual model. Back trajectories can also provide additional evidence that the behavior of the photochemical dispersion model is reasonable and are useful tools for understanding the relative influence of source areas within the region.

Back trajectories were estimated for each episode by using the NOAA Air Resources Laboratory (ARL) Hybrid Single Particle Lagrangian Integrated Trajectory Model (HYSPLIT, see: http://www.arl.noaa.gov/ss/models/hysplit.html). HYSPLIT uses meteorological model data from the National Centers for Environmental Prediction (NCEP). Trajectories for the June-July 2006 period were modeled using the three-dimensional wind fields provided by the Eta Data Assimilation System (EDAS). The EDAS datasets archived by ARL are based on 3-hour data over a 40-km horizontal grid (EDAS40). EDAS40 is a reanalysis system based on Eta model simulations heavily weighted by a very large collection of surface and upper air observations. HYSPLIT further resolves EDAS40 output into a much finer grid space. Although subject to wind field estimation errors in complex terrain, HYSPLIT with EDAS40 input has been observed to perform well in a variety Air Pollution Control Division analyses. HYSPLIT windfields will sometimes miss the thermally-driven upslope flows along the Front Range, but catch these flows surprisingly well for many episodes.

Back trajectories were calculated for the Rocky Flat North (RFN) and Fort Collins West (FTCW) sites. RFN and FTCW are both high-concentration monitors. Back trajectories for RFN can show the influence of sources within the Denver metro area and the Platte

Valley. Back trajectories for FTCW can show the influence of sources within the Platte Valley, local emissions, and the Denver metro area. FTCW trajectories can vary significantly from those calculated for RFN. Taken together, these sites are fairly representative of the temporal and spatial variability of windfields and source region influences across the Front Range for a given episode.

Composite 48-hour back trajectories were generated for each day of three ozone episodes during the photochemical model base year of 2006. These episodes coincide with periods modeled with the CAMx photochemical model. These three episodes represent three distinct meteorological regimes when high ozone concentrations were modeled in the DMA//NFR. The EPA recommends that various meteorological conditions be modeled for the attainment demonstration in order to estimate the benefit of the various control strategies. The back trajectory analysis demonstrates that the two-month period of June-July 2006 contains a variety of meteorological regimes with elevated ozone ensuring a more representative analysis of the control strategy packages in this SIP.

Back trajectories were developed for three ozone episodes in 2006:

- June 17-19, 2006
- July 13-15, 2006
- July 27-29, 2006

Substantial transport of regional background ozone and precursor compounds contributes to elevated ozone levels along the northern Front Range during most high ozone episodes. The potential effects of long-range transport and local sources were investigated by calculating 48-hour HYSPLIT back-trajectories for each of the days in the three high ozone episodes in 2006. Trajectories arrived at each monitor location at 4:00 PM MDT, a time that approximates the midpoint for periods of elevated concentrations on most episode days. Composite back trajectories were generated and these include three arrival heights: 10 meters, 100 meters and 1000 meters. Analysis for a variety of arrival height levels makes it possible to assess the transport of low-level air parcels into the area as well as air parcels aloft. It also provides an indication of the level of wind shear in the atmosphere as well as the presence of absence of decoupled air masses.

Day-specific trajectories for each episode were also estimated for the 5:00 AM through 5:00 PM MDT period. Daily back trajectories were calculated using 10 meters as the arrival height.   The day specific trajectory analyses consist of four trajectories, each starting at 5 AM and arriving at 8 AM, 11 AM, 2 PM and 5 PM with 1-hour interval markers.

3.2.1 Trajectory Analysis June 17-19, 2006

Figure 3-1 shows that, during the 48-hours proceeding June 17 and 18, the air mass source was generally from the west and northwest. Transport distances were also substantial, suggesting that there was limited potential for stagnation and an increased potential for good dispersion. On June 19 when the highest monitored concentrations were measured, the air mass source was in the eastern plains of Colorado. Transport distances were minimal, suggesting an increased potential for stagnation and limited dispersion. On June 19, a thermally driven upslope condition occurred over the Platte Valley and the Front Range, and this is consistent with the conceptual model for high-ozone events. Upslope occurred at each of the three arrival heights for both sites, and the 6 PM MDT Denver sounding showed that the top of the mixed layer was at about 19,000 feet above sea level. This would indicate that there was deep mixing of the atmosphere sufficient to mix any aged air mass aloft down to the surface. This day was representative of two processes described in the conceptual model where upslope involves local sources and deep vertical mixing is important in ozone formation and accumulation in the non-attainment area.

High ozone concentrations were monitored at RFN (94 ppb), FTCW (87 ppb) and SBC (87 ppb) on June 19. The 94 ppb ozone recorded at RFN was the highest monitored concentration at that site in 2006. On June 17 and 18, area-wide ozone concentrations were about 60-80 ppb over the entire network.

Back trajectories in Figure 3-2 show that the local scale transport was generally from the eastern plains of Colorado towards the RFN and FTCW monitors. Thermally driven upslope flow would have transported precursors from the Platte Valley in Weld County to FTCW and precursors from the Denver area to RFN. Local control strategies would be expected to have a more significant impact under conditions found on this day.

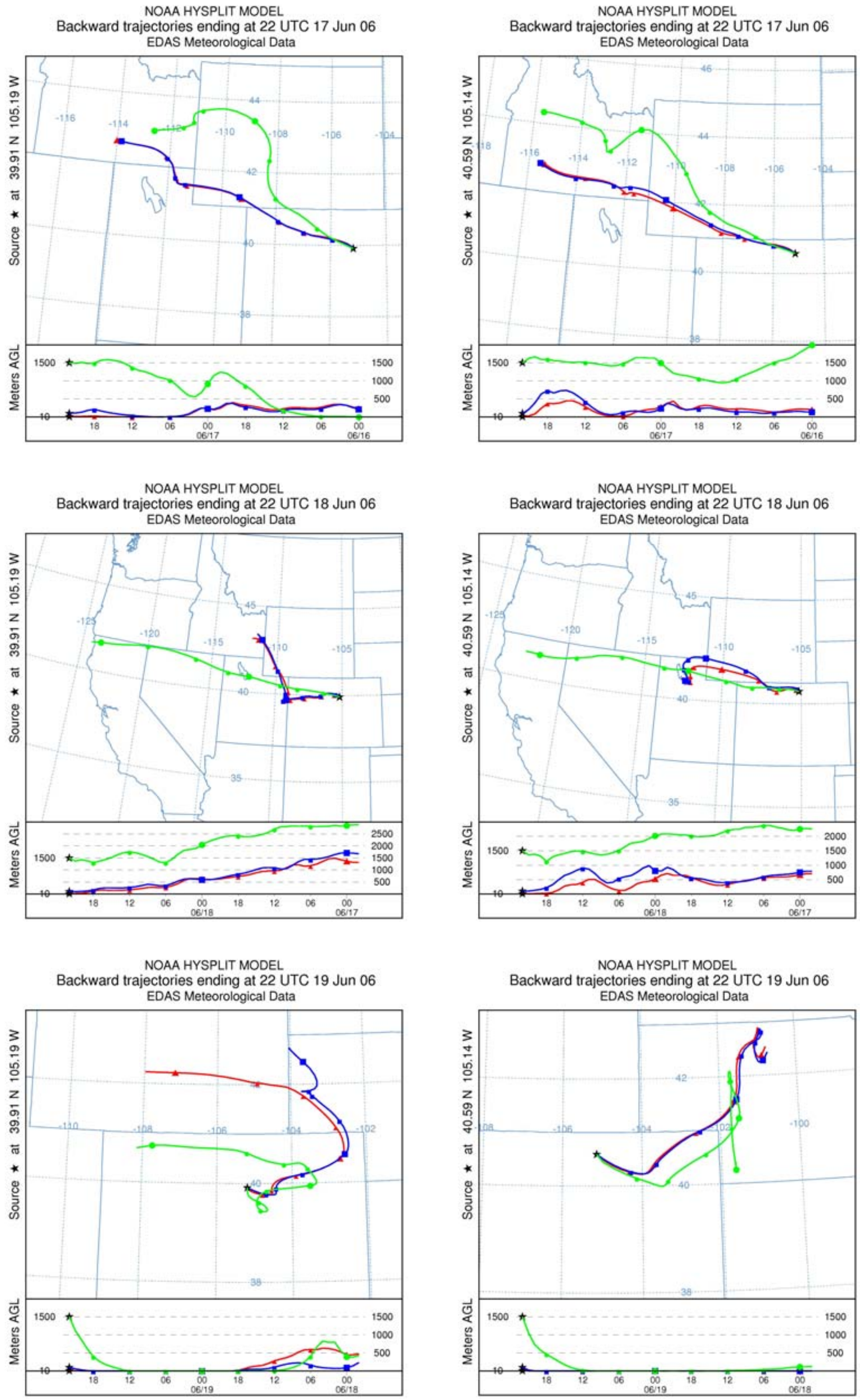

Figure 3-1: HYSPLIT 48-hour back trajectories for 10 (red), 100 (blue), and 1000 (green) meter elevations for June 17-19, 2006, at RFN (left) and FTCW (right), 6-hour interval markers, 4 PM MDT.

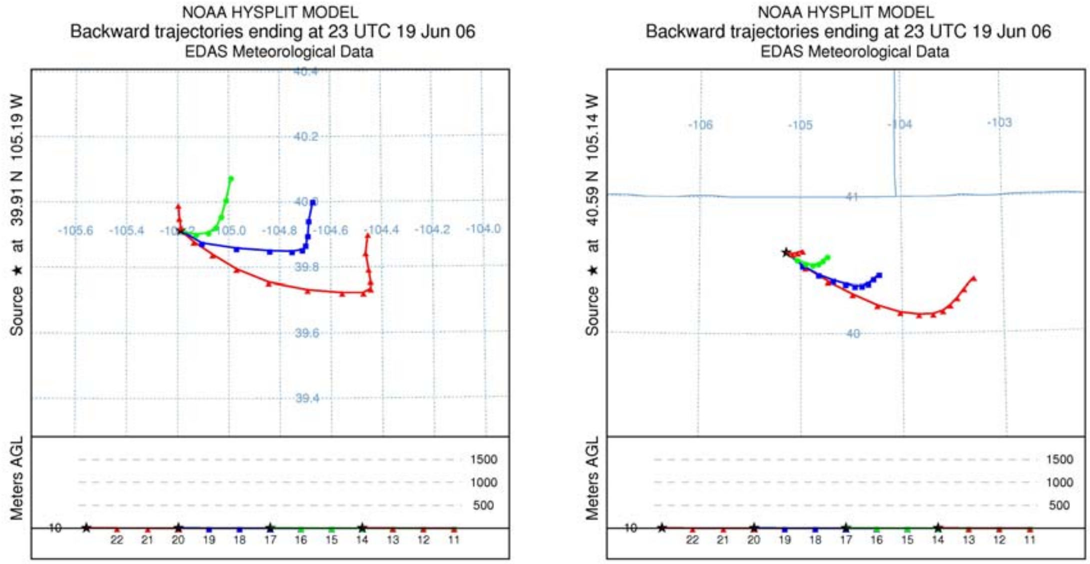

Figure 3-2: June 19, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

3.2.2 Trajectory Analysis July 13-15, 2006

Figure 3-3 presents backward trajectories for the July 13-15, 2006, episode. The composite backward trajectories suggest that at both the upper and lower levels, the air mass originated west of the Front Range on July 13 and 14 with some additional influence from plains sources on July 14. On July 15, the transport was generally from the south. A large upper level high pressure system moved into the region during this period. Data from a single Boulder ozonesonde is available for this episode (from the NOAA Earth Systems Research Laboratory Global Monitoring Division (NOAA ESRL GMD), see: http://www.esrl.noaa.gov/gmd/ozwv/). Results from the July 14 ozonesonde, launched at noon MDT, are presented in Figure 3-4 and show that ozone concentrations ranged from about 74 to 91 ppb in the atmosphere below 17,000 feet above sea level, with the highest concentrations at the top of this layer. This is evidence of a large reservoir of ozone aloft within the residual layer and suggests that this episode is representative of those strongly affected by transport and storage aloft within the core of an upper level high pressure system. Denver mixing heights at 6 PM MDT on July 13, 14, and 15 were approximately 21,000, 17,500, and 19,000 feet above sea level respectively; and these mixing levels also support the hypothesis that ozone retained within a deep residual layer within the upper level high pressure had an impact on ground level concentrations each day.

High eight-hour ozone concentrations were monitored at HLD (85 ppb), CHAT (92 ppb), WCH (87 ppb), and the Weld County Tower (90 ppb) on July 13. Notably, ozone concentration at RFN (81 ppb) and FTCW (82 ppb) were below the standard. Ozone levels were elevated at most locations in the network on June 13. On July 14, ozone concentrations were high at SBC (86 ppb), RFN (91 ppb), and RMNP (91 ppb). The 97 ppb ozone concentration recorded at FTCW on July 14 was the highest monitored concentration at that site in 2006. Elevated concentrations continued on July 15 at SBC (86 ppb), RFN (90 ppb), and FTCW (87 ppb).

Figure 3-5 through Figure 3-7 show same-day back trajectories for four arrival times during the daylight hours for July13 through 15. Each shows some influence from transport from the west. Transport distances are highest on the 13th but are quite short on the 14th and 15th. Transport from the west was greatest on the 13th. Local source areas had more of a same-day influence on the 14th and 15th. On the 13th, surface ozone concentrations may have been more heavily influenced by regional transport and ozone in the residual layer. On the 14th and 15th, surface ozone may have been influenced by both retention of ozone within the residual layer and local sources. Local controls would be more likely to have an impact during conditions similar to those on the 14th and 15th than the 13th.

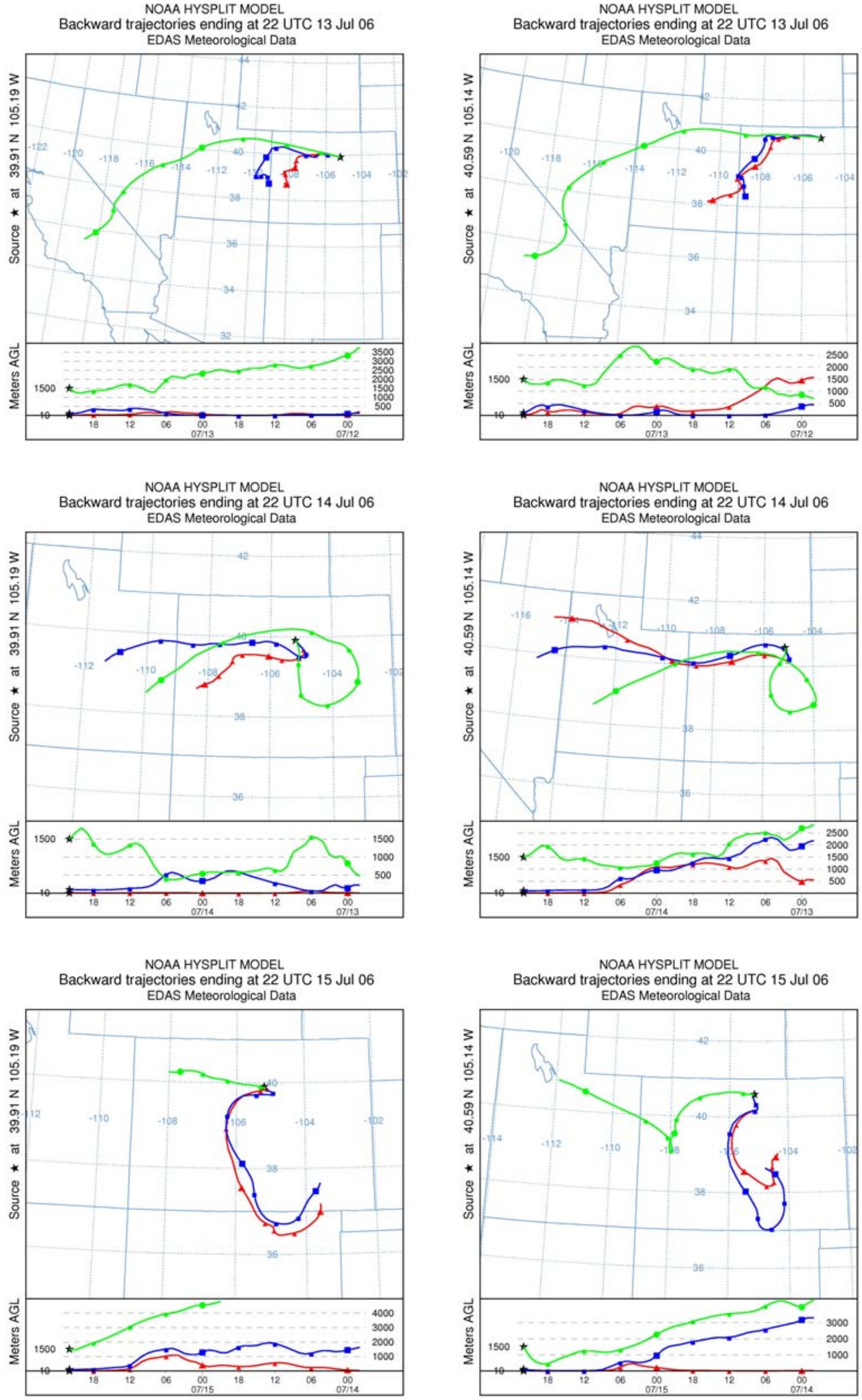

Figure 3-3: HYSPLIT 48-hour back trajectories for 10 (red), 100 (blue), and 1000 (green) meter elevations for July 13-15, 2006, at RFN (left) and FTCW (right), 6-hour interval markers, 4 PM MDT.

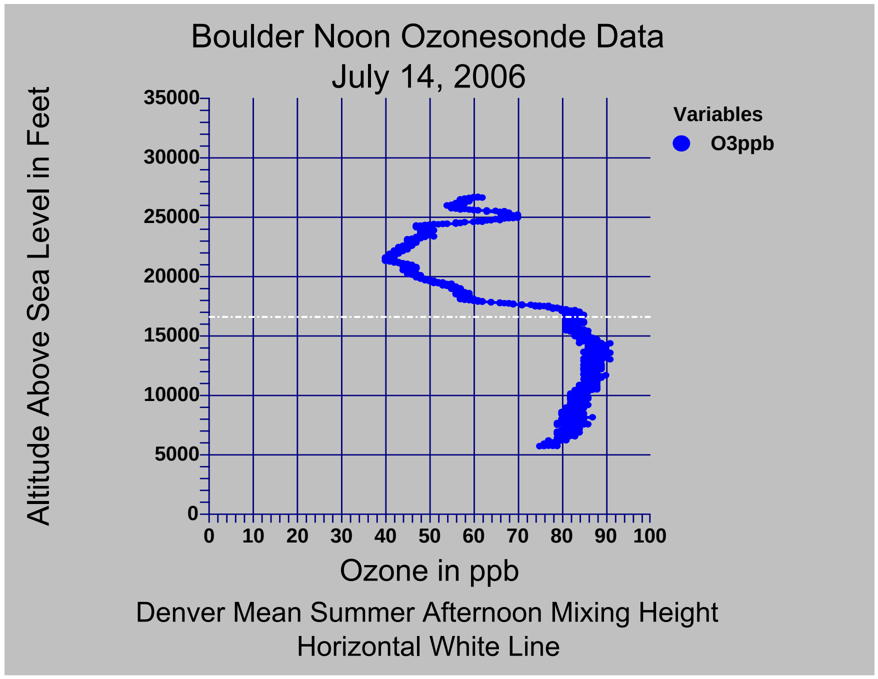

Figure 3-4: Boulder ozonesonde data for Noon MDT July 14, 2006, showing elevated ozone concentrations from the surface to 17,000 feet above sea level.

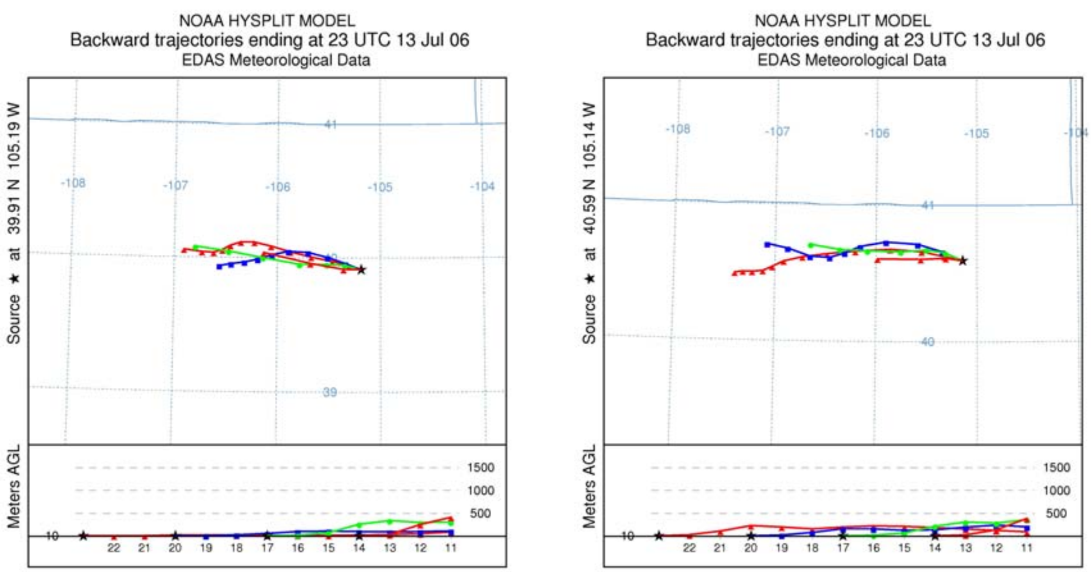

Figure 3-5: July 13, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

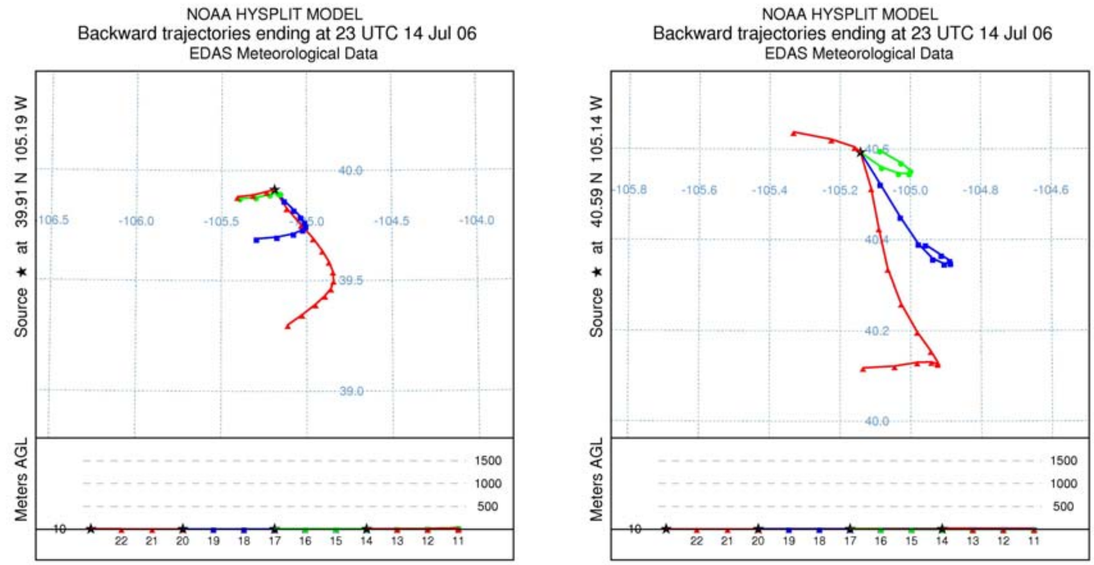

Figure 3-6: July 14, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

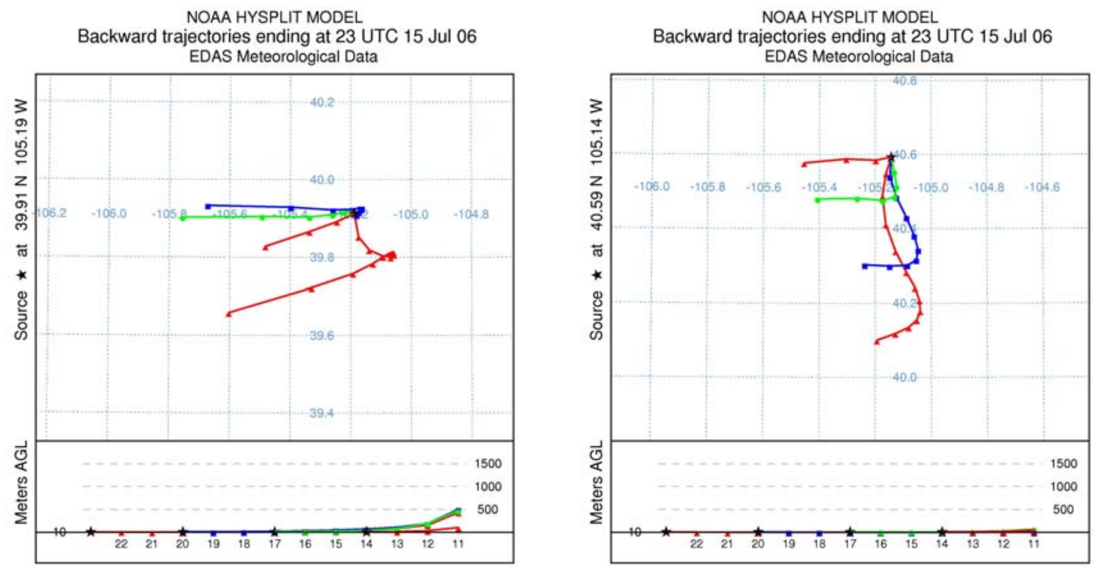

Figure 3-7: July 15, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

3.2.3 Trajectory Analysis July 27-29, 2006

The composite trajectory analysis for July 27-29, 2006, (Figure 3-8) shows a complex pattern with generally favorable conditions for high ozone concentrations. A broad upper level high pressure system west of the state on the 27th moved over Colorado on the 28th and 29th. Transport to RFN for July 27 shows that source regions were within Colorado, while the back trajectories for FTCW indicate that the air mass had origins as far away as Idaho and Montana. On the 28th, sources for air arriving at near-surface levels for both sites were within Colorado, while parcels arriving at the 1500-meter level came from northern Wyoming. On the 29th, transport source regions for both monitors were largely within eastern Colorado and Western Kansas. Transport distances for the 10-meter and 100-meter arrival levels were relatively short on both the 28th and 29th, suggesting poor dispersion conditions. Denver mixing heights at 6 PM MDT were roughly 17,500, 13,000, and 14,000 feet above sea level on the 27th, 28th, and 29th, respectively.

Elevated ozone concentrations were monitored at CHAT (86 ppb) on July 27 and at RFN (88 ppb) on July 28. Widespread excedances of the ozone standard occurred on July 29 especially at CARRIAGE (92 ppb), CHAT (88 ppb), WCH (96 ppb), RFN (93 ppb), NREL (94 ppb) and FTCW (95 ppb) and Weld (87 ppb) on July 27.

The composite trajectory analysis for July 27-29, 2006 indicates that stagnant and recirculation conditions existed over the Front Range both at the surface and aloft as illustrated in Figure 3-8. The vertical plot for the composite trajectory indicate that there was turbulence in the atmosphere where upper air and surface air was mixed. Both the stagnant conditions and the interaction between the upper level and surface conditions represent conditions for the conceptual model. This is also one of the best periods for analyzing the effects of local controls on ozone levels along the Front Range. Generally, the daily trajectory plots for July 27-29 indicate that the surface air over the Front Range was recirculated or stagnant.

Figure 3-9 through Figure 3-11 show same-day back trajectories for four arrival times during the daylight hours for the July 27-29, 2006 episode. The same-day trajectories generally show upslope transport from key source areas such as the Platte Valley, Weld

County, and the Denver metro area. The trajectories for FTCW on July 27 are the exception here, showing transport from the west and north. Transport distances are also typically short, and this is consistent with limited dispersion conditions.   This episode is another good example of one in which thermally-driven upslope affects transport of local emissions and vertical mixing taps into ozone and its precursors that reside in the residual layer aloft. This episode should be quite well suited to the evaluation of local control strategy evaluations.

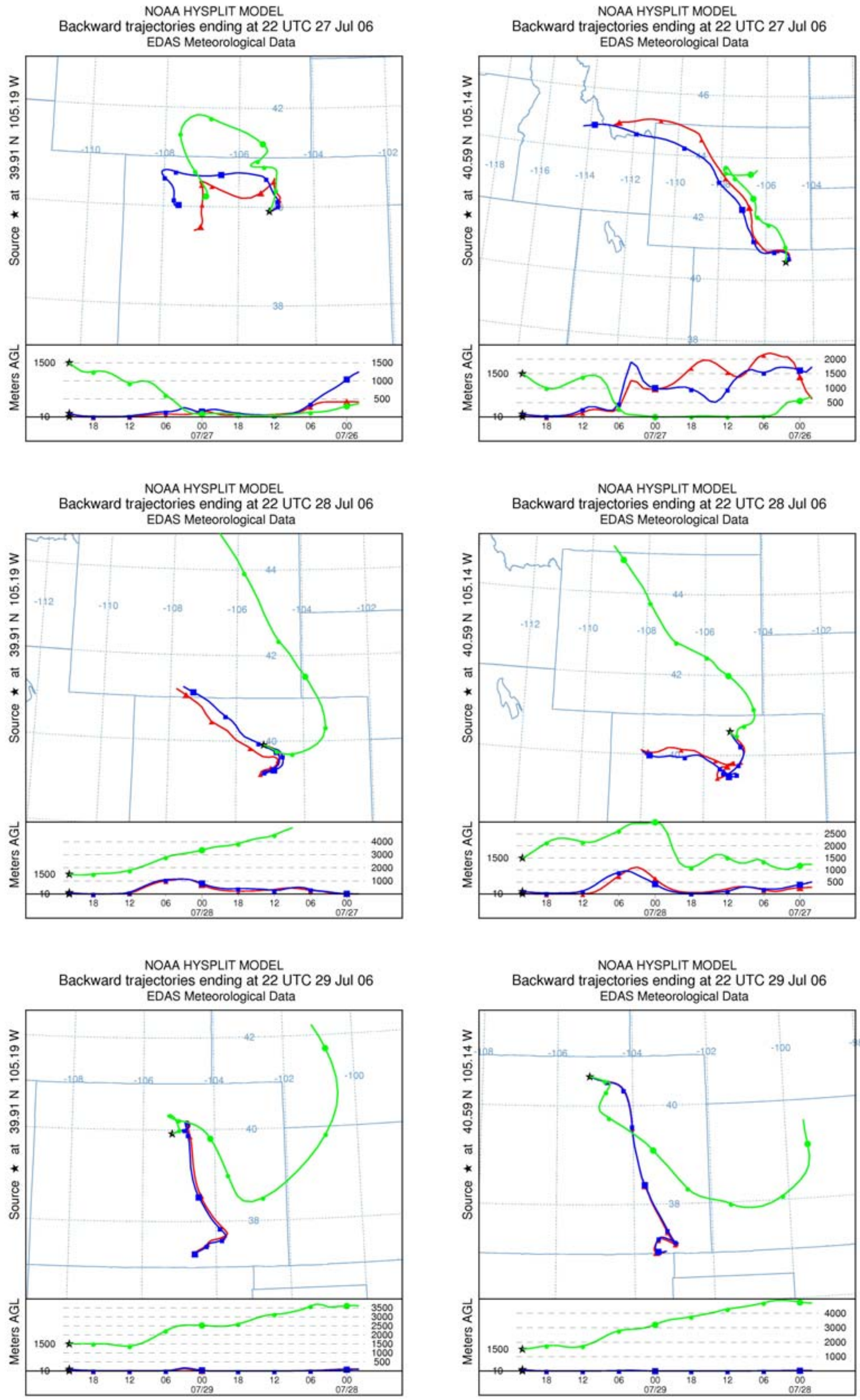

Figure 3-8: HYSPLIT 48-hour back trajectories for 10 (red), 100 (blue), and 1000 (green) meter elevations for July 27-29, 2006, at RFN (left) and FTCW (right), 6-hour interval markers, ending 4 PM

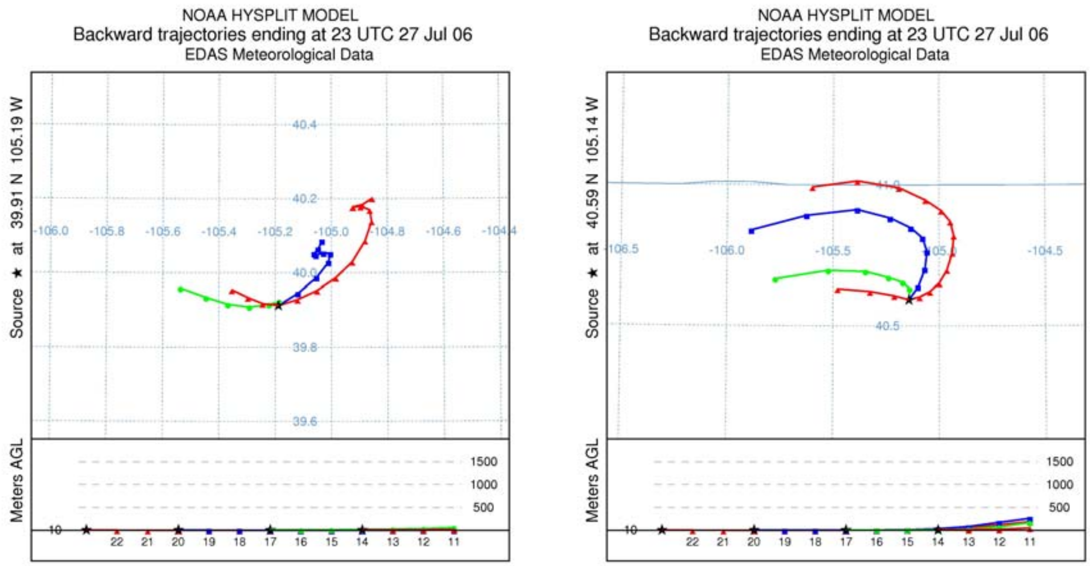

Figure 3-9: July 27, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

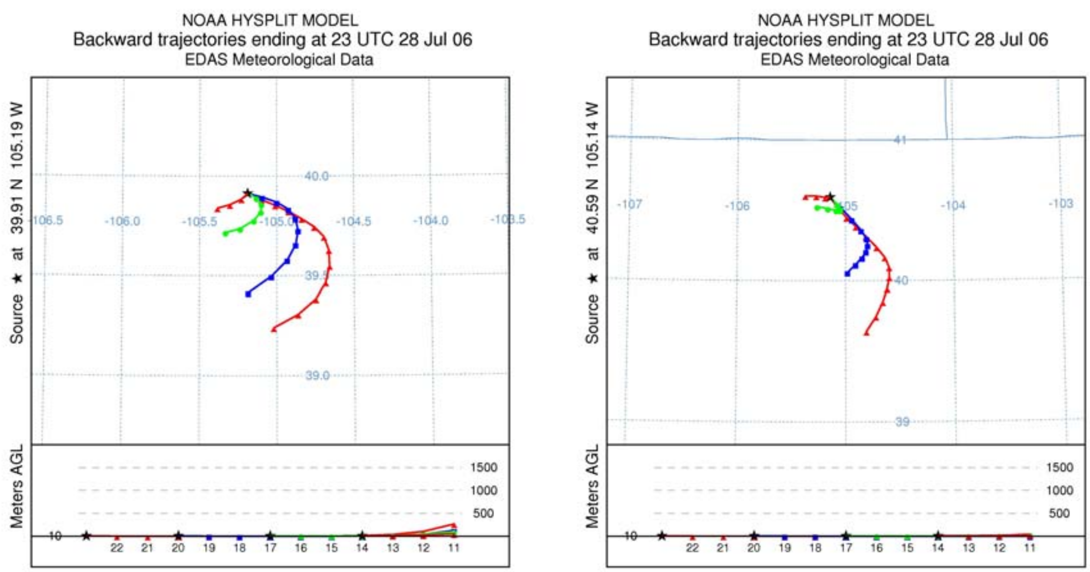

Figure 3-10: July 28, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

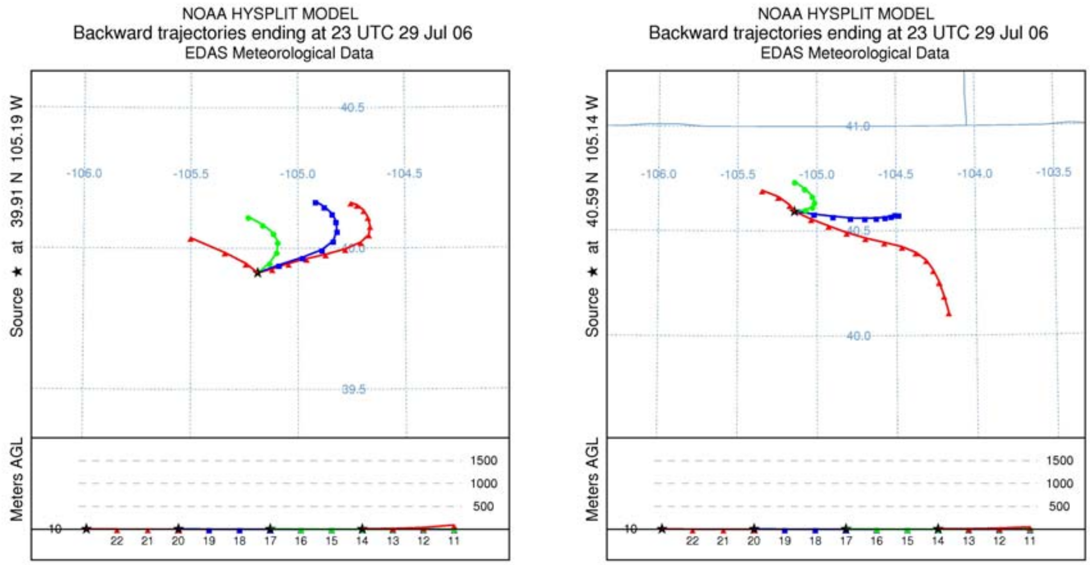

Figure 3-11: July 29, 2006, 10-meter back trajectories from 5 AM to 5 PM (MDT) for RFN (left) and FTCW (right). Four trajectories, each starting at 5 AM and arriving at 8 AM (short red), 11 AM (green), 2 PM (blue) and 5 PM (long red) with 1-hour interval markers.

3.2.4 Back Trajectory Climatology for the Summer of 2006

The NOAA ARL HYSPLIT model has also been used to calculate same-day back trajectories for each day during the May 17 through August 15 period of 2006. Figure 3-12 shows back trajectory points for this entire period. Back trajectories were calculated for surface arrival for each of the eight hours associated the daily maximum 8-hour ozone concentrations at FTCW, RFN, Highlands Ranch, and Rocky Mountain National Park. Back trajectories were up to 12 hours in length with an average start time of about 6:30 AM MDT. Each point represents one hour of transport. The EDAS40 data set was used to drive HYSPLIT. This spread of points provides a comprehensive picture of the possible air mass source areas for these sites during the summer of 2006.

This map shows that the plains, Platte Valley and metropolitan areas of the Front Range are typical source areas for these four monitors, and this is consistent with the conceptual model that has already been discussed. Transport from the west also occurred, especially at Rocky Mountain National Park.

It is possible to estimate the average air quality contributions of any area covered by back trajectory points using a moving spatial average method. The results of such an analysis are presented in Figure 3-13. For this analysis, the concentration values associated with a given sample were assigned to each of the calculated back trajectory points for that sample. A moving spatial average was applied to all of the point concentrations for the entire year. A computer routine placed an oval window with a height of 0.2 degrees latitude and width of 0.2 degrees longitude over each grid node (the grid node spacing was 0.07 degrees latitude in the Y direction and 0.07 degrees longitude in the X direction). If the number of points in the oval was 90 or higher, the routine calculated the mean concentration for that node. The distribution of mean values on the map was then contoured using the Kriging method. Limiting the averaging to nodes with a high number of points reduces the chances that a few points associated with a high or low sample concentration bias the estimates of source contributions from that locale. The resulting map provides an estimate of the mean contribution for any area covered by the analysis.

The map in Figure 3-13 shows the resulting summer mean 8-hour maximum ozone for that occurred when an air mass was from a given source area. The Denver metro area and the Platte Valley are responsible for the highest concentrations. More specifically, the cool pool area of the Platte Valley in Weld County (where drainage flow creates a deeper decoupled air mass that is typically the last location to se inversion burn off) results in a mean daily maximum 8-hour ozone concentration of 71 ppb at the four Front Range monitors considered. This is the average concentration based on all four monitors. This plot clearly supports the conceptual model and shows that local plains sources and pooling of emissions within the Platte Valley contribute to the highest concentrations at monitors subject to thermally driven upslope flows during the afternoon. Flow from the west is typically responsible for lower mean concentrations over the course of this three-month period.

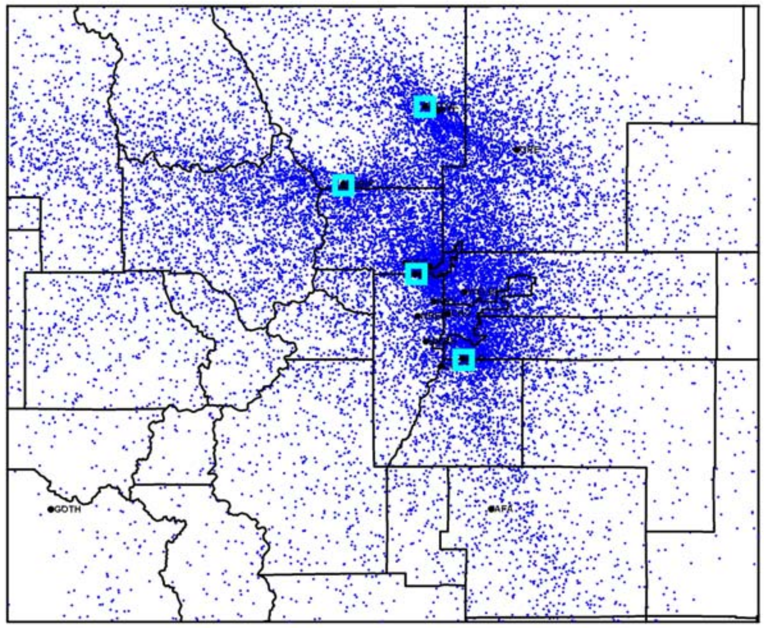

Figure 3-12: NOAA HYSPLIT same-day back trajectory points for May 17 through August 15, 2006, for FTCW, RMNP, HLD, and RFN – back trajectories up to 12 hours in length for each hour that was used to calculate a daily 8-hour maximum ozone concentration, each point representing one hour, with average start times of 6:30 AM MDT.

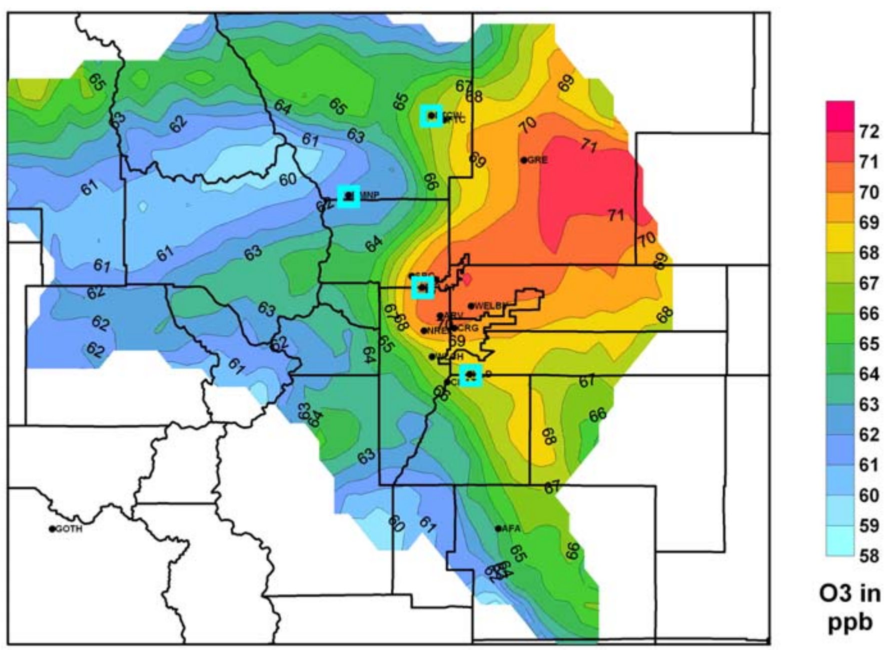

Figure 3-13: Contours of the mean May 17 – August 15, 2006, Front Range daily maximum 8-hour ozone concentrations resulting from transport from given source areas, based on a moving spatial average analysis of concentrations associated with HYSPLIT back trajectory points for FTCW, RMNP, RFN, and HLD monitors. These are the average concentrations that result at these four monitors when an air mass originates in a given area.

3.2.5 Trajectory Analysis Conclusions

The trajectory analyses for three key episodes show that they represent a variety of meteorological and transport conditions. In particular they show gradations between long-distance transport from the west and more localized upslope flows within eastern Colorado. In the conceptual model, the roles of upper level transport and storage and surface upslope transport from local sources have been highlighted. While June 17 and 18 and July 13 were dominated by long-range transport from the west and the impacts of ozone aloft, the remaining episode days show a combination of influences. In particular, the meteorology of these days favored contributions from ozone within the residual layer and short-range transport from local sources on the eastern plains. The range of conditions supports the conceptual models and demonstrates that the modeling period includes a representative variety of meteorological conditions.

In addition, the climatological analysis of back trajectories for FTCW, RMNP, RFN, and HLD and the moving spatial analysis of source areas based on these trajectories demonstrate that local sources along the Platte Valley, in the Denver metro area, and within Weld County play a key role in ozone formation during thermally-driven upslope conditions. This is consistent with the conceptual model. While MM5 does not always reproduce these thermally-driven upslope flows, it does so often enough to insure some confidence in the overall performance of the photochemical modeling.

4 Review of Modeled Metrics and Modeled Attainment Demonstration

4.1 Additional Modeling Metrics

EPA's 8-hour ozone modeling guidance recommends calculating additional modeling metrics from the current year base case to future year emissions scenarios to assure that modeled ozone concentrations are going down. These additional modeling metrics examine the ozone differences between the current year base case and future year emission scenarios in the modeling domain to assure that ozone is going down, on average, across the entire nonattainment area (NAA) rather than just limited to a few key monitoring sites.

To support the attainment demonstration in the Denver Ozone SIP, additional modeling metrics are used to assess the changes in ozone levels at grid cells in the NAA from 2006 base case to 2010 base case to 2010control cases. In the figures that follow, "Base" represents the 2010 base case, "Cntrl1" represents the Control 1 scenario,, and "Cntrl2" represents the Control 2 scenario (i.e., proposed state-only strategies that are not included in the SIP but will provide additional reductions in the DMA/NFR area). All three of the metrics presented below (grid cells, grid cell hours and total ozone) show decreases in peak elevated ozone ≥ 85 ppb from emissions reductions due to existing controls and regulations and continued decreases due to the Control 1 and Control 2 scenarios.

ENVIRON/Alpine Geophysics (Morris, et al 2008a) calculated the change in daily maximum 8-hour ozone concentrations between the 2006 base case and 2010 emission scenarios across grid cells in the Denver NAA and across all days in the June-July 2006 modeling episode. The changes 8-hour ozone concentrations were calculated for values above four separate threshold concentrations: 85, 80, 75 and 70 ppb. The additional modeling metrics consist of the following:

- <u>Total Ozone</u>: Defined as the difference between the modeled daily maximum 8-hour ozone concentrations and the threshold concentration, for modeled values above the threshold, summed across all grid cells in the Denver NAA and modeling days during June-July 2006.

- Grid Cells: Number of grid cell-days with modeled daily maximum 8-hour ozone concentrations greater than the threshold for all grid cells in the NAA and days from the June-July 2006 episode.
- Grid Cell-Hours: Number of grid cell-hours with modeled running 8-hour ozone concentrations greater than the threshold for all grid cells in the NAA and hours during the June-July 2006 episode.

4.1.1 Relative Change in Grid Cells

As can be seen in Figure 4-1 the emissions reductions from the 2006 base case to the 2010 base case achieve a 14% reduction in grid cells ≥ 85 ppb and an additional 3.5% reduction in grid cells due to the Control 1 strategies. Continued reduction of emissions due to Control 2 strategies (through state-only or voluntary measures) continues to demonstrate reductions of cells ≥ 85 ppb. Grid cells ≥80 ppb, ≥ 75 ppb and ≥70 ppb show an initial reduction due to existing controls and regulation from the 2006 base case to the 2010 base case and show ≥1% reduction due to the Control 1 and Control 2 scenarios.

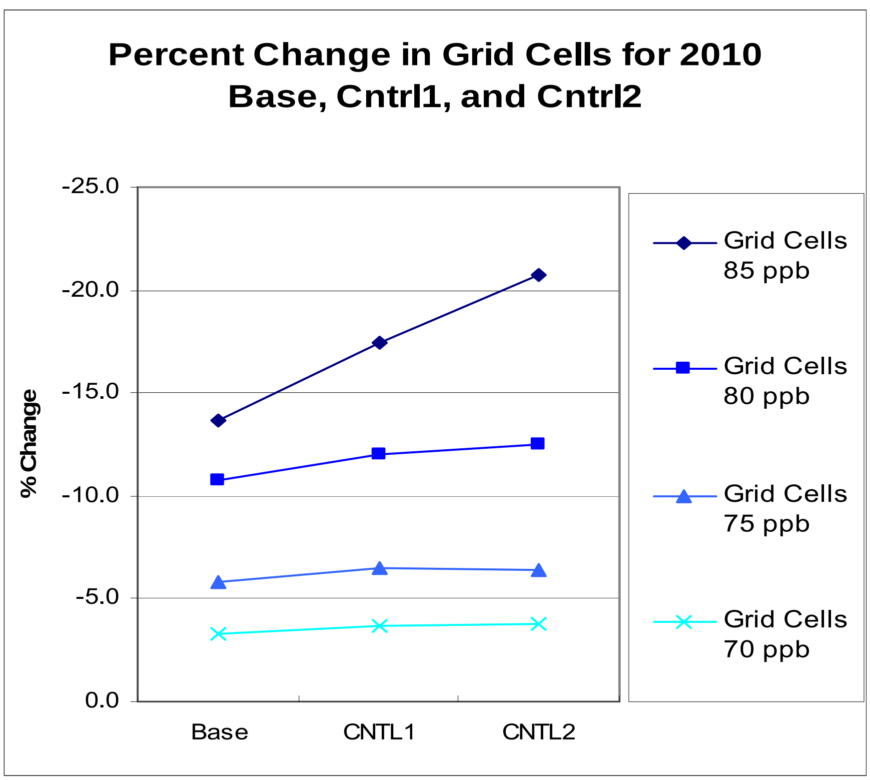

Figure 4-1: Relative Change in Grid Cells

4.1.2 Relative Change in Grid Cell-Hours

As can be seen in Figure 4-2 the emissions reductions from the 2006 base case to the 2010 base case achieve a 22% reduction in grid cells-hours ≥ 85 ppb and an additional 3% reduction in grid cells due to the Control 1 strategies. Continued reduction of emissions (through state-only or voluntary measures) continues to demonstrate reduction of cells-hours ≥85 ppb. Grid cell-hours ≥80 ppb, ≥75 ppb and ≥70 ppb show an initial reduction due to existing controls and regulation from the 2006 base case to the 2010 base case and show ≥1% increased reduction in cell-hours due to the SIP and state-only controls.

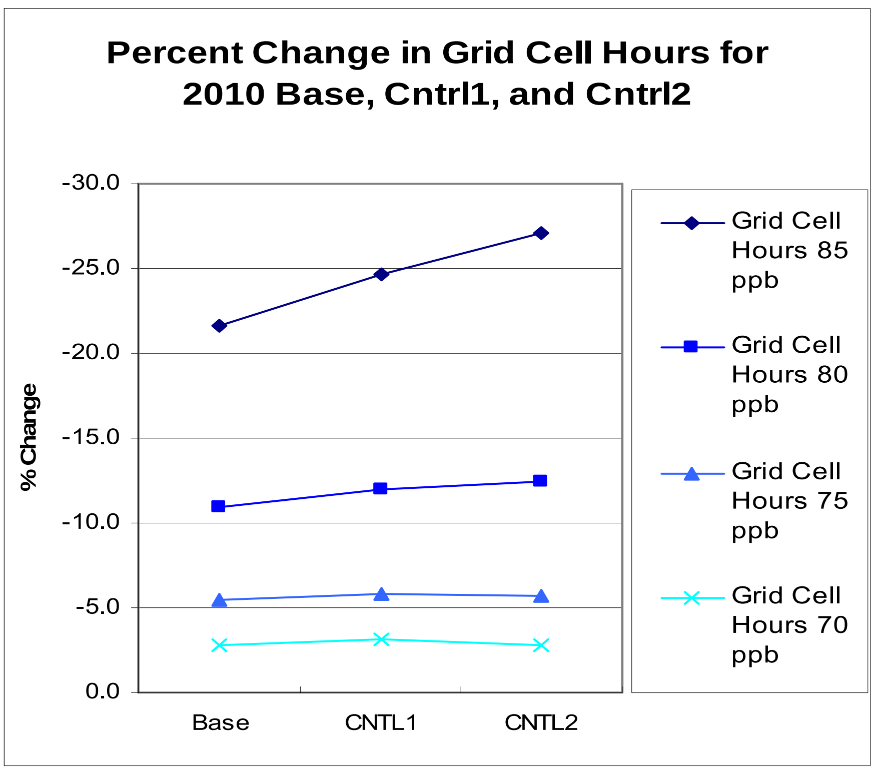

Figure 4-2: Relative Change in Grid Cell-hours

4.1.3 Relative Change in Total 8-Hour Ozone

As can be seen in Figure 4-3 below, the emissions reductions from the 2006 base case to the 2010 base case achieve a 21% reduction in total 8-hour ozone ≥ 85 ppb and an additional 7% reduction in total 8-hour ozone due to the Control 1 strategies. Continued reduction of emissions (through state-only or voluntary measures) continues to demonstrate reduction of total 8-hour ozone ≥85 ppb. Total 8-hour ozone ≥80 ppb, ≥75 ppb and ≥70 ppb show an initial reduction due to existing controls and regulation from the 2006 base case to the 2010 base case and show ≥1% increased reduction in cell-hours due to the Control 1 and Control 2 strategies.

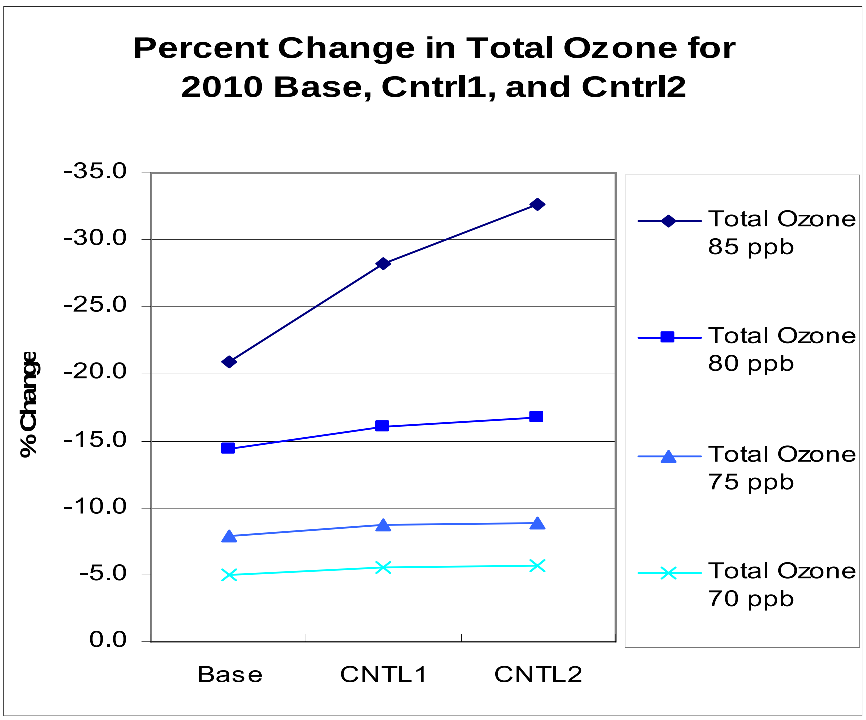

Figure 4-3: Relative Change in Total 8 hour Ozone

In summary, the additional model metrics presented in Figure 4-1 through Figure 4-3 demonstrate that the emission reductions between 2006 and 2010 are having their intended effect of being effective at reducing the elevated 8-hour ozone concentrations. The changes in Total Ozone and Grid Cells greater than 85 ppb modeling metrics between the 2006 and 2010 base cases are -21% and -14%, respectively. These reductions are even greater for the 2010 Control 1 case (-28% and -17%) and even greater still for the 2010 Control 2 scenario.

4.2 Review Alternative Attainment Test Methodology

While EPA's modeling guidance offers several potential approaches for establishing base year design values, the guidance recommends the preferred methodology for establishing a base year design value as follows:

> "For the modeled attainment tests we recommend using the average of the three design value periods which include the baseline inventory year. Based on the attributes listed above (in the guidance), the average of the three design value periods best represents the baseline concentrations, while taking into account the variability of the meteorology and emissions (over a five year period)."

At the start of the work on the SIP in 2007 and throughout development of the proposed plan, the modeling analysis has used the 2005-2007 three-year design value as representative of the ozone situation facing the region at the time. In the SIP, attainment of the 8-hour ozone standard was demonstrated at all of the monitored locations by 2010 for the 8-hour ozone nonattainment as a result of the reductions expected from existing programs and regulations. Table 4-1 presents as summary of the current attainment demonstration in the Denver Ozone SIP. Data from the 2008 ozone season (though currently not formally quality assured by the State or EPA) is now available and the average of the three Design Values in the 2004-2008 periods can be calculated, as the recommended method by EPA.

Table 4-1: 2010 Base Case Design Values for Each Monitoring Site for Modeled Days greater than 0.075 ppm

Site Name	8-Hour Ozone Current (2005-2007) Base Case Design Values (ppm)	Modeled Base Case Relative Response Factors	Calculated 8-Hour Ozone Future (2010) Base Case Design Values (ppm)	Truncated 8-Hour Ozone Future (2010) Base Case Design Values (ppm)
Welby	0.070	1.0042	0.0702	0.070
Arvada	0.079	1.0026	0.0792	0.079
NREL	0.082	1.0039	0.0823	**0.082**
Rocky Flats North	**0.085**	0.9994	0.0849	**0.084**
S. Boulder Creek	0.081	0.9976	0.0808	0.080
Fort Collins	0.074	0.9878	0.0730	0.073
Fort Collins West*	**0.086**	0.9874	0.0849	**0.084**
Carriage	0.074	1.0022	0.0741	0.074
Welch	0.075	1.0004	0.0750	0.075
CAMP	0.056	1.0017	0.0560	0.056
Weld County Tower	0.078	0.9964	0.0777	0.077
Highland	0.078	0.9916	0.0773	0.077
Chatfield Res.	0.084	0.9934	0.0834	**0.083**
Rocky Mtn. N.P.	0.076	0.9903	0.0752	0.075

* FCW has only 2 years of complete data available, 2006 and 2007

In this supplemental analysis, the EPA's recommended methodology is applied to establish the base year Design Values and project the 2010 base case Design Value. This methodology requires that the average of the base year Design Value over 2004-2008 be rounded to the 4th place and presented to the 4th place in ppm. After application of the Relative Response Factors, the future year (2010) Design Values are rounded to the 4th place and then truncated for comparison with the NAAQS. Table 4-1 presents the results of applying EPA's recommended base year Design Value calculation approach. As shown in Table 4-2, by applying EPA's recommended design value methodology, the ozone standard is achieved at all the monitoring sites with more of a safety margin than the results presented in Table 4-2 using the three-year average (2005-07) base case design values for the 2010 base case.

Table 4-2: 2010 Base Case Design Values Utilizing EPA's Recommended DVB Calculation Methodology

Site Name	Current (2004-08*) Base Case Design Value (ppm)	Modeled Control Case Relative Response Factors	Calculated 2010 Base Case Design Value (ppm)	Truncated 2010 Base Case Design Value (ppm)
Welby	0.0707	1.0042	0.0710	0.071
Arvada	0.0777	1.0026	0.0779	0.077
NREL	0.0808	1.0039	0.0811	0.081
Rocky Flats North	0.0840	0.9994	0.0839	**0.083**
S. Boulder Creek	0.0791	0.9976	0.0789	0.078
Fort Collins	0.0728	0.9878	0.0719	0.071
Fort Collins West**	0.083	0.9874	0.0820	**0.082**
Carriage	0.0728	1.0022	0.0730	0.073
Welch	0.0740	1.0004	0.0740	0.074
CAMP	0.0560	1.0017	0.0561	0.056
Weld County Tower	0.0769	0.9964	0.0766	0.076
Highland	0.0760	0.9916	0.0754	0.075
Chatfield Res.	0.0829	0.9934	0.0824	**0.082**
Rocky Mtn. N.P.	0.0759	0.9903	0.0752	0.075

* Thru August 31, 2008. 2008 data have not been fully quality assured at this time;

** FCW only has three years of data and is presented as a Design Value to three places

Table 4-3 presents the future year Design Values from the 2010 Control 1 scenario modeling using EPA's recommended DVB calculation approach. Table 4-3 also demonstrates that the ozone standard will be achieved at all the monitor sites using the 2010 Control 1 scenario.

Table 4-3: 2010 "Control 1" Design Values Utilizing EPA's Recommended DVB Calculation Methodology

Site Name	Current (2004-08*) Base Case Design Value (ppm)	Modeled Control Case Relative Reduction Factors	Calculated 2010 Control Case Design Value (ppm)	Truncated 2010 Control Case Design Value (ppm)
Welby	0.0707	1.0039	0.0709	0.071
Arvada	0.0777	1.0022	0.0779	0.077
NREL	0.0808	1.0027	0.0810	0.081
Rocky Flats North	0.0840	0.9981	0.0838	**0.083**
S. Boulder Creek	0.0791	0.9963	0.0788	0.078
Fort Collins	0.0728	0.9853	0.0717	0.071
Fort Collins West**	0.083	0.9852	0.0818	0.081
Carriage	0.0728	1.0015	0.0729	0.072
Welch	0.0740	1.0002	0.0740	0.074
CAMP	0.0560	1.0009	0.0560	0.056
Weld County Tower	0.0769	0.9925	0.0763	0.076
Highland	0.0760	0.9900	0.0752	0.075
Chatfield Res.	0.0829	0.9921	0.0822	**0.082**
Rocky Mtn. N.P.	0.0759	0.9892	0.0751	0.075

* Thru August 31, 2008. 2008 data have not been fully quality assured at this time;

** FCW only has three years of data and is presented as a Design Value to three places

4.3 Alternative 2010 Ozone Projections

ENVIRON/Alpine Geophysics (Morris, et al, 2008a) analyzed several alternative 2010 ozone projection procedures for the 2010 base case, Control 1 and Control 2 scenarios to estimate the uncertainties in the projection procedures and provide confidence that passing the modeled attainment demonstration indicates attainment will likely be achieved in 2010 under the 2010 base case, Control 1 or Control 2 emission scenarios. These alternative ozone projection procedures differ in the days used and how modeled ozone near the monitor is selected to construct the Relative Response Factors (RRFs). Six additional ozone projection procedures were analyzed, in addition to the EPA guidance default.

- Minimum 5 Days to Develop RRF using 85-70 ppb Sliding Threshold (5dth): In the EPA default approach, days are selected for use RRFs based on whether the maximum daily maximum 8-hour ozone concentration near the monitor (with 7 x 7 array of grid cells) in the 2006 base case is greater than a threshold, with the threshold determined when at least 10 days are obtained for the RRF. In this alternative projection approach, we require a minimum of 5 modeled days to construct the RRFs.
- Use of 80 ppb Cutoff Threshold and Minimum of 1 Day (1dth80): The second alternative ozone projection approach uses an 80 ppb cutoff threshold and RRFs are allowed to be calculated with as few as one modeling day.
- Use of 75 ppb (1dth75) and 70 ppb (1dth70) Cutoff Thresholds: In those two alternative projection approaches the cutoff threshold is reduced to 75 and 70 ppb.
- Use of 5 x 5 and 3 x 3 Array of Grid Cells: Select the maximum daily maximum 8-hour ozone concentration from a 5 x 5 or 3 x 3 array of grid cells centered on the monitor, instead of using a 7 x 7 array as used in the EPA default procedure

Table 4-4 lists the projected 2010 DVFs at the key RFNO and FTCW monitoring sites for the EPA guidance default and the six alternative ozone projection procedures discussed above. Table 4-4 shows the ozone cutoff thresholds and number of days used in calculating the RRFs for each alternative 2010 ozone project methods, and, at the RFNO and FTCW monitoring sites.

- 2010 Base Case: For the 2010 base case, the projected 2010 DVF using the EPA guidance default approach was 84.9 ppb at both the RFNO and FTCW monitoring sites. Some of the six alternative projection approaches result in increases, whereas others in decreases in the projected 2010 DVFs at these two sites relative to the EPA guidance default approach. The projected DVFs at RFNO for the 2010 base case range from 84.5 to 85.2 with an average value of 84.9 ppb. A similar range for the FTCW monitor is 84.6 to 85.2 ppb with an average of 84.9 ppb. At the RFNO monitoring site, 3 of the 7 projection methods pass the modeled attainment demonstration test (43%), while at the FTCW 5 of the 7 methods pass the test (71%).
- 2010 Control 1 Case: A majority of the 2010 ozone projection procedures pass the modeled attainment demonstration test at both the RFNO (4 out of 7, 57%) and FTCW (6 out of 7, 86%) monitoring sites. At the RFNO monitoring site, the projected DVFs for the 2010 Control 1 scenario range from 84.3 to 85.1 ppb with an average of 84.8 ppb. And at the FTCW monitoring site the projected DVFs range from 84.4 to 85.0 ppb with an average of 84.7 ppb.
- 2010 Control 2 Case: The 2010 projected DVFs at RFNO for the 2010 Control 2 case are similar to the 2010 Control 1 case ranging from 84.3 to 85.1 ppb, with an average of 84.8 ppb. More benefits are seen at FTCW where the 2010 projected DVFs range from 84.3 to 84.8 ppb with an average of 84.5 ppb.

An examination of the different 2010 ozone projection methods across monitoring sites shows no method is tending toward estimating higher or lower DVFs than the EPA default method across all monitoring sites. This is shown clearly in Table 4-4 for the RFNO and FTCW monitoring sites where, in most cases, a method in which the projected DVF at RFNO is greater than the EPA default method is below the EPA default method at FTCW and vice versa.

In conclusion, the alternative ozone projection approaches support the findings using the EPA default approach that the 2010 base case will likely achieve attainment in the Denver region of the 0.08 ppm 8-hour ozone NAAQS. The ozone projection methods indicate that there will be more certainty that the Denver region will achieve 8-hour ozone attainment in 2010 under the 2010 Control 1 and Control 2 emission scenarios.

Table 4-4: Projected 2010 8-hour ozone Design Values (DVFs) at the Rocky Flats North (RFNO) and Fort Collins West (FTCW) monitoring sites using the EPA guidance default approach, the six alternative projection approaches and the 2010 Base, Control 1 and Control 2 modeling results.

Alternative 2010 Ozone Projection Procedures									
Name	**DVC**	**EPA**	**5dth**	**1dth80**	**1dth75**	**1dth70**	**5x5**	**3x3**	**Avg**
2010 Base Case (Base) DVFs (ppb)									
Rocky Flats North	85.0	84.9	85.2	85.1	84.9	85.0	85.0	84.5	84.9
Fort Collins - West	86.0	84.9	84.6	84.6	84.9	85.1	84.8	85.2	84.9
2010 Control Strategy No. 1 (Cntl1) DVFs (ppb)									
Rocky Flats North	85.0	84.8	85.1	85.0	84.8	85.0	84.9	84.3	84.8
Fort Collins - West	86.0	84.7	84.4	84.4	84.7	84.9	84.6	85.0	84.7
2010 Control Strategy No. 2 (Cntl2) DVFs (ppb)									
Rocky Flats North	85.0	84.7	85.1	84.9	84.8	84.9	84.8	84.3	84.8
Fort Collins - West	86.0	84.5	84.3	84.3	84.5	84.7	84.5	84.8	84.5
Cut-Off Concentration (ppb)									
Rocky Flats North		78	81	80	75	70	76	75	
Fort Collins - West		76	81	80	75	70	75	73	
Number of Days Used									
Rocky Flats North		10	6	7	19	27	11	10	
Fort Collins - West		10	5	5	13	22	10	10	

4.4 Modeled vs. Measured VOC/NOx Ratios

The CDPHE/APCD collected 3-hour VOC samples at several sites during a few days of the June-July 2006 modeling period. As part of the model performance evaluation ENVIRON/Alpine Geophysics compared these ambient VOC samples with modeled data. In the comparisons, the observed VOC species were converted to the Carbon Bond V (CB05) lumped VOC species, which was the chemical mechanism used in CAMx for the Denver SIP. The modeled and observed CB05 species were summed to get the total predicted and observed VOC concentrations, respectively. Ethane (ETHA) was not included in the total VOC species when summing the CB05 lumped species. Also note that since the VOC sampling did not collected measurements for methanol and ethanol, those species were also not accounted for when summing the CB05 species.

The comparison that ENVIRON/AG (Morris, et al, 2008b) conducted indicated that the model systematically under predicts the observed VOC concentrations at the CAMP monitoring site, whereas for NOx and CO there are days with under predictions and days with over predictions. On average NOx is under predicted as well. Given the location of the CAMP monitor in downtown Denver, VOC, NOx and CO emissions are dominated by on-road mobile sources. The comparisons of monitored and modeled data provide an opportunity to evaluate the on-road mobile source emissions with the caveat that the ambient measurement occurs at a specific point and time and the modeled concentrations are averaged over a 4-km grid space. Since a direct comparison of ambient data and modeled data cannot be made, better indications of the accuracy of the on-road mobile source emissions are the VOC/NOx and CO/NOx key indicator ratio comparisons. Comparisons of the predicted and observed VOC/NOx ratios provide an indication of whether the model is reproducing the correct chemical regime in the DMA.

Of the 15 days with morning VOC/NOx comparisons, very good comparisons are seen on 11 (73%) of the days. One of the days where the model under predicted the VOC/NOx ratio one was July 4th that has atypical traffic patterns which is not simulated well in the CONCEPT modeling. Two of the days where the VOC/NOx ratio was over predicted were weekend days. However on two other weekend days, good performance was demonstrated.

When ENVIRON/AG compared individual VOC species, the modeled versus ambient measurement data indicated that Ethane (ETHA) is under predicted by approximately a factor of 10 at the CAMP monitor with observed values of ~25 ppbC and predicted values of ~2.5 ppbC. The under prediction of ethane was even greater at the two Weld County monitoring sites where the CB05 paraffin species was also under predicted. As ethane is primarily associated with natural gas, the under prediction of ethane indicates that organic emissions from natural gas related and oil and gas development sources are understated in the inventory.

In addition to the underestimation of observed ethane and paraffin VOC species noted above, the comparison also revealed that carbonyl VOC species were also systematically under predicted by the model. The under prediction of acetaldehyde may be due in part to the SMOKE VOC speciation profile for on-road mobile sources not accounting for ethanol blended gasoline whose combustion produces higher acetaldehyde than conventional gasoline. However, the reasons for the large under prediction of formaldehyde were less clear. Formaldehyde is an important VOC species that initiates the radical cycle. The under prediction of formaldehyde may help explain why the model tends to form ozone too slowly and does not obtain as high ozone peaks as observed.   The consequence of under estimating VOC emissions is that the effectiveness of controls is under estimated on mass basis.

The CO/NOx ratios were over predicted on most days, which may indicate that MOBILE6 is overestimating the on-road mobile source CO emissions. These are similar to other studies where the CO/NOx ratio is over predicted and may not be unique to the Denver emission inventory (Pollack, et. al., 2004).

4.5 Model Uncertainty and Limitations

A common thread throughout the modeling and WOE analyses is the uncertainty in the modeling process. While modeling is by far the best tool for evaluating proposed control strategies, it is imperative to recognize its limitations and the uncertainty in the model predictions.

The photochemical modeling process is composed of a suite of mathematical models that are used to evaluate current and future air quality processes. The suite of mathematical models have inherent limitations owing to the necessary simplifications and approximations made in formulating the governing equations, implementing them for numerical solution on fast computers, and in supplying them with input data sets and parameters that are themselves approximations of the full state of the atmosphere and emission processes. Each component adds its own uncertainty to the process, so that the overall uncertainty is a composite of hundreds of individual uncertainties. To put the air quality model results in full perspective, the technical support document contains a full analysis of the model performance evaluation for the meteorological and photochemical model.

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Fortunately, photochemical grid models have proven to be fairly robust in hundreds of applications, and provide reasonable answers under most circumstances. Nonetheless, the policy maker must be aware that the model can only provide general guidance for control strategy development, and cannot be expected to predict future ozone concentrations with high precision.

The uncertainties in the modeling process are inevitably reduced over time, but will never be entirely eliminated. Thus, controls must be implemented before it is possible to judge their impact with as much precision as we would like. The WOE process allows for a middle ground, where a reasonable control package is sufficient to demonstrate probable attainment.

A brief summary of photochemical model performance used for the Denver Ozone SIP and Plan are summarized as follows:

- The model has a tendency to under predict the observed peaks in ozone concentration that is believed to be due in part to:
  - The inability of the meteorology model to push the ozone and its precursors far enough into the foothills;
  - The inability to replicate retention of ozone aloft for a sustained period of days; and
  - On some days, the estimation of the contributions of transport and the amount of ozone generated in the Denver urban plume.
- The model meets EPA's peak, bias and error ozone performance goals for ozone modeling on a vast majority of the modeled days. The model meets EPA guidance performance on a vast majority of the modeled days with the goal that most of the matched pairs near the monitor are within ± 20% of the observed value. A summary of the model's performance for the matched pairs is as follows:
  - Maximum modeled daily maximum is 76% within ± 20% of the observed value;
  - Closest modeled daily maximum is 91% within ± 20% observed value; and
  - Spatial paired modeled daily maximum is 82% within ± 20% observed value.
  - There is agreement between the modeled and measured volatile organic compounds/nitrogen oxides (VOC/NOx) ratios in Denver on most days suggesting that the mobile sources inventory is representative and the model is simulating the correct chemical regimes.

The model performance evaluations included in the Technical Support Appendices indicate that the photochemical grid modeling is the best available tool to assess progress in reducing ozone concentrations. Further, to mitigate the limitations of the modeling platform, the results are not used in an absolute sense, but rather are used in relative sense.

5 Assess the Efficacy of SIP, State-only and Voluntary Control Strategies

The reduction in emissions from the 2006 base case to the 2010 Control 1 case, which includes reductions from current state and federal regulations and newly proposed state regulations for inclusion in the SIP, reduces VOC and NOx emissions by 11% from the 2006 base case. Photochemical grid modeling has shown that these reductions reduce ozone concentrations in the nonattainment area.

The proposed state-only regulations controlling mobile source emissions and oil and gas facilities in the nonattainment area and statewide, plus a request of EPA for a change in RVP in the NFR area, anticipate an approximate additional 50-60 tpd of VOC reduction and 20-21 tpd of NOx reduction state-wide and in the nonattainment area. Photochemical grid modeling has shown that these reductions will provide additional reduction in ozone concentration levels in the nonattainment area.

In addition in the DMA/NFR there have been and will continue to be a myriad of voluntary measures that are not directly accounted for in the current and projected emissions inventories. Such programs include:

- The summertime Ozone Alert Program where citizens are alerted when elevated ozone levels are predicted and are encouraged to reduce their ozone-causing activities.
- The Regional Air Quality Council's "Let's Take Care of Our Summer Air" public awareness program that includes media advertising and community outreach to encourage citizen action to reduce ozone-causing activities.
- Lawn mower exchange programs in the Denver area and the North Front Range that offers discounts for citizens to replace and recycle old gasoline-powered mowers with electric mowers and lawn equipment.
- Replacement of faulty gas caps on cars and trucks through employer-sponsored activities and fleet testing programs.
- Marketing efforts with Colorado Wyoming Petroleum Marketers Association and other gasoline retailers to educate motorists at their stores to "Stop at the Click,"

refuel in the evening, and maintain their vehicles to reduce ozone-forming emissions.

- Efforts by the Regional Air Quality Council and the Colorado Department of Public Health and Environment repair or salvage high-emitting vehicles that are identified on the road by remote-sensing technology.
- Pollution Prevention programs implemented by local business and industry to reduce their loss of product and prevent emissions of ozone-causing emissions.
- Employer-based travel reduction programs that are implemented by the Denver Regional Council of Governments, area transportation management associations, the Regional Transportation District, local governments, and local businesses that encourage reduced automobile travel and increased use of alternative transportation and workplace options.
- Efforts by the Regional Air Quality Council, local school districts, and government and private fleets to reduce emissions from diesel vehicles through education and application emission control and anti-idling equipment.
- Car Care Fairs where area motorists can have their cars and trucks evaluated to improve vehicle performance and increase gas mileage.
- Implementation of land use and design policies by local governments to encourage sustainable development practices and mixed-use, transit-oriented development.
- Efforts by the State of Colorado to improve energy efficiency in state government and promote energy efficient practices throughout the state.
- Household chemical recycling events conducted by local governments and local health departments through the Denver area and North Front Range.
- Greenprint Denver, an initiative of the Denver Mayor's Office, promotes energy efficient practices, sustainable development, increased use of alternative fuels and low-emission vehicles, recycling programs, and increased tree planting.
- The Colorado Department of Transportation's (CDOT) Air Quality Programmatic Agreement is being crafted to identify and commit to a number of proactive measures that will reduce mobile source air toxics and greenhouse gas emissions throughout Colorado, in addition to criteria air pollutants. Due to the inherent nature of air quality, it is more efficient to mitigate these impacts utilizing a programmatic approach rather than negotiating individual mitigation for new environmental documents. It is hoped that this agreement will be signed by the

participating parties (between CDOT, EPA, Colorado Department of Health and Environment (CDPHE), Federal Highway Authority (FHWA), Federal Transit Administration (FTA), Regional Air Quality Council (RAQC), and Regional Transportation District (RTD)) by the end of 2008.

6 Weight of Evidence – Conclusions

The final WOE combines and weighs the various supplemental analyses with the results of the attainment test resulting in an aggregated, qualitative, and quantitative conclusion as to whether the proposed set of control strategies will result in the Denver Metro Area and North Front Range reaching attainment in 2010. A number of conclusions can be drawn from the weight of evidence:

- Trends in emissions correlate well with surrogate indicators such as fleet turnover.
- Meteorological variability is a key component for ozone formation and is reflected in the year-to-year variability of peak ozone levels. A key metric for upper level high pressure strength has remained steady or trended downward in recent years, suggesting a reasonable likelihood for moderate high pressure strength in the next few years, which would favor attainment.
- Analysis of the weekend-weekday effect for the Front Range shows a strong effect in Central Denver and weaker effects in outlying areas. This points to the possibility for NOx control disbenefits in central Denver due to the role of NOx quenching here. The spatial pattern of the weekend effect is consistent with the localized NOx disbenefit identified in the photochemical modeling.
- If the emissions trends are correct, then the Relative Response Factors (RRFs) are likely to be directionally correct.
- Reductions in VOC emissions are expected to reduce ozone.
- Reductions in NOx emissions are expected to reduce ozone, possibly with greater efficiency than VOC reductions, at troublesome monitors outside of the urban core of metro Denver. Increases in ozone concentrations in the urban core of metro Denver due to NOx emissions reductions do not appear to be significant.
- The aggregate trend in weather-corrected 4^{th} maximum time series suggests that ozone levels have been flat from 2004 through 2008, although individual concentrations have been highly variable. This suggests that without additional emission reductions the region will remain at or near the level of the standard.

- The base case modeling of the June-July 2006 timeframe encompasses the various local meteorological regimes under which elevated ozone levels have and are expected to occur.
- Other modeled metrics indicate that there are reductions in Total Ozone, Grid Cells, and Grid Cell-Hours of 15% to 30% for thresholds of 85 ppb and 80 ppb from the 2006 base case through the 2010 base case, the 2010 Control 1 case and the 2010 Control 2 case.
- A comparison of ambient and modeled data indicates that VOC emissions from the oil and gas sector may be under estimated. The consequence of under estimating VOC emissions is that the effectiveness of controls is under estimated on mass basis.
- At this time, the photochemical modeling is considered to be the best predictor of future ozone levels.

In conclusion, the collective supplemental analyses contained in this weight of evidence document support the current photochemical model attainment demonstration for the 0.08 ppm 8-hour ozone NAAQS using the EPA default approaches for the 2010 base case, 2010 Control 1, and the 2010 Control 2 scenarios. In addition, at this time, the photochemical modeling is considered to be the best predictor of future ozone levels.

The collective supplemental analyses in this weight of evidence analysis support the findings using the EPA methods, as specified in the EPA modeling guidance, that the 2010 base case will likely achieve attainment of the 0.08 ppm 8-hour ozone NAAQS in the Denver Metro Area and North Front Range. As demonstrated using alternative attainment test methodologies, the same WOE indicators demonstrate that there will be more certainty that the Denver region will achieve 8-hour ozone attainment in 2010 under the 2010 Control 1, and Control 2 emissions scenario. The preponderance of evidence suggests that the region will attain the standard in 2010 under the base case, Control 1, and Control 2 scenarios, but the safety margin is small.

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