Technical Support Document for the May 24, 2010, Stratospheric Ozone Intrusion Exceptional Event

Prepared by the Technical Services Program
Air Pollution Control Division
Colorado Department of Public Health and Environment
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1.0 Executive Summary.

The Colorado Department of Public Health and Environment, Air Pollution Control Division, has prepared this report for the United States Environmental Protection Agency (EPA) to demonstrate that the elevated ozone concentrations along Colorado's Front Range and the exceedance of the 8-hour National Ambient Air Quality Standard (NAAQS) for ozone at Manitou Springs on May 24, 2010, was caused by a natural event, specifically a stratospheric intrusion of ozone. This event meets the criteria outlined by the final "Treatment of Data Influenced by Exceptional Events" Rule (72 FR 13560). This report and the analysis and data contained within it clearly show that this exceptional event passed the four required tests (a) through (d) under 40 CFR 50.14 (3)(iv). These tests are:

(a) The event satisfies the criteria set forth in 40 CFR 50.1(j) which requires that an exceptional event "affects air quality, is not reasonably controllable or preventable..." and that such events are "...natural event[s]". The Exceptional Events Rule Preamble as well as 40 CFR 50 Appendices I & P specifically list stratospheric intrusions of ozone as natural events that could affect ground-level ozone concentrations.

(b) There is a clear causal relationship between the measurement under consideration and the event that is claimed to have affected the air quality in the area.

(c) The event is associated with a measured concentration in excess of normal historical fluctuations, including background; and

(d) There would have been no exceedance or violation but for the event.

The features and characteristics of an intense surface and upper level storm system over Colorado on May 24, 2010, show that a stratospheric intrusion and associated tropopause fold affected the Front Range region of Colorado and that this naturally occurring event satisfies the requirements of test (a):

1) A tropopause height as low as 500 millibars (mb) in Colorado on May 24 was anomalous and demonstrated atmospheric conditions typically associated with a stratospheric intrusion.
2) High values of Isentropic Potential Vorticity or IPV are diagnostic for the presence of stratospheric air. High IPV values close to the surface on May 24, 2010, were indicative of the presence of a tropopause fold associated with a stratospheric intrusion. Vertical cross sections of IPV for May 24 demonstrated that the fold in the tropopause extended as low as 4 to 5 kilometers above sea level over central and southern Colorado at midday, and this was well below the long-term mean of 12 kilometers for the month of May.
3) Unusually high total column ozone values as measured by satellites over Colorado on May 24, 2010, provide evidence for a lowered tropopause and conditions necessary for a stratospheric intrusion of ozone into the troposphere.
4) Deep vertical mixing in the planetary boundary layer over central Colorado and parts of the Front Range on May 24, 2010, was sufficient to mix stratospheric ozone in a tropopause fold to the surface.

5) A plot of surface dewpoint temperatures and one-hour ozone for 12:00 MST and a vertical cross section of relative humidity across the state show that dry air under the influence of a stratospheric intrusion and elevated ozone coincided temporally and spatially with several other indicators of a stratospheric intrusion event on May 24, 2010.

The conditions caused by this intense weather system also satisfy the conditions specified in test (b):

1) A strong, statistically significant relationship between local surface ozone and local IPV at the 310 degrees Kelvin potential temperature surface proves that the high surface ozone was caused by an intrusion of stratospheric air - but for the intrusion of stratospheric ozone, the high concentrations observed on May 24, 2010, would not have occurred.

Analysis of ozone monitoring data and meteorological data also prove that this event meets the requirements of test (c):

1) A statistical analysis of historical one-hour ozone concentrations for the days from May 17 through May 31 shows that the one-hour concentrations measured during the May 24, 2010, stratospheric ozone intrusion are outliers and represent a rare event.
2) Satellite-derived total column ozone over Colorado was as high as 425 to 450 Dobson Units on May 24, 2010. Values in this range are infrequent and well above the long-term mean for May of 320 Dobson Units, and this is indicative of conditions favorable for a stratospheric intrusion.
3) Tropopause heights over Colorado on May 24, 2010, were anomalously close to the earth's surface and near the 500-millibar level which is substantially lower than the May mean of 200 millibars.

Finally, the data and analyses presented in this report prove that but for the stratospheric intrusion the high ozone concentrations would not have occurred. This satisfies the requirements of test (d):

1) Time series and contours of hourly ozone on May 24, 2010, demonstrate that the peak area of elevated ozone rapidly evolved in place over the Front Range region and gradually moved to the east-northeast and diminished as the storm system moved through. Under these meteorological conditions, the locations, sequence, and short-term nature of pulses in surface ozone prove that but for a stratospheric intrusion the elevated ozone would not have occurred.
2) A strong, statistically significant relationship between local ozone and local IPV at the 310 degrees Kelvin potential temperature surface proves that the high surface ozone was caused by an intrusion of stratospheric air - but for the intrusion of stratospheric ozone, the high concentrations observed on May 24, 2010, would not have occurred.
3) Furthermore, strong winds at the surface and aloft were recorded over the area that experienced the highest ozone concentrations on May 24, 2010. High-ozone concentrations from anthropogenic sources are inconsistent with strong winds at the surface and aloft which will disperse such ozone and inhibit its build up. The analyses contained in this report show that these high concentrations were caused by natural phenomenon.

2.0 Introduction and Event Overview.

On Monday May 24, 2010, a strong spring storm system triggered an intrusion of stratospheric ozone into the lower portions of the atmosphere as it moved across Colorado. Elevated one-hour and eight-hour ozone concentrations were observed across much of Colorado (see Table 1 for ozone data for the Front Range region). There was an exceedance of the 8-hour ozone standard at Manitou Springs which recorded a maximum concentration of 76 parts per billion (ppb) and concentrations just below the 8-hour standard at several other sites. *This report will demonstrate that the stratospheric intrusion of May 24 caused the elevated ozone concentrations and that these elevated concentrations and the exceedance at Manitou Springs would not have occurred but for the transport and mixing of stratospheric ozone to the surface.*

Table 1. Maximum 1-hour and 8-hour Ozone Concentrations at Air Pollution Control Division Monitors along Colorado's Front Range on May 24, 2010.

Site	Maximum 1-hour Concentration in ppb	Maximum 8-hour Concentration in ppb
Welby	63	57
Highland	93	73
Aurora East	94	75
South Boulder Creek	71	64
Carriage	96	69
Denver Animal Shelter	86	67
Chatfield	96	75
Colorado Springs - Air Force Academy	93	74
Colorado Springs - Manitou Springs	91	76
Arvada	89	67
Welch	92	71
Rocky Flats North	76	65
NREL	*	*
Aspen Park	88	71
Fort Collins - West	75	63
Fort Collins - Rist Canyon	69	60
Fort Collins - CSU	67	58
Weld County Tower	72	64

*Missed due to ongoing site configuration.

2.1 Typical Vertical Structure of the Atmosphere as It Relates to Ozone.

For the purposes of this report we will consider three primary zones in the vertical within the atmosphere. The first of these is the troposphere. The second is the tropopause, a zone of transition between the troposphere and the third zone, the stratosphere. The troposphere is the lower portion of the atmosphere. It is the layer within which most of the weather that affects the surface occurs. Naturally occurring ozone and ozone from anthropogenic sources are found in the troposphere. The stratosphere is characterized by a deep temperature inversion that typically separates it from the troposphere. Air within the stratosphere and troposphere do not easily mix. Very high concentrations of naturally occurring ozone are found in the stratosphere, and this ozone reduces the transmittance of ultraviolet light to the surface. Consequently, it is often referred to as "good" ozone.

The depth of the troposphere at any location varies with season and the type of weather system affecting the area. It also varies with latitude. It is typically deeper near the equator and shallower at the poles. Data provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado, from their web site at http://www.esrl.noaa.gov/psd/ , indicates that the mean height of the top of the troposphere in Colorado during May is about 12 kilometers or 39,400 feet above sea level (based on NOAA National Center for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) Reanalysis data - see Kalnay et al., 1996). The top of the troposphere can be thought of as the location of the tropopause.

The NCEP/NCAR reanalysis data shows that the mean tropopause height over Denver in May is at the 198-millibar (mb) level of the atmosphere. This is based on data from 1995 through 2011. Figure 1 below shows that the mean elevation or height of the 200 mb level, which is approximately equivalent to 198 mb, in May is about 12,000 meters or 12 kilometers (~39,400 feet) above sea level. Atmospheric scientists typically report vertical levels of the atmosphere in terms of meters, kilometers, or atmospheric pressure-levels in millibars. These units will be used in this report, but data will also often be reported in feet above sea level to provide a clearer frame of reference for those not used to the units used by atmospheric scientists.

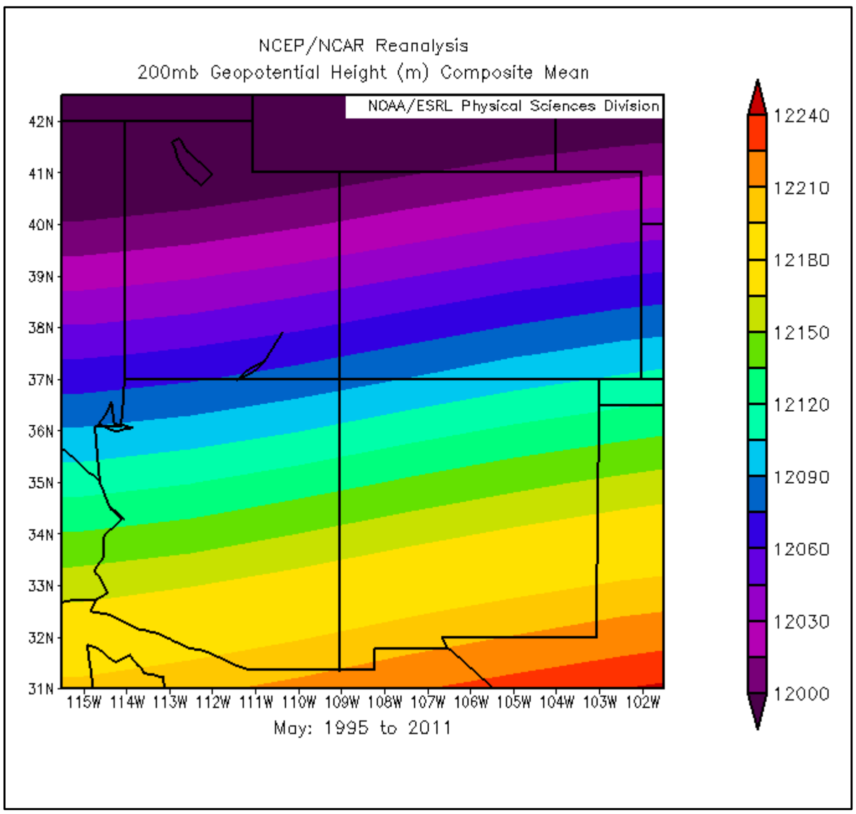

Figure 1. Mean height above sea level in meters of the 200-mb level for May based on NCEP/NCAR reanalysis data from 1995 through 2011.

This is essentially the mean height of the top of the troposphere, the bottom of the stratosphere, and the tropopause itself. (Data provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado, from their web site at http://www.esrl.noaa.gov/psd/ .)

The NOAA/ESRL Global Monitoring Division (GMD) in Boulder Colorado launches specialized weather balloons equipped with ozone monitors in Boulder on a weekly basis. These balloon systems are called ozonesondes. A plot of ozone concentrations as a function of altitude for the May 29, 2009, ozonesonde flight is shown in Figure 2 (data from NOAA ESRL GMD at: http://www.esrl.noaa.gov/gmd/ozwv/). This vertical ozone profile is close to normal for May and does not show any signs of a stratospheric intrusion event. It also highlights some of the typical features of the atmosphere in May over Colorado. On this day, the tropopause was located at about 12.75 kilometers or 12,750 meters above sea level (roughly 42,000 feet). Ozone concentrations in the troposphere below this level ranged from 30 to 90 ppb. Surface ozone was measured at 50 ppb. Ozone concentrations in the stratosphere, however, increased rapidly above the tropopause to concentrations near 8,000 ppb at 29 kilometers or about 95,000 feet above sea level.

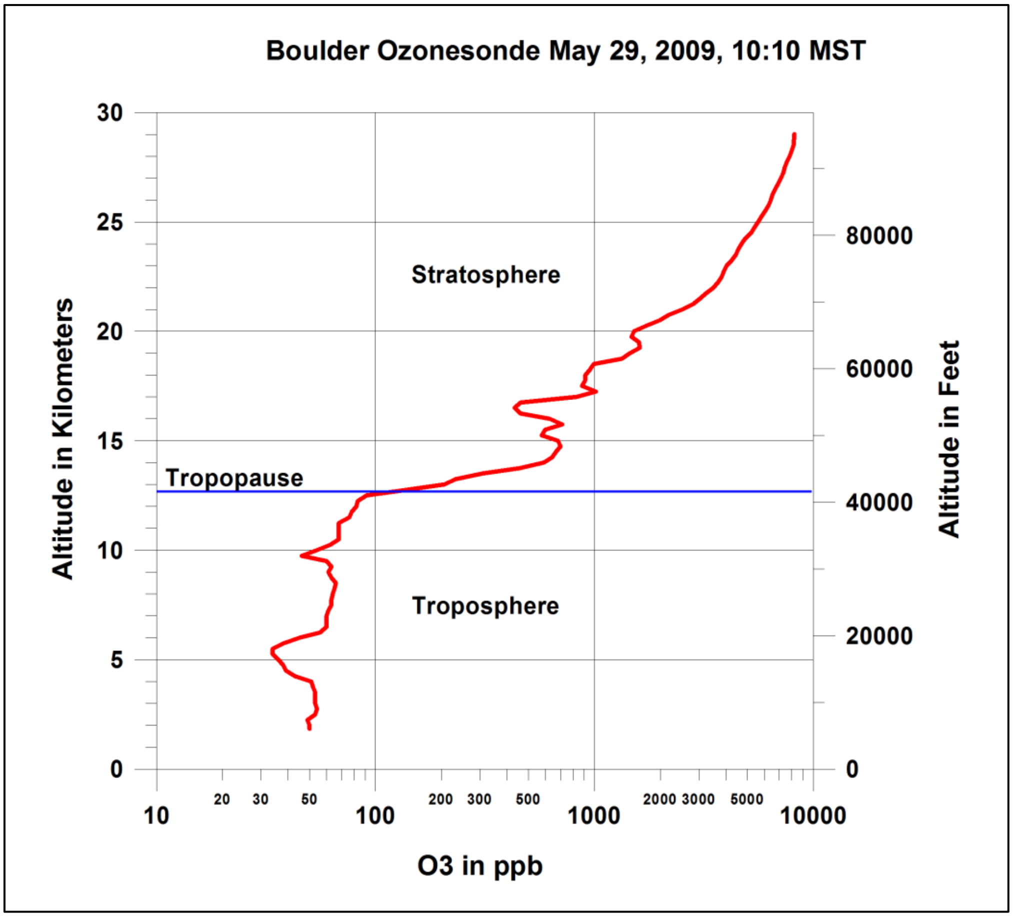

Figure 2. Vertical profile of ozone concentrations in ppb versus altitude above sea level from the May 29, 2009, Boulder ozonesonde launched at 10:10 AM MST (data from NOAA ESRL GMD at: http://www.esrl.noaa.gov/gmd/ozwv/). Ozone concentrations are plotted on a log scale to make it easier to see the full range of concentrations.

The vertical profile in Figure 2 clearly shows a pronounced separation between the stratosphere and the troposphere that keeps the very high concentrations of naturally-occurring stratospheric ozone out of the troposphere. Ordinary processes in the atmosphere do allow for some exchange of air between the troposphere and stratosphere. Many of these cause subtle changes in concentrations of ozone in the troposphere and at ground level. Some, however, can cause dramatic influxes of ozone from the stratosphere to the troposphere. The processes that lead to significant intrusions of stratospheric ozone into the troposphere are briefly discussed in the next section.

2.2 Tropopause Folds and Intrusions of Stratospheric Ozone into the Troposphere.

Folding of the tropopause can bring a tongue or lobe of stratospheric air downward into the troposphere in the wake of strong upper level storm systems or troughs. According to Holton et al. (1995), a tropopause fold is "a process in which a thin band of stratospheric air intrudes more or less deeply into the troposphere…" This phenomenon and its relationship to ozone has been the subject of many research papers including classic papers by Danielsen (1968) and Shapiro (1980). In the mid-latitudes of the northern hemisphere, it is most likely to occur in the spring. The folding and descent of the tropopause typically occurs south and southwest of the surface and upper-level low pressure systems and behind the advancing cold front associated with a strong spring storm (Browning et al., 2000). This folding and descent of stratospheric air into the troposphere brings with it dry stratospheric air, stratospheric ozone, and other chemical constituents and atmospheric properties associated with the stratosphere (Browning et al., 2000; Danielsen, 1968; and Shapiro, 1980). These chemical constituents and properties are often diagnostic of the intrusion itself in the context of the path and progression of a storm system across an area.

One of the most important diagnostic properties of a stratospheric intrusion is isentropic potential vorticity or IPV. This property is a function of a parcel of air's rotation and its static stability. In the absence of heating or friction, IPV is conservative. In other words, a parcel of air will have the same IPV as it flows from one location to another. IPV therefore serves as a tracer for stratospheric air. IPV is high in the stratosphere and low in the troposphere. As a fold in the tropopause introduces stratospheric air into the troposphere, the intruding air will often maintain high values of IPV.

IPV has arcane units, but it is usually represented in terms of potential vorticity units or PVU. Air in the troposphere typically has IPV values of about 1 PVU or less. For atmospheric scientists studying the tropopause, the boundary between the stratosphere and the troposphere, the most common choice of values of IPV considered to be representative of the tropopause is 2 PVU (Kunz et al., 2011). Kunz et al. (2011) have found that IPV at the tropopause can vary between 1.5 and 5.0 PVU. For the sake of simplicity, however, we will use IPV values of 2 PVU and higher as indicators of air originating from the tropopause surface or the stratosphere; and this is consistent with many published studies (e.g., Sprenger et al. (2003), and Liniger and Davies (2003)). It will be shown that PVU values in excess of 2 were found at relatively low altitudes within the troposphere during the intrusion event of May 24, 2010.

Another atmospheric property that can be used to characterize intrusion events is potential temperature. Potential temperature is the temperature of a parcel of air if compressed to sea level pressure without adding or subtracting energy. Potential temperature tends to increase with altitude, and it is typically reported in units of degrees Kelvin (K). Kunz et al. (2011) have shown that at 40 degrees north latitude or the approximate latitude of Colorado's Front Range, the tropopause tends on average to be near the 330 K potential temperature surface during the months of March, April, and May. In June, July, and August, the tropopause at this latitude tends on average to be between the 340 K and 350 K surfaces. For late May, one would expect that on average the tropopause would be somewhere between the 330 K and 340 K potential temperature surfaces in the atmosphere. It will be shown that the tropopause dipped well below these levels during the intrusion event of May 24, 2010, and that plots of isentropic potential vorticity on the 310 K potential temperature surface show a pronounced intrusion over Colorado.

The work of Langford et al. (2009) demonstrates that stratospheric intrusions can cause elevated ozone along Colorado's Front Range and exceedances of the National Ambient Air Quality Standards (NAAQS):

> "A deep tropopause fold brought 215 ppbv of O3 to within 1 km of the highest peaks in the Rocky Mountains on 6 May 1999. One-minute average O3 mixing ratios exceeding 100 ppbv were subsequently measured at a surface site in Boulder, and daily maximum 8-hour O3 concentrations greater or equal to the 2008 NAAQS O3 standard of 0.075 ppmv were recorded at 3 of 9 Front Range monitoring stations. Other springtime peaks in surface O3 are also shown to coincide with passage of upper level troughs and dry stable layers aloft. These results show that the stratospheric contribution to surface ozone is significant, and can lead to exceedance of the 2008 NAAQS O3 standards in a major U.S. metropolitan area."

Langford and coauthors describe events that occurred in April and May of 2009 that are likely very similar to the event in question in this report. The State of Wyoming Department of Environmental Quality/Air Quality Division (No Date) has also documented exceedances of the 8-hour NAAQS in May of 2007 at South Pass in Wyoming caused by a similar intrusion phenomenon.

Langford and coauthors indicate that their "findings support the conclusion of Lefohn et al. (2001) that" intrusions "can lead to high surface O3 events in the western U.S. during springtime that exceed current NAAQS standards." Other scientists (Karyampudi et al., 1996) have shown that localized or mesoscale tropopause folding occurs along the Front Range. The passage of a storm system across the mountain barrier leads to a leeward, wave-pattern enhancement of the intrusion east of the Divide. Data presented in this report will show that the pattern of high ozone concentrations in Colorado on May 24, 2010, is consistent with enhanced folding and downward mixing and transport of stratospheric ozone on the eastern side of the Continental Divide. The Air Pollution Control Division believes that enhanced intrusions just east of the Front Range have been observed on a number of occasions during the spring in the last several years. Because the May 24 event followed the classic pattern of a Colorado stratospheric intrusion and because of the abundance of supporting data available for this event, the analysis that follows will likely serve as a model for a number of events that have been recorded since 2010.

2.3 Synoptic Meteorological Features of The May 24, 2010, Stratospheric Intrusion.

On May 24, 2010, at 12:00 PM MDT or 11:00 PM MST a deep surface low pressure system was located just to the north of Denver near the Colorado-Wyoming border. Figure 3 below shows the location of the 992-mb surface low at 11:00 MST based on initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid North American Model (NAM12). A dry air surge is apparent over the Front Range just behind a cold front which was moving through Eastern Colorado. Relative humidity dropped to 20% and lower behind the front. Strong surface pressure gradients were present over the Northern Front Range. Figure 4 provides a close-up view of the surface features with the surface low north of Denver, the cold front in eastern Colorado with dry air behind it, and wind flow vectors showing strong southwesterly to west-southwesterly downslope flow south of the low.

A close-up view of the 700-mb features (at roughly 9,840 feet MSL in central Colorado) is presented in Figure 5. In addition to very strong southerly flow ahead of the surface cold front, this plot shows strong westerly to southwesterly downslope flow of 40 to 50 knots along the Front Range south of Denver and north of the Colorado-New Mexico state line.

The surface low was associated with an intense and fast-moving upper-level trough. Figure 6 shows the 500-mb features from the 18Z NAM12 initial analysis for 11:00 MST. The trough, which was moving toward the northeast, was located over Colorado with its axis running from northwest Colorado through southeastern Colorado. Figure 6 also shows those winds at 500 mb that were above 60 knots (69 mph). A zone of strong winds was at the center of the trough over eastern Colorado, with speeds between 60 and 100 knots (69-115 mph). Figure 7 presents the streamlines or flow directions for winds at 500 mb at 11:00 MST. Winds over central and eastern Colorado at this jet stream level were from the south through southwest. The 500-mb level was at approximately 18,300 feet MSL in central Colorado.

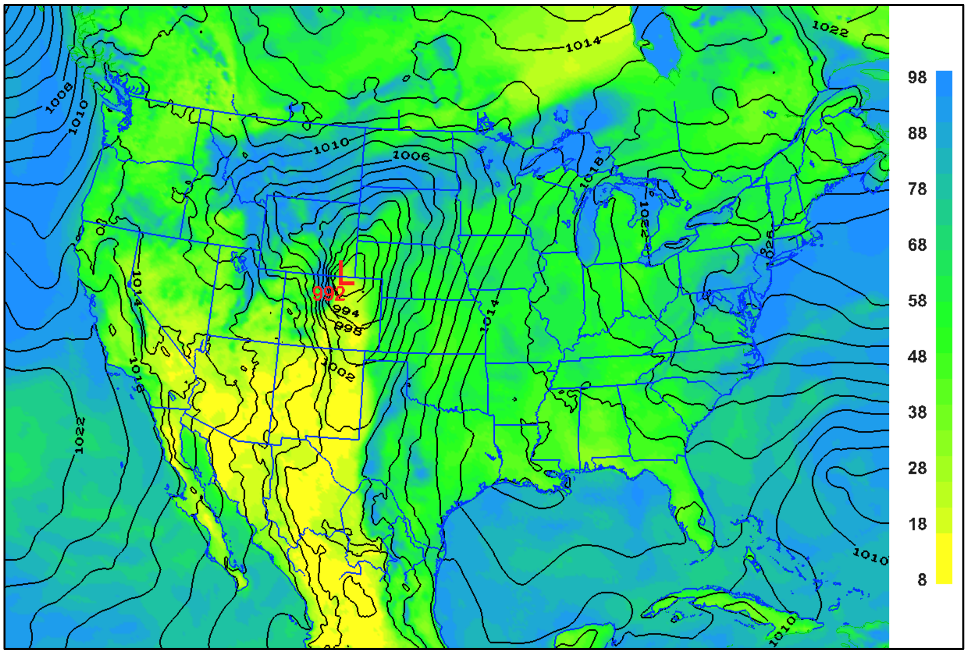

Figure 3. Mean seal-level pressure contours and relative humidity in percent (right scale) at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

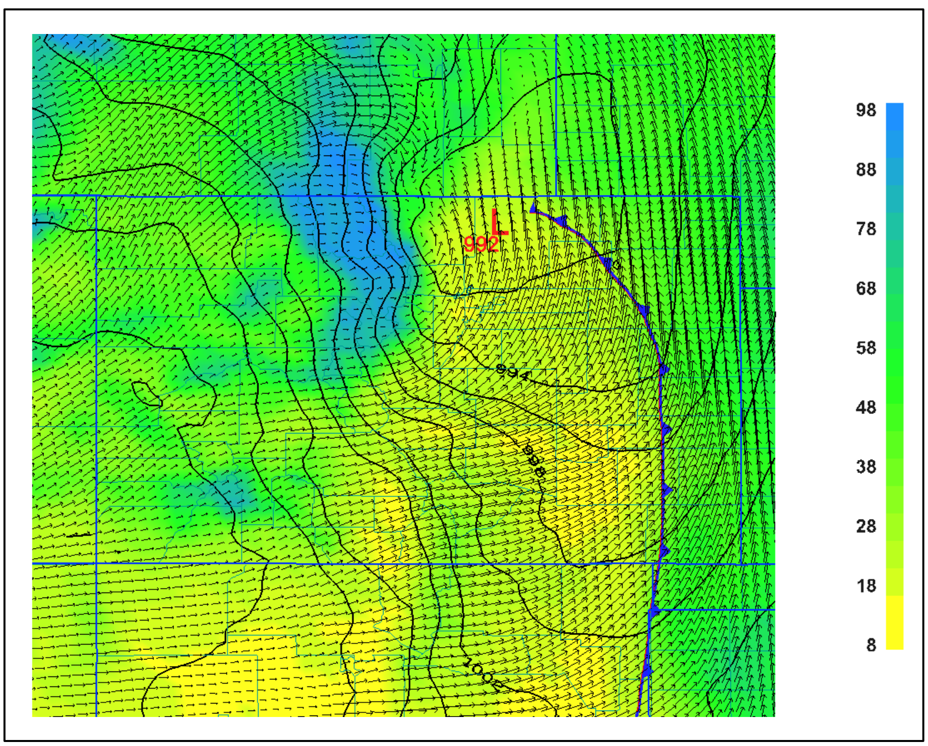

Figure 4. Mean seal-level pressure contours, relative humidity in percent (right scale), wind flow vectors, and cold front over Colorado at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

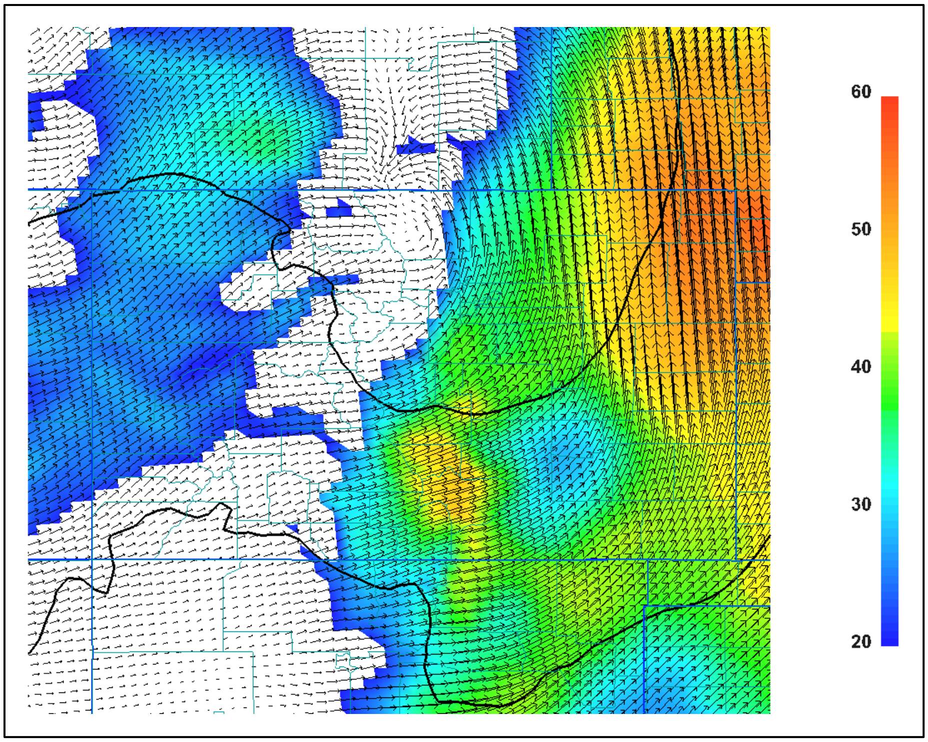

Figure 5. 700 mb geopotential height contours, those wind speeds between 20 and 60 knots (right scale, 23-69 mph), and wind flow vectors over Colorado at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

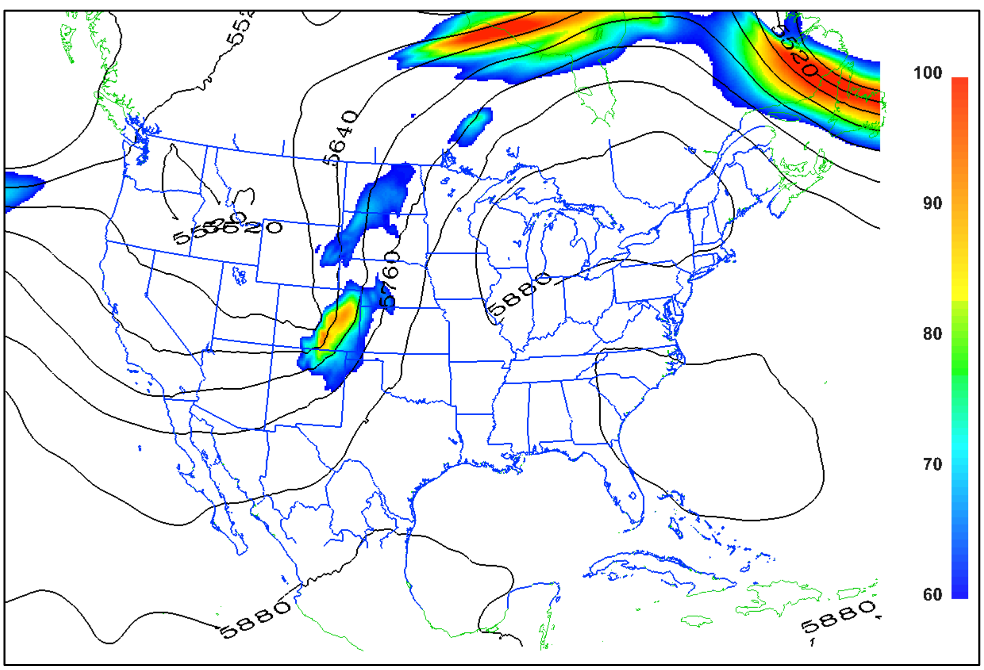

Figure 6. 500-mb geopotential heights in meters and wind speeds in knots (right scale, only those above 60 knots or 69 mph are plotted) at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

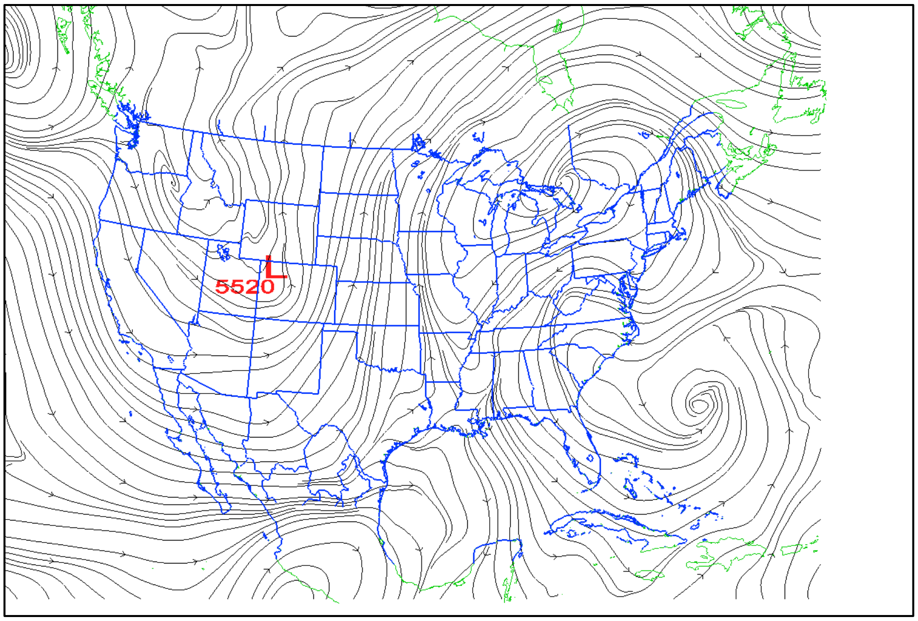

Figure 7. 500-mb wind streamlines and flow directions at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

The 11:00 MST analysis for the 250-mb level is presented in Figure 8. This is also from the 18Z initial analysis of the 18Z NAM12 model. This map shows the geopotential heights in meters and those wind speeds above 75 knots (86 mph). Winds over central and eastern Colorado at this jet stream level were generally between 75 and 100 knots (86-115 mph). Streamlines or wind flow directions for 250 mb at 11:00 MST are presented in Figure 9. At this level of the atmosphere, the trough is also crossing Colorado with an axis tilted along a northwest to southeast line. The 250-mb level was at approximately 34,450 feet MSL in central Colorado.

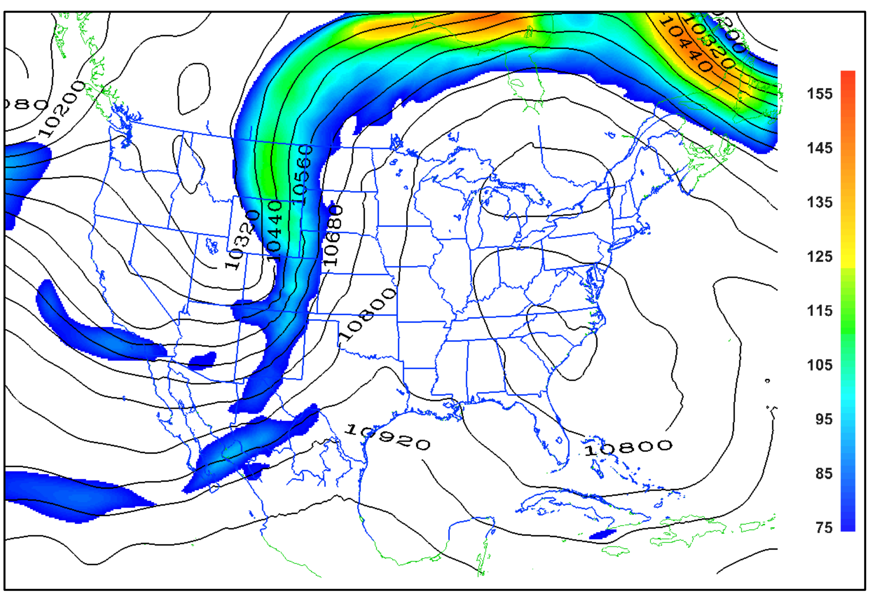

Figure 8. 250-mb geopotential heights in meters and wind speeds in knots (right scale, only those above 75 knots or 86 mph are plotted) at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

Taken together, the surface, 700 mb, 500 mb and 250 mb features show a focus of atmospheric energy and winds over Colorado. Based on patterns evident in these features and the idealized model for the location of an intrusion (Browning et al., 2000) , one would expect to observe an intrusion over central Colorado. Figures 10 and 11 show the surface wind gusts recorded in Colorado between 10:45 and 11:00 MST, and 11:45 and 12:00 MST, respectively. Winds routinely gusted between 40 and 60 mph across a wide area of eastern Colorado as the storm passed through. Cross-mountain flow at the surface and 700-mb level and extending as high as the 600-mb level may have contributed to a mountain wave and enhanced mesoscale tropopause folding in central Colorado. The area of enhanced downslope winds east of the mountains, the dry surface air in this region, and the zone of highest surface ozone described in Section 2.4 support the idea that mesoscale tropopause folding was responsible for high ozone concentrations in central Colorado. *Strong winds at the surface and aloft were recorded over the area that experienced the highest ozone concentrations. High-ozone concentrations from anthropogenic sources are inconsistent with strong winds at the surface and aloft which will disperse such ozone and inhibit its build up.*

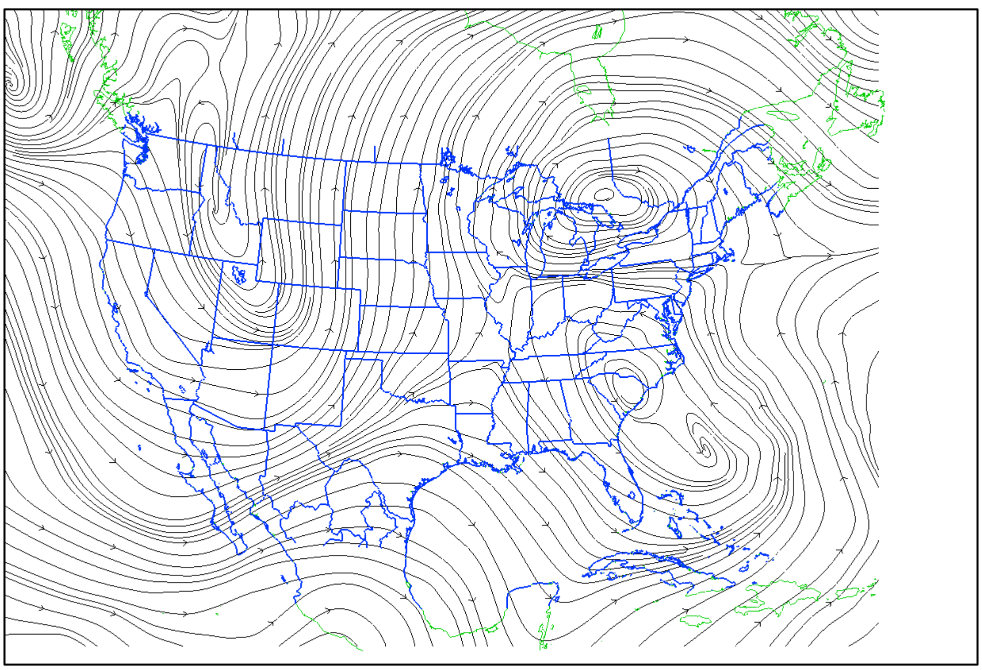

Figure 9. 250-mb wind streamlines and flow directions at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

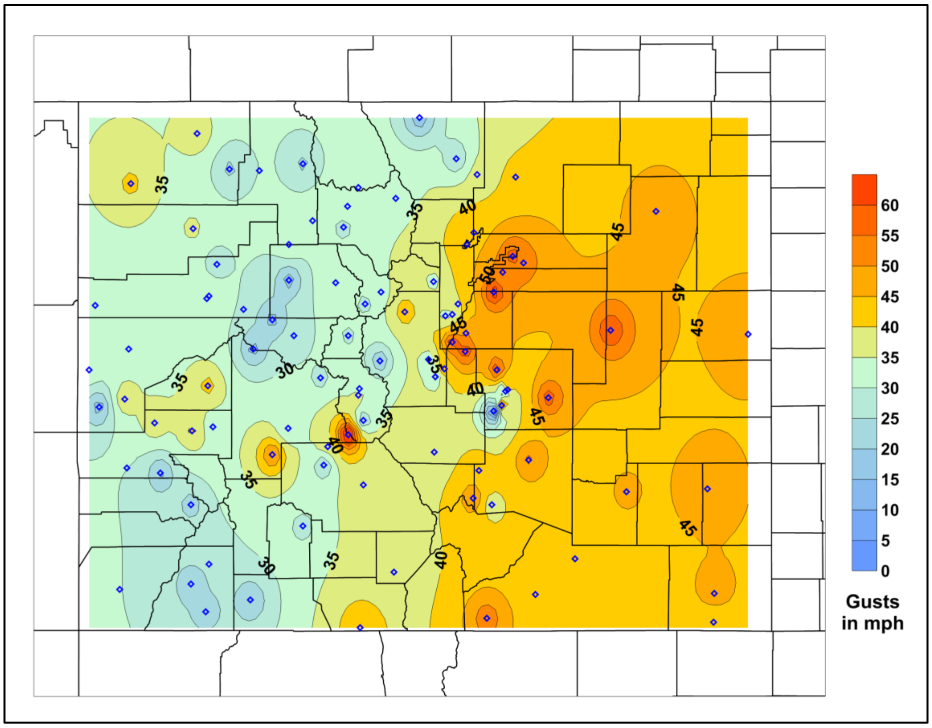

Figure 10. Contours of surface wind gusts in mph between 10:45 and 11:00 MST on May 24, 2010, from the University of Utah's MesoWest web products (http://mesowest.utah.edu/index.html). Weather station locations are indicated with blue diamonds.

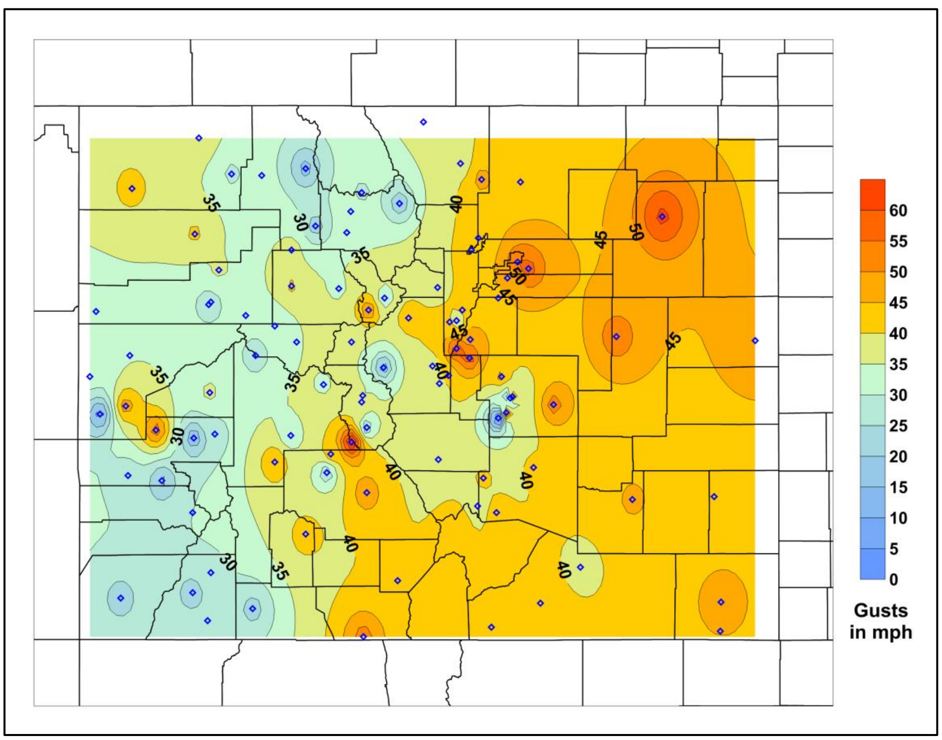

Figure 11. Contours of surface wind gusts in mph between 11:45 and 12:00 MST on May 24, 2010, from the University of Utah's MesoWest web products (http://mesowest.utah.edu/index.html). Weather station locations are indicated with blue diamonds.

2.4 Diagnostic Evidence for High Surface Ozone Concentrations Directly Caused by the May 24 Stratospheric Intrusion.

A variety of data provides additional diagnostic evidence for the presence of a stratospheric intrusion and surface ozone of stratospheric origin in Colorado on May 24, 2010. The first of these is tropopause height. The height of the tropopause is typically much lower within an upper-level trough and lower still within a tropopause fold. Figure 12 shows the height of the tropopause in terms of pressure levels from the NOAA/NCEP Rapid Update Cycle (RUC) run at 17Z for forecast hour 19Z on May 24, 2010. That would be forecast conditions for 12:00 MST. Only tropopause heights low enough to be in the 315 to 515 mb level are plotted. The first thing that is apparent in this plot is that a zone of lowered tropopause heights (tropopause and stratosphere closer to the ground) is aligned with the upper level trough shown in several figures in Section 2.3. The second factor of note is the presence of a small area of tropopause heights as low as 500 mb in central Colorado. Here the RUC model has captured the area of the state where the tropopause fold occurred.

Recall from Section 2.2 that the mean location of the tropopause in May in Colorado is at the 200 mb level. *A tropopause height as low as 500 mb in Colorado in May is an anomaly and demonstrates conditions typically associated with a stratospheric intrusion.*

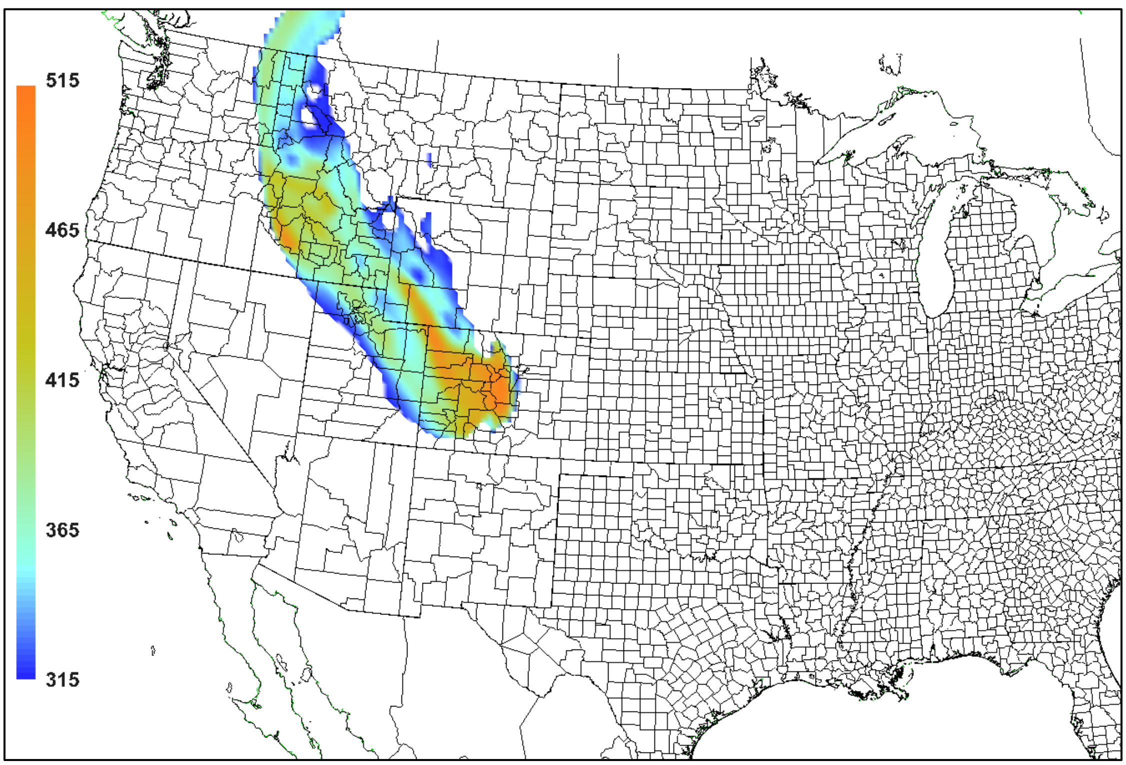

Figure 12. Height of the tropopause in terms of pressure levels from the NOAA/NCEP Rapid Update Cycle (RUC) run at 17Z for forecast hour 19Z on May 24, 2010. Only tropopause heights low enough to be in the 315 to 515 mb level are plotted.

Vertical cross sections of the atmosphere across Colorado at the time of the event also show the presence of the tropopause fold over the center portion of the state. Figures 13, 14, and 15 present isentropic potential vorticity or IPV on west-to-east transects along the Wyoming border, in the center of Colorado, and along the New Mexico border, respectively. These plots are based on the initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid NAM12 model. They represent conditions at 12:00 MST. Only IPV values greater than 2 PVU are plotted. As indicated in Section 2.2, IPV values greater than 2 indicate air of stratospheric origin.

It is apparent in all three cross sections that the tropopause (the 2 PVU level as discussed in Section 2.2) is generally below 10,000 meters or 10 kilometers MSL over much of the region. This is consistent with the lowered tropopause within the upper-level trough. The cross sections show discrete tongues or layers of folding extending as low as 4,000 to 5,000 meters or 4 to 5 kilometers MSL. Figure 14 shows that the heart of the intrusion was in central Colorado and as low as 13,000 feet MSL, or at mountain top level in the central Rockies. *Vertical cross sections of IPV demonstrate that the fold in the tropopause extended as low as 4 to 5 kilometers above sea level over central and southern Colorado at midday on May 24, 2010, and this was well below the long-term mean of 12 kilometers for the month of May*.

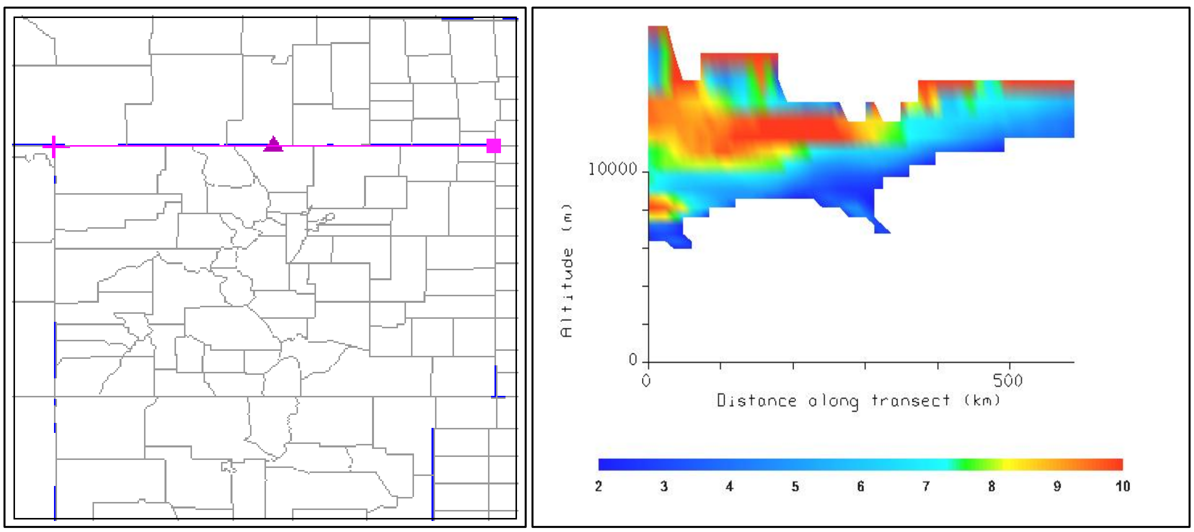

Figure 13. Vertical cross-section of IPV in the atmosphere along the Colorado-Wyoming border (location shown in left panel) in PVU values of 2 or greater as a function of altitude above sea level in meters - based on the initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid NAM12 on May 24, 2010.

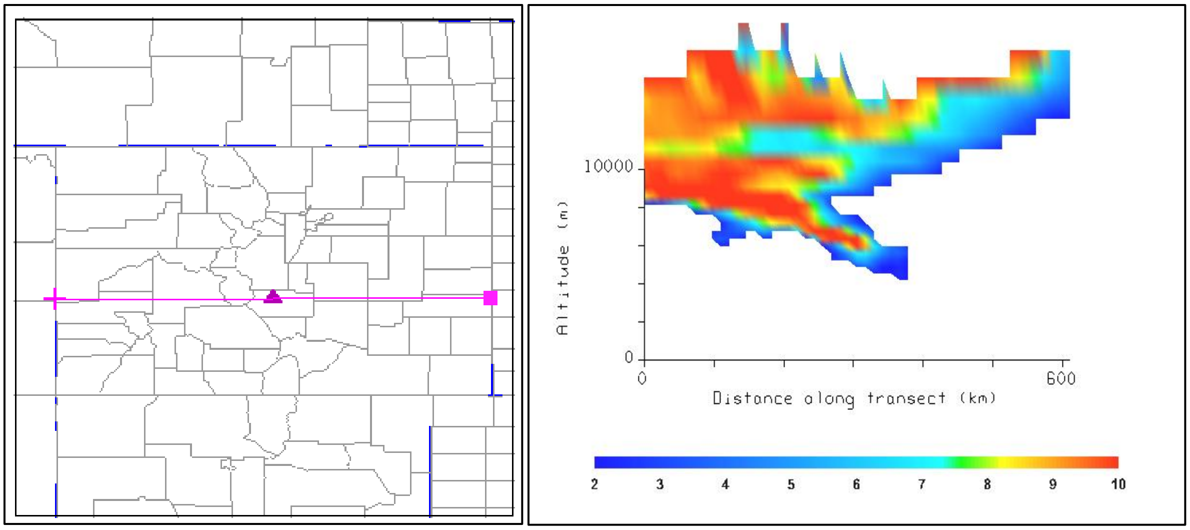

Figure 14. Vertical cross-section of IPV in the atmosphere in central Colorado (location shown in left panel) in PVU values of 2 or greater as a function of altitude above sea level in meters - based on the initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid NAM12 on May 24, 2010.

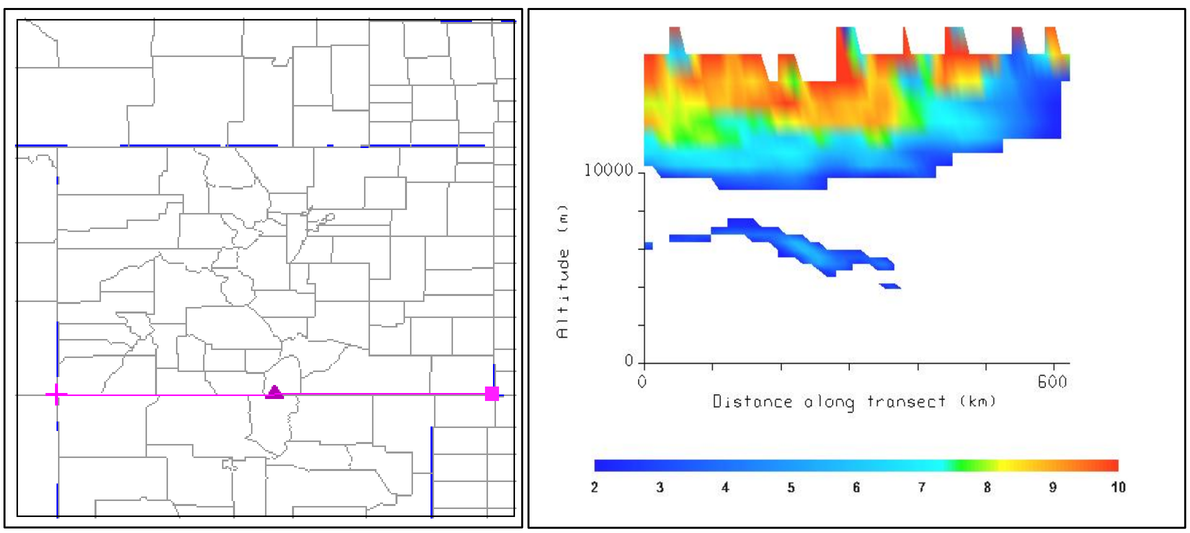

Figure 15. Vertical cross-section of IPV in the atmosphere along the Colorado-New Mexico border (location shown in left panel) in PVU values of 2 or greater as a function of altitude above sea level in meters - based on the initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid NAM12 on May 24, 2010.

Another set of indicators for the occurrence of a stratospheric intrusion of ozone in Colorado on May 24 are maps of total atmospheric column ozone derived from satellite measurements from the Global Ozone Monitoring Experiment 2 (GOME2) and Ozone Monitoring Instrument (OMI) satellite measurement systems. Total column ozone is higher within upper-level troughs and storm systems (Danielsen, 1968, and Krueger, 1989). A simple but partial explanation for this is that the ozone-rich stratosphere occupies a greater fraction of the vertical column in troughs where the tropopause is lower and the stratosphere is thicker. Higher concentrations of ozone are therefore closer to the ground in upper-level troughs, and tropopause folds typically extend downward from areas of higher total column ozone.

GOME2 total column ozone for May 24, 2010, is shown in Figure 16. This map was provided by the NOAA Satellite and Information Services National Environmental Satellite, Data and Information Service (NOAA NESDIS) at this site: http://www.osdpd.noaa.gov/ml/air/gome.html . The data show a lobe of increased total ozone aligned with the upper-level trough discussed in Section 2.3. Values as high as 425 to 450 Dobson Units (or DU, a standard measure of total column ozone) were measured in the western half of Colorado. Figure 17 shows the total column ozone from the OMI system (Veefkind et al., 2006) for May 24. The OMI data are Level 3 or at the third level of data quality assurance. Total column ozone is enhanced along the axis of the upper-level trough and is as high as 400 to 450 DU where the trough crosses Colorado.

Newchurch et al. (2003) report a monthly mean total ozone value of about 320 DU for May for Boulder, Colorado, based on May data from 1997 through 2001. Data from the NOAA ESRL Global Monitoring Division (http://www.esrl.noaa.gov/gmd/index.html) for 2000 through 2009 in Figure 18 show that values in the 400 to 450 DU range are infrequent and tend to occur in the winter and spring. High values of total ozone and tropopause folding can occur fairly frequently in the winter but are less likely to affect surface ozone concentrations because the surface atmosphere can often be decoupled during the winter months. *Unusually high total column ozone values over Colorado on May 24, 2010, provide evidence for a lowered tropopause and conditions necessary for a stratospheric intrusion of ozone into the troposphere.*

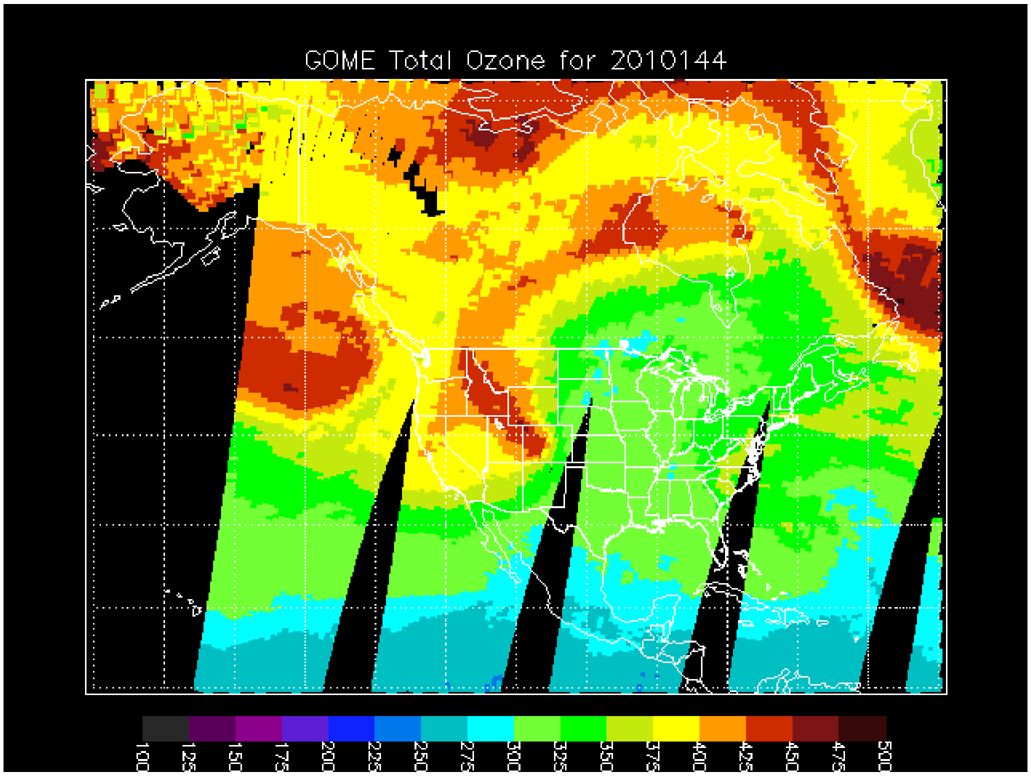

Figure 16. GOME2 total column ozone in Dobson Units for May 24, 2010, showing a band of high ozone along the upper-level trough (source: http://www.osdpd.noaa.gov/ml/air/gome.html)

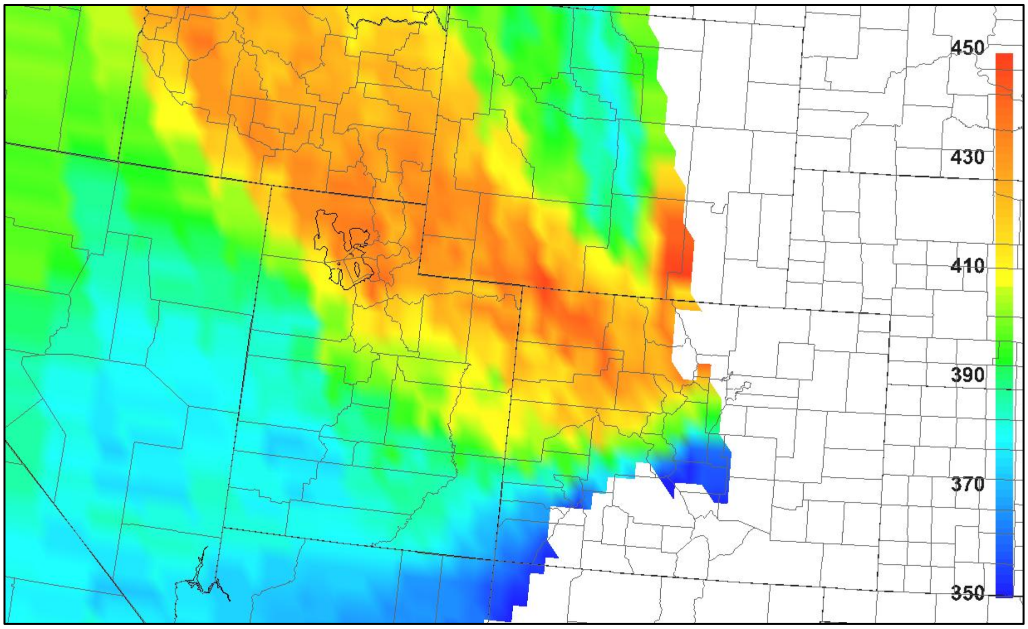

Figure 17. OMI Level 3 total column ozone in Dobson Units for May 24, 2010, showing a band of high ozone along the upper-level trough (only values above 350 Dobson Units are plotted).

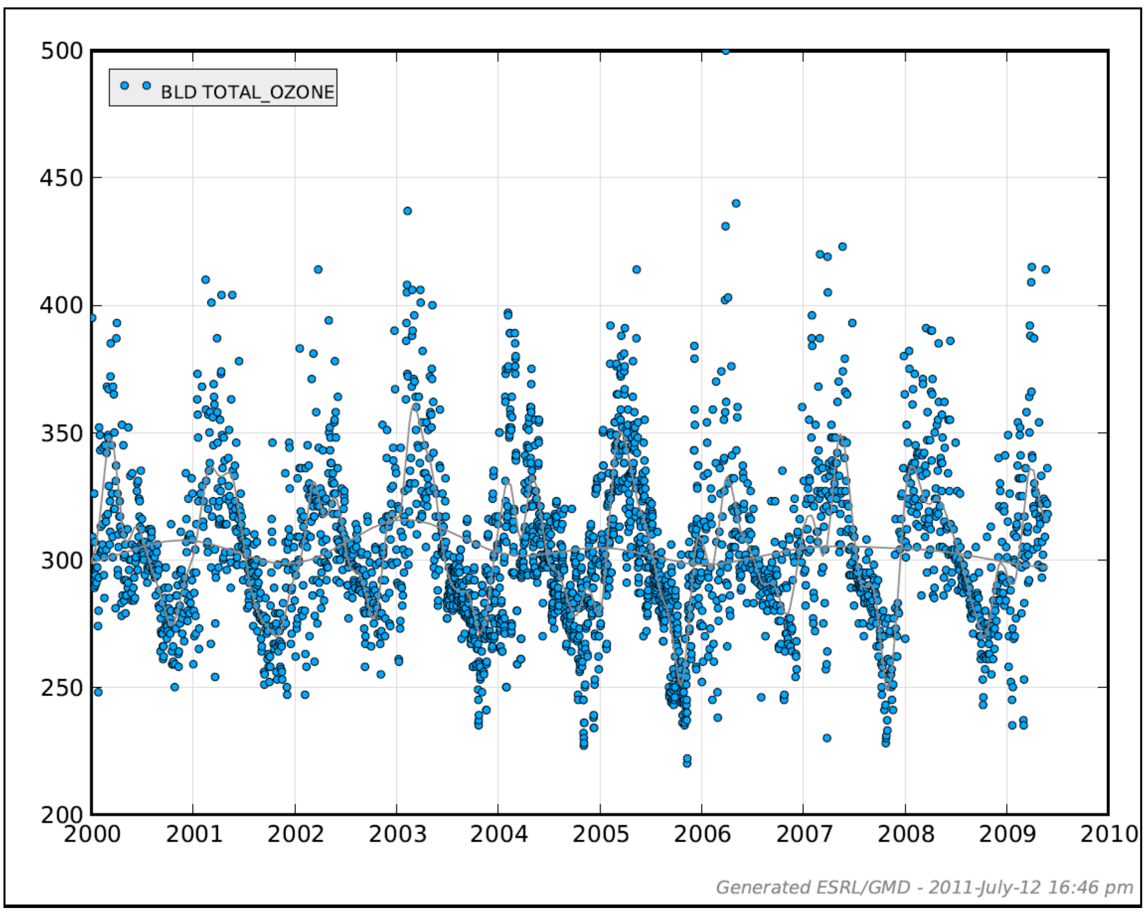

Figure 18. Total column ozone in Dobson Units for Boulder, Colorado, for 2000-2009 courtesy of the NOAA ESRL Global Monitoring Division (http://www.esrl.noaa.gov/gmd/index.html).

Figure 19 shows the IPV at 1200 MST, mean sea level pressure at 11:00 MST, and planetary boundary layer (PBL) height above ground at 11:00 MST on May 24. The IPV values are for the 310 K surface from the NOAA/NCEP Global Data Assimilation System (GDAS) run at 18Z and forecast hour 1 or 12:00 MST. The mean sea level pressure and PBL data are from the 18Z initial analysis of the 18Z NAM12 for 11:00 MST. Only values greater than 2 PVU are contoured. The PBL is the depth of the surface mixed layer. The map shows that a zone of deep vertical mixing occurred in the same area as the zone of anomalously lowered tropopause height, excess winds, and, as will be shown later in this section, increased surface ozone. As shown in Figure 14, the tropopause height above sea level (4 to 5 kilometers) was within reach of the vertical mixing in the PBL which extended 3 to 6 kilometers above the terrain which is generally at 1.6 to 3 kilometers above sea level in the area where high ozone concentrations were measure. *Deep vertical mixing in the planetary boundary layer was sufficient to mix stratospheric ozone in a tropopause fold to the surface.*

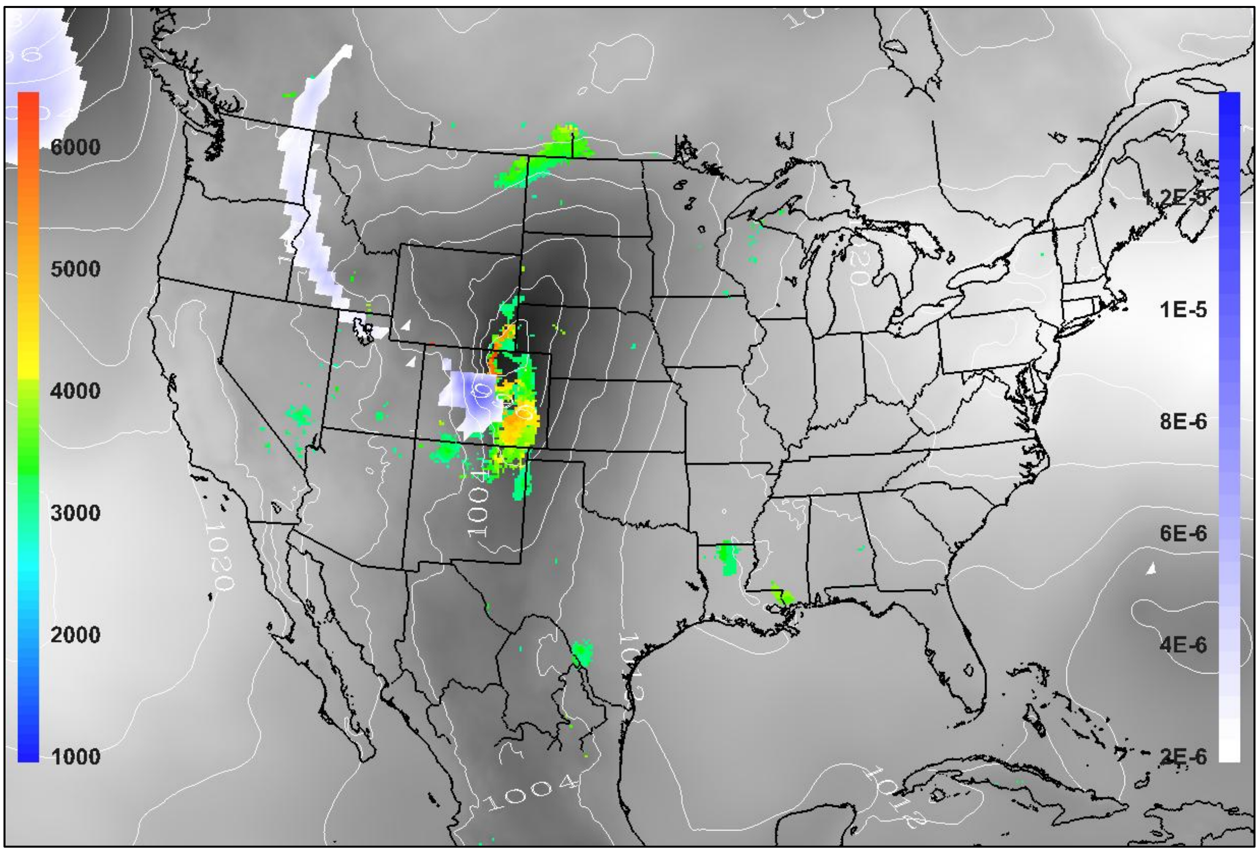

Figure 19. Isentropic Potential Vorticity greater than 2 PVU at the 310 K surface from the 18Z run of GDAS 0.5 degree by 0.5 degree model for 12:00 MST May 24, 2010, shaded in blue (right scale in native IPV units of °K kg^{-1} m^2 s^{-1}); mean sea level surface pressure in mb (white contour lines and gray shading); and planetary boundary layer height or depth of mixed layer above the ground in meters for values greater than 3000 meters (rainbow color gradients and left scale) at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model.

Stratospheric intrusions and tropopause folds bring dry air from the stratosphere to the troposphere and the surface (see Section 2.2). Consequently, we would expect to see dry air at the surface in the wake of an intrusion. Contours of surface dewpoint temperatures in degrees Fahrenheit between 11:45 and 12:00 MST on May 24, 2010, from the University of Utah's MesoWest web products (http://mesowest.utah.edu/index.html) and posted values of one-hour average ozone in ppb at hour ending at 12:00 MST across Colorado are presented in Figure 20. Very low dewpoints in the range of 0 to -24 Fahrenheit are common from Jefferson County south to the New Mexico border. Figure 21 presents a vertical cross section of relative humidity across the middle of Colorado at 11:00 MST on May 24, 2010, from the 18Z initial analysis of the 18Z NAM12 model. This cross section shows very dry air in a lowered stratosphere with dry surface air over central Colorado. *A plot of surface dewpoint temperatures and one-hour ozone for 12:00 MST and a vertical cross section of relative humidity across the state show that dry air under the influence of a stratospheric intrusion and elevated ozone coincided temporally and spatially with several other indicators of a stratospheric intrusion event on May 24, 2010.*

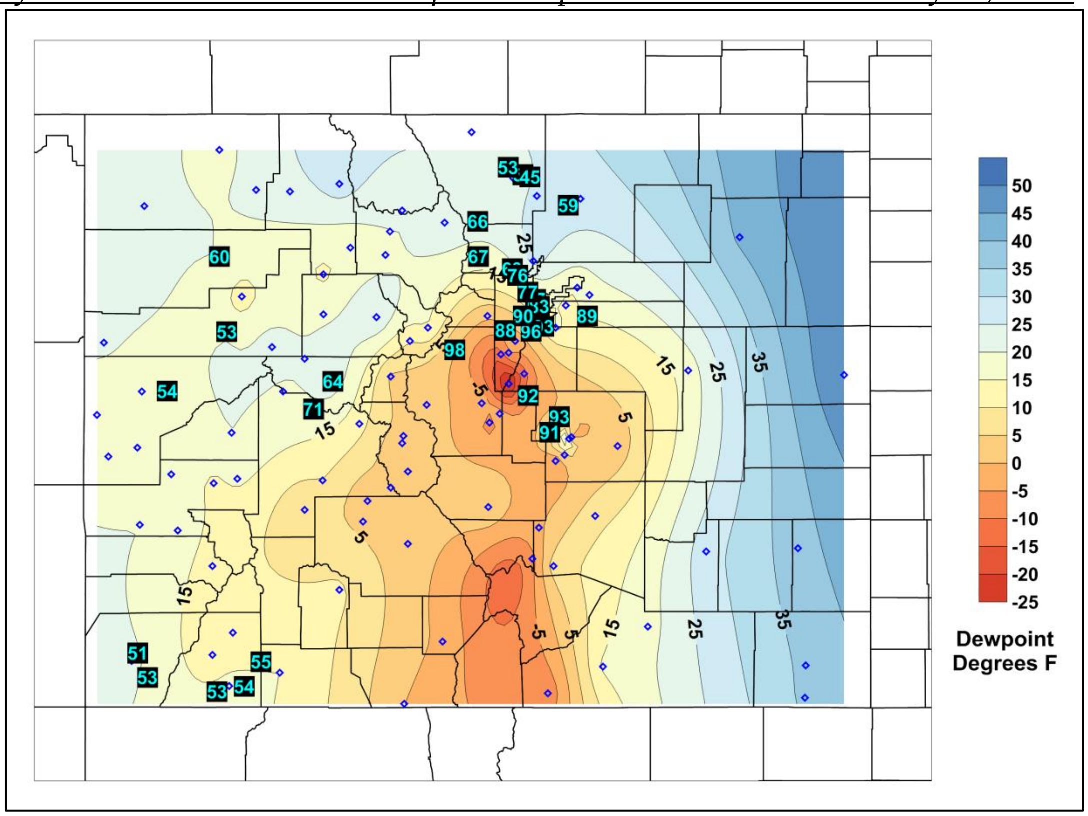

Figure 20. Contours of surface dewpoint temperatures in degrees Fahrenheit between 11:45 and 12:00 MST on May 24, 2010, from the University of Utah's MesoWest web products (http://mesowest.utah.edu/index.html) and one-hour average ozone in ppb (square labels) at hour ending at 12:00 MST across Colorado. Weather station locations are indicated with blue diamonds.

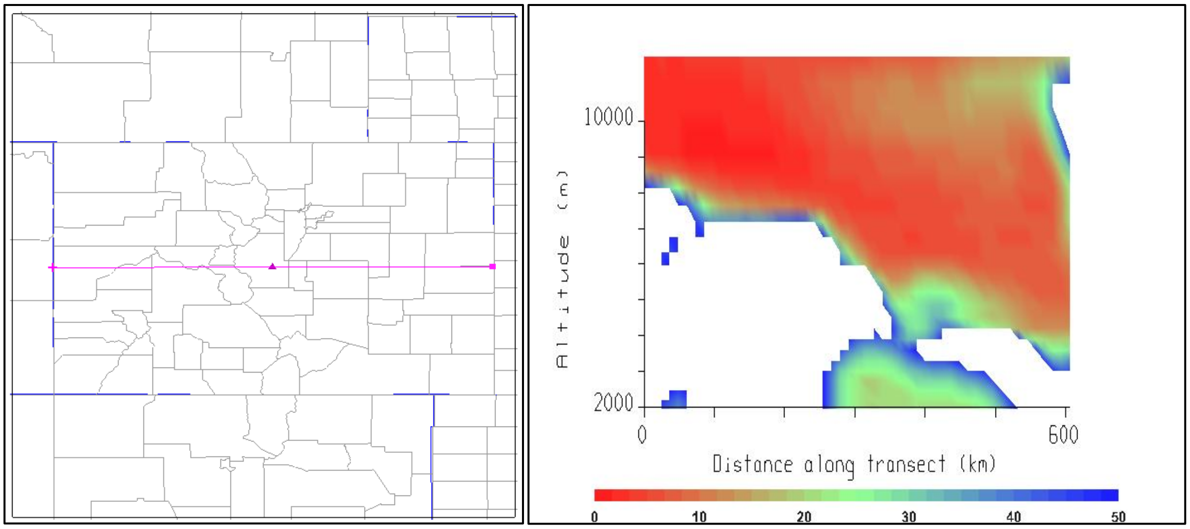

Figure 21. Vertical cross-section of relative humidity in percent (only values in the range of 0 to 50% are plotted – bottom color bar) relative to altitude above sea level in meters in the atmosphere in central Colorado (location shown in left panel) - based on the initial analysis data from the 18Z run of the NOAA/NCEP 12-kilometer grid NAM12 on May 24, 2010.

A plot of IPV in PVU units at the 310 K potential temperature surface or isentrope and one-hour ozone concentrations in ppb at 12:00 MST on May 24, 2010, is presented in Figure 22. The IPV values are from the 18Z run of GDAS 0.5 degree by 0.5 degree model for 12:00 MST May 24, 2010. As indicated in Section 2.2, the normal range of potential temperatures for the tropopause might be expected to be 330 to 340 K in May. This plot shows that the tropopause was much lower. In addition, high one-hour concentrations of ozone tend to be highest near the core of the intrusion.

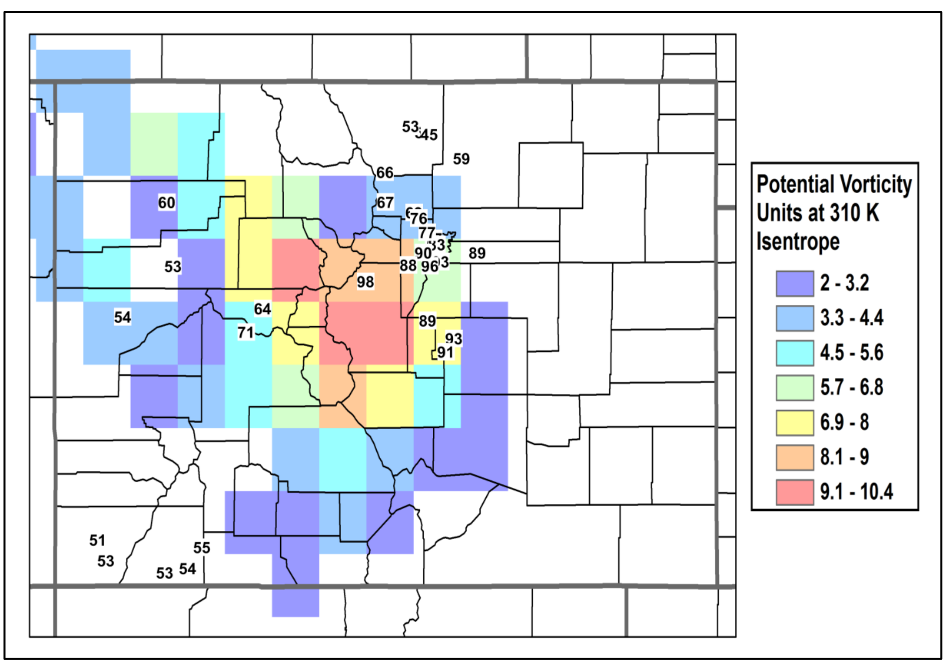

Figure 22. IPV in PVU units at the 310 K potential temperature surface or isentrope and one-hour ozone concentrations in ppb at 12:00 MST on May 24, 2010. The IPV values are from the 18Z run of GDAS 0.5 degree by 0.5 degree model for 12:00 MST May 24, 2010.

The Air Pollution Control Division has compared the modeled GDAS IPV and one hour ozone concentrations for 12:00 MST at each monitor in Figure 22. A linear regression provided the best fit with an r-squared value of 0.71, and the results of the regression are shown in Figure 23. The linear fit shows a strong relationship between local IPV at 310 K and local ozone, and this fit is statistically significant at the 95% confidence level. High ozone is generally associated with IPV values greater than 2 PVU and increases more or less linearly with increasing IPV. _The statistically significant relationship between local surface ozone and local IPV at the 310 degrees Kelvin potential temperature surface proves that the high surface ozone was caused by an intrusion of stratospheric air - but for the intrusion of stratospheric ozone, the high concentrations observed on May 24, 2010, would not have occurred._

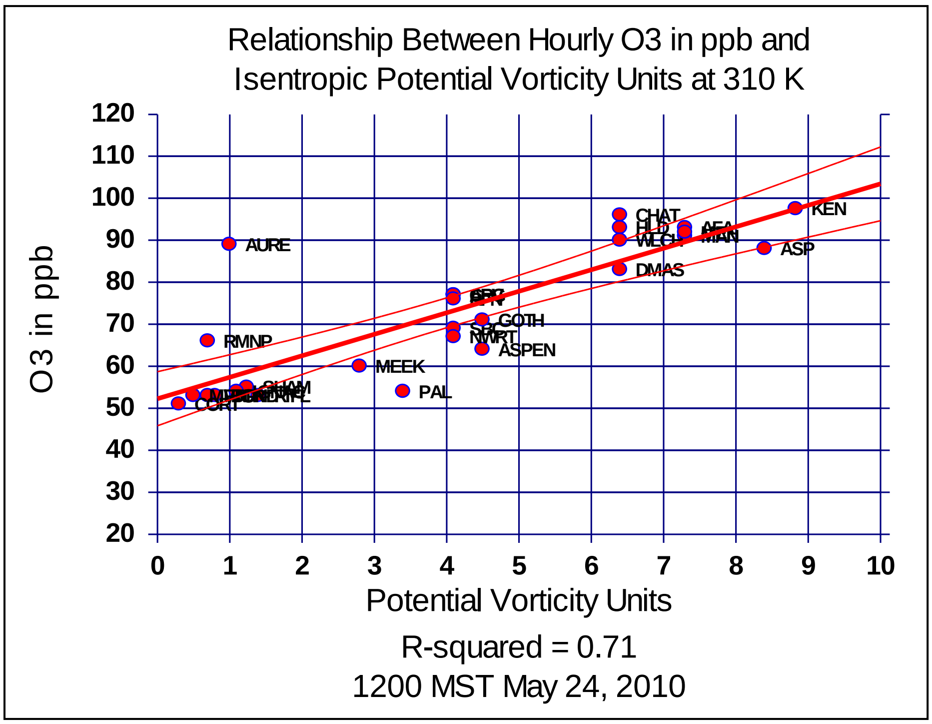

Figure 23. Linear regression between one-hour ozone concentrations and modeled GDAS IPV for 12:00 MST for 27 surface ozone monitoring sites in Colorado on May 24, 2010.

An analysis of time series of hourly ozone concentrations on May 23 and 24 provides additional clues about the progression, timing, and nature of the elevated ozone associated with this intrusion. Figure 24 shows the hourly times series for May 23-24, 2010, at Fort Collins West (FTCW), Great Basin National Park (GBNP, at 6,760 feet MSL), Dinosaur National Monument (DNM), and Kenosha Pass (KEN, at 10,180 feet MSL). GBNP is operated by the National Park Service (NPS) and is located in extreme east-central Nevada where the upper-level trough would have had an effect earlier than in Colorado. DNM is also operated by the NPS and is located in Utah just across the Colorado border in northwestern Colorado. Kenosha Pass is operated by the U.S. Forest Service and located in Park County southwest of Denver.

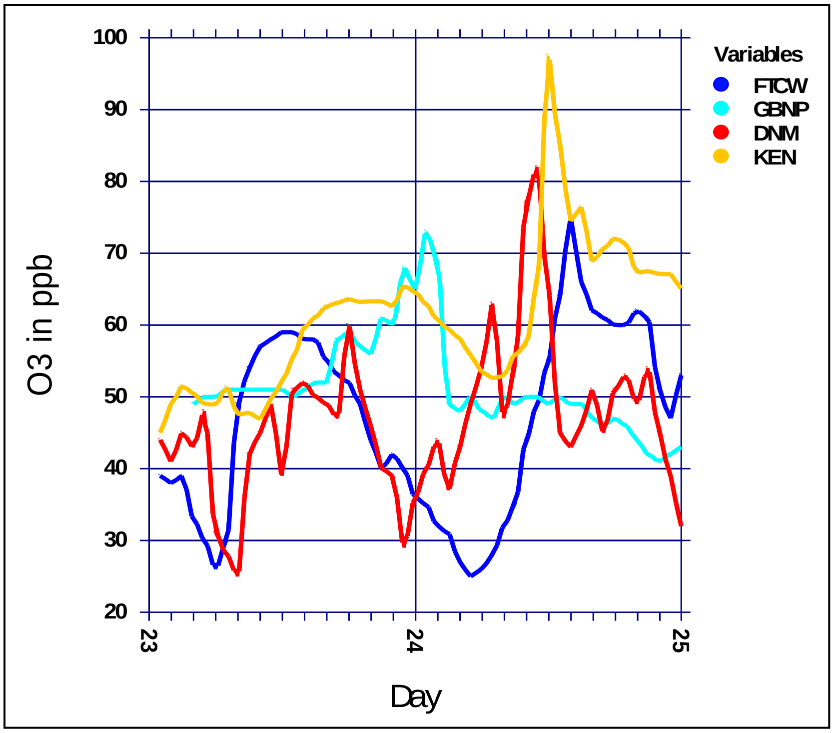

Figure 24. Time series of hourly average ozone concentrations in ppb for May 23-24, 2010, at Fort Collins West (FTCW), Great Basin National Park (GBNP), Dinosaur National Monument (DNM), and Kenosha Pass (KEN) - time in MST and concentrations for hour ending at time.

Ozone began to climb at GBNP in Nevada at 16:00 MST on May 23 and spiked with a peak of 73 ppb at 01:00 MST on May 24 before recovering at around 03:00 MST. At DNM near the Utah-Colorado border, ozone began to climb early in the morning on May 24 and peaked at 82 ppb at 11:00 MST. The rapid climb in ozone at KEN began late in the morning, and ozone peaked at 98 ppb for the hour ending at 12:00 MST. FTCW had the latest peak with 75 ppb at 14:00 MST. The time series in Figure 25 are for Colorado Front Range monitoring sites and Gothic, Colorado, a central Colorado site at 9,600 feet MSL operated by the EPA CASTNET program. The timing, shape, and duration of the ozone intrusion signature are similar for each of these sites, with peak ozone occurring between 12:00 and 14:00 MST. Site altitude and peak ozone concentrations are not well correlated for this event. This supports the hypothesis that a mesoscale wave phenomenon contributed to a region of high ozone that included the Front Range and adjacent plains. The lee-wave enhanced tropopause fold likely moved closer to the surface as it passed to the east of the Continental Divide and the crest of the Front Range mountains.

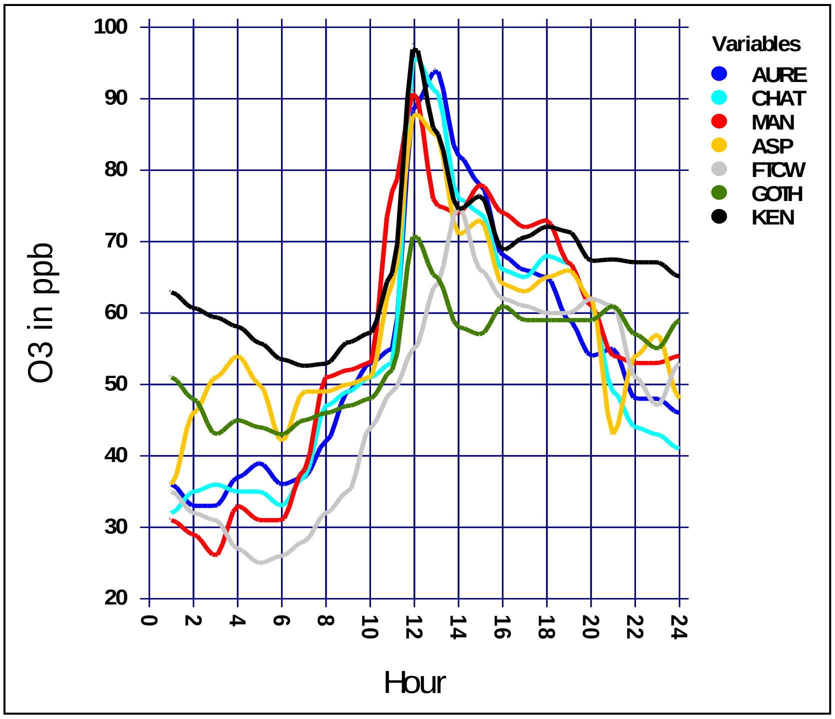

Figure 25. Time series of hourly average ozone concentrations in ppb for May 24, 2010, at Aurora East (AURE) Chatfield Reservoir (CHAT), Manitou Springs (MAN), Aspen Park (ASP), Fort Collins West (FTCW), Gothic (GOTH), and Kenosha Pass (KEN)) - time in MST and concentrations for the hour ending at the indicated time.

The fast increase in ozone and rapid development and resolution of a short-term spike seen in Figures 24 and 25 are also diagnostic for an intrusion when the meteorological conditions are consistent with tropopause folding and a lowered tropopause. Fifteen-minute average ozone data for Kenosha Pass showed an increase from 61 ppb to 115 ppb in just 75 minutes as air from the fold reached the surface. That's an unusual increase of 54 ppb. While dramatic, short-term spikes can be associated with anthropogenic ozone, they are typically not found across a wide area. In addition, the spikes seen in Figures 24 and 25 are in synch with the location and progression of the meteorological features indicative of an intrusion.

Contours of hourly ozone also support the idea that a mesoscale intrusion brought peak impacts along the Front Range. Figures 26 through 29 show contours of the hourly ozone concentrations for hours 11:00 MST through 14:00 MST, respectively. These are based on the available data for the sites shown in Figures 20 and 22. Some smoothing associated with the Kriging contouring algorithm has reduced some of the peak concentrations discussed above. *Time series and contours of hourly ozone on May 24 demonstrate that the peak area of elevated ozone rapidly evolved in place over the Front Range region and gradually moved to the east-northeast and diminished as the storm system moved through. Under these meteorological conditions, the locations, sequence, and short-term nature of pulses in surface ozone prove that but for a stratospheric intrusion the elevated ozone would not have occurred.*

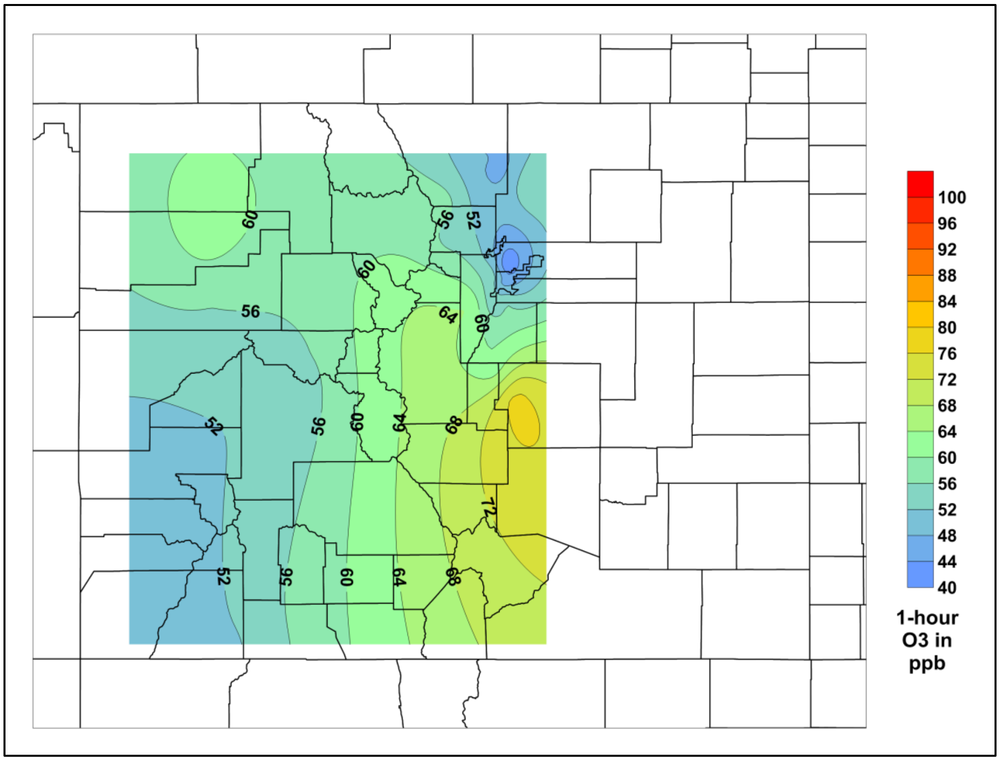

Figure 26. Contours of one-hour ozone concentrations in ppb for the hour ending at 11:00 MST, May 24, 2010.

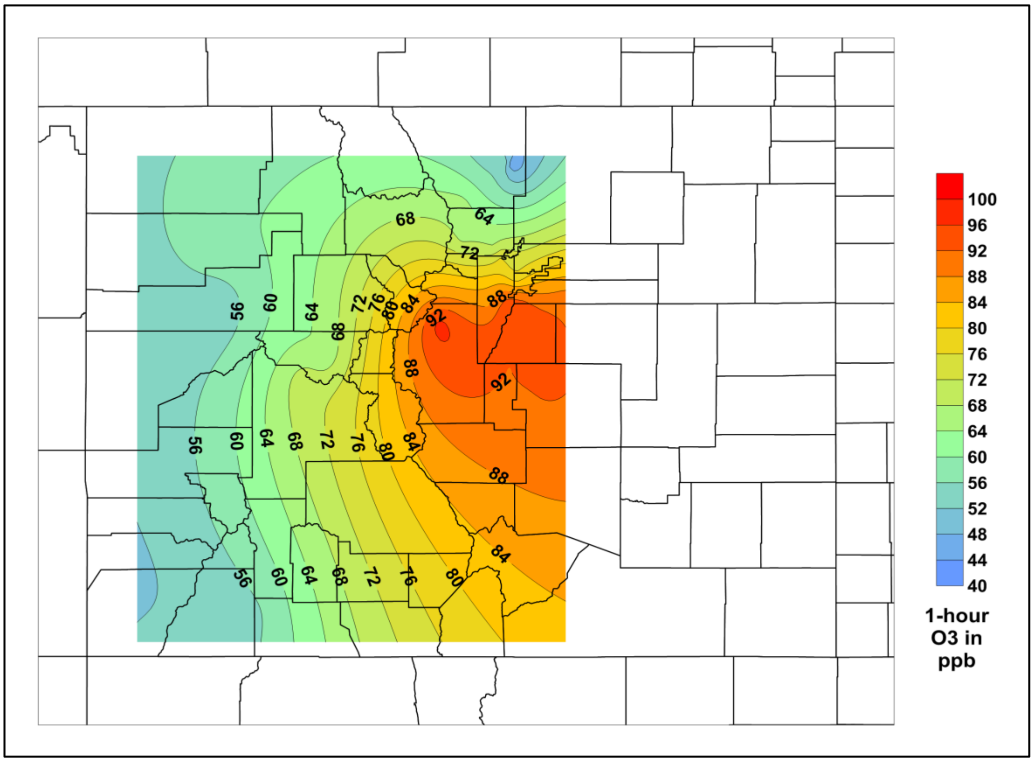

Figure 27. Contours of one-hour ozone concentrations in ppb for the hour ending at 12:00 MST, May 24, 2010.

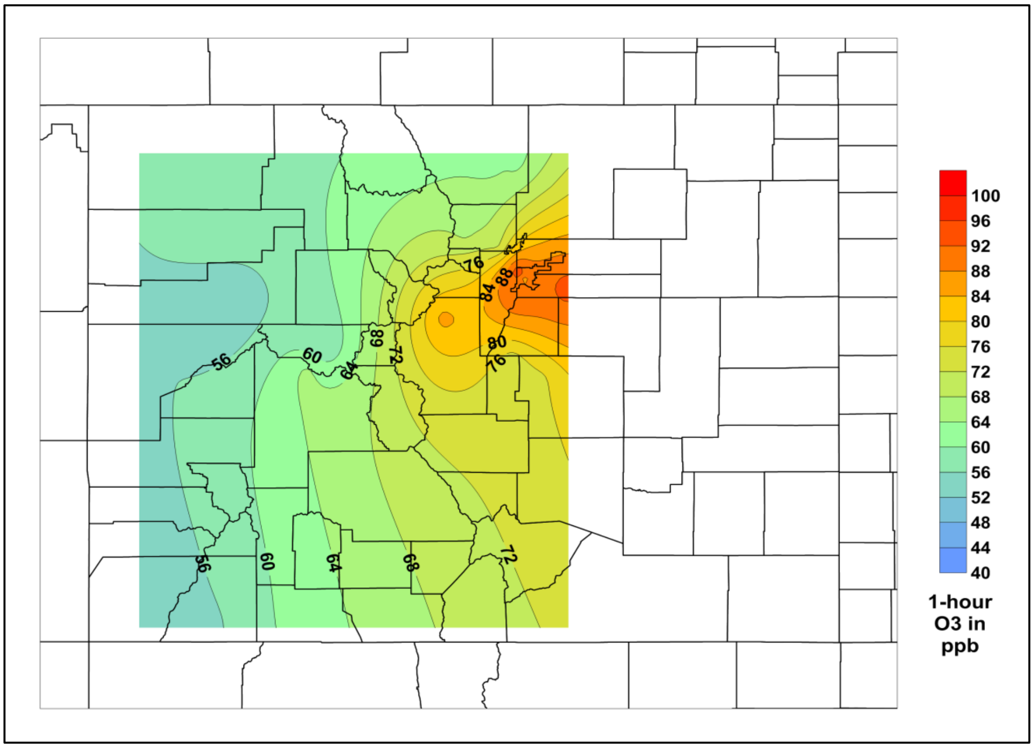

Figure 28. Contours of one-hour ozone concentrations in ppb for the hour ending at 13:00 MST, May 24, 2010.

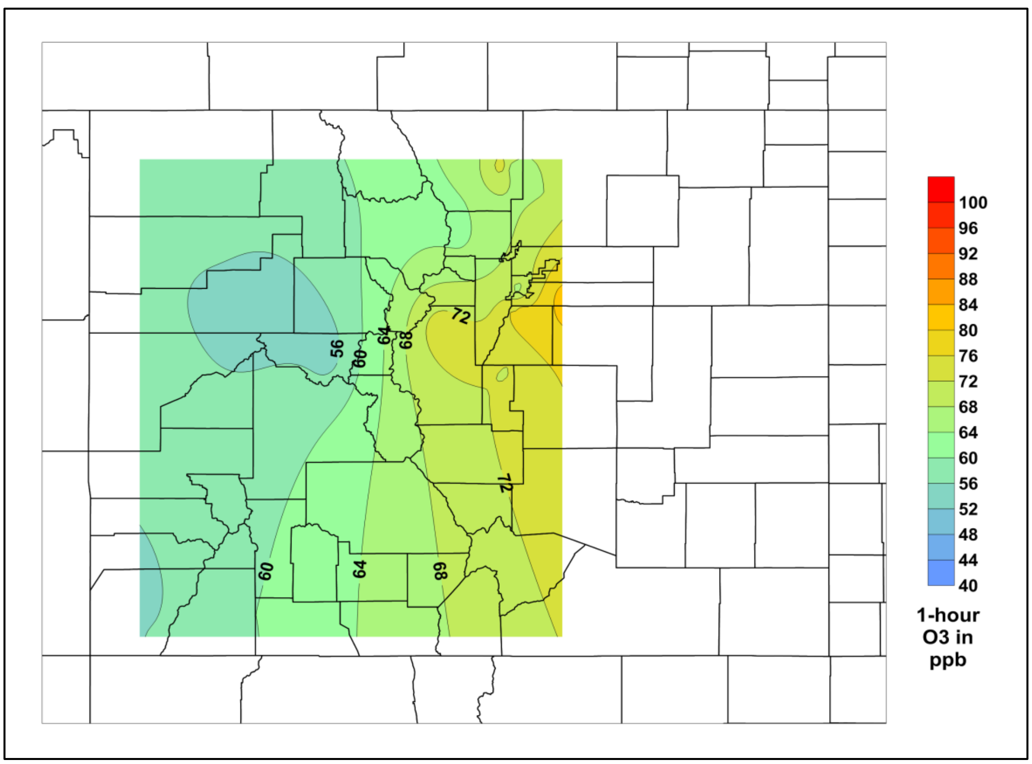

Figure 29. Contours of one-hour ozone concentrations in ppb for the hour ending at 14:00 MST, May 24, 2010.

3.0 Air Pollution Control Division Ozone Monitoring Data and Statistics

On May 24, 2010 the Colorado Front Range area experienced a Stratospheric Ozone Intrusion (SI). Evidence of this is seen in the values listed in Table 2. The table lists the ozone concentrations at each of the Air Pollution Control Division (APCD) Front Range sites beginning at 09:00 and ending at 21:00 Mountain Standard Time (MST) on the day in question. The data used were compiled from the one-hour average ozone concentrations obtained from the EPA Air Quality System (AQS) database. The yellow shaded boxes show the values that were submitted to AQS with an "RO" Qualifier Code, indicating an SI had occurred. The numbers that are bolded in the yellow shaded boxes are the maximum one-hour values recorded by the monitors during the time period in question. They are also listed in the "1-Hr Max" column at the far right of the table. When data are flagged in the AQS database they are given a code based on the reasoning for its flagging. In this instance, an "RO" code indicates that a natural event has occurred, in the form of an SI.

The major evidence for the intrusion is meteorological, and has to do with the timing of the tropopause fold itself. Once that timing was established, the determination on the start and end times of the data affected by the intrusion was made by looking for large jumps in concentration near those times. At many of the sites the intrusion is marked by ten ppb or larger changes in concentration from one hour to the next. However, since a ten ppb jump can occur routinely during an anthropogenic ozone event, it is necessary to perform a supporting meteorological analysis for the parallel identification of the intrusion event. For many of the sites the start of the intrusion can be clearly seen.

As an example, the Chatfield site recorded the largest hour to hour concentration change with a increase of 43 ppb from 10:00 to 11:00. Figure 30 shows a graph of the one-hour ozone concentrations at Chatfield for May 23rd, 24th and 25th. The blue line shows the average of the historical one-hour concentrations (from midnight on May 23rd to 23:59 on May 25th, from the startup date of the monitor through 2009) and the red line shows the one-hour concentrations during the event (from midnight on May 23rd, 2010 to 23:59 on May 25th, 2010). The start of the intrusion is easy to spot, as the large jump in concentration is seen going from the 10:00 to 11:00 hour on May 24. The 2010 concentrations for the days before and after the event follow the same general pattern as the historical concentrations.

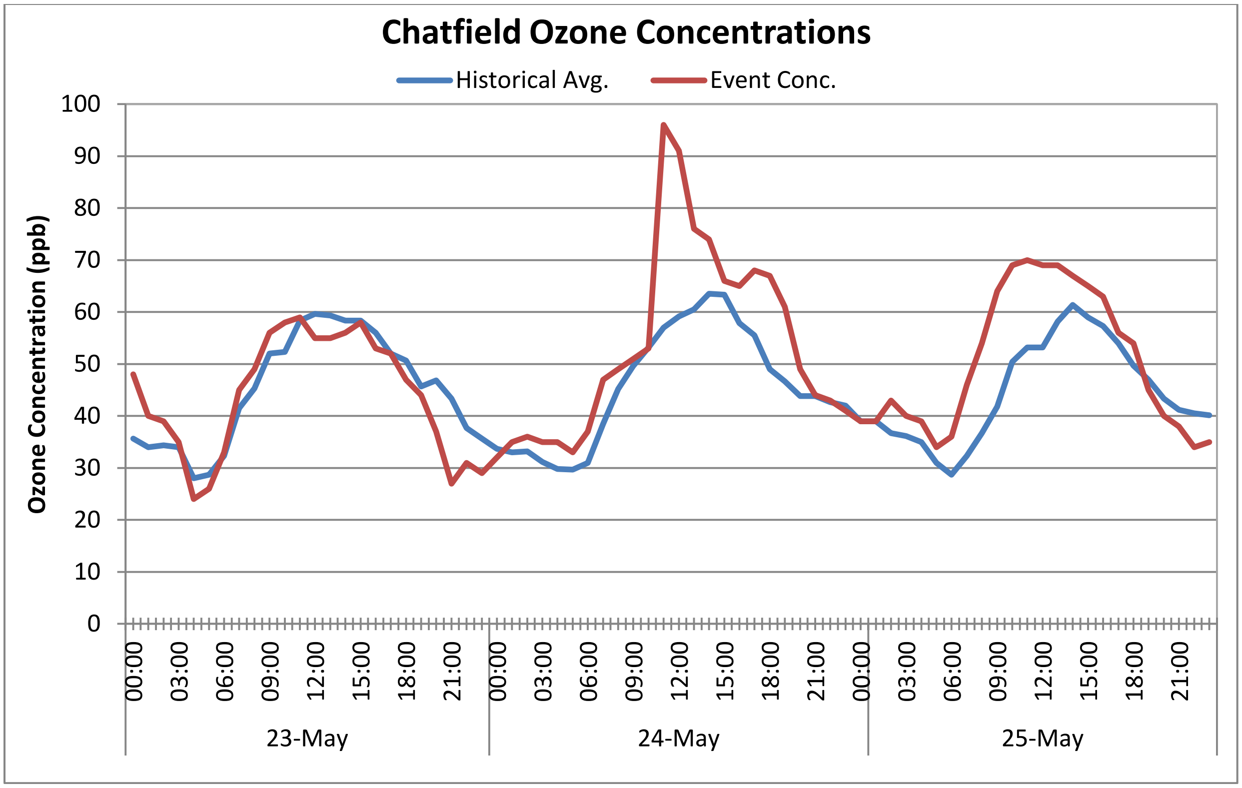

Figure 30. Chatfield Ozone Concentrations

The maximum one-hour ozone concentration recorded at APCD monitors along the Front Range was 96 ppb at two sites, Carriage and Chatfield, and is indicated in the table as red bolded values in the "1-Hr Max" column. Both sites are in the Denver Metro area. Five other sites recorded concentrations that were greater than 90 ppb. Three sites recorded concentrations between 80 and 89 ppb, with four sites recording concentrations between 70 and 79 ppb, and the three remaining sites recording maximum values of 63 to 69 ppb. All but two of the sites recorded maximum one-hour concentrations between 11:00 and 13:00. These two sites are NREL and Welby. The maximum concentration at Welby was recorded at 15:00. The maximum there likely would have been recorded during the time period the others were, but the instrument was offline for maintenance from 11:00 to 13:00. The concentrations recorded there in the hours following the ozone maximums are similar to those recorded by the other instruments. As for NREL, no data was recorded for the time period because the site was being reconfigured.

The data show that the intrusion hit the more southerly Front Range monitors first, and then expanded northeastward, which matches what was noted in the meteorological analysis. The southern monitors of Chatfield, Highlands, CO Springs – Air Force Academy, CO Springs – Manitou, and Aspen Park all had peak ozone concentrations recorded at 11:00, as did Rocky Flats – North. While that site is not in the southern metro area, it is close to the foothills and higher in elevation than other metro sites. The last sites to reach their maximum one-hour ozone concentration were the northern-most sites in the Fort Collins area. Their peak concentrations were reached at 13:00.

Table 2. Stratospheric Ozone Intrusion Event Data

Stratospheric Ozone Intrusion Event May 24, 2010 1 Hour Ozone Data Submitted to AQS with "RO" Qualifier Codes (shaded)																
Site Information		**5/24/10**												**1Hr**	**8 Hr**	**Historical Percentile**
Site	**AQSID**	**09:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**Max**	**Max**	**+/- 2 Weeks**
Welby	080013001	40	40	-	-	-	60	**63**	60	60	58	41	17	24	**63**	**57**	**76%**
Highland	080050002	53	56	**93**	91	76	72	64	63	64	64	51	35	23	**93**	**73**	**100%**
Aurora East	080050006	53	55	89	**94**	82	78	68	66	65	59	54	55	48	**94**	**75**	**Insufficient Data**
South Boulder Creek	080130011	52	53	69	**71**	66	66	62	61	60	58	48	44	44	**71**	**64**	**86%**
Carriage	080310014	47	51	77	**96**	72	69	61	59	61	62	50	37	24	**96**	**69**	**99%**
Denver Animal Shelter	080310025	41	47	83	**86**	65	65	57	59	62	63	59	40	19	**86**	**67**	**Insufficient Data**
Chatfield	080350004	51	53	**96**	91	76	74	66	65	68	67	61	49	44	**96**	**75**	**100%**
CO Spring - Academy	080410013	49	75	**93**	75	73	76	69	66	68	67	48	40	45	**93**	**74**	**100%**
CO Springs - Manitou	080410016	53	77	**91**	75	74	78	74	72	73	67	61	54	53	**91**	**76**	**100%**
Arvada	080590002	51	53	77	**89**	70	68	61	59	60	58	46	30	38	**89**	**67**	**99%**
Welch	080590005	52	55	90	**92**	71	71	60	61	66	64	56	45	47	**92**	**71**	**100%**
Rocky Flats North	080590006	51	52	**76**	75	67	68	59	60	61	61	60	59	55	**76**	**65**	**90%**
NREL	080590011	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**Ongoing Site Configuration**
Aspen Park	080590013	51	64	**88**	85	71	73	64	63	65	66	62	43	54	**88**	**71**	**Insufficient Data**
Fort Collins - West	080690011	44	49	55	64	**75**	66	62	61	60	60	62	61	51	**75**	**63**	**85%**
Fort Collins – Rist Canyon	080690012	44	48	53	61	**69**	63	60	59	59	59	56	52	53	**69**	**60**	**Insufficient Data**
Fort Collins - CSU	080691004	38	44	45	62	**67**	63	55	56	57	57	54	54	45	**67**	**58**	**87%**
Weld County Tower	081230009	49	56	59	**72**	68	67	66	63	60	60	57	59	58	**72**	**64**	**84%**

The values for the maximum eight-hour average concentration and the "Historical Percentages" are also included for comparison. The maximum eight-hour value recorded during the event was 76 ppb at the Colorado Springs – Manitou site. As can be seen in the table, three sites along the Front Range recorded eight-hour average maximum values that were equal to or greater than the standard of 75 ppb. Another four sites had eight-hour values that were between 70 and 74 ppb. Eight sites recorded eight-hour values between 60 and 69 ppb. The two remaining sites that were operational recorded eight-hour values that were below 60 ppb.

The "Historical Percentile" in Table 2 is calculated by taking the number of historical samples (from the two week time period surrounding the event) with values less than the value in question (the one-hour daily maximum concentration), dividing it by the total number of samples (or boundary/sample size), then multiplying by 100%. In cases where the value in question is the highest value with no tie, the result is 100%. Eight sites recorded maximum one-hour ozone concentrations that were equal to or greater than at least 90% of their historical concentrations. Four sites had one-hour maximum values that were in the 80 to 89% range of their historical values, with one site recording a maximum that was greater than 76% of the historical maximums. The remaining four sites had insufficient data records to be able to calculate a historical percentage, as they have been in operation for less than three years, or were not online during the SI event.

The historical data used for all the statistical analysis of the monitored values is centered on a two week period surrounding the dates in question, and runs from 05/17/2010 through 05/31/2010, from the start year of the site until 2009. Table 3 lists the monitoring sites considered in this analysis, their AQS IDs, the beginning and ending year of the data set, and the total number of samples in the data set. There are four sites that began operations in 2009 and were considered to have an insufficient amount of data to be included in the historical data analysis. These are the Aurora East, Denver Municipal Animal Shelter, Aspen Park, and Fort Collins – Rist Canyon sites. While they are not included in the historical analysis, their monitored values are included in the May 2010 exceptional event data set seen in Table 2. Therefore, 13 of the 18 operating sites along the Front Range are discussed from this point on.

Table 3. Historical Data Summary

Stratospheric Ozone Intrusion Event May 17-31 Annual Historical Data Summary				
Site	**AQS ID**	**Beginning Year**	**Ending Year**	**Number of Samples**
Welby	080013001	1990	2009	291
Highland	080050002	1990	2009	284
Aurora East[1]	080050006	*(2009)*	*(2009)*	*Insufficient*
South Boulder Creek	080130011	1995	2009	223
Carriage	080310014	1990	2009	291
Denver Municipal Animal Shelter[1]	080310025	*(2009)*	*(2009)*	*Insufficient*
Chatfield	080350004	2004	2009	90

[1] These sites have less than three years of historical data, and as such their data sets are considered insufficient for the purposes of this report.

Stratospheric Ozone Intrusion Event May 17-31 Annual Historical Data Summary				
Site	**AQS ID**	**Beginning Year**	**Ending Year**	**Number of Samples**
CO Spring - Academy	080410013	1997	2009	195
CO Springs - Manitou	080410016	2004	2009	90
Arvada	080590002	1990	2009	300
Welch	080590005	1992	2009	267
Rocky Flats North	080590006	1993	2009	254
NREL	080590011	1995	2009	225
Aspen Park[1]	080590013	*(2009)*	*(2009)*	*Insufficient*
Fort Collins - West	080690011	2006	2009	58
Fort Collins – Rist Canyon[1]	080690012	*(2009)*	*(2009)*	*Insufficient*
Fort Collins - CSU	080691004	1990	2009	298
Weld County Tower	081230009	2003	2009	105

Table 4 is a listing of the sites used in the data analysis, along with “Historic” and “Event” means and standard deviations. Again, the time period covered by the “Event” values in this table begins at 09:00 MST on 5/24/2010 and ends at 21:00 MST on the same day, and the “Historic” values used for the average and standard deviation calculations are the daily one-hour maximum ozone concentrations at each site for the time periods listed in Table 3. The values were calculated using an arithmetic average and one standard deviation. Each site recorded an “Event” daily maximum one-hour value that was higher than the average of the historical daily one-hour maximums for that specific time period. Also shown in the table are the values for the 95% Upper Confidence Limit (UCL). The “Event Max” values at each site are also higher than the 95% UCL, making them statistically significantly higher values.

Table 4. Historical and Event Related Statistical Data

Site	AQS ID	Avg. of Historical Daily Max (ppb)	Std. Dev. of Historical Daily Max (ppb)	Event Max (ppb)	Event Mean (ppb)	Event Std. Dev. (ppb)	Historical 95% Upper Confidence Limit[2] (ppb)
Welby	080013001	56	12	63	46	16	57
Highland	080050002	58	12	93	62	20	59
South Boulder Creek	080130011	57	14	71	58	9	59
Carriage	080310014	54	14	96	59	18	56
Chatfield	080350004	63	11	96	66	16	65
CO Spring - Academy	080410013	56	9	93	65	15	57
CO Springs - Manitou	080410016	59	9	91	69	11	61
Arvada	080590002	56	13	89	58	16	58

[2]The 95% Upper Confidence Limit was calculated as 95% $UCL = \bar{X} + t_{\alpha,n-1} s/\sqrt{n}$, where $\bar{X}$ is the sample mean, s is the sample standard deviation, n is the sample size, α is the desired significance level, and $t_{\alpha,n-1}$ is the upper critical value of the t-distribution with $n-1$ degrees of freedom.

Site	AQS ID	Avg. of Historical Daily Max (ppb)	Std. Dev. of Historical Daily Max (ppb)	Event Max (ppb)	Event Mean (ppb)	Event Std. Dev. (ppb)	Historical 95% Upper Confidence Limit[2] (ppb)
Welch	080590005	52	12	92	64	15	54
Rocky Flats North	080590006	61	12	76	62	8	62
NREL	080690011	62	12	75	59	8	65
Fort Collins - CSU	080691004	54	12	67	54	8	55
Weld County Tower	081230009	62	10	72	61	6	64

Another illustration of the statistical significance of the data can be seen in the box and whisker plot in Figure 31. The historical dataset used for the boxes and whiskers is over the same two week time period as that mentioned in Table 3. The top and bottom edges of the boxes represent the 75th and 25th percentiles of the historic daily maximum one-hour concentrations, or the third and first quartiles, respectively. The center line in the box is the median value, or the second quartile. The “whiskers” represent the range that is 1.5 times the interquartile range (IQR). The IQR is the difference between the third and first quartiles. Any data points that lie above or below the extent of the whiskers are considered outliers, as they are more than 1.5 times greater than the IQR above the upper quartile. The maximum one-hour concentrations recorded during the stratospheric intrusion 13 hour time period are plotted as the black asterisks. The one-hour maximums at each site (with a sufficient historical data record) that are significantly different from their respective historical data sets should be considered statistical outliers. Also shown on the plot are dashes representing the 80th, 90th, 95th and 99th percentile values for each site.

Seven sites had “Event” maximum one-hour ozone concentrations that were greater than or equal to 1.5 times the IQR. All but one of the remaining sites (Welby) had maximum concentration values that were greater than their 80th percentile values. The monitor at Welby exhibited the lowest maximum concentration largely because it was offline during the main part of the event.

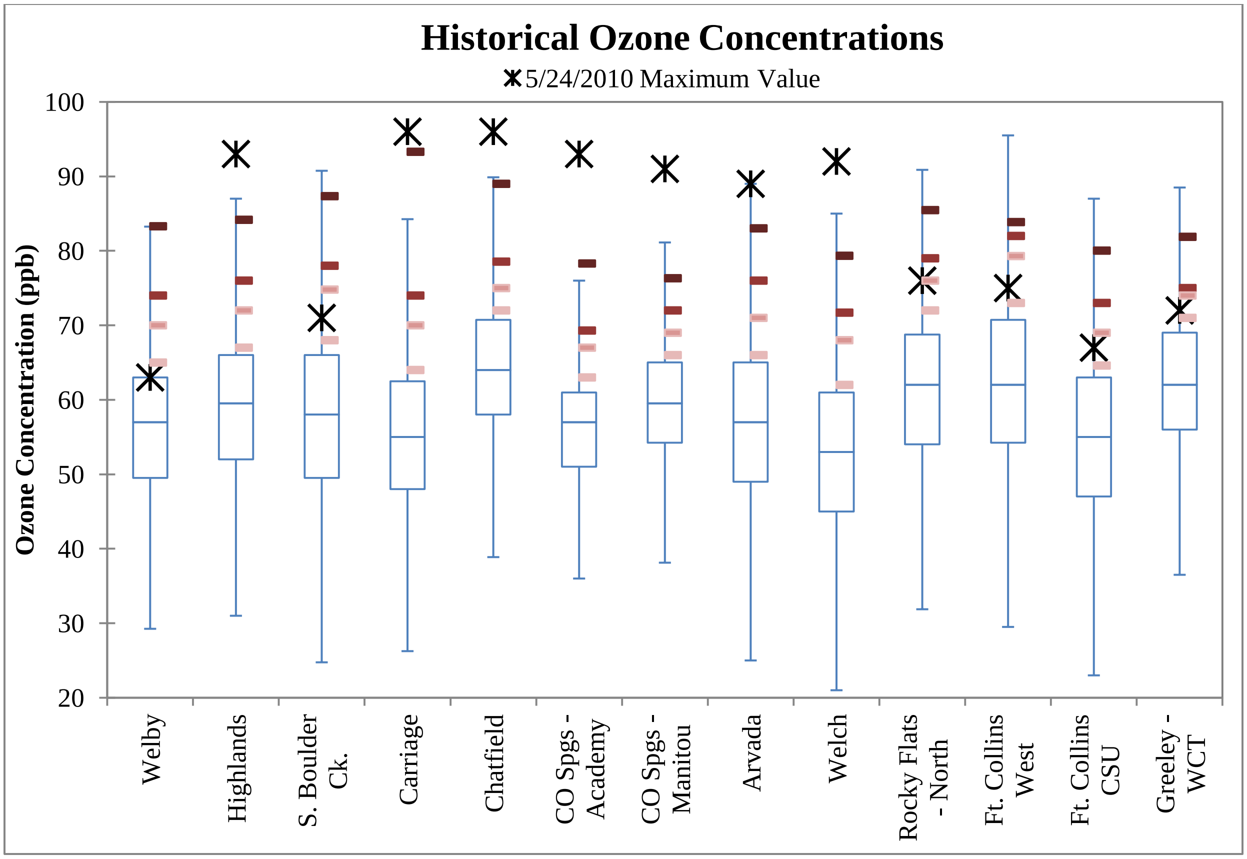

Figure 31. Historical Ozone Concentrations Box and Whisker Plot

Figure 32 is a graph of average ozone concentrations along the Front Range. The blue line is the average of all the historical concentrations, hour by hour, for each of the days in the same two week time period (5/17/2010 through 5/31/2010) at each of the 13 sites in the Front Range with a sufficient data set (up through 2009). The red line is the average of the ozone concentrations at each of the same 13 Front Range sites for the two week time period in 2010. It illustrates the much larger concentrations recorded during the stratospheric intrusion event on 5/24/2010.

In summary, the data listed with "RO" qualifier codes in Table 2. Stratospheric Ozone Intrusion Event Data (yellow shaded boxes) are inflated due to the presence of a Stratospheric Ozone Intrusion. As such, they should be considered statistically significantly different from their cumulative dataset, and be removed from the calculation of the 8-hour ozone standard. In support of this conclusion, the 95% UCL was calculated for each site with a sufficient historical data record, as was the Historical Percentile. Every site recorded a one-hour maximum ozone concentration value during the SI event that was well above not only the 95% UCL, but also the mean of the historical daily maximum concentrations for 5/24/2010, and the mean of the historical concentrations for the 09:00 to 21:00 time period on 5/24/2010 - clearly indicating the statistical significance of the "Event" data.

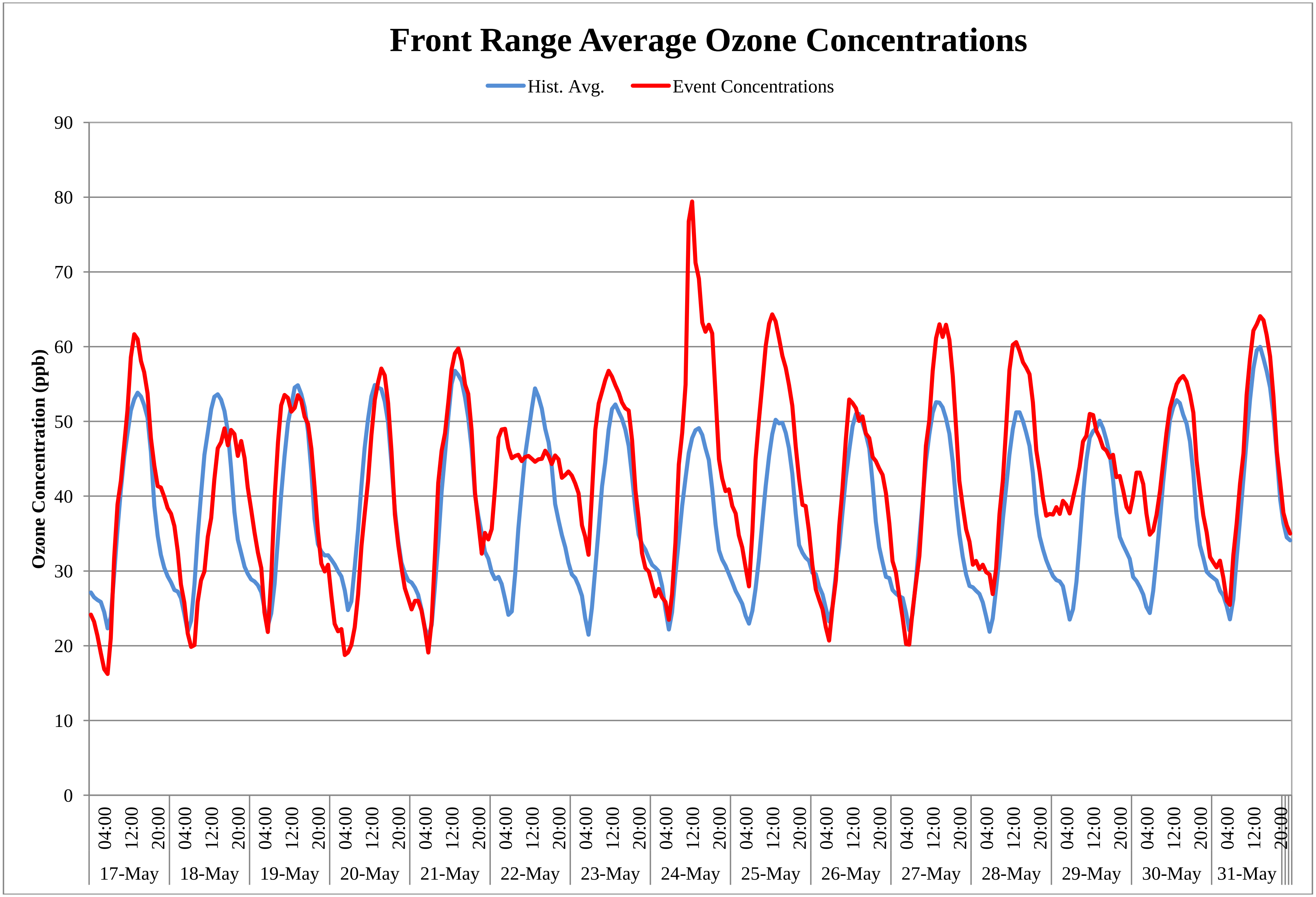

Figure 32. Front Range Average Ozone Concentrations

3.1 Data QA/QC and Equipment

Quality Assurance/Quality Control procedures were followed in accordance with 40 CFR Part 58, Appendix A, Section 3.2 *Measurement Quality Checks of Automated Methods* and the *Quality Assurance Project Plan* for the Colorado Department of Public Health and Environment's Air Pollution Control Division monitoring projects. All instruments met the required nightly span/zero, weekly automated precision and the two-week manual precision check requirements, with the exception of the analyzer at Highlands (080050002). This analyzer did not have any manual precisions performed between 4/26/2010 and 6/7/2010. Upon an inspection of the data, it was observed that the nightly span checks were within the proper operating tolerances, and that the data for the period was indeed valid. In addition to the span and precision checks, all analyzers had been calibrated within a three month period prior to May 24, 2010, with the exception of the Chatfield monitor (080350004). This monitor was calibrated on 1/29/2010 and again on 7/29/2010. A review of the automated and manual span/precision results indicates that the data over the time period are valid. The results of these nightly span/zero, precision, and calibration checks are kept on hand at the Colorado Department of Public Health and Environment's Air Pollution Control Division office. Copies of the data can be obtained from the Division upon request.

4.0 Colorado Department of Health and Environment Air Pollution Control Division Response Plan for Stratospheric Intrusions of Ozone.

Ozone from the stratosphere and the mechanisms through which it is transported and mixed to the surface are not controllable. Furthermore, stratospheric intrusions of ozone occur during meteorological conditions that are typically associated with reduced anthropogenic ozone. These conditions include strong storm systems, brisk winds at the surface and aloft, good mixing, frontal passage, and a change of air mass.

The Air Pollution Control Division, however, has implemented a program of forecasting for stratospheric intrusions of ozone for anywhere in Colorado for any season or day of the year. Five Ozone Action Day Alerts for stratospheric intrusions have been issued since 2010. The first and second of these were issued for the event in question:

> "Issued: 5/24/2010 2:53:00 PM
> Action Day – Ozone
>
> Effective: 5/24/2010 4:00:00 PM - 5/24/2010 11:00:00 PM
> Ozone from the stratosphere is mixing to ground level behind a cold front moving through eastern Colorado Monday afternoon. Ozone will reach the Moderate to Unhealthy-for-Sensitive-Groups [category] across the entire Front Range region. Active children, active adults, and those with respiratory illnesses such as asthma … should limit prolonged outdoor exertion until 11 PM Monday."

The full text for each of the 5 action days is contained in Attachment A. Spring intrusion events and dust storms often occur at the same time. A number of the alerts in Attachment A also warn of blowing dust in parts of Colorado.

5.0 Summary and Conclusions

On Monday May 24, 2010, a strong spring storm system triggered an intrusion of stratospheric ozone into the lower portions of the atmosphere as it moved across Colorado. Elevated one-hour and eight-hour ozone concentrations were observed across much of Colorado. There was an exceedance of the 8-hour ozone standard at Manitou Springs which recorded a maximum concentration of 76 parts per billion (ppb) and concentrations just below the 8-hour standard at several other sites. *The data and analyses presented in this report demonstrate that the stratospheric intrusion of May 24 caused the elevated ozone concentrations and that these elevated concentrations and the exceedance at Manitou Springs would not have occurred but for the transport and mixing of stratospheric ozone to the surface.*

The intrusion of stratospheric air and ozone into the troposphere and subsequent mixing of ozone to surface sites is well understood and has been documented in the scientific literature. Previous studies point to the contributions of stratospheric intrusions associated with tropopause folds to exceedances of the 8-hour NAAQS for ozone in both Colorado and Wyoming. This report provides in-depth evidence that a similar intrusion event caused the elevated ozone concentrations observed at Colorado monitoring sites on May 24, 2010.

On May 24, 2010, at 12:00 PM MDT or 11:00 PM MST a deep surface low pressure system was located just to the north of Denver near the Colorado-Wyoming border. A dry air surge moved across the Front Range just behind a cold front which was moving through Eastern Colorado. Strong surface pressure gradients were present over the Northern Front Range leading to strong southwesterly to west-southwesterly downslope winds across portions of the Front Range. Cross-mountain flow at the surface and 700-mb level and extending as high as the 600-mb level may have contributed to a mountain wave and enhanced mesoscale tropopause folding in central Colorado. *Strong winds at the surface and aloft were recorded over the area that experienced the highest ozone concentrations. High-ozone concentrations from anthropogenic sources are inconsistent with strong winds at the surface and aloft which will disperse such ozone and inhibit its build up.*

A variety of data provides diagnostic evidence for the presence of a stratospheric intrusion and surface ozone of stratospheric origin in Colorado on May 24, 2010. The first of these is tropopause height. The height of the tropopause is typically much lower within an upper-level trough and lower still within a tropopause fold. The mean location of the tropopause in May in Colorado is at the 200-mb level. *Tropopause heights dropped to about 500 mb during the May 24 event. A tropopause height as low as 500 mb in Colorado in May is an anomaly and demonstrates conditions typically associated with a stratospheric intrusion.* *Additional meteorological data proves that deep vertical mixing in the planetary boundary layer was sufficient to mix stratospheric ozone in a tropopause fold to the surface.*

Isentropic Potential Vorticity (IPV) is a conservative property and values of 2 PVU or higher can indicate the presence of air from the stratosphere. *Vertical cross sections of IPV demonstrate that a fold in the tropopause extended as low as 4 to 5 kilometers above sea level over central and southern Colorado at midday on May 24, 2010, and this was well below the long-term mean of 12 kilometers for the month of May*.

Another set of indicators for the occurrence of a stratospheric intrusion of ozone in Colorado on May 24 are maps of total atmospheric column ozone derived from satellite measurements from the Global Ozone Monitoring Experiment 2 (GOME2) and Ozone Monitoring Instrument (OMI) satellite systems. Total column ozone is higher within upper-level troughs and storm systems (Danielsen, 1968, and Krueger, 1989). A simple but partial explanation for this is that the ozone-rich stratosphere occupies a greater fraction of the vertical column in troughs where the tropopause is lower and the stratosphere is thicker. Higher concentrations of ozone are therefore closer to the ground in upper-level troughs, and tropopause folds typically extend downward from areas of higher total column ozone. *Unusually high total column ozone values over Colorado on May 24, 2010, provide evidence for a lowered tropopause and conditions necessary for a stratospheric intrusion of ozone into the troposphere.*

Stratospheric intrusions and tropopause folds bring dry air from the stratosphere to the troposphere and the surface. Consequently, we would expect to see dry air at the surface in the wake of an intrusion. *A plot of surface dewpoint temperatures and one-hour ozone for 12:00 MST and a vertical cross section of relative humidity across the state show that dry air under the influence of a stratospheric intrusion and elevated ozone coincided temporally and spatially with several other indicators of a stratospheric intrusion event on May 24, 2010.*

The Air Pollution Control Division has compared the modeled IPV and one hour ozone concentrations for 12:00 MST at each monitor of interest in Colorado. A linear regression provided the best fit with an r-squared value of 0.71. The linear fit shows a strong relationship between local IVP at 310 K and local ozone, and this fit is statistically significant at the 95% confidence level. *The statistically significant relationship between local ozone and local IPV at the 310 degrees Kelvin potential temperature surface proves that the high surface ozone was caused by an intrusion of stratospheric air - but for the intrusion of stratospheric ozone, the high concentrations observed on May 24, 2010, would not have occurred.*

An analysis of time series of hourly ozone concentrations on May 23 and 24 provides additional clues about the progression, timing, and nature of the elevated ozone associated with this intrusion. The fast increase in ozone and rapid development and resolution of a short-term spike are also diagnostic for an intrusion when the meteorological conditions are consistent with tropopause folding and a lowered tropopause. Fifteen-minute average ozone data for Kenosha Pass showed an increase from 61 ppb to 115 ppb in just 75 minutes as air from the fold reached the surface. That’s an unusual short-term increase of 54 ppb. While dramatic, short-term spikes can be associated with anthropogenic ozone, they are typically not found across a wide area.

In addition, the spikes observed on May were in synch with the location and progression of the meteorological features indicative of an intrusion. Contours of hourly ozone also support the idea that a mesoscale intrusion brought peak impacts along the Front Range. *Time series and contours of hourly ozone on May 24 demonstrate that the peak area of elevated ozone rapidly evolved in place over the Front Range region and gradually moved to the east-northeast and diminished as the storm system moved through. Under these meteorological conditions, the locations, sequence, and short-term nature of pulses in surface ozone prove that but for a stratospheric intrusion the elevated ozone would not have occurred.*

All of the data and analyses presented in this report rule out anthropogenic sources for the high ozone concentrations on May 24, 2010, and consistently point to a stratospheric intrusion associated with a strong spring storm. In addition, a statistical analysis of historical one-hour ozone concentrations for the days from May 17 through May 31 shows that the one-hour concentrations measured during the May 24, 2010, stratospheric ozone intrusion are outliers and represent a rare event.

The elevated ozone concentrations observed at Colorado monitors and the exceedance at Manitou Springs would not have occurred but for the transport and mixing of stratospheric ozone to the surface.

Ozone from the stratosphere and the mechanisms through which it is transported and mixed to the surface are not controllable. Furthermore, stratospheric intrusions of ozone occur during meteorological conditions that are typically associated with reduced anthropogenic ozone. These conditions include strong storm systems, brisk winds at the surface and aloft, good mixing, frontal passage, and a change of air mass.

The Air Pollution Control Division, however, initiated year-round daily forecasts for stratospheric intrusions in 2010 during the May 24 event. Two Ozone Action Day Alerts were issued for the Front Range region on May 24. Three additional alerts have been issued through June of 2011. These alerts notify the public, the media, and local health officials of potential health concerns associated with high ozone concentrations from a stratospheric intrusion. Alert information is distributed on the Division's web site, through listserv messages, hotline recordings, and AIRNow forecasts.

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Attachment A: Ozone Action Day Alerts for Stratospheric Intrusions of Ozone

<u>May 24, 2010</u>:

Air Quality Advisory

Issued: 5/24/2010 2:53:00 PM
Action Day - Ozone
Effective: 5/24/2010 4:00:00 PM - 5/24/2010 11:00:00 PM

Ozone from the stratosphere is mixing to ground level behind a cold front moving through eastern Colorado Monday afternoon. Ozone will reach the Moderate to Unhealthy-for-Sensitive-Groups across the entire Front Range region. Active children, active adults, and those with respiratory illnesses such as asthma people should limit prolonged outdoor exertion until 11 PM Monday

Other Areas:

Blowing Dust Advisory for eastern Colorado until 10 PM Monday May 24, 2010. Issued by the Colorado Department of Public Health and Environment at 3 PM Monday May 24, 2010. Click this text for additional info.

Localized blowing dust is possible across Eastern Colorado Monday afternoon and evening. Winds gusting 45 to 85 mph in these areas may contribute to blowing dust. Greeley, Fort Morgan, Brush, Sterling, Akron, Limon, Burlington, Colorado Springs, Lamar, Pueblo, Springfield, and nearby areas may be affected.

Issued: 5/24/2010 1:52:00 PM
Action Day - Ozone
Effective: 5/24/2010 1:00:00 PM - 5/24/2010 4:00:00 PM

Ozone from the stratosphere is mixing to ground level behind a cold front moving through eastern Colorado Monday afternoon. Ozone will reach the Unhealthy-for-Sensitive-Groups across the entire Front Range region. Active children, active adults, and those with respiratory illnesses such as asthma people should limit prolonged outdoor exertion until 11 PM Monday

Other Areas:

Blowing Dust Advisory for South-central and Southeastern Colorado from 11:00 AM until Midnight Monday May 24, 2010. Issued by the Colorado Department of Public Health and Environment at 9:30 AM Monday May 24, 2010.

Blowing dust is possible across areas of South-central and Southeastern Colorado Monday afternoon and evening as strong winds blow across dry areas of Colorado and New Mexico.

Winds gusting 45 to 60 mph in these areas may contribute to blowing dust. Alamosa, Trinidad, Lamar, Pueblo, Colorado Springs, and nearby areas may be affected. **The blowing dust will end during the evening, but there could be elevated levels of Particulates into the early morning hours.** This will be dust that had been suspended in the atmosphere earlier in the day and transported long distances after the winds have subsided below levels needed to cause blowing dust. If significant blowing dust is present and reducing visibility to less than 10 miles across a wide area, the elderly, the very young, and those with respiratory problems should avoid prolonged exertion; everyone else should limit prolonged exertion. Limiting outdoor exposure is also advised.

Issued: 5/24/2010 9:14:00 AM
No Advisories - No Action Day
Effective: 5/23/2010 4:00:00 PM - 5/24/2010 4:00:00 PM

Other Areas:

Blowing Dust Advisory for South-central and Southeastern Colorado from 11:00 AM until Midnight Monday May 24, 2010. Issued by the Colorado Department of Public Health and Environment at 9:30 AM Monday May 24, 2010.

Blowing dust is possible across areas of South-central and Southeastern Colorado Monday afternoon and evening as strong winds blow across dry areas of Colorado and New Mexico. Winds gusting 45 to 60 mph in these areas may contribute to blowing dust. Alamosa, Trinidad, Lamar, Pueblo, Colorado Springs, and nearby areas may be affected. **The blowing dust will end during the evening, but there could be elevated levels of Particulates into the early morning hours.** This will be dust that had been suspended in the atmosphere earlier in the day and transported long distances after the winds have subsided below levels needed to cause blowing dust. If significant blowing dust is present and reducing visibility to less than 10 miles across a wide area, the elderly, the very young, and those with respiratory problems should avoid prolonged exertion; everyone else should limit prolonged exertion. Limiting outdoor exposure is also advised.

Issued: 4/29/2011 3:06:00 PM
Action Day - Ozone
Effective: 4/30/2011 5:00:00 AM - 4/30/2011 4:00:00 PM
Ozone mixing down from the stratosphere will likely cause ozone at the surface to climb into the Moderate to Unhealthy-for-Sensitive Groups range from early Saturday morning through late afternoon on Saturday. High concentrations are expected across the Front Range region.

Other Areas:

Blowing Dust Advisory for Southwestern, South-central, and portions of Southeastern Colorado from Noon until 9 PM Friday April 29, 2011. Issued by the Colorado Department of Public Health and Environment at 11 AM Friday April 29, 2011. Blowing dust is possible across areas of southwestern, south-central and portions of southeastern Colorado Friday afternoon and evening as strong winds move across drier areas of Colorado, Arizona, New Mexico, and Utah. Winds gusting to 45 to 65 mph in these areas may contribute to blowing dust. Cortez, Durango, Pagosa Springs, Telluride, Alamosa, Pueblo, Trinidad, and nearby areas may be affected. If significant blowing dust is present and reducing visibility to less than 10 miles across a wide area, the elderly, the very young, and those with respiratory problems should avoid prolonged exertion; everyone else should limit prolonged exertion. Limiting outdoor exposure is also advised.

Issued: 5/30/2011 3:55:00 PM
Action Day - Ozone
Effective: 5/30/2011 4:00:00 PM - 5/31/2011 4:00:00 PM
A stratospheric intrusion of ozone along the Front Range will cause ground levels of Ozone to approach the Unhealthy levels this afternoon and evening from Ft Collins south to Colorado Springs.

Active children and adults, and people with respiratory disease, such as asthma, should avoid prolonged outdoor exertion; everyone else especially children, should limit prolonged outdoor exertion.

Other Areas:

Blowing Dust Advisory for Southeastern Colorado and the San Luis Valley

Effective: 11 AM Monday till 10 PM Monday, May 30, 2011

In areas of southeastern Colorado and the San Luis Valley that have received less than a half inch of precipitation in the last two weeks blowing dust is possible today. This area is south of a line from Colorado Springs east to the Kansas line and the San Luis Valley. If visibility is less than 10 miles in widespread blowing dust, then the elderly, children, and those with respiratory illnesses such as asthma should limit prolonged exertion. Everyone else should consider limiting prolonged exertion.

Issued: 7/1/2011 2:24:00 PM
Effective: 7/1/2011 4:00:00 PM - 7/1/2011 11:00:00 PM

Action Day for Ozone for Southwest Colorado to include Montezuma and La Plata counties Friday afternoon and evening.

The Colorado Department of Public Health and Environment has issued an Action Day for Ozone for Southwest Colorado to include Montezuma and La Plata counties. This Action Day is valid from 4 PM through 11 PM Friday July 1, 2011. Cities in this area include but are not limited to, Cortez and Durango.

Ozone levels could climb into the Unhealthy for Sensitive Groups category Friday afternoon and evening.

Active children and adults, and people with lung disease, such as asthma, should reduce prolonged or heavy outdoor exertion.