$PM_{2.5}$ State Implementation Plan

Photochemical Modeling

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1.0 Photochemical Modeling

Photochemical models are relied on by federal and state regulatory agencies to support their planning efforts. Used properly, models can assist policy makers in deciding which control programs are most effective in improving air quality, and meeting specific goals and objectives. During the winter, $PM_{2.5}$ pollution in northern Utah is formed predominantly through secondary chemical reactions in the atmosphere. This buildup of pollution then gets trapped in the valleys during temperature inversions. For this reason a modeling system that simulates the interactions of weather, pollution and chemistry is the most appropriate tool to judge the effectiveness of pollution reduction strategies. The Community Multiscale Air Quality (CMAQ) model, approved and recommended by EPA for this type of application, has been used for the Utah 24-$PM_{2.5}$ SIP. This section reviews the development and evaluation of the photochemical system used for the Utah 24-hr $PM_{2.5}$ analyses.

1.1 CMAQ Photochemical Model

Version 4.7.1 of the CMAQ model was selected to perform the photochemical modeling for the Utah PM2.5 SIP. CMAQ was selected because it is the open source atmospheric chemistry model co-sponsored by EPA and the National Oceanic Atmospheric Administration (NOAA). A detailed overview of CMAQ, in the form of the CMAQ Model Science Documentation can be found at:

http://www.epa.gov/asmdnerl/CMAQ/CMAQscienceDoc.html

This section will describe the configuration of CMAQ, including information on the input processors (e.g., MCIP, ICON, BCON, JPROC) and the Chemistry-Transport Model (CCTM) science modules (e.g. vertical advection, diffusion).

1.1.1 MCIP

MCIP version3.6 was used to take WRF meteorological data and create meteorology files that can be used in the SMOKE emissions model and CMAQ. MCIP was used to trim the 4-km WRF domain (82 x 100 grid cells) to match the emissions processing and photochemical (CMAQ) modeling domain (79x 97 grid cells) that covers the non-attainment areas of northern Utah (Figure 1.1).

UDAQ used the vertical layer collapsing option in MCIP. UDAQ did this primarily as a computational time saver as numerous base and future year and emission control strategy simulations need to be performed. Table 1.1 gives the vertical layers for MCIP. MCIP is collapsed to 17 layers, keeping the height of the first 10 layers the same as the WRF configuration, and then collapsing the upper vertical layers. A photochemical modeling sensitivity was performed without MCIP layer collapsing and no difference was seen in

the concentrations of $PM_{2.5}$ and its precursors (e.g., NOx and O_3) in the lowest model layers when comparing the layer collapsing and no layer collapsing simulations.

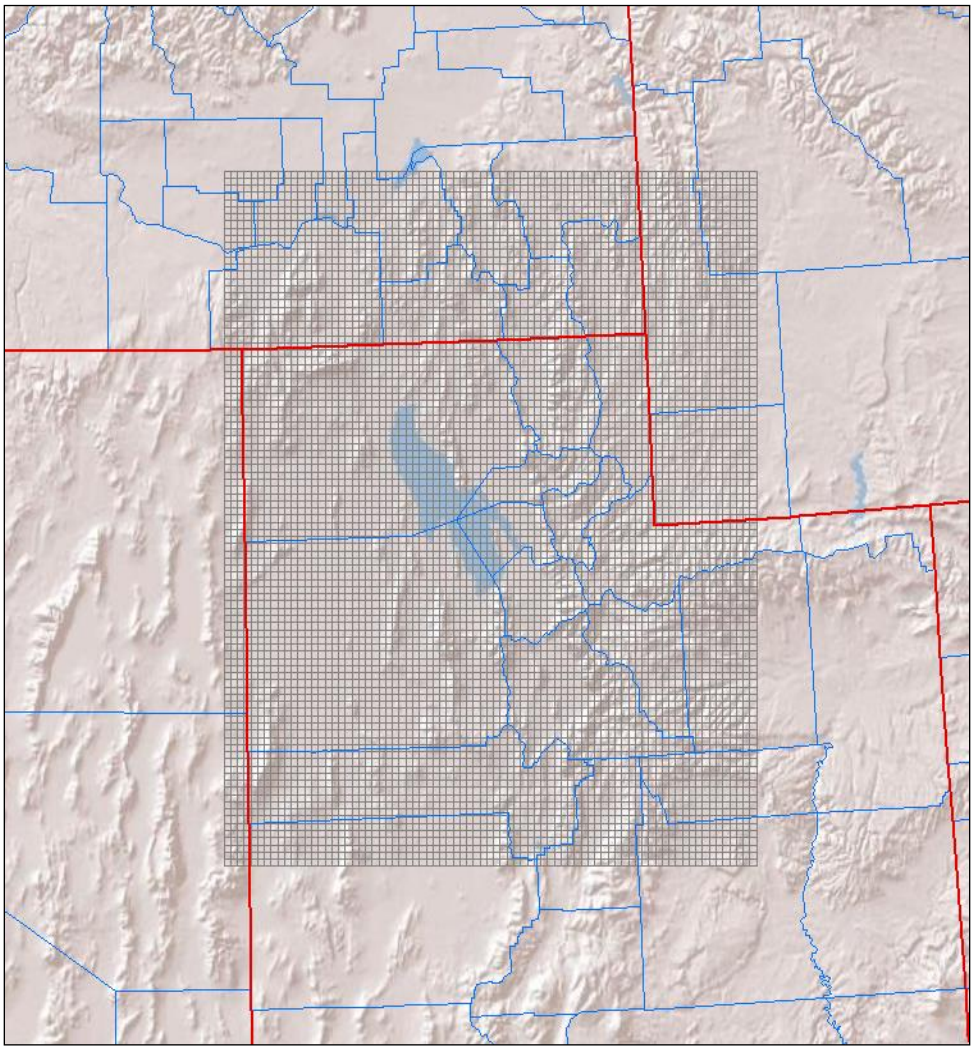

Figure 1.1: Northern Utah photochemical modeling domain

Table 1.1: Vertical Layers of CMAQ meteorological and emissions data.

WRF Model Layer	Sigma	Height (meters)	MCIP Model Layer	Height (meters)
34 – top	0.000	14,662	17	14,662
33	0.050	12,822		
32	0.100	11,356		
31	0.150	10,127		
30	0.200	9,066	16	9,066
39	0.250	8,127		
28	0.300	7,284		
27	0.350	6,517		
26	0.400	5,812		
25	0.450	5,160		
24	0.500	4,553	15	4,553
23	0.550	3,948		
22	0.600	3,448		
21	0.650	2,942	14	2,942
20	0.700	2,462		
19	0.740	2,095		
18	0.770	1,828	13	1,828
17	0.800	1,569		
16	0.820	1,400		
15	0.840	1,235		
14	0.860	1,071	12	1,071
13	0.880	911		
12	0.900	753	11	753
11	0.910	675		
10	0.920	598	10	598
9	0.930	521	9	521
8	0.940	445	8	445
7	0.950	369	7	369
6	0.960	294	6	294
5	0.970	220	5	220
4	0.980	146	4	146
3	0.985	109	3	109
2	0.990	73	2	73
1	0.995	36	1	36
0 – ground	1.000	0	0 – ground	0

1.1.2 Initial (ICON) and Boundary (BCON) Conditions

The ridge-dominated synoptic meteorology during $PM_{2.5}$ cold pool episodes features weak transport winds and near calm surface winds. As a result, transport of $PM_{2.5}$ and precursors from the rural regions at the domain periphery is very small. In addition, most of the observed Wasatch Front and Cache Valley $PM_{2.5}$ is formed in-situ (and trapped) via fresh locally derived emission sources and secondary chemistry. In essence, Utah's cold pools represent an isolated system that is controlled only by locally derived emissions, meteorology, and chemistry.

CMAQ model simulations are initialized prior to the start of $PM_{2.5}$ build-up. The very small initial concentrations of diurnally produced gaseous concentrations have little consequence to the ultimate build-up of $PM_{2.5}$. UDAQ has configured CMAQ to use EPA default profiles for background chemistry concentrations. UDAQ supplements the initialization and boundary default profiles by using rural values taken from bordering National Park air quality monitoring stations for chemistry initialization.

1.1.3 Photolysis Rates (JPROC)

Photolysis rates for CMAQ are produced by the JPROC preprocessor. JPROC produces a photolysis rate lookup table that consists of photolysis rates at various latitudes, altitudes, and sun angle. UDAQ modified the JPROC lookup table to better represent the snow cover that occurs in Northern Utah during wintertime. To do this modification, UDAQ made changes to the surface albedo of wavelengths less than 500 nanometers in the subroutine *setalb.f*. Surface albedo can range from 0.05 with no snow cover to 0.9 with complete snow cover. The albedo for wavelength less than 500 nanometers was changed from approximately 0.05 to 0.55 to represent snow covered ground. The surface albedo of 0.55 was chosen to represent an average albedo for the snow cover during winter $PM_{2.5}$ episodes.

1.1.4 CMAQ Chemistry Transport Mode (CCTM)

There are numerous configuration options in CCTM that can be selected to optimize the CMAQ model. For Utah wintertime $PM_{2.5}$ simulations, the CCTM options were set as follows:

```
#> user choices: various modules

 set Revision = release       # release = latest CVS revision
#set Revision = '"CMAQv4_7.1"'

set ModDriver = ( module ctm                $Revision; )
```

```
# set ModDriver = ( module ctm_yamo           $Revision; )

 if ( $?ParOpt ) then
    set ModPar = ( module par                $Revision; )
    else
    set ModPar = ( module par_noop           $Revision; )
endif

 set ModInit   = ( module init               $Revision; )
# set ModInit   = ( module init_yamo          $Revision; )

#set ModAdjc   = ( module adjcon_noop        $Revision; )
 set ModAdjc   = ( module denrate            $Revision; )
# set ModAdjc   = ( // yamo option does not need denrate )

 set ModCpl    = ( module gencoor            $Revision; )

#set ModHadv   = ( module hadv_noop          $Revision; )
 set ModHadv   = ( module hppm               $Revision; )
# set ModHadv   = ( module hyamo              $Revision; )

 set ModVadv   = ( module vadv_noop          $Revision; )
# set ModVadv   = ( module vppm               $Revision; )
# set ModVadv   = ( module vyamo              $Revision; )

#set ModHdiff  = ( module hdiff_noop         $Revision; )
 set ModHdiff  = ( module multiscale         $Revision; )

#set ModVdiff  = ( module vdiff_noop         $Revision; )
#set ModVdiff  = ( module eddy               $Revision; )
#set ModVdiff  = ( module acm2               $Revision; )
 set ModVdiff  = ( module acm2_inline        $Revision; )

#set ModPhot   = ( module phot_noop          $Revision; )
 set ModPhot   = ( module phot_table         $Revision; )
#set ModPhot   = ( module phot_sat           $Revision; )
#set ModPhot   = ( module phot_inline        $Revision; )

# set ModChem   = ( module chem_noop          $Revision; )
#set ModChem   = ( module smvgear            $Revision; )
#set ModChem   = ( module ros3               $Revision; )
#set ModChem   = ( module ebi_cb05cl         $Revision; )
 set ModChem   = ( module ebi_cb05cl_ae5     $Revision; )
#set ModChem   = ( module ebi_saprc99        $Revision; )
#set ModChem   = ( module ebi_saprc99_ae5    $Revision; )

# set ModAero   = ( module aero_noop          $Revision; )
#set ModAero   = ( module aero4              $Revision; )
 set ModAero   = ( module aero5              $Revision; )

# set ModAdepv  = ( module aero_depv_noop     $Revision; )
 set ModAdepv  = ( module aero_depv2         $Revision; )

#set ModCloud  = ( module cloud_noop         $Revision; )
#set ModCloud  = ( module cloud_acm          $Revision; )
 set ModCloud  = ( module cloud_acm_ae5      $Revision; )
```

```
 set ModPa     = ( module pa                 $Revision; )

 set ModUtil   = ( module util               $Revision; )

#> user choices: emissions processing in chem or vdiff (default) ...
#set Cemis        # Uncomment to process in chem

#> user choices: mechanism
#set Mechanism = cb05cl_ae4_aq
 set Mechanism = cb05cl_ae5_aq
#set Mechanism = saprc99_ae4_aq
#set Mechanism = saprc99_ae5_aq
 set Tracer    = trac0               # default: no tracer species

#> user choices: set process analysis linkages - TURN OFF PROCESS
ANALYSIS
#set PABase    = $GlobInc
#set PAOpt     = pa_noop
```

Of note is the use of the Carbon Bond-05 chemistry mechanism (`cb05cl_ae5_aq`). Also, the vertical advection module is de-activated (`module vadv_noop)`. Deactivating the vertical advection in the CCTM improved model performance significantly (see Section 1.2.1). In order to assess control strategies to reduce Utah 24-hr $PM_{2.5}$, the air quality model must replicate the formation of secondarily formed ammonium nitrate. The configuration of the CCTM that led to the best performance of ammonium nitrate was with vertical advection de-activated.

Numerous model sensitivities were performed by UDAQ over the past 2 to 3 years that led to the conclusion to deactivate vertical advection. UDAQ performed sensitivities in consultation with EPA, testing aspects of CMAQ that are important to the simulation of secondary nitrate. Tests were performed on the vertical diffusion module in CCTM, examining if there is an optimal setting for eddy diffusivity, friction velocity, and roughness length. Sensitivities on horizontal diffusion were performed to test its role in $PM_{2.5}$ formation. Likewise, numerous sensitivities were performed on the emissions and meteorological inputs. In the end, the best model performance occurs when de-activating vertical advection in CMAQ.

1.1.5 Ammonia Inventory Adjustments

Ammonia (NH_3) plays an important role as it reacts with nitric acid (HNO_3) for the formation of ammonium nitrate (NH_4NO_3). There is uncertainty in the emissions inventory of NH_3 as it is not currently measured at UDAQ's monitoring site. Studies performed at Utah State University have shown NH_3 to be in abundance in the Cache Valley and that the limiting reagent is HNO_3 in the formation of NH_4NO_3. A study by Brigham Young University in the winter of 2009 obtained measurements of NH_3 from a URG Corp. Ambient Ion Monitor (AIM) stationed at the Hawthorne monitoring site in

Salt Lake City. URG measurements showed concentrations of NH_3 nearly steady at 15 to 20 ppbv throughout the high $PM_{2.5}$ episodes.

UDAQ made adjustments in the NH_3 inventory to better represent the results of these special measurement studies. In consultation with EPA Region 8, UDAQ added 0.005 mol/s of NH_3 to every model grid cell and to every time step of the merged SMOKE emissions file. Figure 1.2 shows ammonia concentrations from CMAQ without any adjustments. Much of the Wasatch Front has minimal NH_3 concentrations which limit the formation of NH_4NO_3 in the CMAQ model. Figure 1.3 shows ammonia concentrations from CMAQ with the added 0.005 mol/s of NH_3 in the SMOKE files. NH_3 levels are between 10 and 20 ppb along the Wasatch Front and often greater than 20 ppb in the Cache Valley. This adjustment to the ammonia inventory allows for CMAQ concentrations of NH_3 to match concentrations collected from previous special studies.

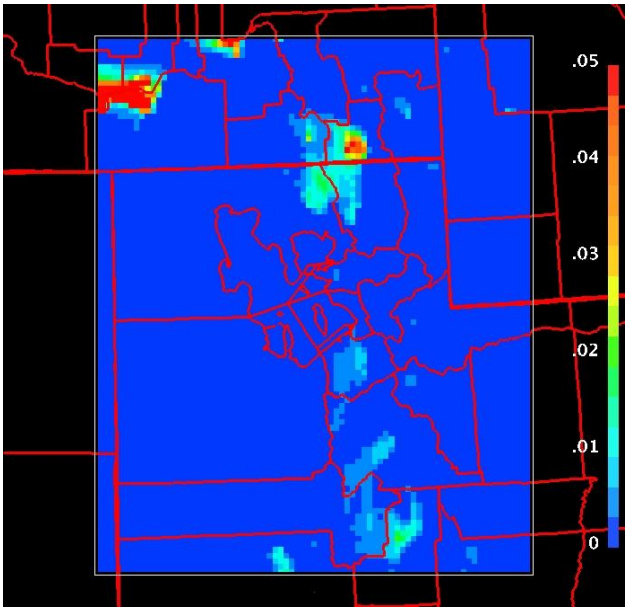

Figure 1.2: Ammonia concentrations (ppm) from CMAQ.

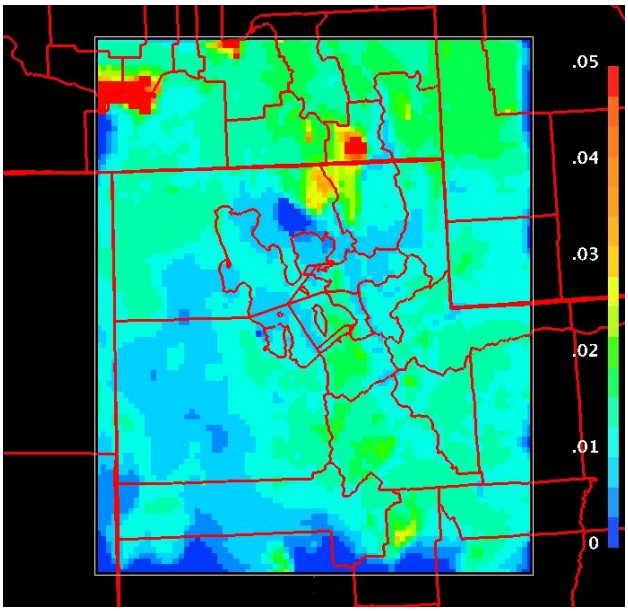

Figure 1.3: Adjusted ammonia concentrations (ppm) from CMAQ by adding 0.005 mol/s to SMOKE emission files.

1.2 CMAQ Model Performance

The model performance evaluation focused on the magnitude, spatial pattern, and temporal profile of modeled and measured concentrations. In addition, a statistical model performance evaluation based on EPA guidance was conducted. This exercise is intended to assess whether, and to what degree, confidence in the model is warranted (and to assess whether model improvements are necessary (i.e., de-activating vertical advection)).

CMAQ model performance was assessed with observed air quality datasets at UDAQ-maintained air monitoring sites (Figure 1.4). Measurements of observed $PM_{2.5}$ concentrations along with gaseous precursors of secondary particulate (e.g., NO_x, ozone) and carbon monoxide are made throughout winter at some of the locations in Figure 1.4. $PM_{2.5}$ speciation performance was assessed using the three Speciation Monitoring Network Sites (STN) located at the Hawthorne site in Salt Lake City, the Bountiful site in Davis County, and the Lindon site in Utah County.

UDAQ modeled three high $PM_{2.5}$ 'episodes' Utah 24-$PM_{2.5}$ SIP:

- 2007 January 11 – 20
- 2008 February 14 - 19
- 2009 December 13 – 2010 January 15

The long 2009-2010 episode contains four separate high $PM_{2.5}$ episodes with buildup and washout. This episode will be used in this section for the CMAQ model performance and subsequently for the Model Attainment Test. The shorter 2007 and 2008 episodes will be used more as a Weight of Evidence – Additional Modeling, and not as part of the attainment demonstration. In short, the 2009-2010 is the Attainment Modeling episode and the 2007 and 2008 episodes are additional evidence that the CMAQ modeling performs reasonable well for specific episodes in the winters of 2007 and 2008. The performance of the 2007 and 2008 episodes are given in 24-hr $PM_{2.5}$ time series plots in Appendix C.

For the model performance of the 2009-2010 Attainment episode, the focus will be on four main monitoring sites. These main sites are:

- Hawthorne site in Salt Lake City
- Ogden site in Weber County
- Lindon site in Utah County
- Logan site in Cache County

In addition to these sites, the performances for all other monitoring locations are given in Appendix A.

The CMAQ modeling performance for the precursors (NOx, Ozone) of secondarily formed $PM_{2.5}$, along with performance of carbon monoxide are given in Appendix B. The monitor sites that measure NOx, Ozone, and CO during the winter season are Hawthorne, Ogden, North Provo, and Logan.

Also, time series performance analysis of the particulate components (nitrate, ammonium, sulfate, organic carbon, elemental carbon) at the three Speciation Trends Network sites located in Northern Utah (Hawthorne, Bountiful, Lindon) are given in Appendix D.

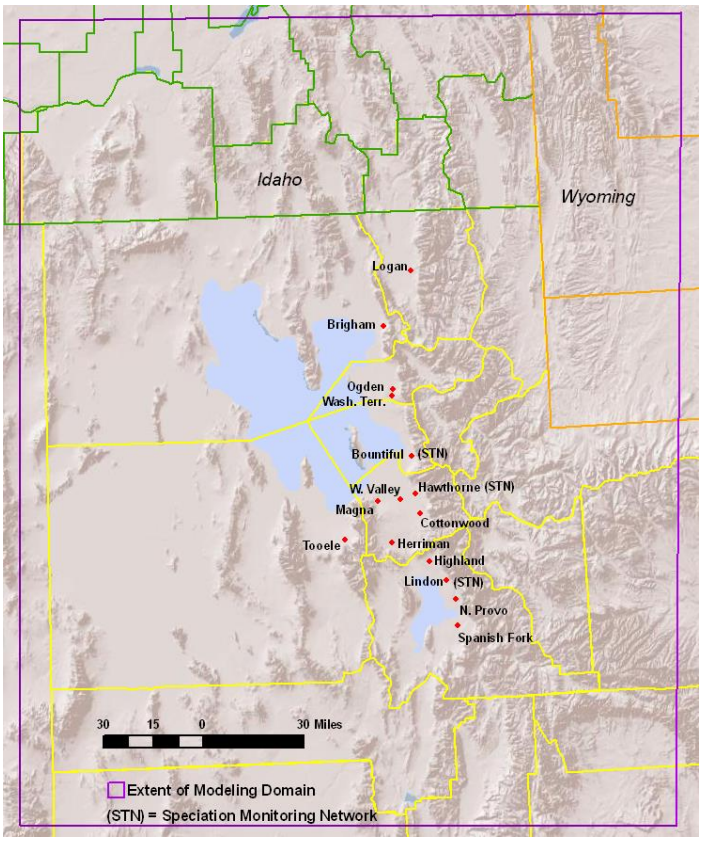

Figure 1.4: UDAQ monitoring network.

1.2.1 24-hr PM2.5 and PM2.5 Speciation Performance

Time series of 24-hr PM2.5 concentrations for 13 Dec. 2009 – 15 Jan. 2010 modeling period are shown in Figs. 1.5 – 1.8 at the Hawthorne site in Salt Lake City (Fig. 1.5), the Ogden site in Weber County (Fig 1.6), the Lindon site in Utah County (Fig. 1.7), and the Logan site in Cache County (Fig. 1.8). For the most part, CMAQ replicates the buildup and washout of each individual episode. Also, when vertical advection is de-activated, CMAQ can reproduce the high 24-hr $PM_{2.5}$ concentrations observed during the most of the episodes.

It is often seen that CMAQ "washes" out the $PM_{2.5}$ concentrations a day or two earlier than that seen in the observations. For example, on the day 21 Dec. 2009, the concentration of $PM_{2.5}$ continues to build while CMAQ has already cleaned the valley basins of high $PM_{2.5}$ concentrations. At these times, the observed cold pool that holds the $PM_{2.5}$ is often very shallow and the winds just above this cold pool are southerly and strong before the approaching cold front. This situation is very difficult for a meteorological and photochemical model to reproduce. An example of this situation is shown in Fig. 1.9, where the lowest part of the Salt Lake Valley is still under a very

shallow stable cold pool, yet higher elevations of the valley have already been cleared of the high $PM_{2.5}$ concentrations.

During the 24 – 30 Dec. 2009 episode, a weak meteorological disturbance brushes through the northernmost portion of Utah. It is noticeable in the observations at the Ogden monitor on 25 Dec. as $PM_{2.5}$ concentrations drop on this day before resuming an increase through Dec. 30. The meteorological model, and thus CMAQ, correctly pick up this disturbance. However, rather than a partial clearing, as seen in the observations, the model completely clears out the building $PM_{2.5}$; and thus CMAQ performance suffers at the most northern Utah monitors of Ogden and Logan. The monitors to the south (Hawthorne, Lindon) are not influenced by this disturbance and the building of $PM_{2.5}$ is replicated by CMAQ. This highlights another challenge of modeling $PM_{2.5}$ episodes in Utah. Often during cold pool events, weak disturbances will pass through Utah that will de-stabilize the valley inversion and cause a partial clear out of $PM_{2.5}$. However, the $PM_{2.5}$ is not completely cleared out, and after the disturbance exits, the valley inversion strengthens and the $PM_{2.5}$ concentrations continue to build. Typically, CMAQ completely mixes out the valley inversion during these weak disturbances.

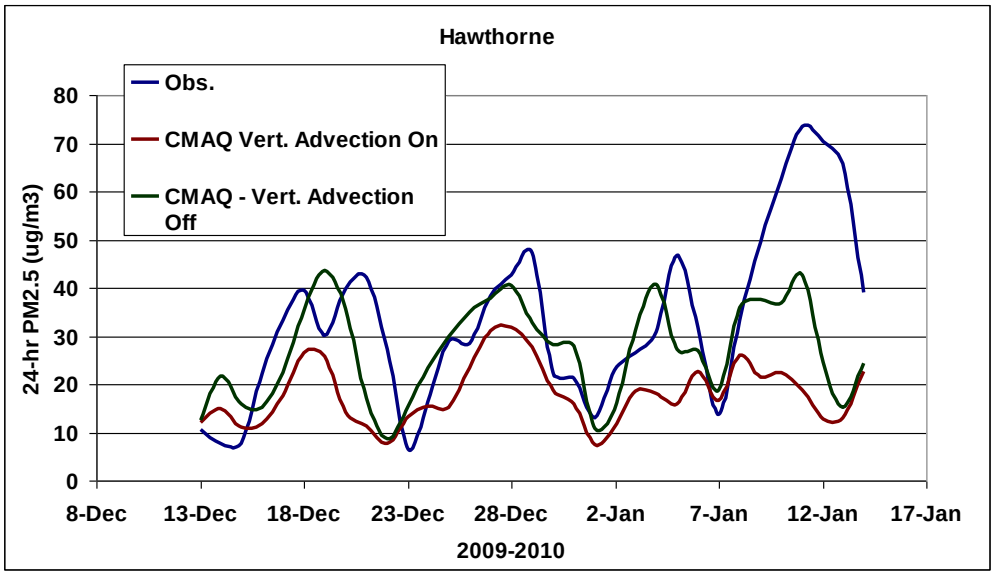

Figure 1.5: 24-hr $PM_{2.5}$ time series. Observed PM2.5 (blue trace), modeled with vertical advection deactivated (green trace), and modeled with vertical advection activated (red trace).

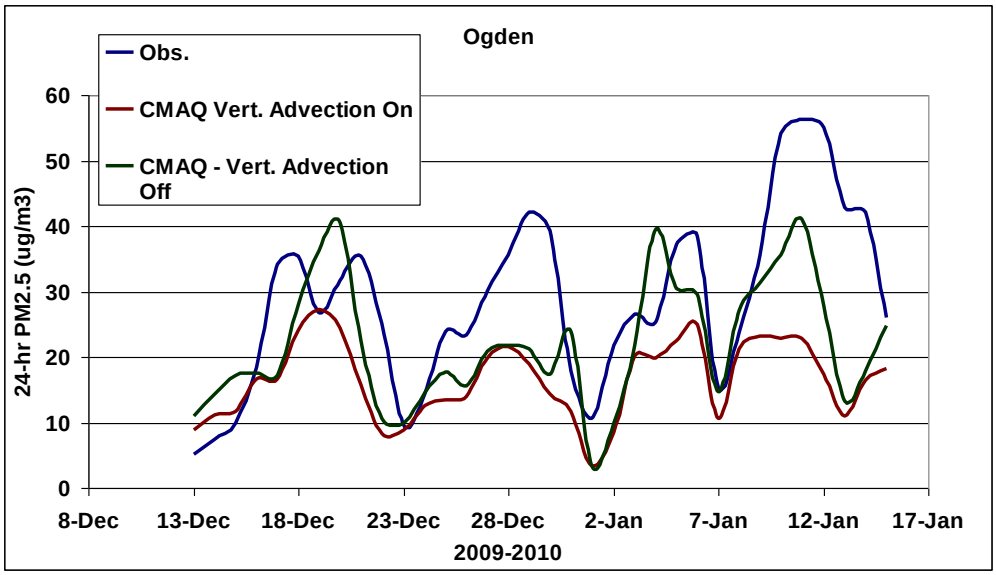

Figure 1.6: 24-hr $PM_{2.5}$ time series - Ogden monitoring site.

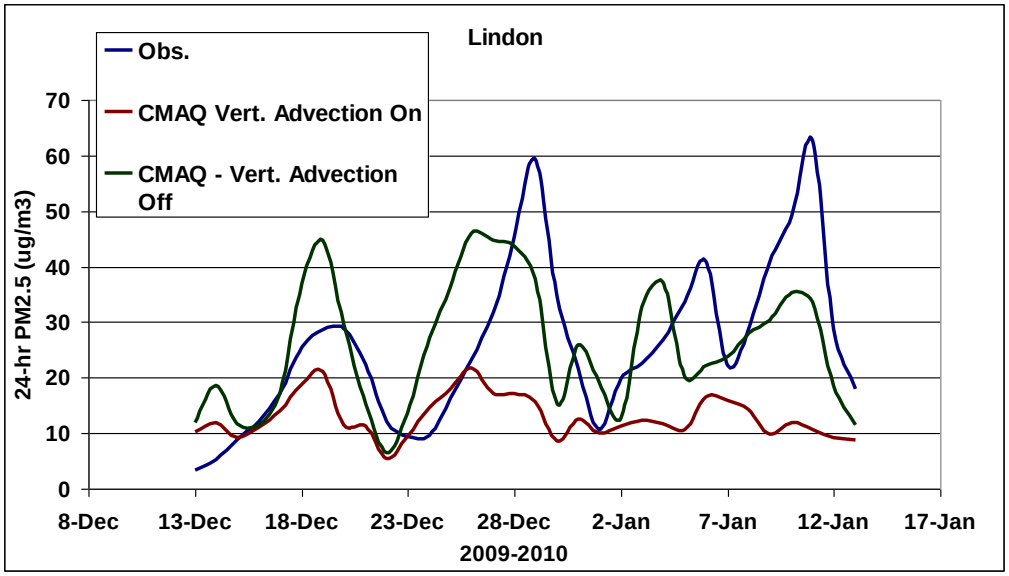

Figure 1.7: 24-hr $PM_{2.5}$ time series - Lindon monitoring site.

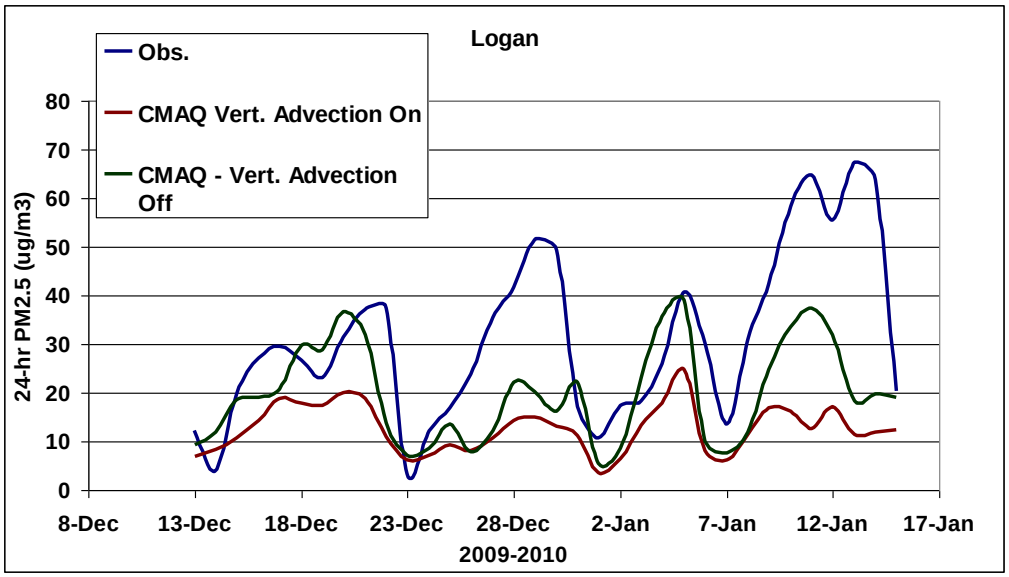

Figure 1.8: 24-hr $PM_{2.5}$ time series - Logan monitoring site.

Figure 1.9: An example of the Salt Lake Valley at the end of a high PM2.5 episode. The lowest elevations of the Salt Lake Valley are still experiencing an inversion and elevated PM2.5 concentrations while the $PM_{2.5}$ has been 'cleared out' throughout the rest of the valley. These 'end of episode' clear out periods are difficult to replicate in the photochemical model.

It is clear that model performance improves when turning off the vertical advection module in CMAQ. This configuration allows for an increase in the buildup of $PM_{2.5}$ during the high concentration episodes when compared to the simulation with vertical advection on. However, it is important to verify that the increase in PM2.5 concentrations seen when de-activating the vertical advection is due to an increase in the production of secondary nitrate, which CMAQ struggles to produce when vertical advection is on.

Figure 1.10 – 1.12 are time series of simulated and observed 24-hr nitrate for the 3 STN sites along the Wasatch Front of Utah. There were 12 STN samples collected at the Hawthorne site during modeling time period (blue dots), 11 at the Lindon site and 9 at the Bountiful site. De-activating the vertical advection can increase CMAQ simulated nitrate by greater than 15 ug/m3 during high $PM_{2.5}$ episodes, bringing the simulated concentration more in line with what is observed on the STN filters. It appears the majority of the $PM_{2.5}$ increase that is seen in CMAQ simulations with vertical advection de-activated is due more formation of nitrate, which is desired.

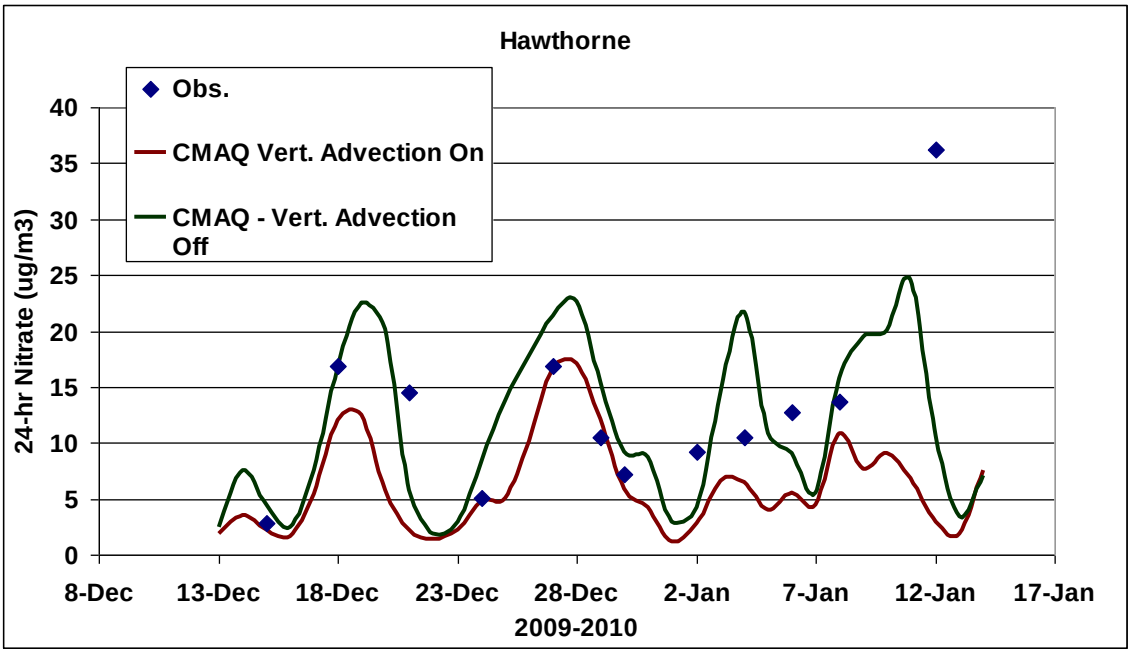

Figure 1.10: 24-hr particulate nitrate time series. Observed nitrate from STN filters (blue dots), modeled with vertical advection deactivated (green trace), and modeled with vertical advection activated (red trace).

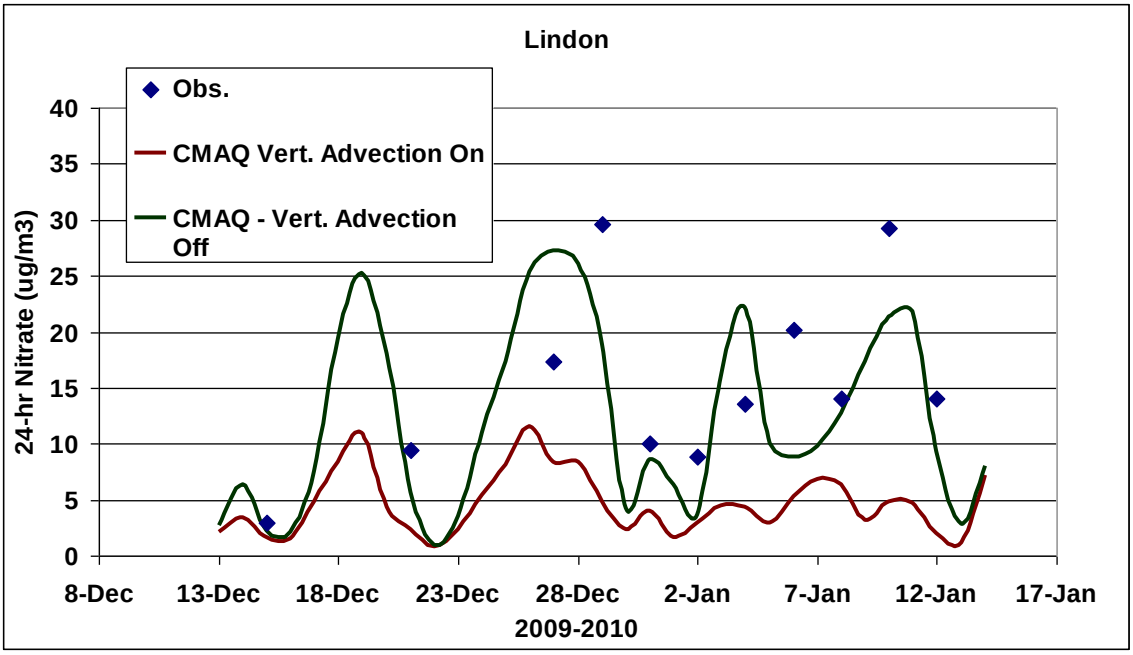

Figure 1.11: Same as Fig. 1.10, except for the Lindon STN monitoring site.

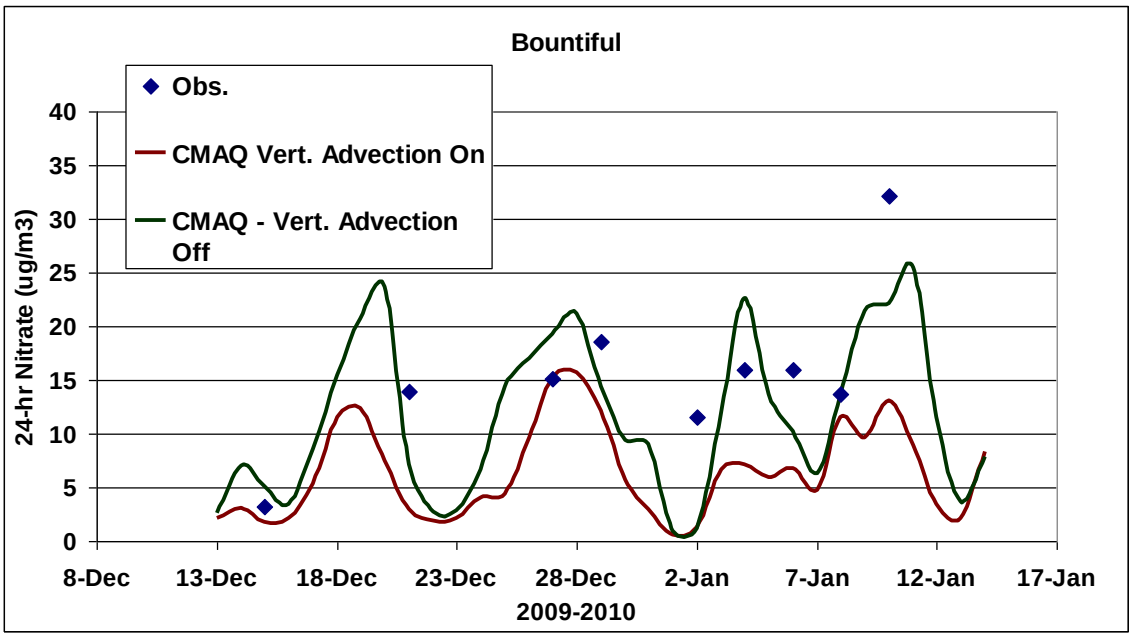

Figure 1.12: Same as Fig. 1.10, except for the Bountiful STN monitoring site.

Figures 1.13 and 1.14 compare the simulation of nitrate for 4-km modeling domain with vertical advection off and vertical advection on for Dec. 29, 2009 at 00 UTC. With vertical advection off (Fig. 1.13), the production of nitrate is greatly increased along the Wasatch Front and the Cache Valley when compared in the vertical advection on simulation (Fig. 1.14). It is most noticeable in Utah county where the nitrate concentration increases from ~5 ug/m3 to >25 ug/m3. Also in the Cache Valley, the turning off of vertical advection increases the nitrate concentrations from ~5 ug/m3 to ~15 ug/m3.

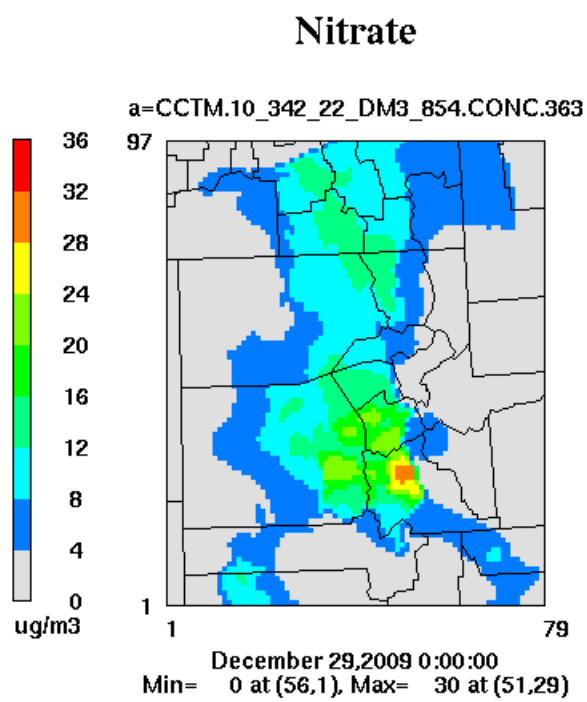

Figure 1.13: Model particulate nitrate with vertical advection deactivated for Dec. 29, 2009.

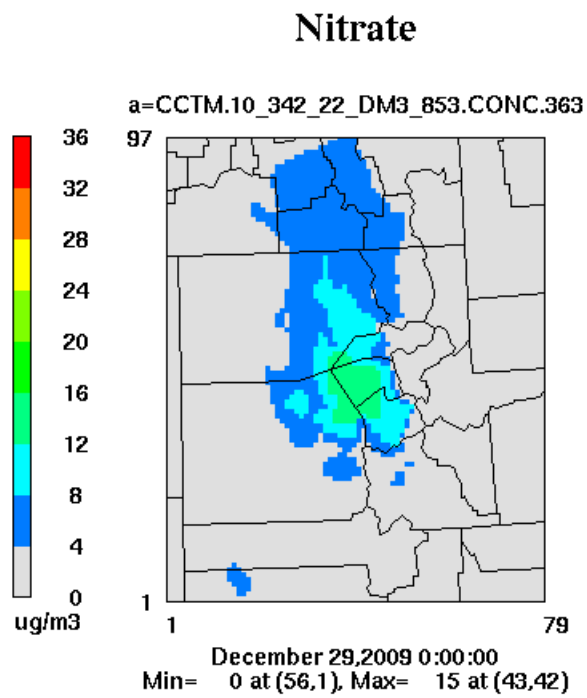

Figure 1.14: Model particulate nitrate with vertical advection activated for Dec. 29, 2009.

$PM_{2.5}$ simulated and observed speciation is shown at the 3 STN sites in Figures 1.15 – 1.17. The observed speciation is constructed using days in which the STN filter 24-hr $PM_{2.5}$ concentration was > 35 ug/m3. For the 2009-2010 modeling period, the observed speciation pie charts was created using 8 filter days at Hawthorne, 6 days at Lindon, and 4 days at Bountiful. The speciation of this small dataset appears similar to a comparison of a larger dataset of STN filter speciated data from 2005-2010 for high wintertime PM2.5 days.

The simulated speciation is constructed using modeling days that produced 24-hr $PM_{2.5}$ concentrations > 35 ug/m3. Using this criterion, the simulated speciation pie chart is created from 18 modeling days for Hawthorne, 14 days at Lindon, and 14 days at Bountiful. At all 3 STN sites, the percentage of simulated nitrate is greater than 40%, while the simulated ammonium percentage is at ~15%. This indicates that the model is able to replicate the secondarily formed particulates that typically make up the majority of the measured $PM_{2.5}$ on the STN filters during wintertime pollution events.

A source apportionment positive matrix factorization (PMF) study indicated that the wood burning inventories may be under-estimated in Northern Utah (Kerry et al., 2013). This under-estimation of wood burning emissions may contribute to the lower model prediction of organic carbon. Thus, UDAQ applied an updated wood burning emission factor that increased organic carbon emissions in 2010 Baseline modeling inventory. This new wood burning inventory (fireplaces, woodstoves, etc.) comes from EPA's new

Residential Wood Combustion estimation tool (released December 2012). The tool uses 2010 US Census Housing data as inputs. The CMAQ model performance with the updated wood burning emission factors in 2010 Baseline inventory is enhanced when compared to 2009-2010 episodic inventory (Appendix D).

There is no STN site in the Logan non-attainment area, and very little speciation information is available in the Cache Valley. Figure 1.18 shows the simulated speciation at Logan. Ammonium (20%) and nitrate (60%) make up a higher percentage of the simulated $PM_{2.5}$ at Logan when compared to sites along the Wasatch Front.

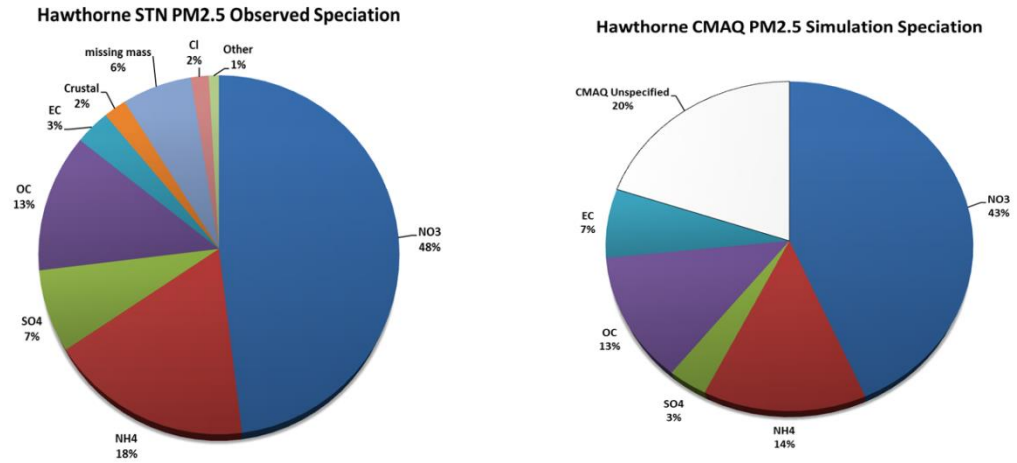

Figure 1.15: The composition of observed and model simulated average 24-hr $PM_{2.5}$ speciation averaged over days when an observed and modeled day had 24-hr concentrations > 35 µg/m^3 at the Hawthorne STN site.

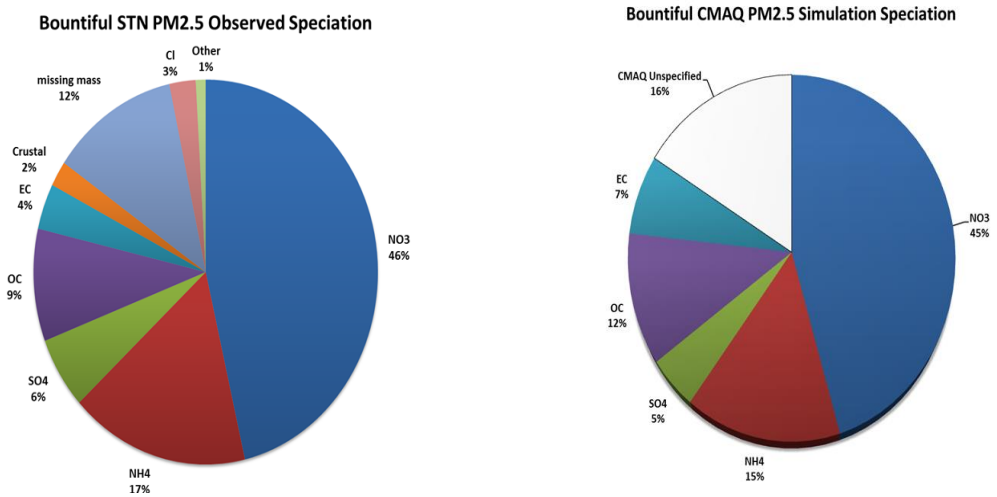

Figure 1.16: The composition of observed and model simulated average 24-hr $PM_{2.5}$ speciation averaged over days when an observed and modeled day had 24-hr concentrations > 35 µg/m^3 at the Bountiful STN site.

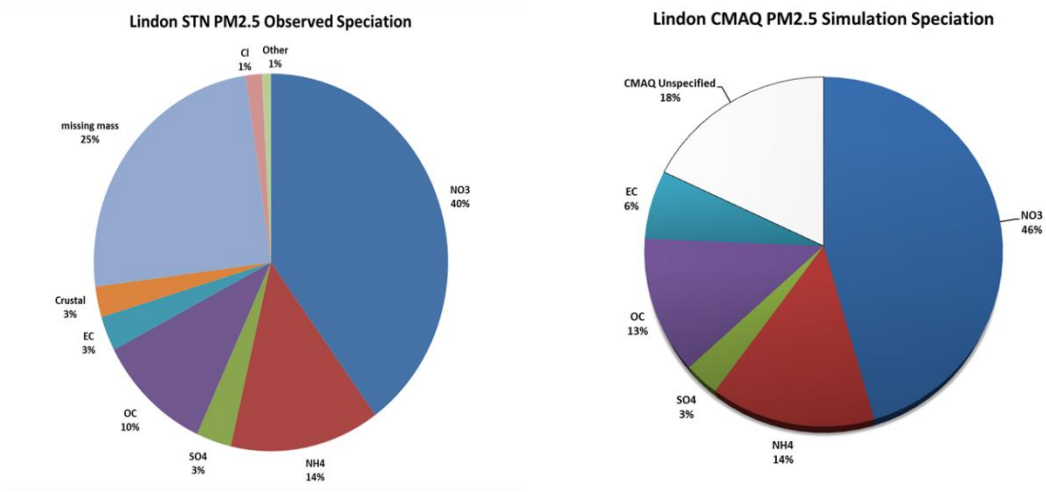

Figure 1.17: The composition of observed and model simulated average 24-hr $PM_{2.5}$ speciation averaged over days when an observed and modeled day had 24-hr concentrations > 35 µg/m^3 at the Lindon STN site.

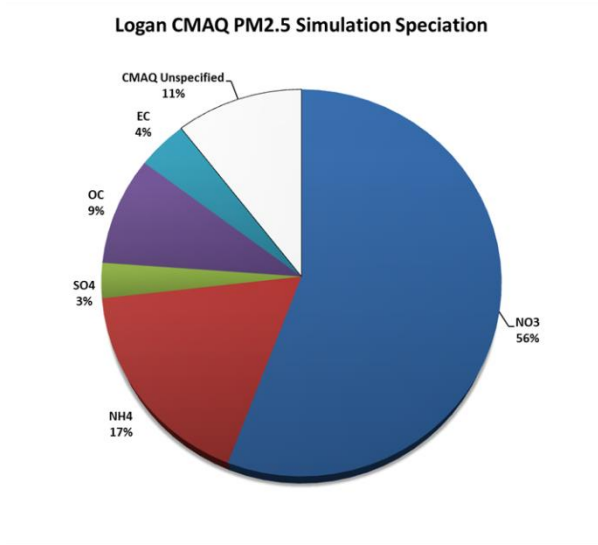

Figure 1.18: The composition of model simulated average 24-hr $PM_{2.5}$ speciation averaged over days when a modeled day had 24-hr concentrations > 35 µg/m^3 at the Logan monitoring site. No observed speciation data is available for Logan.

In addition to the time series analysis, EPA guidance recommends a statistical analysis of $PM_{2.5}$ (http://www.epa.gov/ttn/scram/guidance/guide/final-03-pm-rh-guidance.pdf). Useful metrics mentioned in the EPA guidance include mean fractional bias and mean fractional error, normalized mean bias, and normalized mean error. Model performance statistics for the 2009-2010 modeling episode are given in Table 1.3. Based on these performance scores the CMAQ simulated 24-hr $PM_{2.5}$ concentrations agree well with the observed values, with correlation coefficients above 0.46 at all locations. Overall, CMAQ under-predicts the 24-hr $PM_{2.5}$ (mean bias in Table 1.3), but this can be explained due to the early CMAQ model washouts described in Section 1.1.2.

Table 1.3: Performance statistics for 2009-2010 modeling period at the Hawthorne, Ogden, Lindon, and Logan monitoring sites.

Site	# of Observations	Mean CMAQ simulations (ug/m3)	Mean Observations (ug/m3)	Ratio of Means (Sim/Obs)	Mean Bias (ug/m3)	Mean Fractional Bias (%)	Mean Error (ug/m3)	Mean Fractional Error (%)	Correlation Coefficient
Hawthorne	**34**	**26.9**	**33.1**	**0.81**	**-6.2**	**-6%**	**12.0**	**20%**	**0.46**
Ogden	**34**	**21.8**	**28.8**	**0.76**	**-6.9**	**-12%**	**10.7**	**22%**	**0.57**
Lindon	**34**	**25.4**	**25.6**	**0.99**	**0.0**	**3%**	**10.3**	**22%**	**0.54**
Logan	**34**	**20.0**	**29.3**	**0.68**	**-9.3**	**-16%**	**12.2**	**26%**	**0.51**

Figures 1.19 – 1.22 provide scatter plots of CMAQ simulated versus observed 24-hr $PM_{2.5}$ for the 34 days in the 2009-2010 modeling episode. The correlation coefficient (R^2 value) is greater than 0.50 at the Ogden, Lindon, and Logan monitoring sites, while at Hawthorne the R^2 value is 0.46. These scatter plots show good model performance, except on days when CMAQ exhibits an early episodic washout (i.e., Fig. 1.19).

Further, a subset of data points represented by the yellow triangles in the scatter plots are the modeled days that are used in the Model Attainment Test. From this dataset, it is shown that all modeling days where the 24-hr $PM_{2.5}$ was greater than 30 ug/m^3 were used in the Model Attainment Test at the Hawthorne and Lindon locations, while modeling days where the $PM_{2.5}$ was greater than 24 ug/m^3 were used for Logan and Ogden. CMAQ Model performance statistics for the modeling days used in the Model Attainment Test are shown in Table 1.4.

Bugle and soccer plots of normalized mean bias (NMB) and normalized mean error (NME) are shown in Figures 1.23 – 1.34. These performance metrics are described in *Boylan and Russel 2006* and the performance goal (solid red line) and criteria (dashed red lines) for 24-hr $PM_{2.5}$ are plotted on each figure. *Boylan and Russel 2006* recommend a model performance goal of +50% percent and performance criteria of +75% for NME. The recommendation of NMB is a performance goal of +/- 30% and performance criteria of +/- 60%.

When the observed 24-hr $PM_{2.5}$ is greater than 20 ug/m3 at Hawthorne, all but two days meet the performance goal for NME (Fig. 1.23). Again, these are two days where CMAQ model exhibits an early episodic washout. All days meet the performance criteria for NMB and NME at the Ogden (Fig. 1.26-1.28), Lindon (Fig. 1.29-1.31), and Logan (Fig. 1.32 -1.34) sites, with the majority of days meeting the performance goal. When looking at the subset of days that are used in the Model Attainment Test (yellow data points), all pass the performance goal for NMB and NME except for 2 days at Lindon and 1 day at Ogden. Yet, these days do meet the performance criteria.

Table 1.4: Performance statistics for the subset of the 2009-2010 modeling days that are used in the Model Attainment Test at the Hawthorne, Ogden, Lindon, and Logan monitoring sites.

Site	# of Observations	Mean CMAQ simulations (ug/m3)	Mean Observations (ug/m3)	Ratio of Means (Sim/Obs)	Mean Bias (ug/m3)	Mean Fractional Bias (%)	Mean Error (ug/m3)	Mean Fractional Error (%)
Hawthorne	**13**	**37.4**	**40.9**	**0.91**	**-4.2**	**-9%**	**12.3**	**34%**
Ogden	**13**	**31.9**	**38.0**	**0.84**	**-6.3**	**-17%**	**11.3**	**34%**
Lindon	**13**	**38.3**	**37.6**	**1.01**	**0.5**	**2%**	**12.8**	**36%**
Logan	**11**	**32.9**	**38.6**	**0.85**	**-8.3**	**-19%**	**12.9**	**36%**

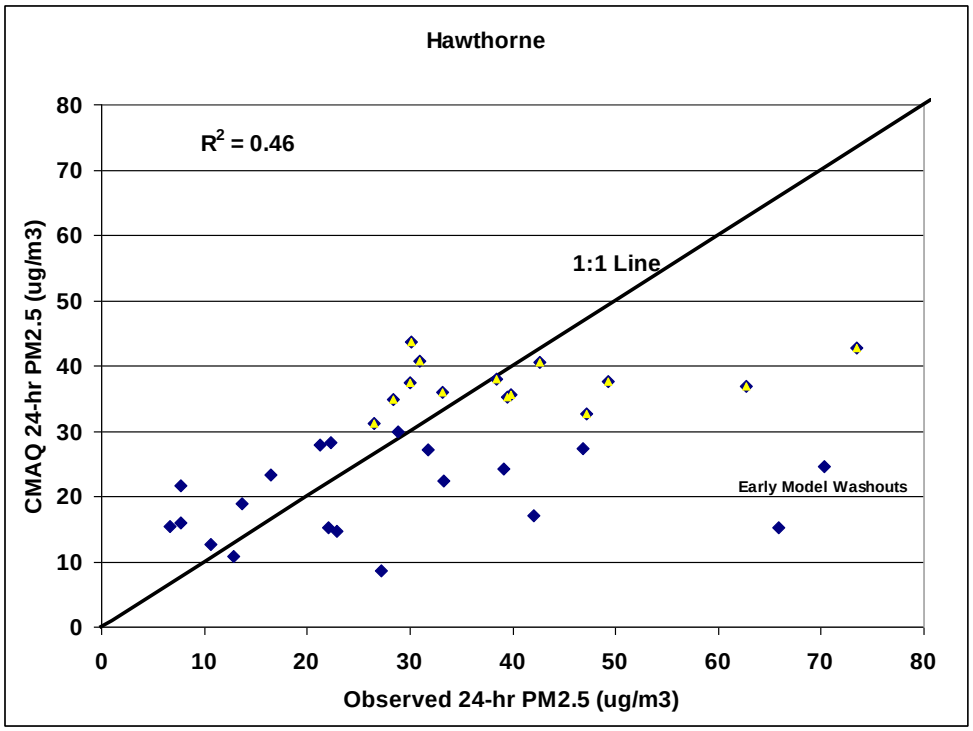

Figure 1.19: Scatter plot of 24-hr $PM_{2.5}$ at the Hawthorne monitoring site. The yellow data point represent the modeling days that are used in the Model Attainment Test.

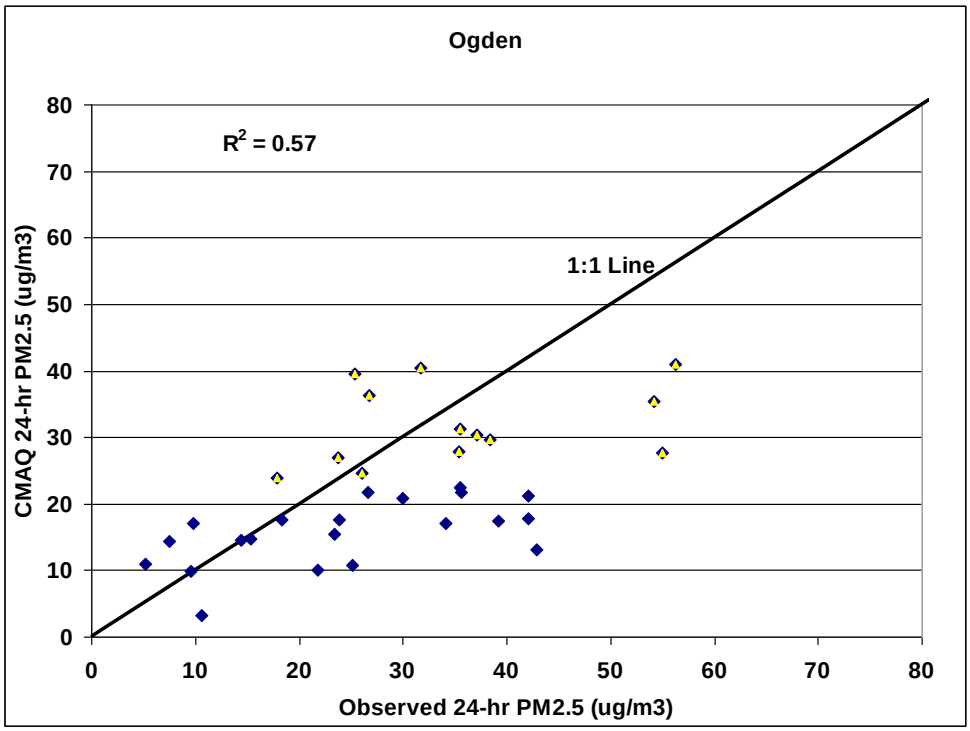

Figure 1.20: Scatter plot of 24-hr $PM_{2.5}$ at the Ogden monitoring site. The yellow data point represent the modeling days that are used in the Model Attainment Test.

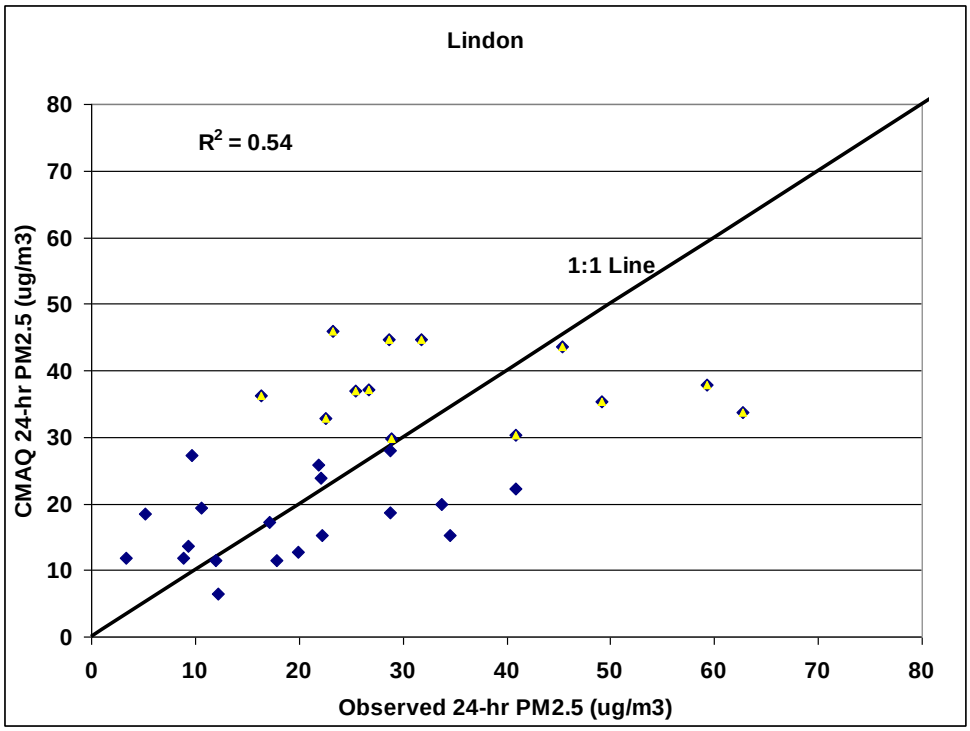

Figure 1.21: Scatter plot of 24-hr $PM_{2.5}$ at the Lindon monitoring site. The yellow data point represent the modeling days that are used in the Model Attainment Test.

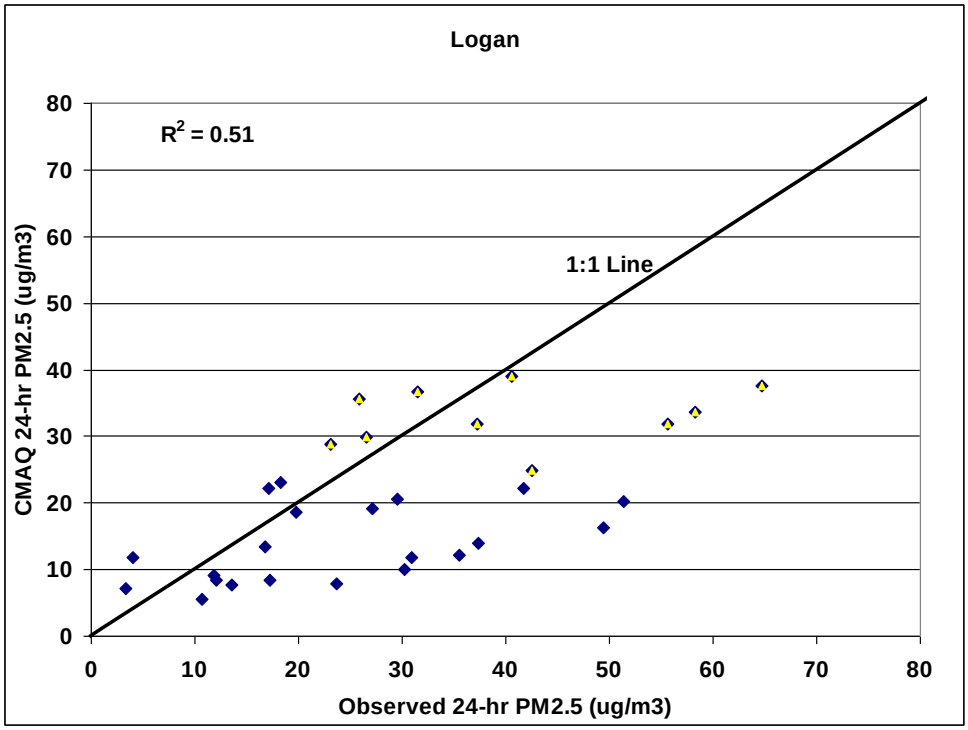

Figure 1.22: Scatter plot of 24-hr $PM_{2.5}$ at the Logan monitoring site. The yellow data point represent the modeling days that are used in the Model Attainment Test.

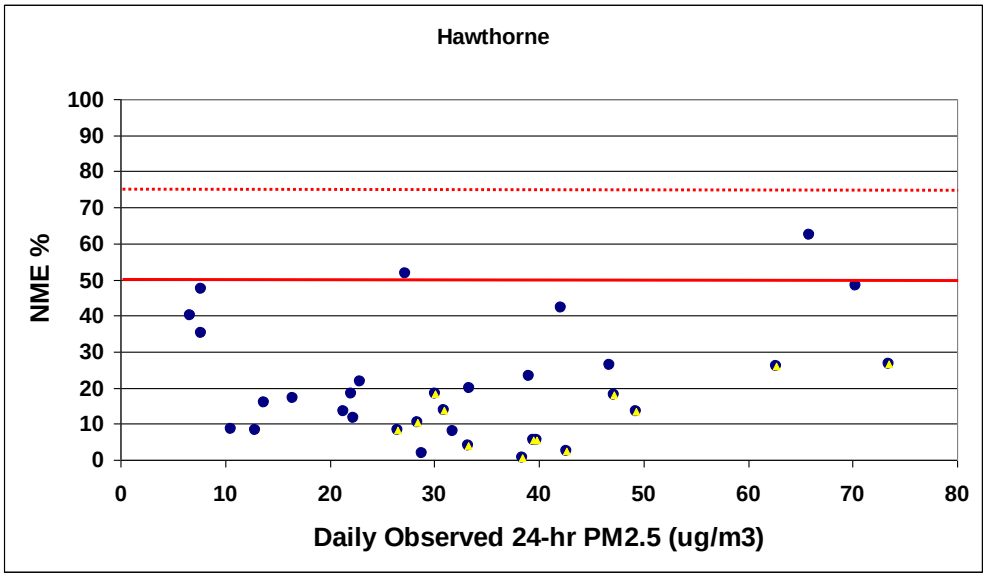

Figure 1.23: Bugle plot of normalized mean errors of 24-hr $PM_{2.5}$ at the Hawthorne monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

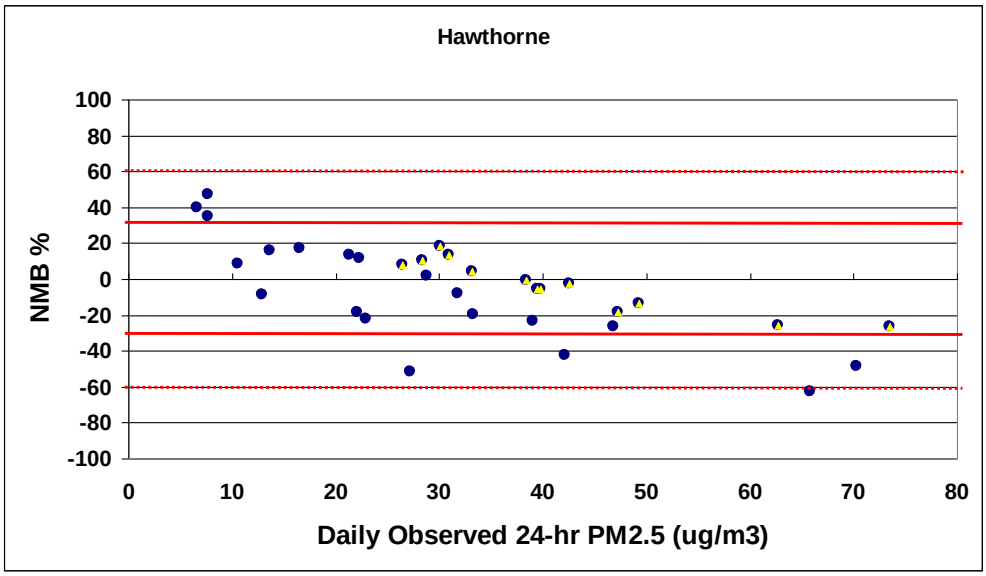

Figure 1.24: Bugle plot of normalized mean bias of 24-hr $PM_{2.5}$ at the Hawthorne monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

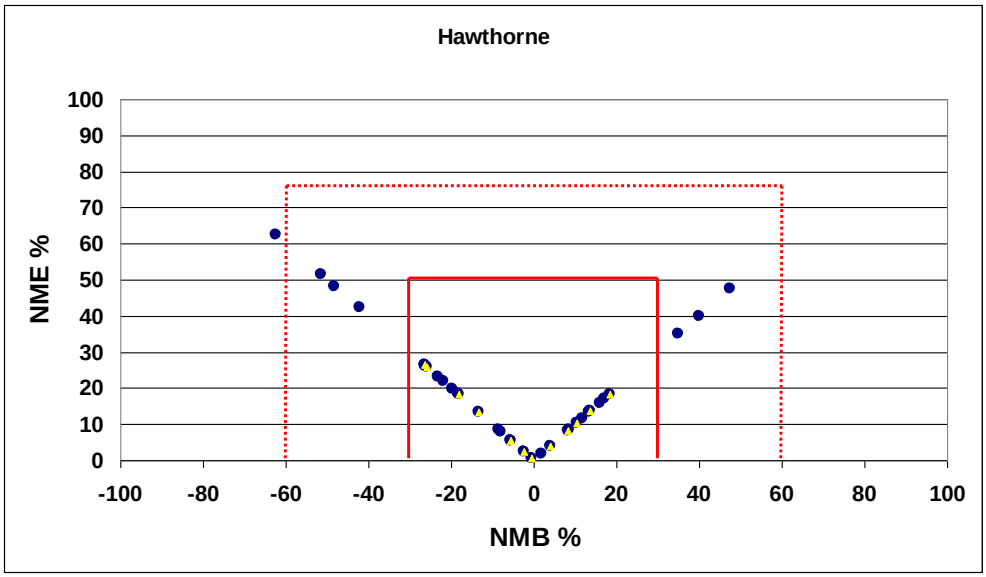

Figure 1.25: Soccer plot of normalized mean errors and biases at the Hawthorne monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

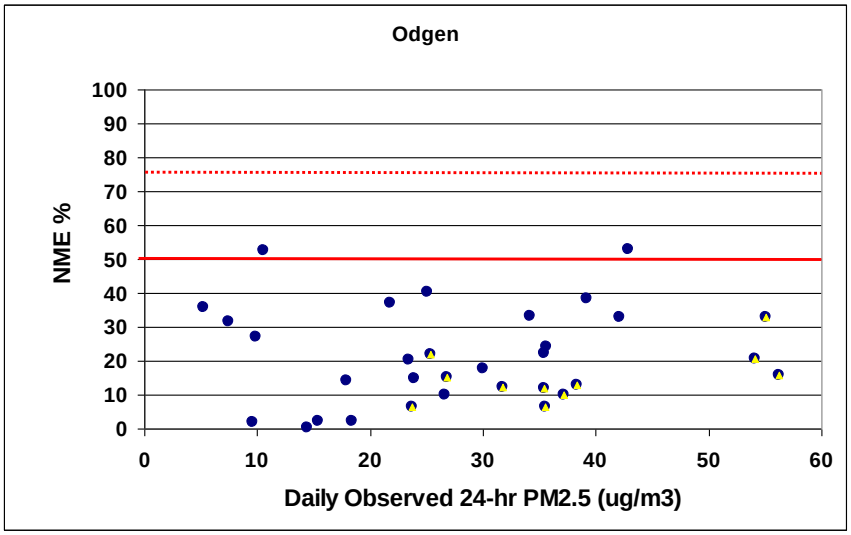

Figure 1.26: Bugle plot of normalized mean errors of 24-hr $PM_{2.5}$ at the Ogden monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

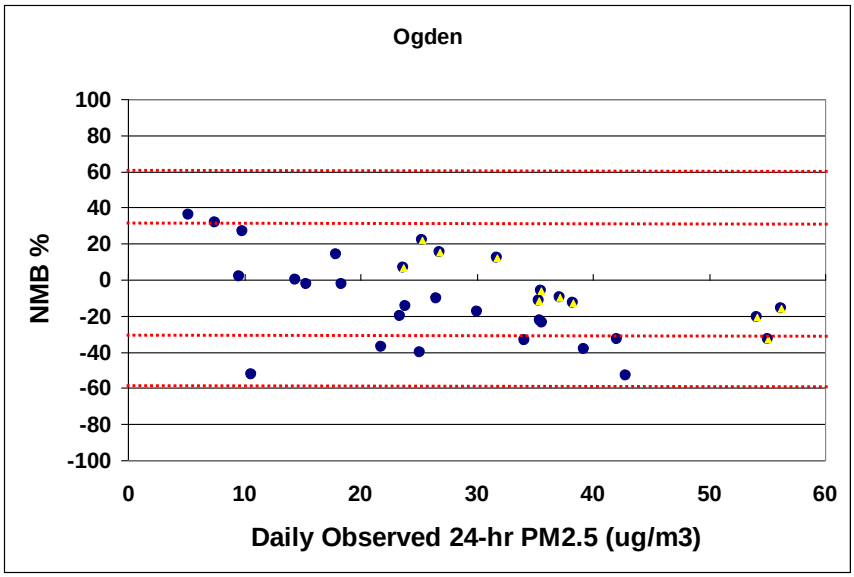

Figure 1.27: Bugle plot of normalized mean bias of 24-hr $PM_{2.5}$ at the Ogden monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

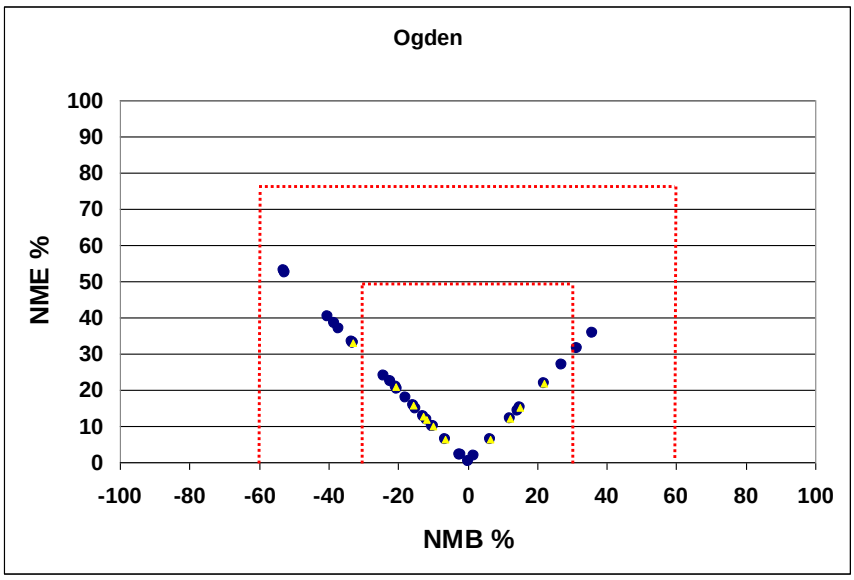

Figure 1.28: Soccer plot of normalized mean errors and biases at the Ogden monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

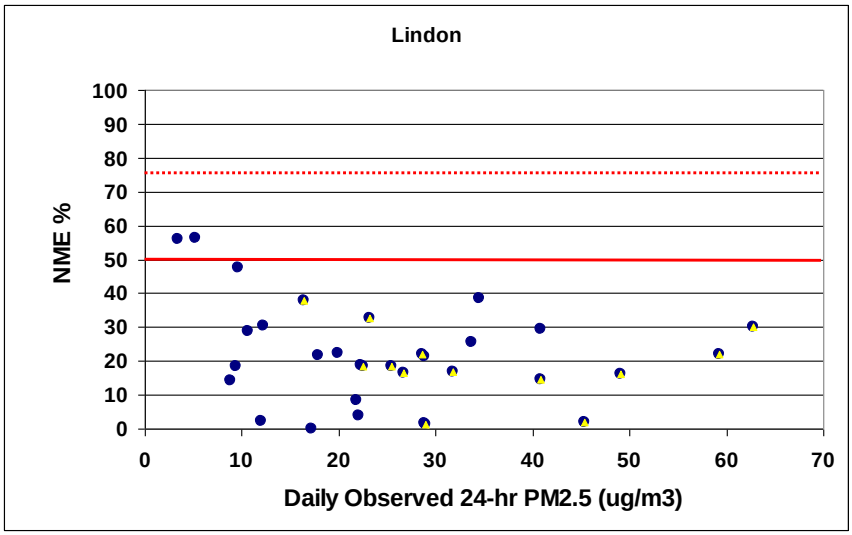

Figure 1.29: Bugle plot of normalized mean errors of 24-hr $PM_{2.5}$ at the Lindon monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

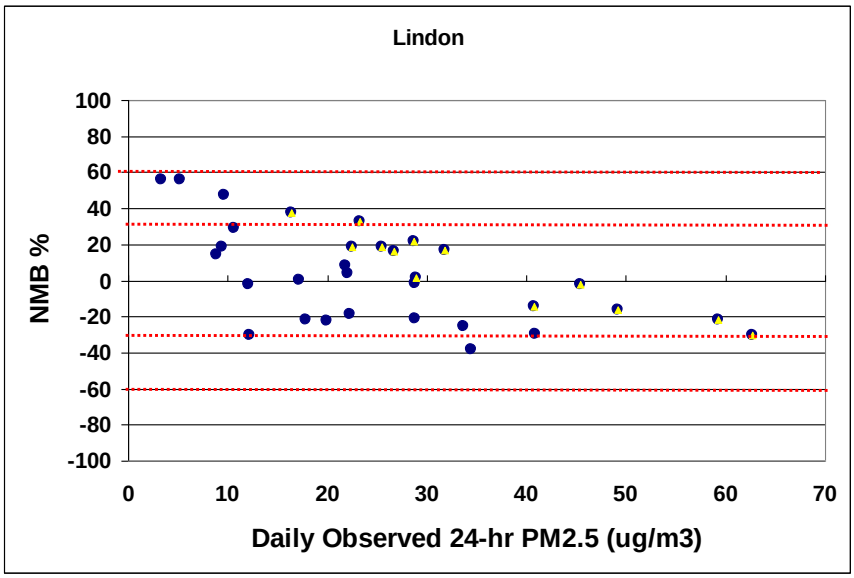

Figure 1.30: Bugle plot of normalized mean bias of 24-hr $PM_{2.5}$ at the Lindon monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

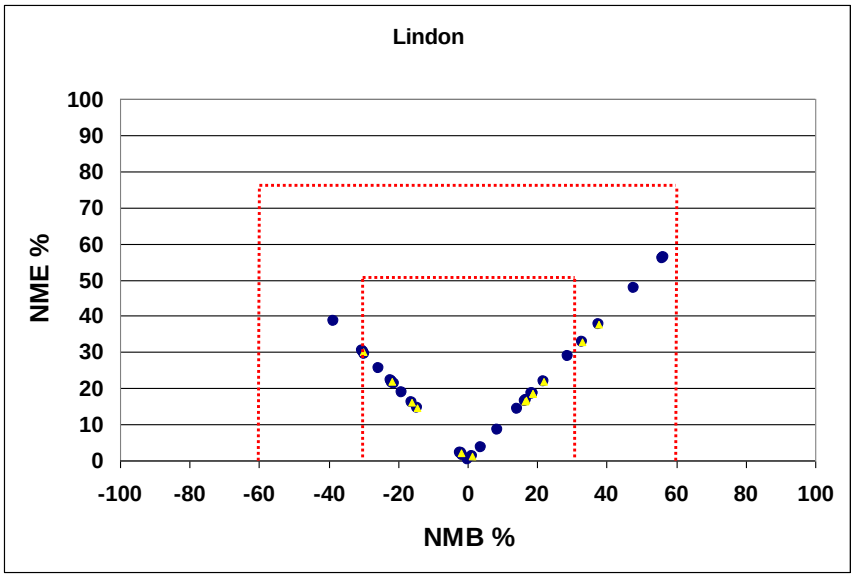

Figure 1.31: Soccer plot of normalized mean errors and biases at the Lindon monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

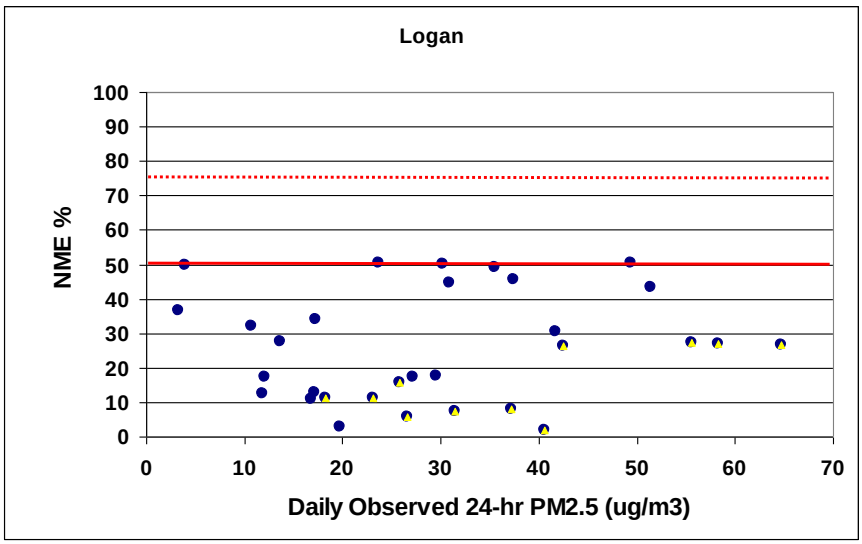

Figure 1.32: Bugle plot of normalized mean errors of 24-hr $PM_{2.5}$ at the Logan monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

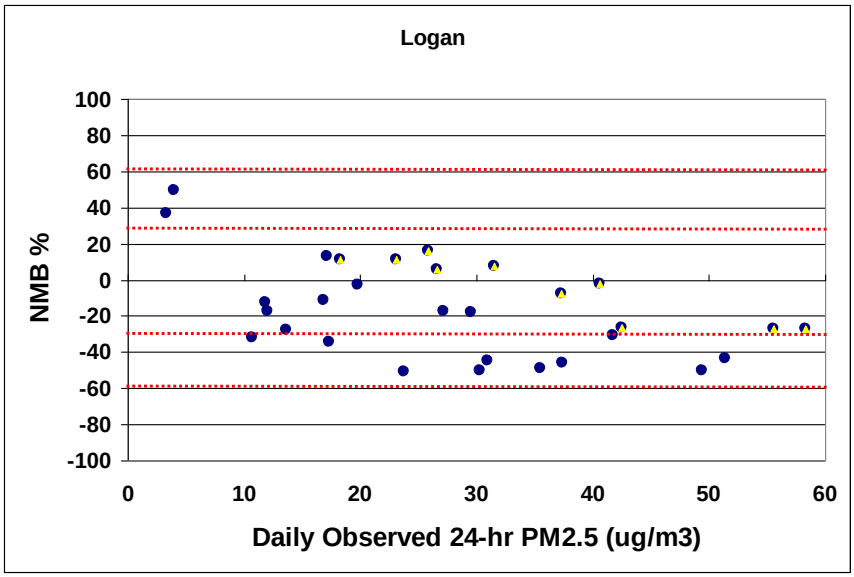

Figure 1.33: Bugle plot of normalized mean bias of 24-hr $PM_{2.5}$ at the Logan monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

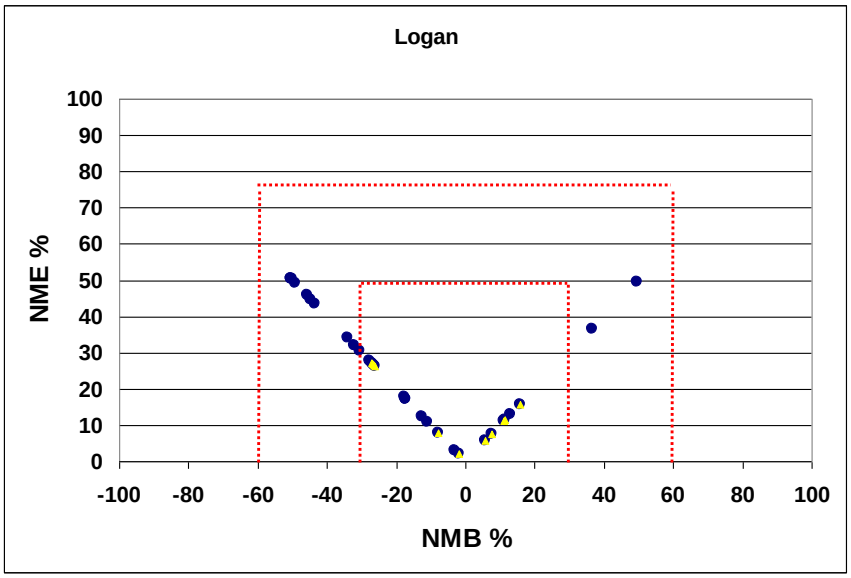

Figure 1.34: Soccer plot of normalized mean errors and biases at the Logan monitoring site. The dashed and solid lines indicate the performance criteria and performance goals in accord with Boylan and Russell (2006). The yellow data point represent the modeling days that are used in the Model Attainment Test.

1.3 Summary Model Performance Evaluation

Model performance for 24-hr $PM_{2.5}$ is good and generally acceptable and can be characterized as follows:

- Good replication of the episodic buildup and clear out of $PM_{2.5}$. Often the model will clear out the simulated $PM_{2.5}$ a day too early at the end of an episode. This clear out time period is difficult to model (i.e., Figure 1.7).

- Good agreement in the magnitude of $PM_{2.5}$, as the model can consistently produce the high concentrations of $PM_{2.5}$.

- Spatial patterns of modeled 24-hr $PM_{2.5}$, show for the most part, that the $PM_{2.5}$ is being confined in the valley basins, consistent to what is observed.

- Model performance statistics of normalized mean error and normalized mean bias show that the model meets performance goals and criteria, with the exception being when the CMAQ model exhibits an early episodic washout.

- The simulation of precursors for secondarily formed $PM_{2.5}$ is much improved when CMAQ model vertical advection is deactivated (Appendix B). This deactivation improves the CMAQ performance of NOx and ozone and allows CMAQ to "hold" these precursors in the lowest model layers leading to an increase (and better performance) for modeled ammonium nitrate.

- Speciation and composition of the modeled $PM_{2.5}$ matches the observed speciation quite well. Modeled and observed nitrate are between 40% and 50% of the $PM_{2.5}$. Ammonium is between 15% and 20% for both modeled and observed $PM_{2.5}$. Model performance of organic carbon is improved by using new emission factors for fireplace and wood stove burinng in 2010 Baseline Inventory (Appendix D).

References

Kelly, Kerry E., Kochenruther, Robert, Kuprov, Roman, Silcox, Geoffrey D., 2013. Receptor model source attributions for Utah' Salt Lake City airshed and the impacts of wintertime secondary ammonium nitrate and ammonium chloride aerosol, Journal of the Air & Waste Management Association, 63:5, 575-590. doi:10.1080/10962247.2013.774819

Appendix A

Appendix A provides CMAQ model 24-hr $PM_{2.5}$ performance results for each monitor that is part of the Model Attainment Test. The monitor sites include:

- Brigham City
- Bountiful
- Magna
- Hawthorne
- Rose Park
- Ogden
- Harrisville
- Tooele
- Logan
- North Provo
- Lindon
- Spanish Fork

Daily filter 24-hr $PM_{2.5}$ measurements are made at the Hawthorne, Ogden, Rose Park, Logan, Lindon, and North Provo monitoring sites. However, there some data is missing from the daily Rose Park measurement dataset. The other sites were on an every three day filter measurement schedule.

The analysis provided in Appendix A includes time series of 24-hr PM2.5 at each site, with CMAQ ran with the vertical advection on and off. This shows the importance of deactivating the vertical advection in order to build $PM_{2.5}$ (secondary nitrate). Additionally, Table A.1 gives the 24-hr $PM_{2.5}$ performance statistics for the monitoring sites that have sufficient observational data to compare with. The sites on an every three day monitoring schedule do not have sufficient enough data for a statistical analysis. The performance statistics are provided for CMAQ simulations with vertical advection and with vertical advection de-activated.

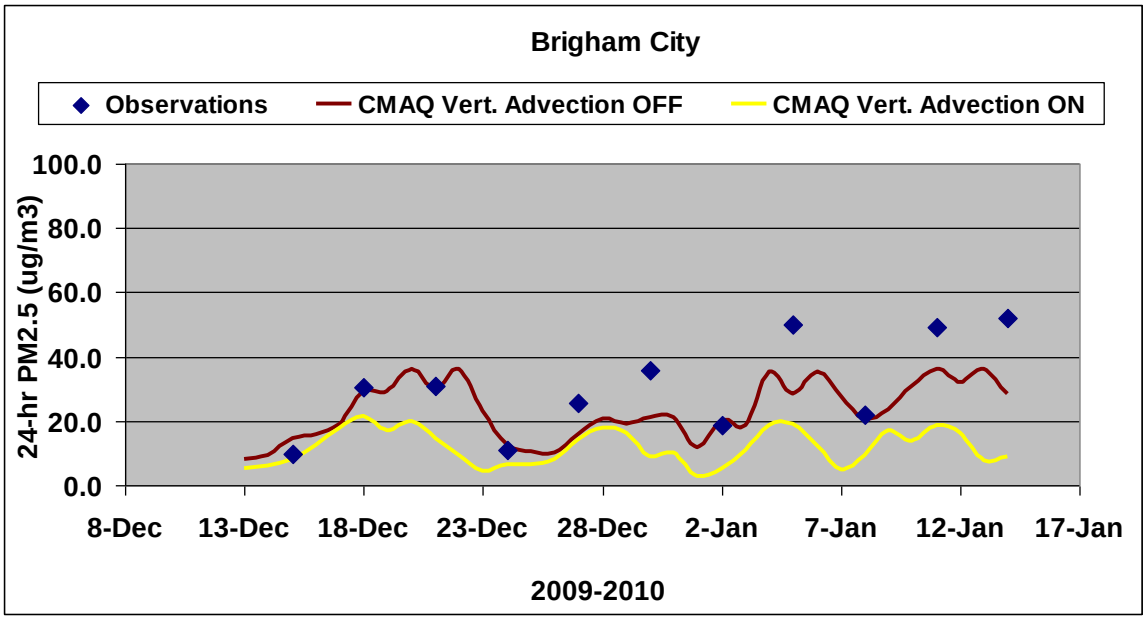

Figure A.1: 24-hr $PM_{2.5}$ time series for Brigham City. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

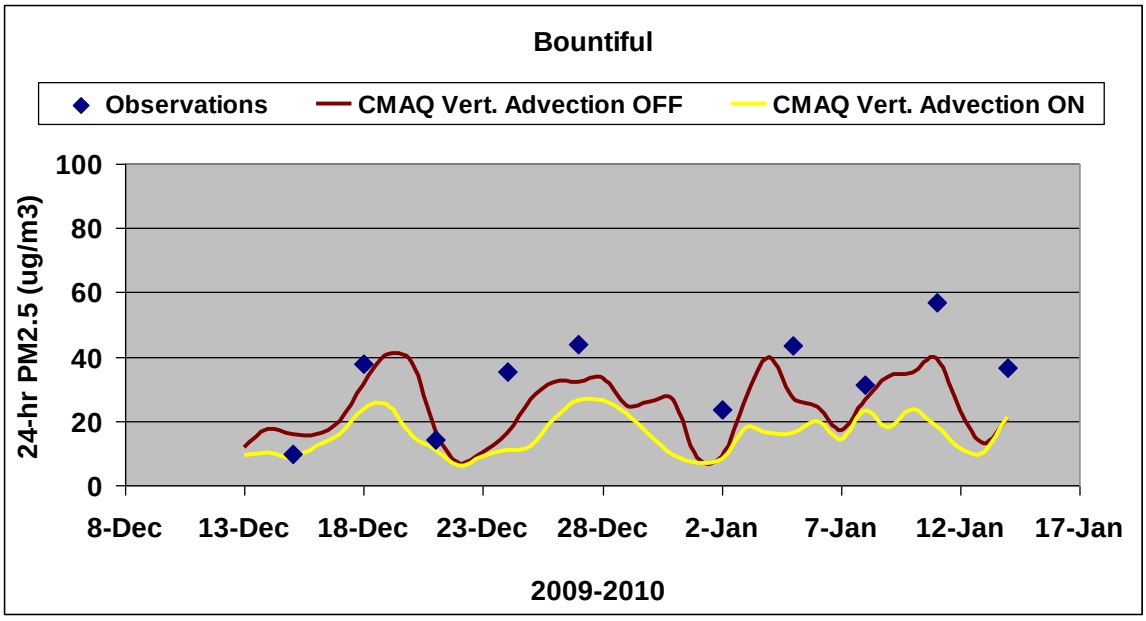

Figure A.2: 24-hr $PM_{2.5}$ time series for Bountiful. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

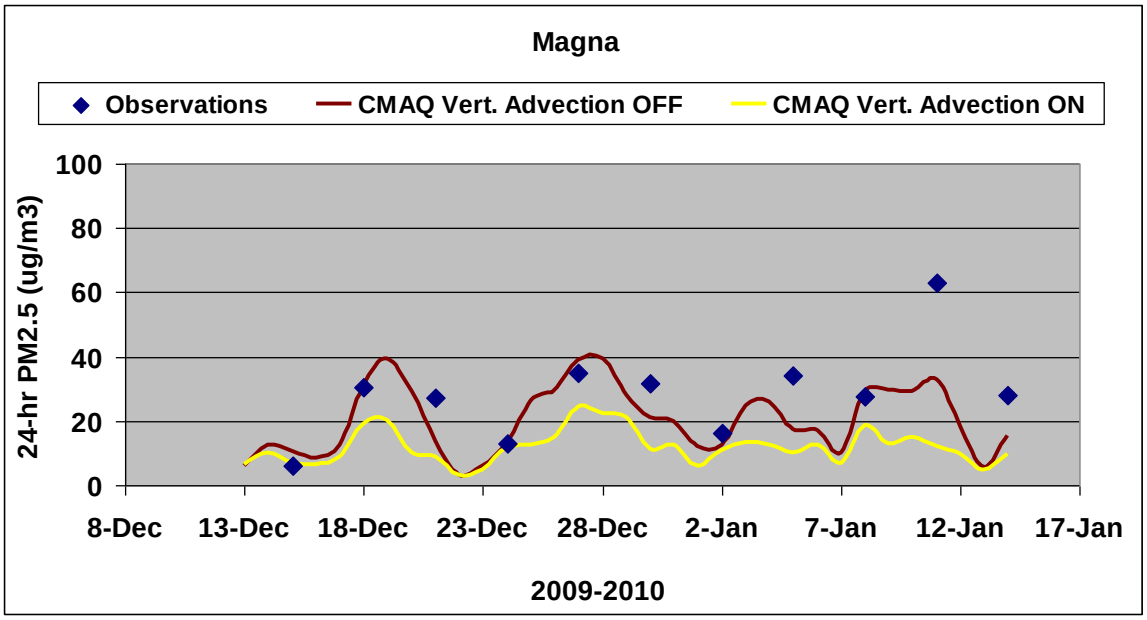

Figure A.3: 24-hr $PM_{2.5}$ time series for Magna. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

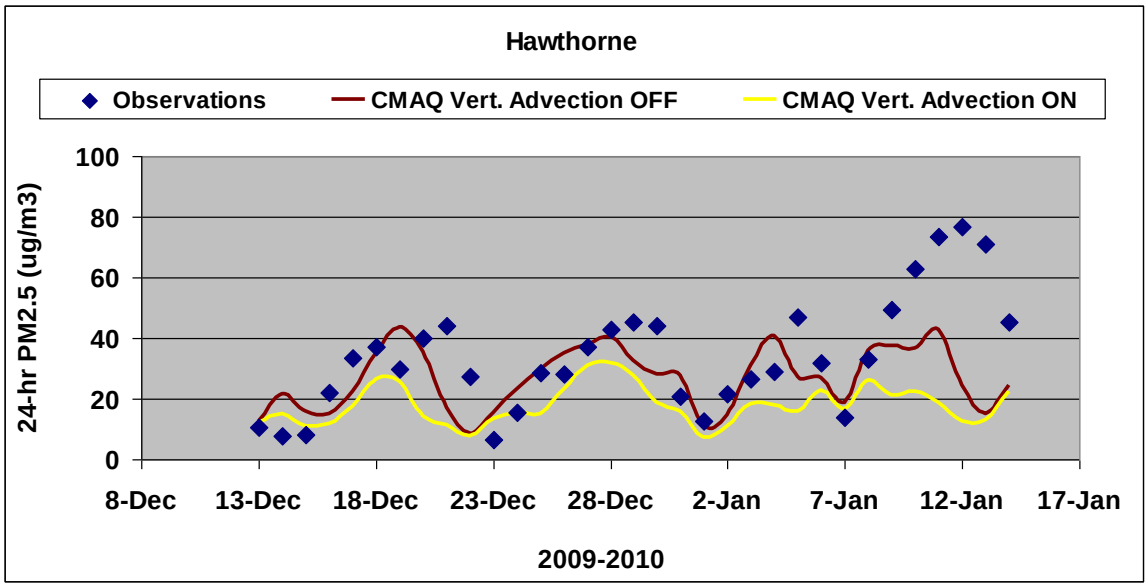

Figure A.4: 24-hr $PM_{2.5}$ time series for Hawthorne. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

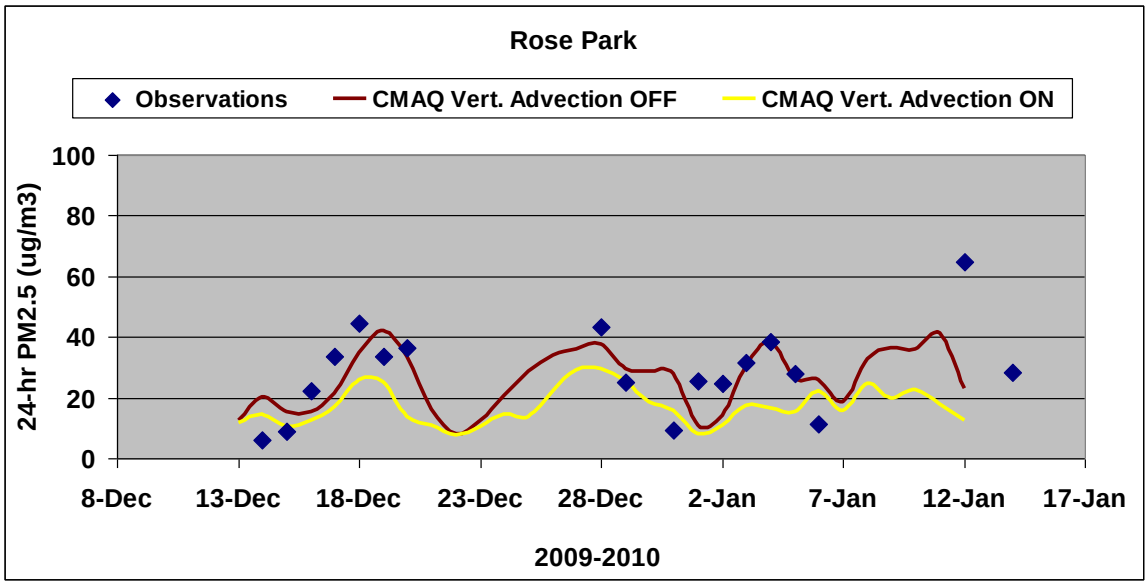

Figure A.5: 24-hr $PM_{2.5}$ time series for Rose Park. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

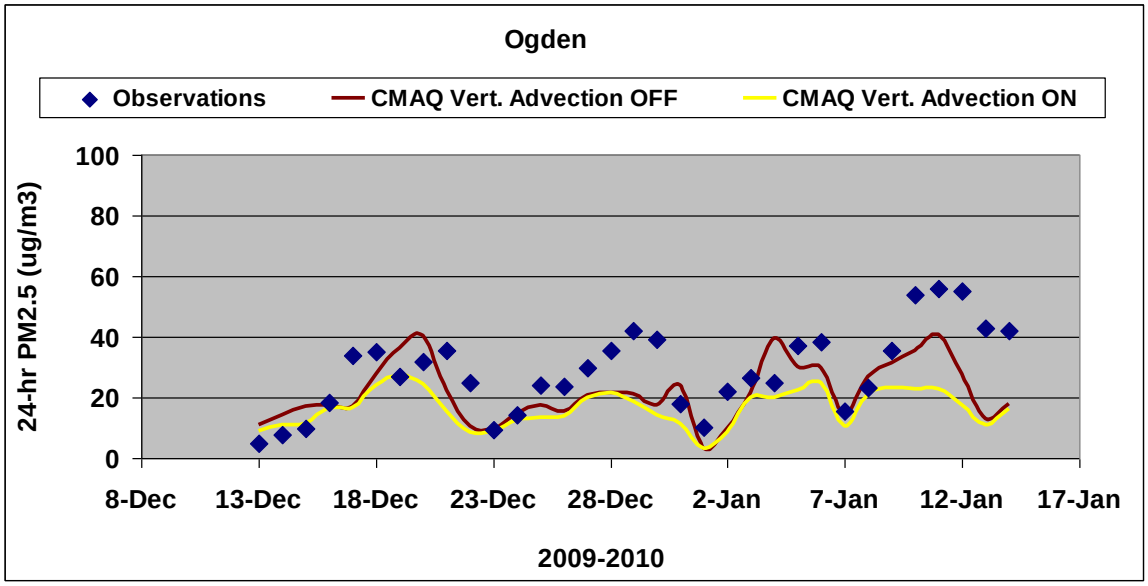

Figure A.6: 24-hr $PM_{2.5}$ time series for Ogden. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

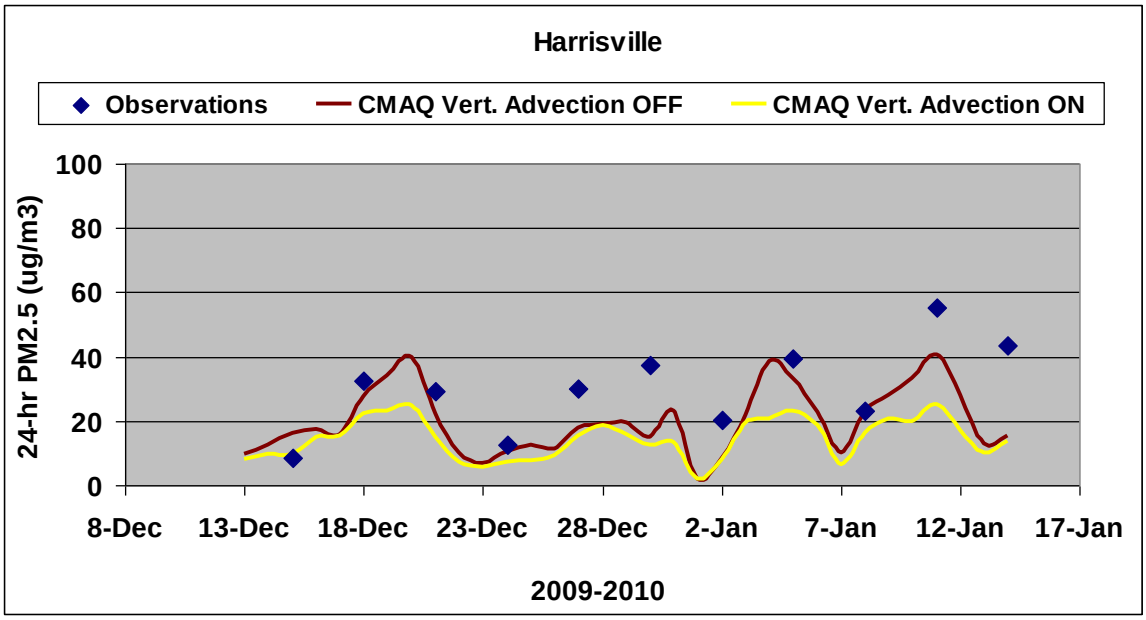

Figure A.7: 24-hr $PM_{2.5}$ time series for Harrisville. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

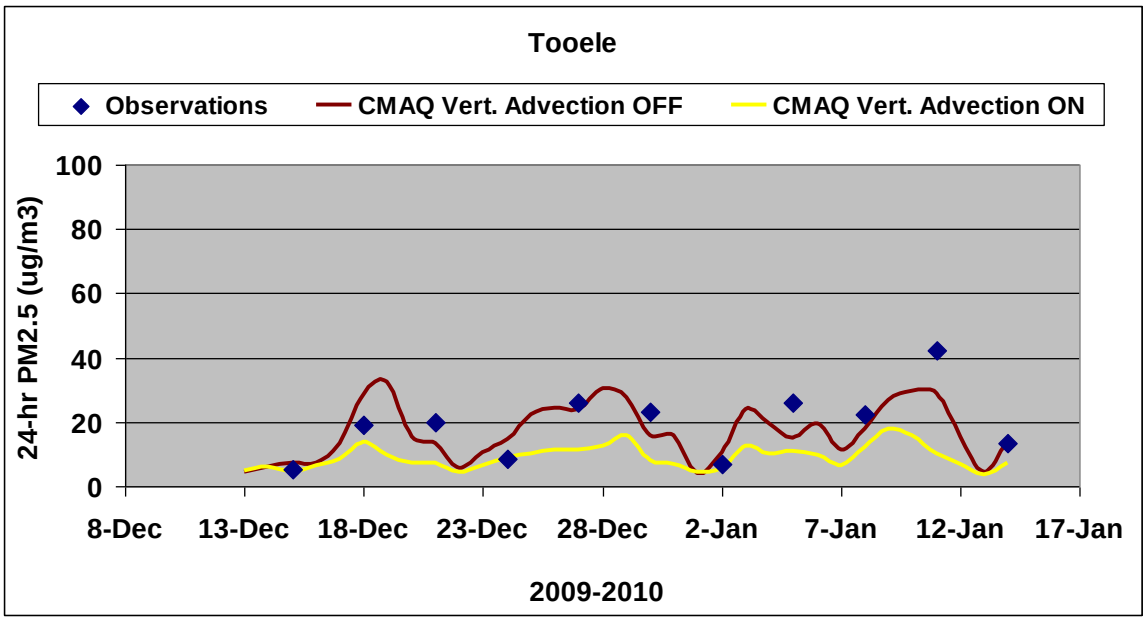

Figure A.8: 24-hr $PM_{2.5}$ time series for Tooele. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

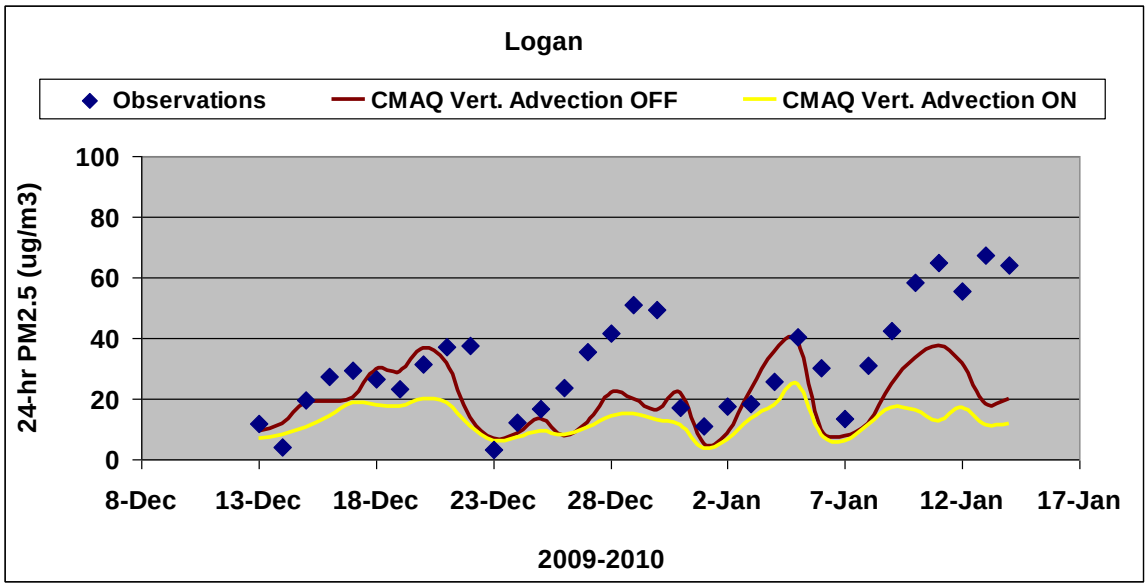

Figure A.9: 24-hr $PM_{2.5}$ time series for Logan. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

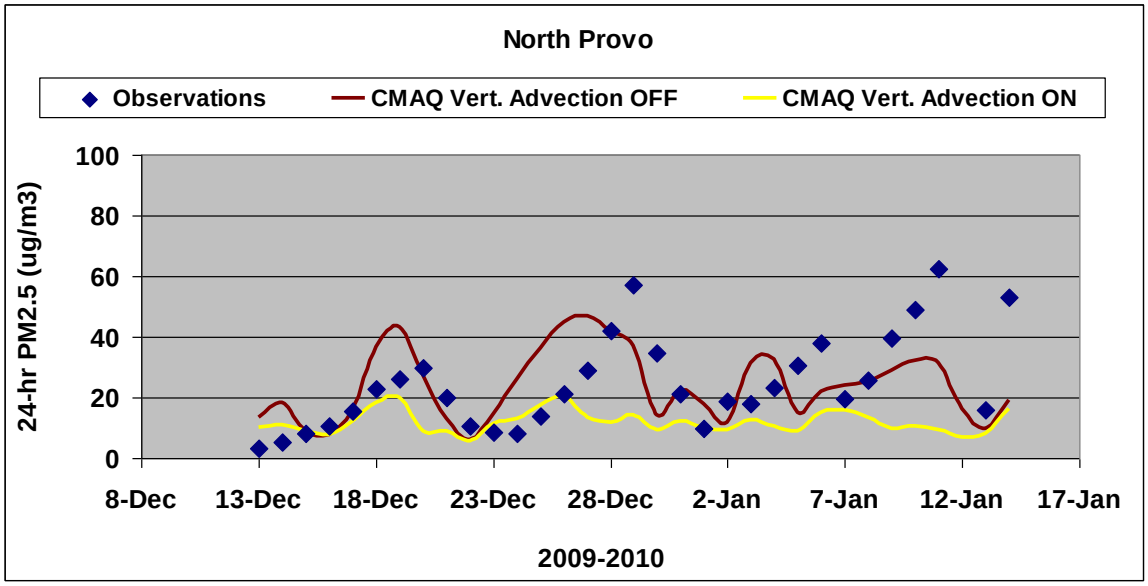

Figure A.10: 24-hr $PM_{2.5}$ time series for North Provo. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

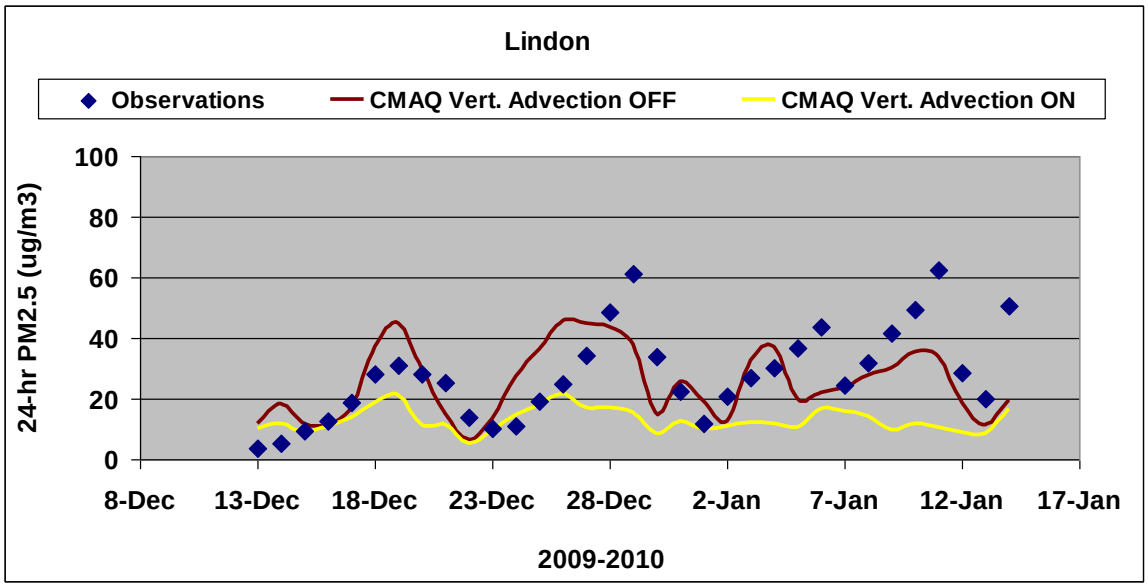

Figure A.11: 24-hr $PM_{2.5}$ time series for Lindon. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

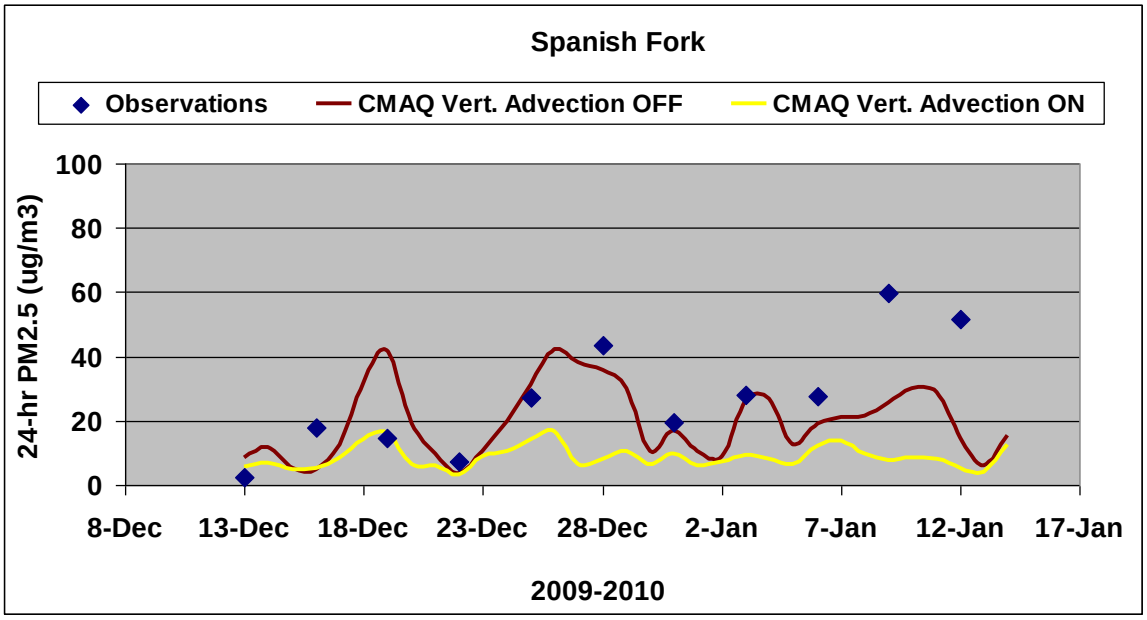

Figure A.12: 24-hr $PM_{2.5}$ time series for Spanish Fork. Observed PM2.5 (blue point), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

Table A.1: Performance statistics for the subset of the 2009-2010 modeling days that are used in the Model Attainment Test at the Hawthorne, Ogden, Lindon, North Provo, Rose Park and Logan monitoring sites. Statistics are given for CMAQ simulations with both vertical advection (VA ON) on and de-activated (VA OFF). Bold statistics indicate the better model performance, which occurs with vertical advection de-activated.

		Mean Bias (ug/m3)	***Mean Error (ug/m3)***	***Normalized Mean Bias (%)***	***Normalized Mean Error (%)***	***Mean Fractional Bias (%)***	**Mean Fractional Error (%)**
Hawthorne	VA ON	-17.8	18.3	-46.1	47.7	-50.8	56.2
	VA OFF	**-6.2**	**12.4**	**-16.2**	**32.0**	**-9.4**	**34.2**
Logan	VA ON	-20.7	20.7	-55.1	55.1	-68.1	68.1
	VA OFF	**-8.4**	**12.9**	**-22.3**	**34.3**	**-19.0**	**36.4**
Lindon	VA ON	-20.8	21.2	-60.4	61.5	-71.6	74.6
	VA OFF	**0.5**	**12.8**	**3.1**	**37.1**	**1.8**	**35.6**
North Provo	VA ON	-16.6	17.6	-54.7	57.9	-62.4	70.2
	VA OFF	**2.5**	**13.4**	**8.1**	**43.9**	**15.6**	**43.0**
Rose Park	VA ON	-11.9	15.9	-38.2	50.9	-31.3	61.9

Appendix B

The CMAQ modeling performance for NOx, Ozone, and Carbon Monoxide

Since the majority of the $PM_{2.5}$ during Utah winters is formed secondarily, it becomes important that CMAQ can adequately simulate the gaseous precursors that chemically produce the secondary particulate. The CMAQ performance of nitrogen oxides (NOx) and ozone (O_3), along with carbon monoxide (CO), a somewhat inert tracer of anthropogenic emissions, are shown at the four sites (Hawthorne, Odgen, North Provo, and Logan) where their measurements are made during the winter months.

The CMAQ performance is evaluated with vertical advection and with vertical advection de-activated. First, tables are shown at each site to provide a summary of model performance in terms of Mean Bias (ppb) and Normalized Mean Bias (%):

- Hawthorne – Table B.1
- Ogden – Table B.2
- North Provo – Table B.3
- Logan – Table B.4

The summary tables are made from data for the modeling days used in the $PM_{2.5}$ Model Attainment Test. That is, the NOx, ozone, and CO summary tables are from just high episodic PM2.5 modeling days, and not the entire 2009-2010 modeling period.

Also shown are time series at each location for a short episode inside the 2009-2010 modeling period. Below is a summary of the time series Figures:

- Hawthorne (Dec. 23 – Dec. 30, 2009)
    - NO – Figure B.1
    - NO_2 – Figure B.2
    - O_3 – Figure B.3
    - CO – Figure B.4
- Ogden (Jan 2 – Jan 4, 2010)
    - NO – Figure B.5
    - NO_2 – Figure B.6
    - O_3 – Figure B.7
    - CO – Figure B.8
- North Provo (Jan 2 – Jan 4, 2010)
    - NO – Figure B.9
    - NO_2 – Figure B.10
    - O_3 – Figure B.11
    - CO – Figure B.12
- Logan (Jan 3 – Jan 5, 2010)
    - NO – Figure B.13
    - NO_2 – Figure B.14

- O_3 – Figure B.15

Model performance for NOx, O_3, and CO can be characterized as follows:

- Simulated NO and CO follows the emissions pattern for both. That is, CMAQ produces the morning and afternoon morning rush hour traffic spikes. The observed NO and CO often has its highest concentrations during nighttime high $PM_{2.5}$ episodes. CMAQ is unable to simulate these high nighttime concentrations, and thus model performance at night is poor. It is not known if the high nighttime observed NO and CO is due to an emissions source missing in the emissions modeling inventory or some physical process (meteorology) not accounted for in the modeling. De-activating vertical advection gives CMAQ the capability to 'hold' more NO and CO in the first modeled layer, thus improving Mean Bias and Normalized Mean Bias. However, even with vertical advection de-activated, CMAQ simulated NO and CO is biased low at all locations. The exception being CO at Hawthorne, where de-activating vertical advection leads high bias.

The ability of CMAQ to 'hold' in more NO with vertical advection de-activated improves the model performance of NO_2 and O_3. At night this improvement is most noticeable. By holding in more NO at night, CMAQ better simulates the depletion of O_3 and the production of nighttime NO_2.

- Ultimately, de-activating vertical advection leads to more production and better performance for particulate nitrate, due to having more NO (and VOCs) in the modeled first layer.

Hawthorne

Table B.1: Mean Bias, Normalized Mean Bias at Hawthorne for NO, NO_2, O_3, and CO. Results are shown for CMAQ simulations with vertical advection (VA ON) and without vertical advection (VA OFF). Bolded values indicated whether the better performance between VA ON and VA OFF.

		Mean Bias (ppb)	Normalized Mean Bias (%)
NO	VA ON	-16	-48
	VA OFF	**-4**	**-13**
NO_2	VA ON	-5	-14
	VA OFF	**1**	**2**
O_3	VA ON	3	40
	VA OFF	**-1**	**-8.2**
CO	VA ON	**-81**	**-12**
	VA OFF	102	15

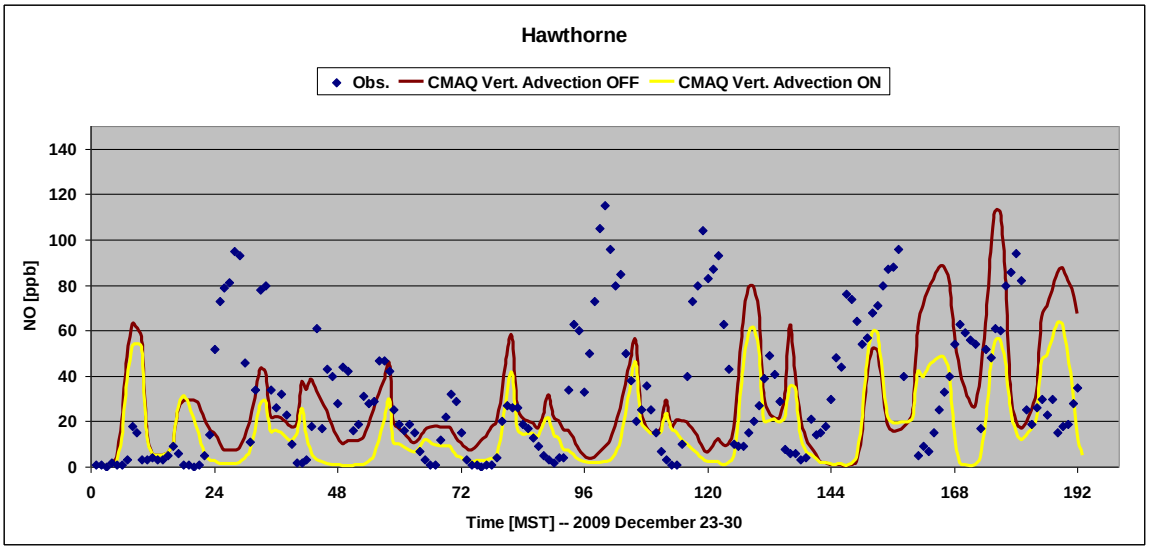

Figure B.1: Nitric oxide (NO) time series at the Hawthorne monitoring site. Observed NO (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

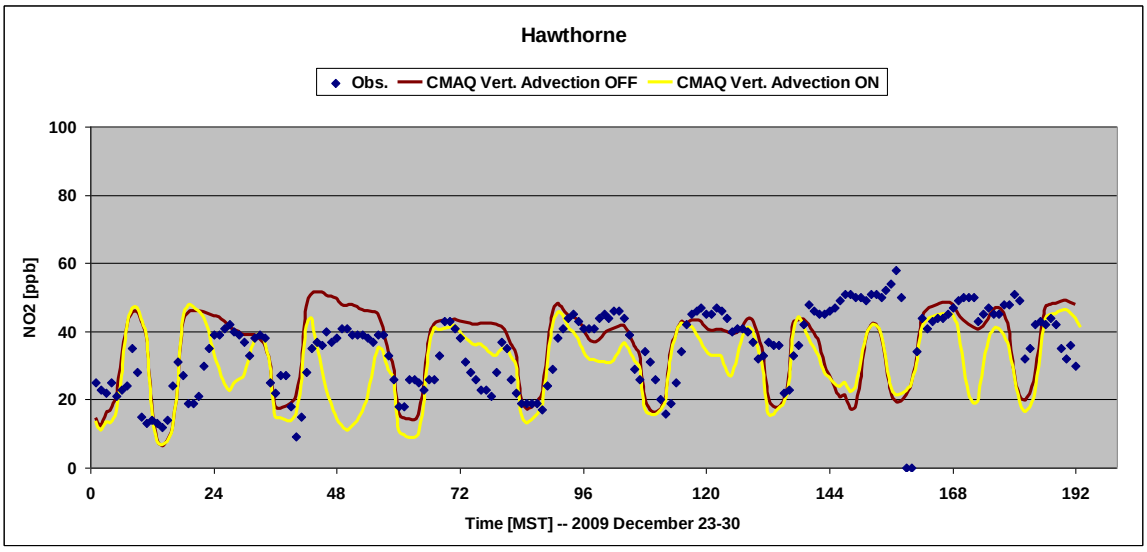

Figure B.2: Nitrogen dioxide (NO_2) time series at the Hawthorne monitoring site. Observed NO_2 (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

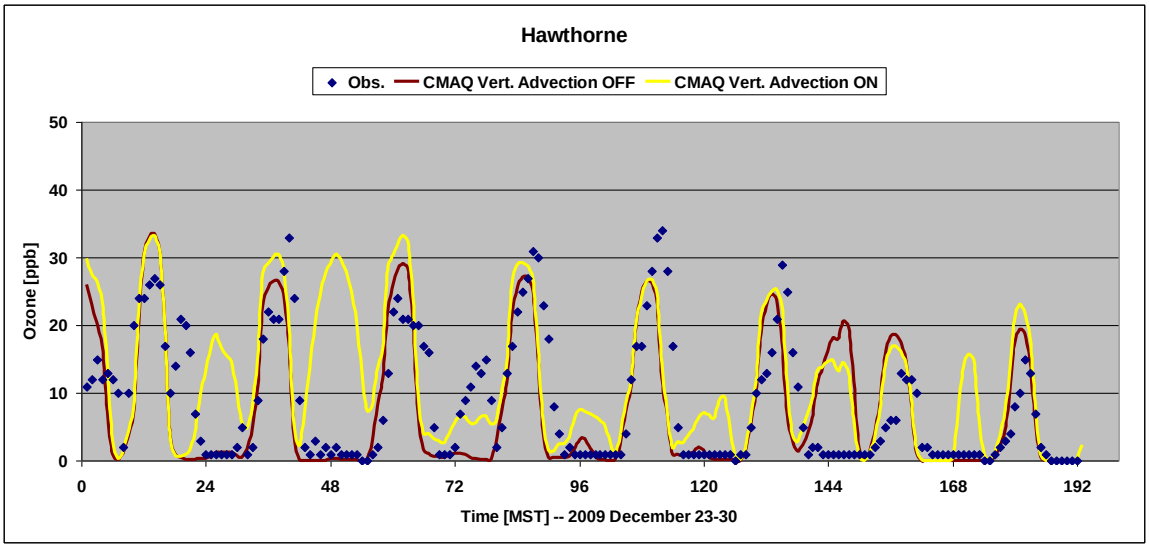

Figure B.3: Ozone (O_3) time series at the Hawthorne monitoring site. Observed O_3 (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

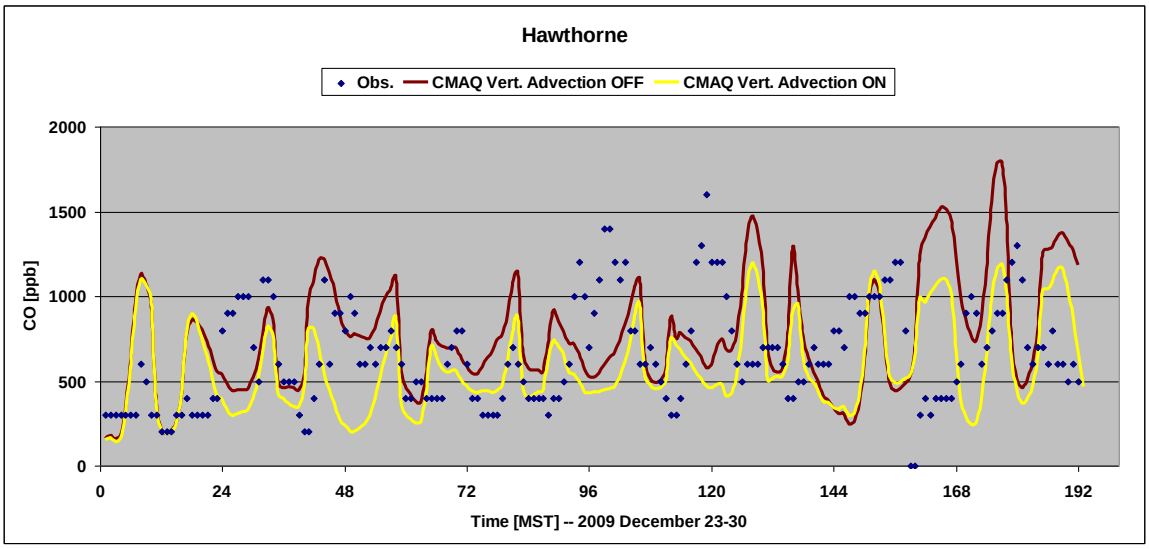

Figure B.4: Carbon Monoxide (CO) time series at the Hawthorne monitoring site. Observed CO (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

Ogden

Table B.2: Mean Bias, Normalized Mean Bias at Ogden for NO, NO_2, O_3, and CO. Results are shown for CMAQ simulations with vertical advection (VA ON) and without vertical advection (VA OFF). Bolded values indicated better performance between VA ON and VA OFF.

		Mean Bias (ppb)	Normalized Mean Bias (%)
NO	VA ON	-31	-66
	VA OFF	**-25**	**-55**
NO_2	VA ON	-7	-19
	VA OFF	**-3**	**-9**
O_3	VA ON	3	32
	VA OFF	**-2**	**-28**
CO	VA ON	-717	-62
	VA OFF	**-530**	**-45**

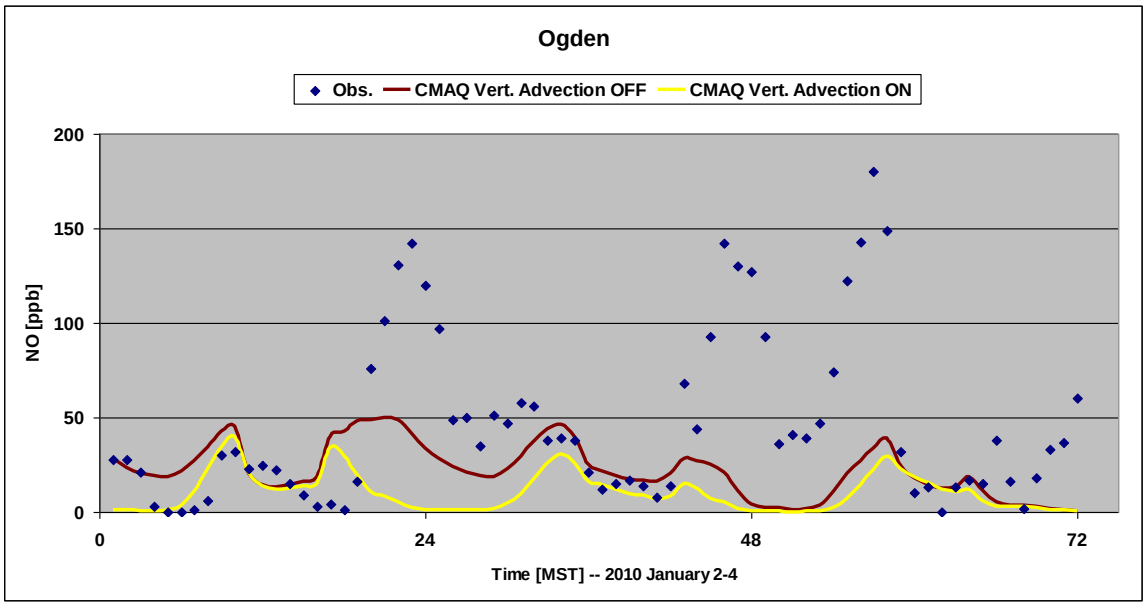

Figure B.5: Nitric oxide (NO) time series at the Ogden monitoring site. Observed NO (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

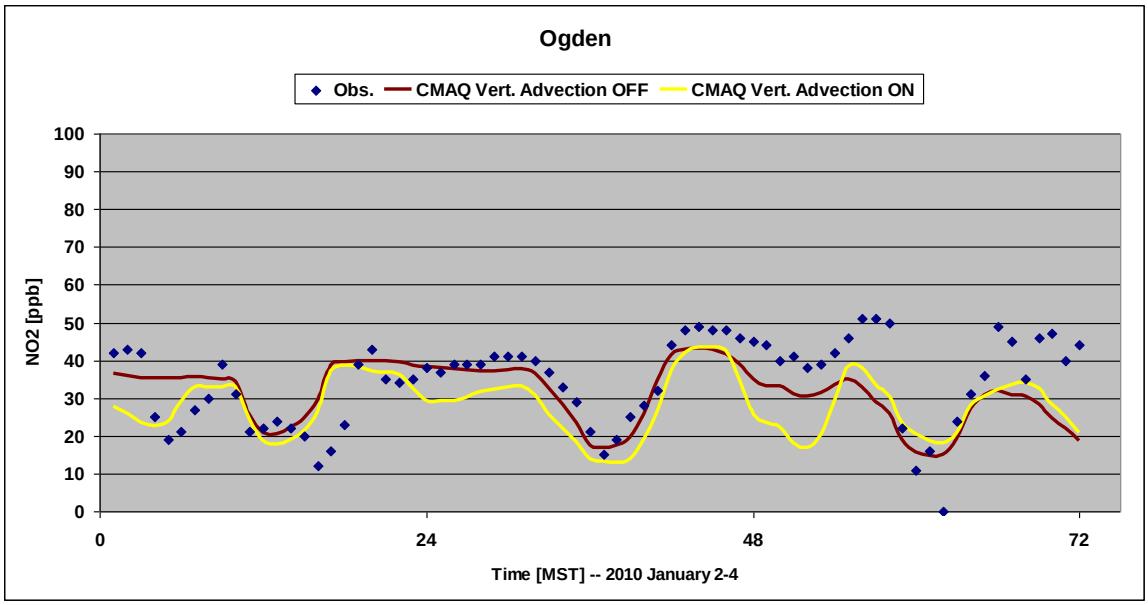

Figure B.6: Nitrogen dioxide (NO_2) time series at the Ogden monitoring site. Observed NO_2 (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

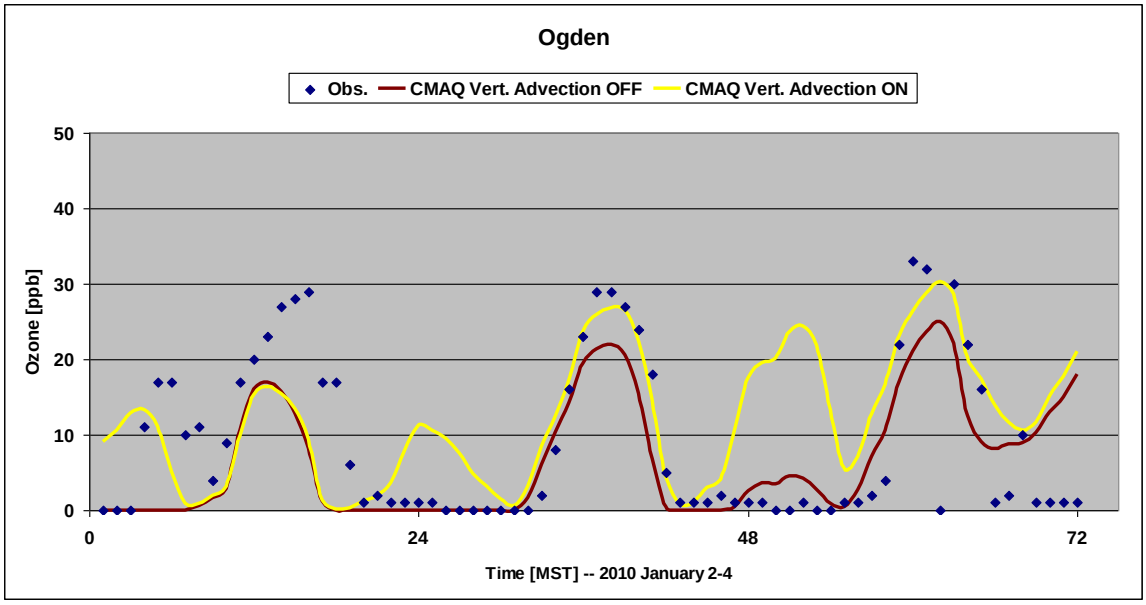

Figure B.7: Ozone (O_3) time series at the Ogden monitoring site. Observed O_3 (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

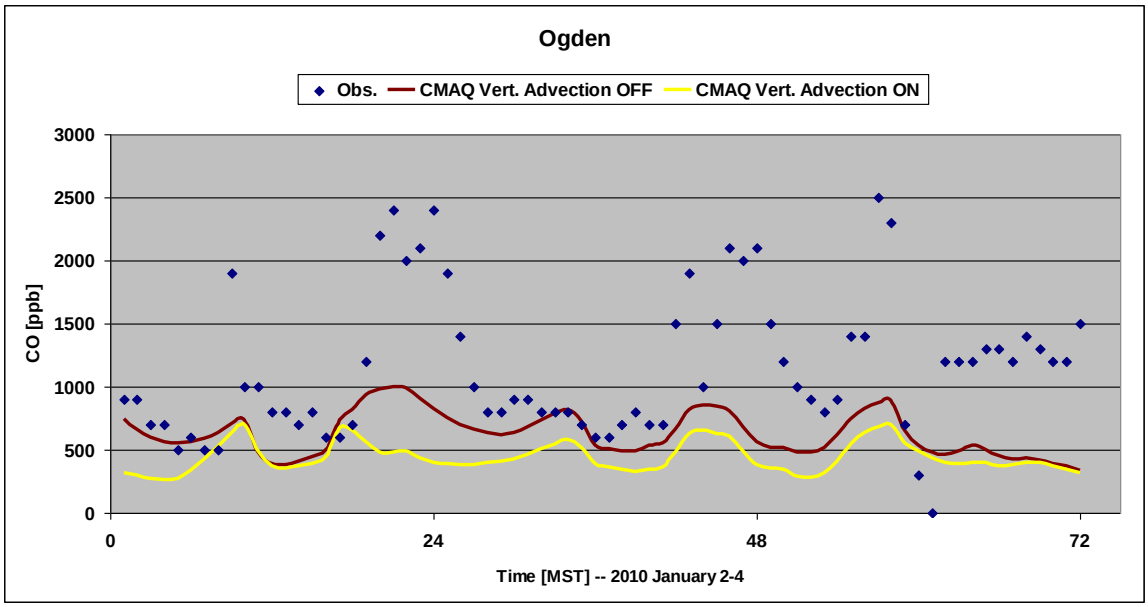

Figure B.8: Carbon Monoxide (CO) time series at the Ogden monitoring site. Observed CO (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

North Provo

Table B.3: Mean Bias, Normalized Mean Bias at North Provo for NO, NO_2, O_3, and CO. Results are shown for CMAQ simulations with vertical advection (VA ON) and without vertical advection (VA OFF). Bolded values indicated better performance between VA ON and VA OFF.

		Mean Bias (ppb)	Normalized Mean Bias (%)
NO	VA ON	-29	-84
	VA OFF	**-24**	**-71**
NO_2	VA ON	-16	-49
	VA OFF	**-11**	**-32**
O_3	VA ON	13	124
	VA OFF	**1**	**8**
CO	VA ON	-510	-62
	VA OFF	**-357**	**-43**

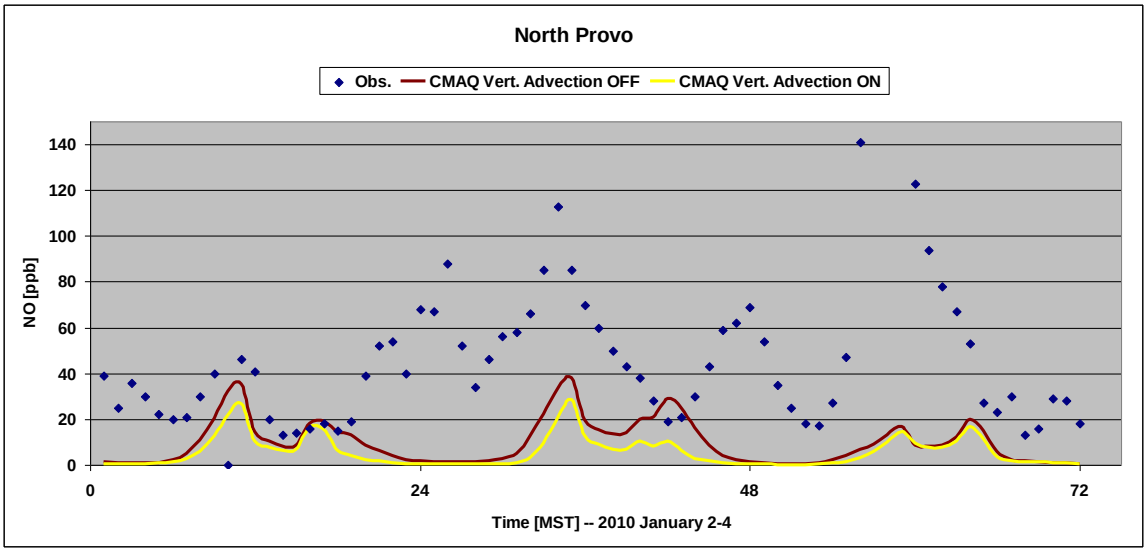

Figure B.9: Nitric oxide (NO) time series at the North Provo monitoring site. Observed NO (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

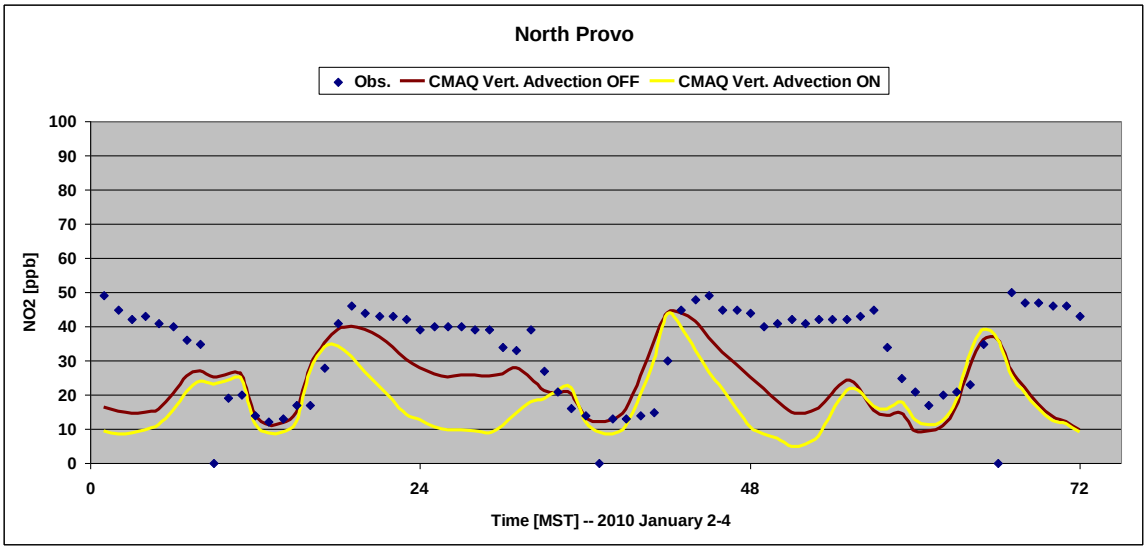

Figure B.10: Nitrogen dioxide (NO_2) time series at the North Provo monitoring site. Observed NO_2 (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

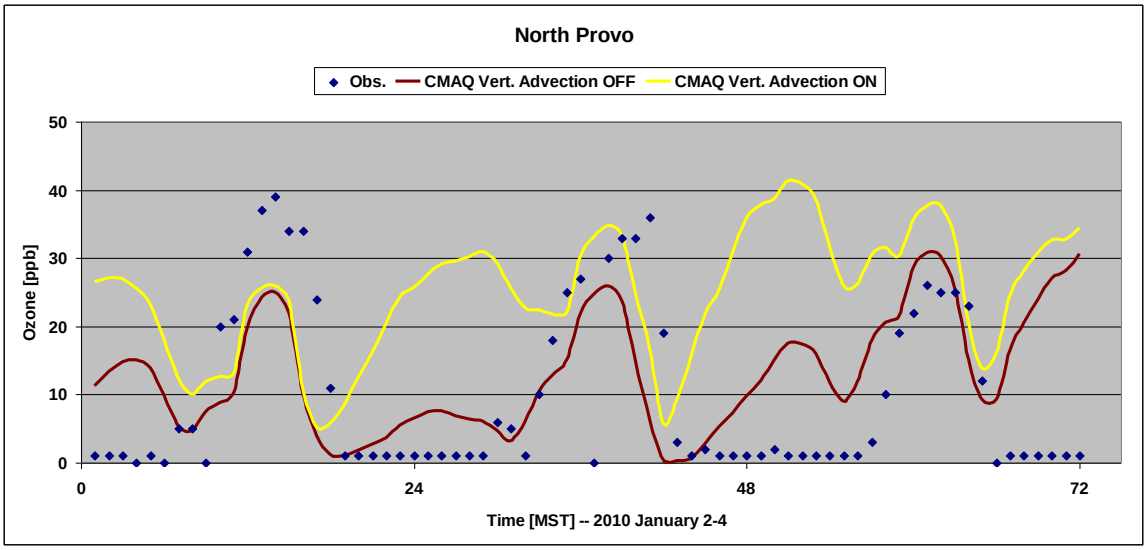

Figure B.11: Ozone (O_3) time series at the North Provo monitoring site. Observed O_3 (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

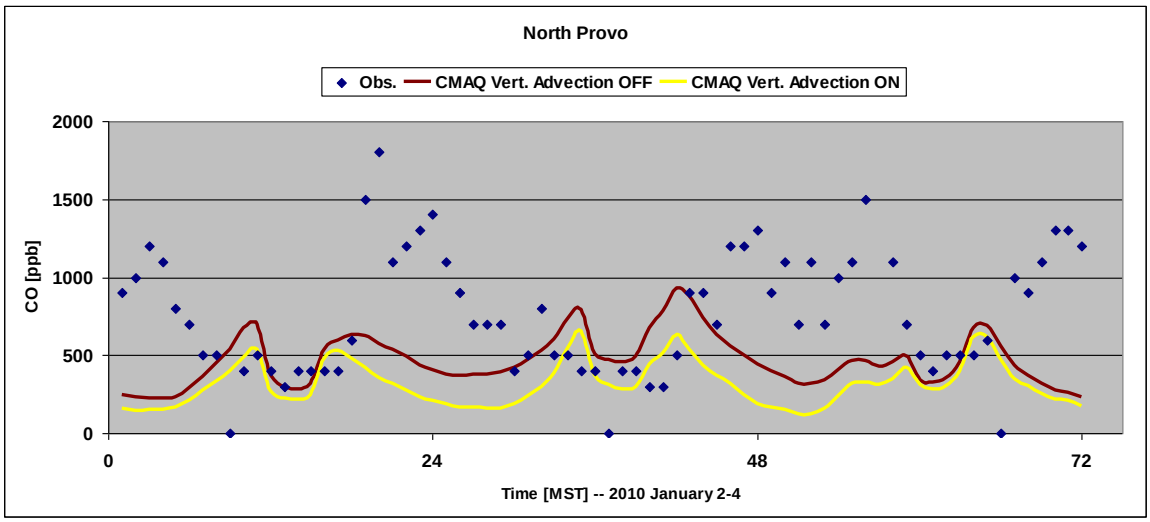

Figure B.12: Carbon Monoxide (CO) time series at the North Provo monitoring site. Observed CO (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

Logan

Table B.4: Mean Bias, Normalized Mean Bias at Logan for NO, NO_2, O_3, and CO. Results are shown for CMAQ simulations with vertical advection (VA ON) and without vertical advection (VA OFF). Bolded values indicate the better performance between VA ON and VA OFF.

		Mean Bias (ppb)	Normalized Mean Bias (%)
NO	VA ON	-10	-57
	VA OFF	**-7**	**-42**
NO_2	VA ON	-6	-22
	VA OFF	**-3**	**-12**
O_3	VA ON	13	165
	VA OFF	**3**	**32**
CO	VA ON	-	-
	VA OFF	**-**	**-**

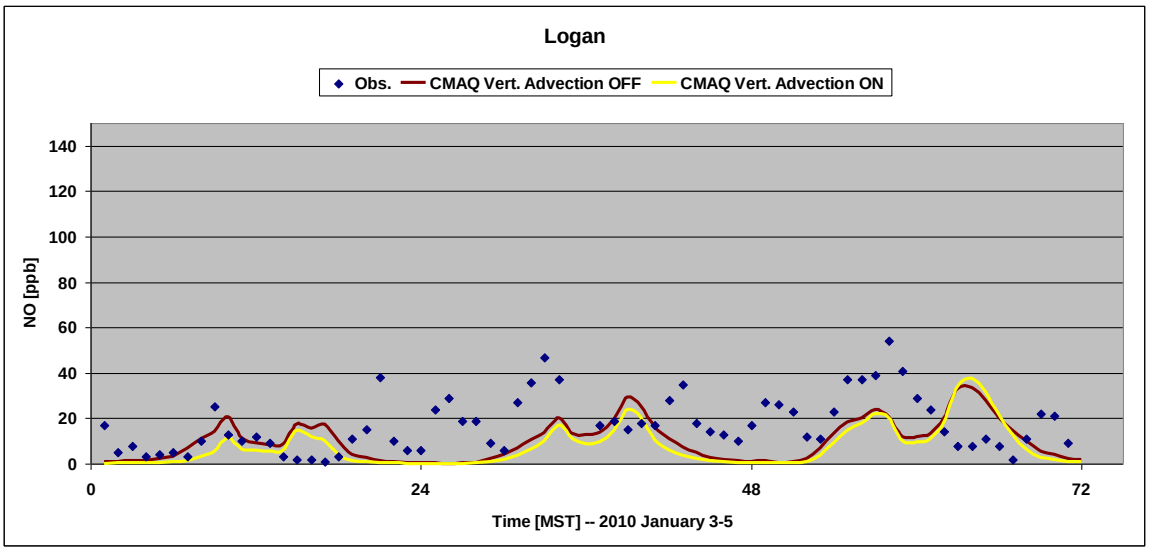

Figure B.13: Nitric oxide (NO) time series at the Logan monitoring site. Observed NO (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

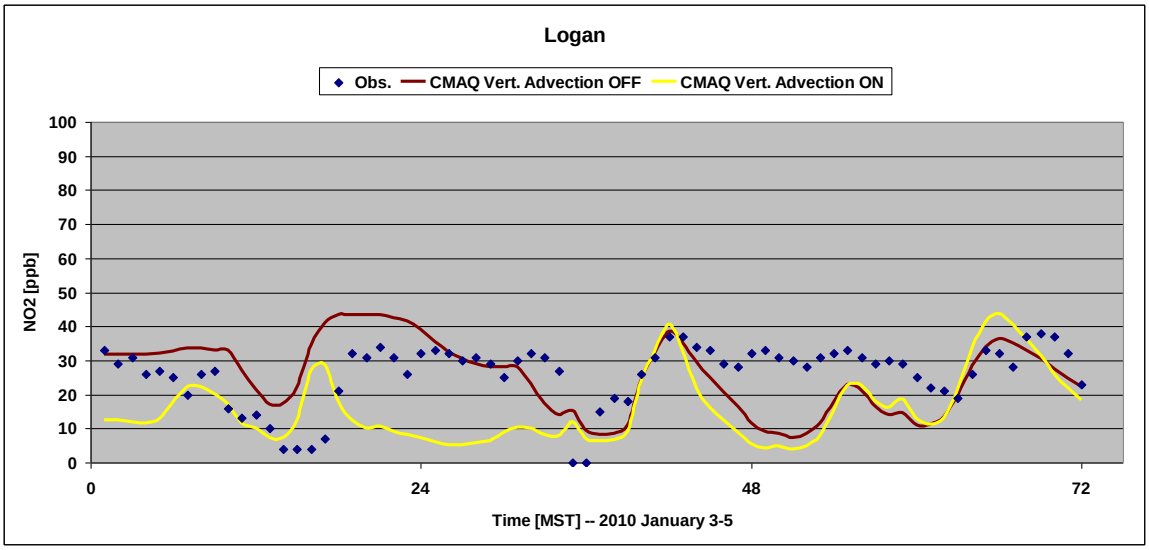

Figure B.14: Nitrogen dioxide (NO_2) time series at the Logan monitoring site. Observed NO_2 (blue points), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

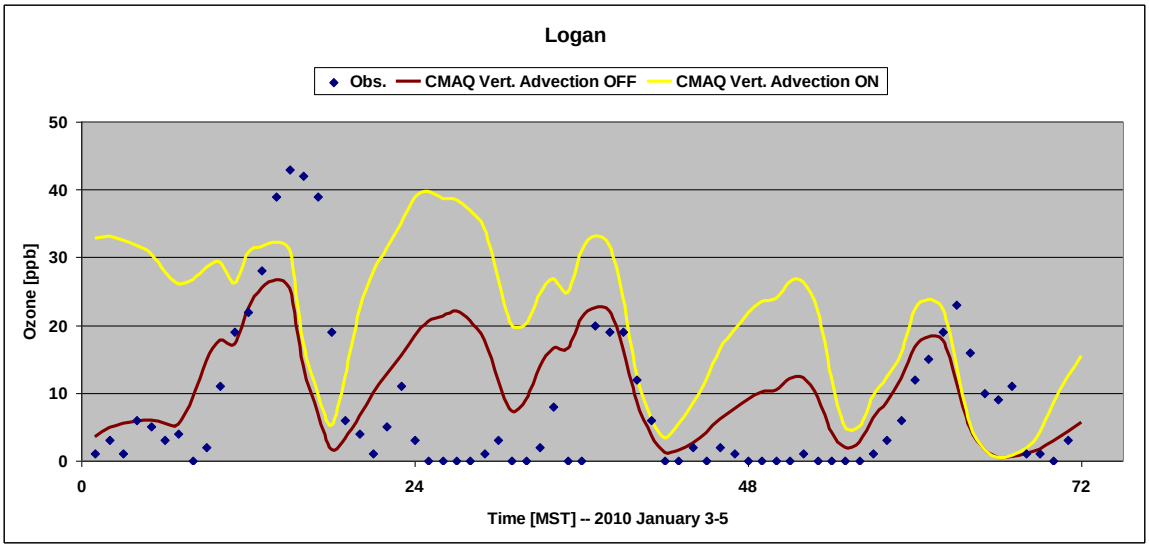

Figure B.15: Ozone (O_3) time series at the Logan monitoring site. Observed O_3 (blue trace), modeled with vertical advection deactivated (red trace), and modeled with vertical advection activated (yellow trace).

Appendix C

January 11-20, 2007 Modeling Episode

In addition to 2009-2010 modeling period that included multiple $PM_{2.5}$ episodes and was used for the Model Attainment Test, UDAQ modeled individual episodes from the winter of 2007 and 2008. By modeling these additional wintertime seasons, UDAQ ensures it is modeling numerous and diverse wintertime conditions that lead to exceedences of 24-hr $PM_{2.5}$ NAAQS. The number of selected episodes for modeling represents an effort above and beyond that which is normally required for a SIP demonstration.

Time-series are presented at various monitoring locations for the January 11-20, 2007 modeling episode. Shown will be CMAQ simulated 24-hr $PM_{2.5}$ with vertical advection de-activated and the observed 24-hr $PM_{2.5}$ concentrations.

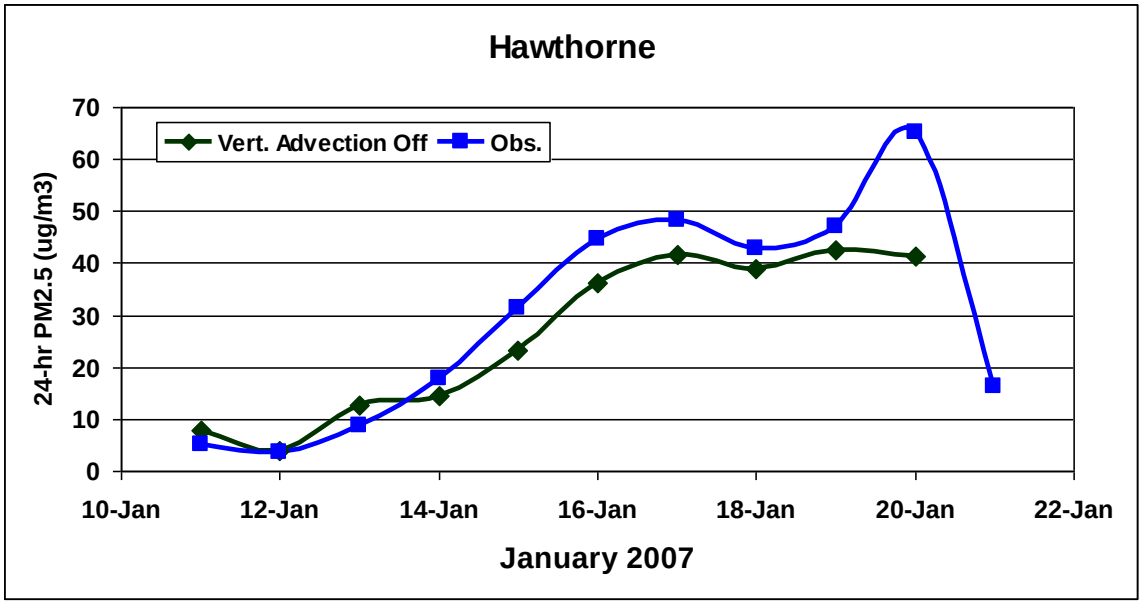

Figure C.1: 24-hr $PM_{2.5}$ time series for Hawthorne. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

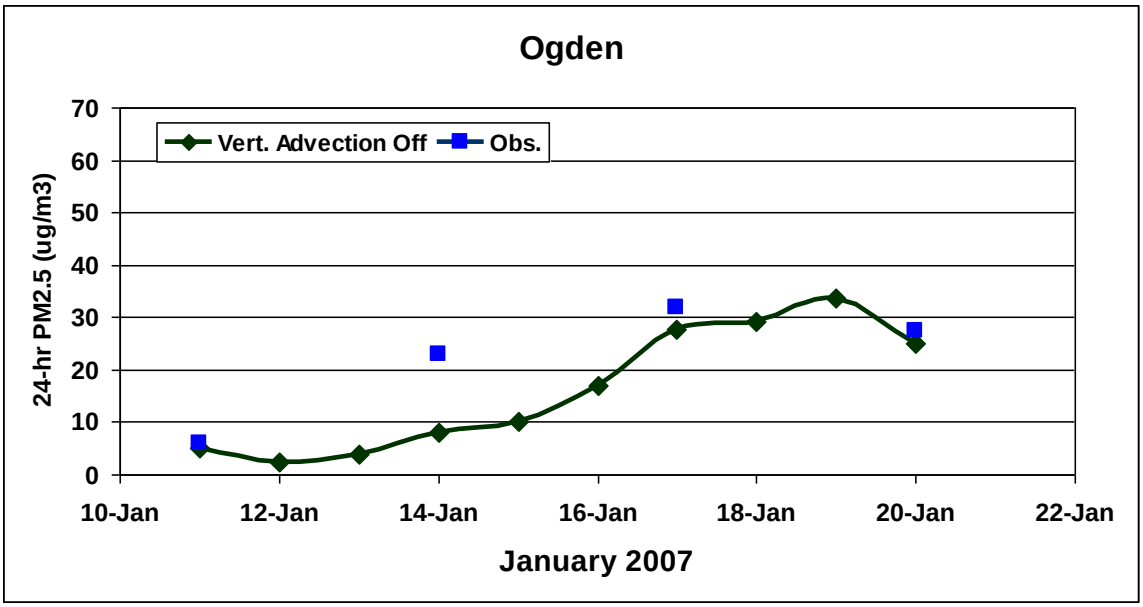

Figure C.2: 24-hr $PM_{2.5}$ time series for Ogden. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

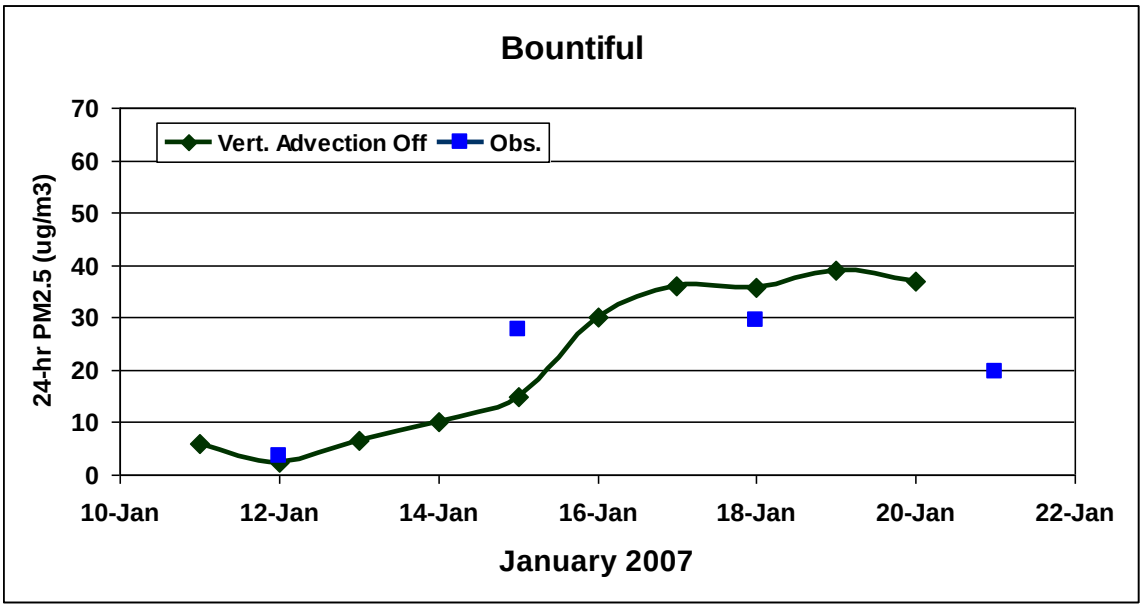

Figure C.3: 24-hr $PM_{2.5}$ time series for Bountiful. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

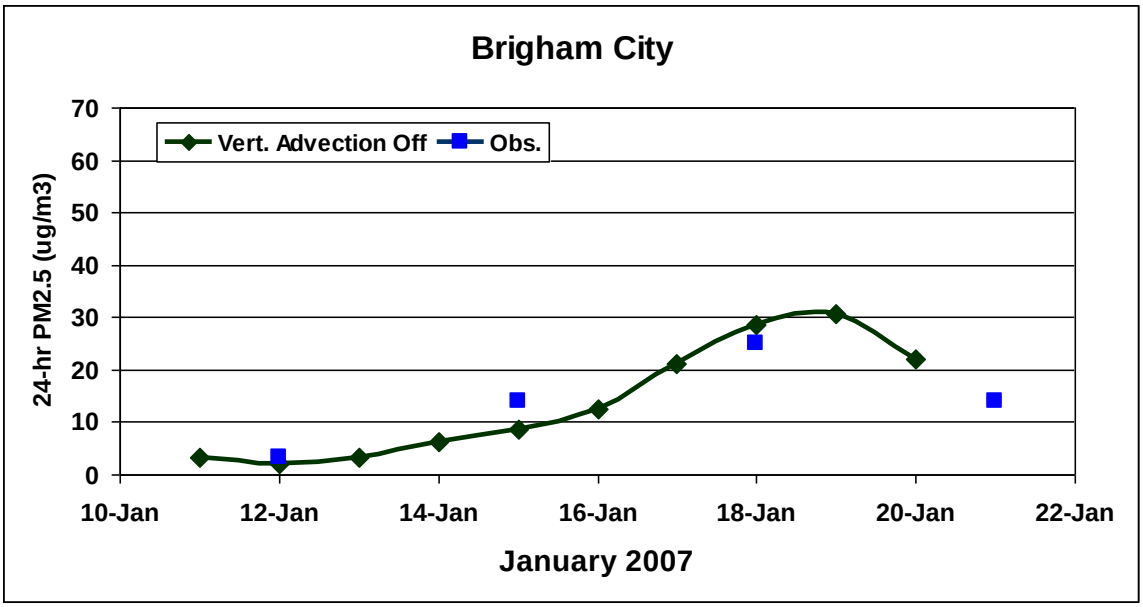

Figure C.4: 24-hr $PM_{2.5}$ time series for Brigham City. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

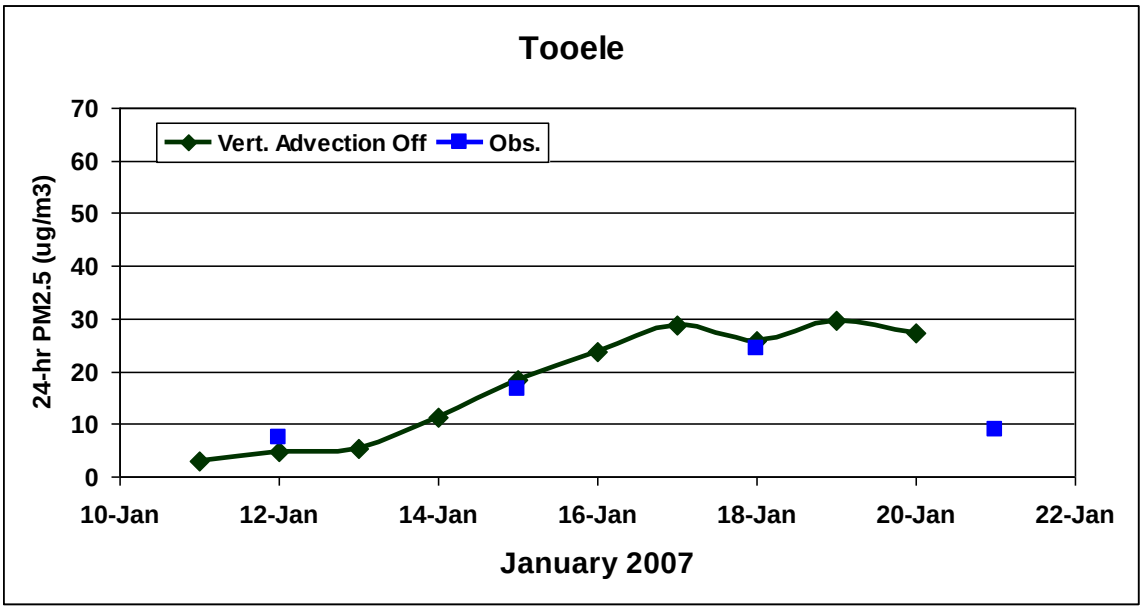

Figure C.5: 24-hr $PM_{2.5}$ time series for Tooele. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

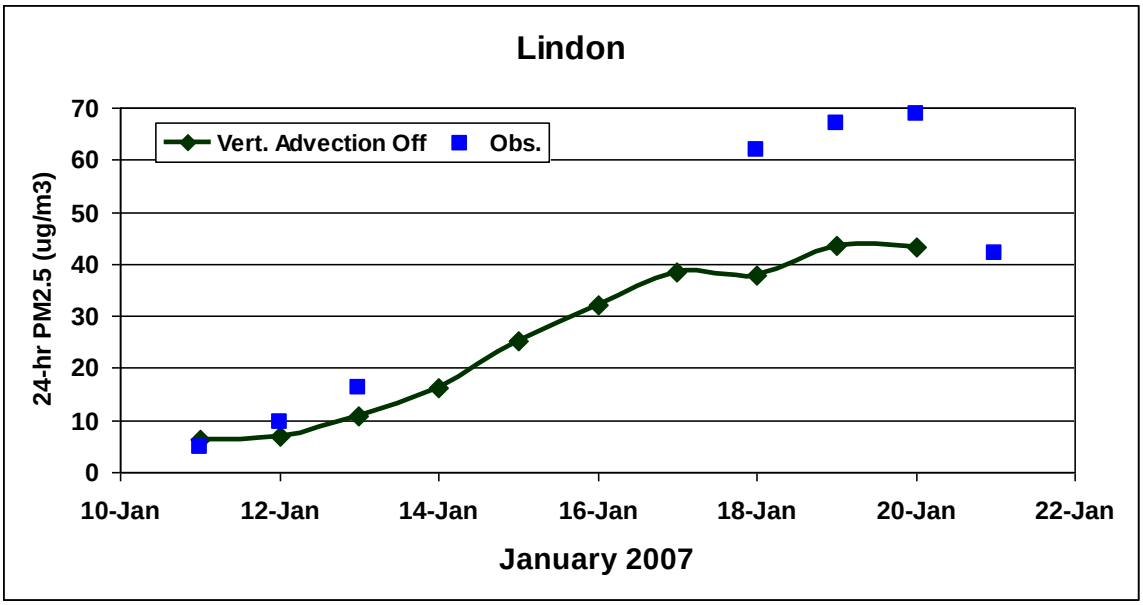

Figure C.6: 24-hr $PM_{2.5}$ time series for Lindon. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

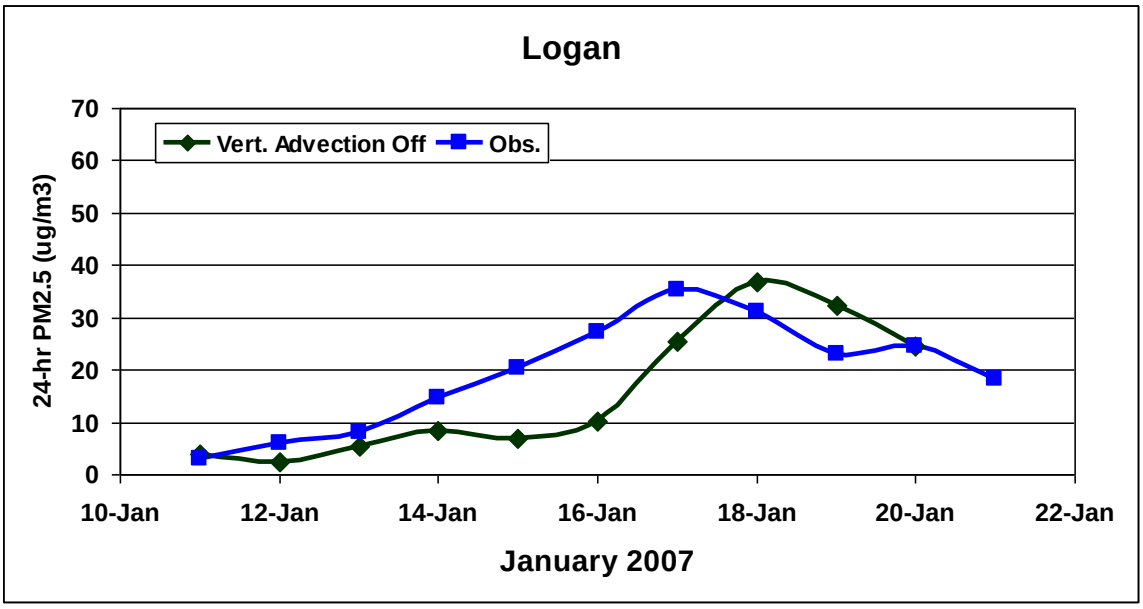

Figure C.7: 24-hr $PM_{2.5}$ time series for Logan. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

February 14-19, 2008 Modeling Episode

Time-series are presented at various monitoring locations for the February 14-19, 2008 modeling episode. Shown will be CMAQ simulated 24-hr $PM_{2.5}$ with vertical advection de-activated and the observed 24-hr $PM_{2.5}$ concentrations.

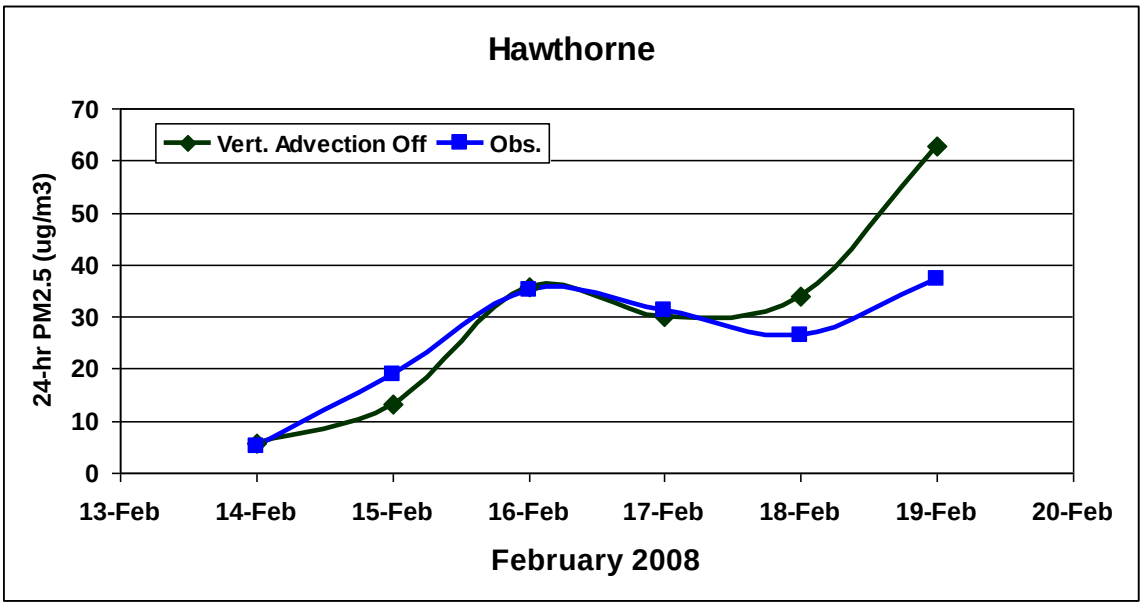

Figure C.8: 24-hr $PM_{2.5}$ time series for Hawthorne. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

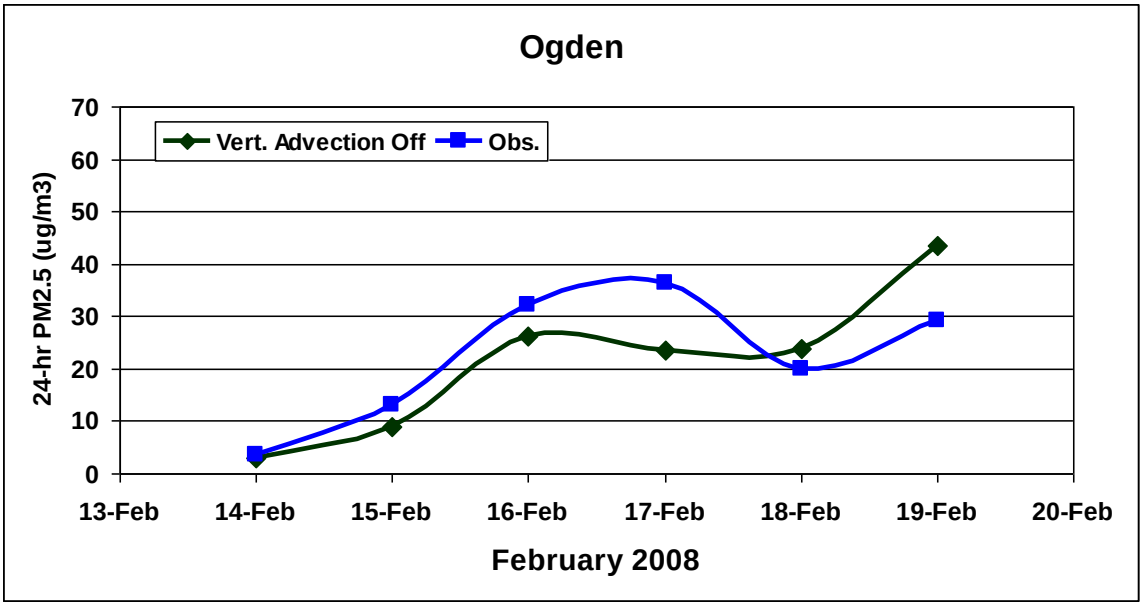

Figure C.9: 24-hr $PM_{2.5}$ time series for Ogden. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

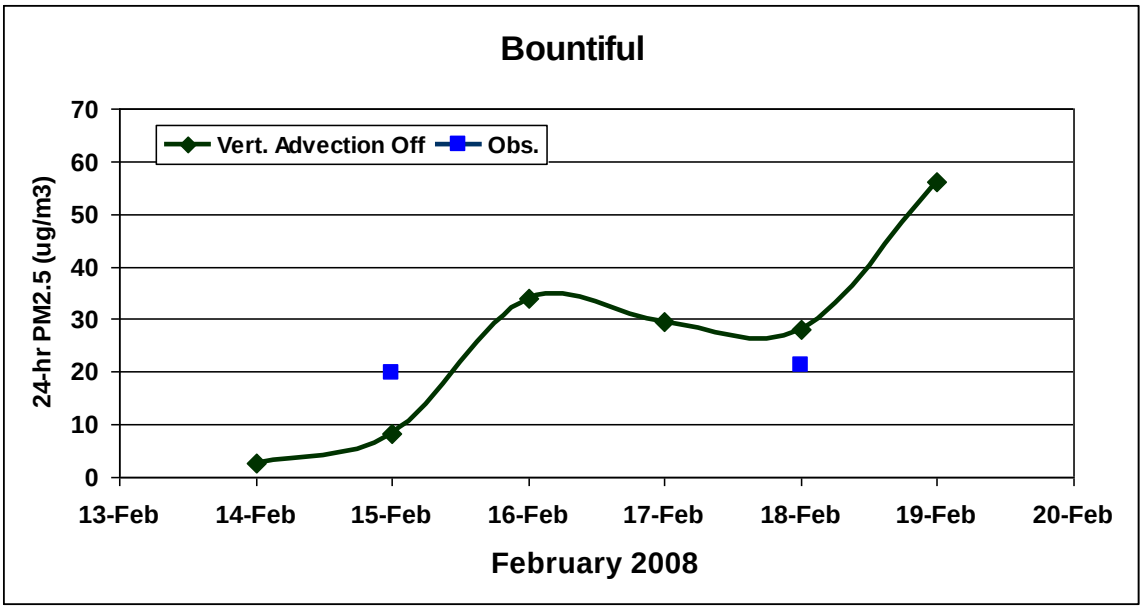

Figure C.10: 24-hr $PM_{2.5}$ time series for Bountiful. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

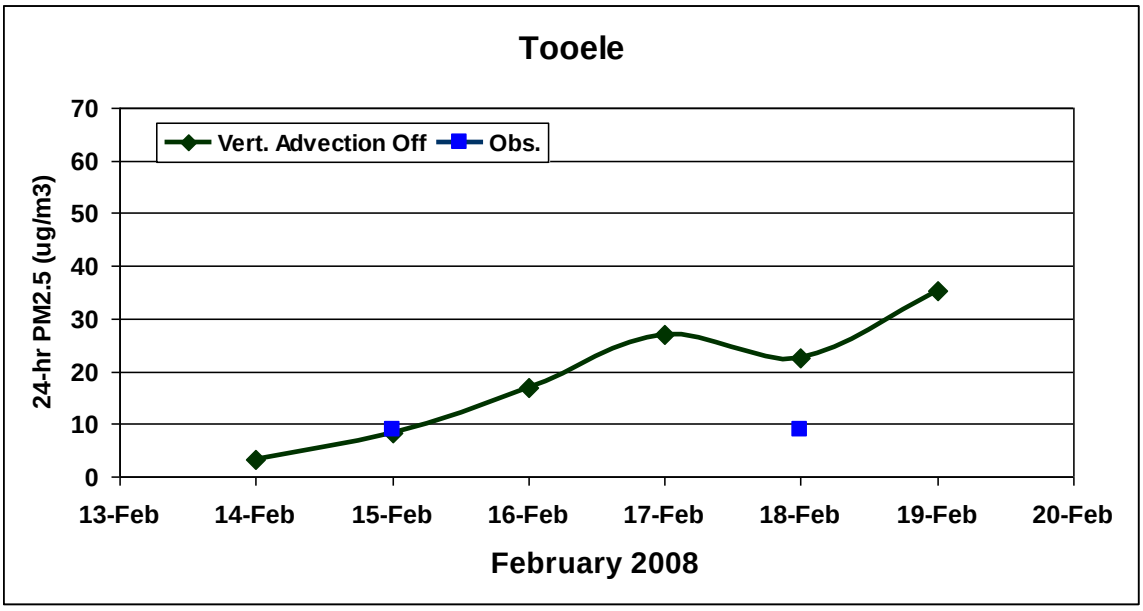

Figure C.11: 24-hr $PM_{2.5}$ time series for Tooele. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

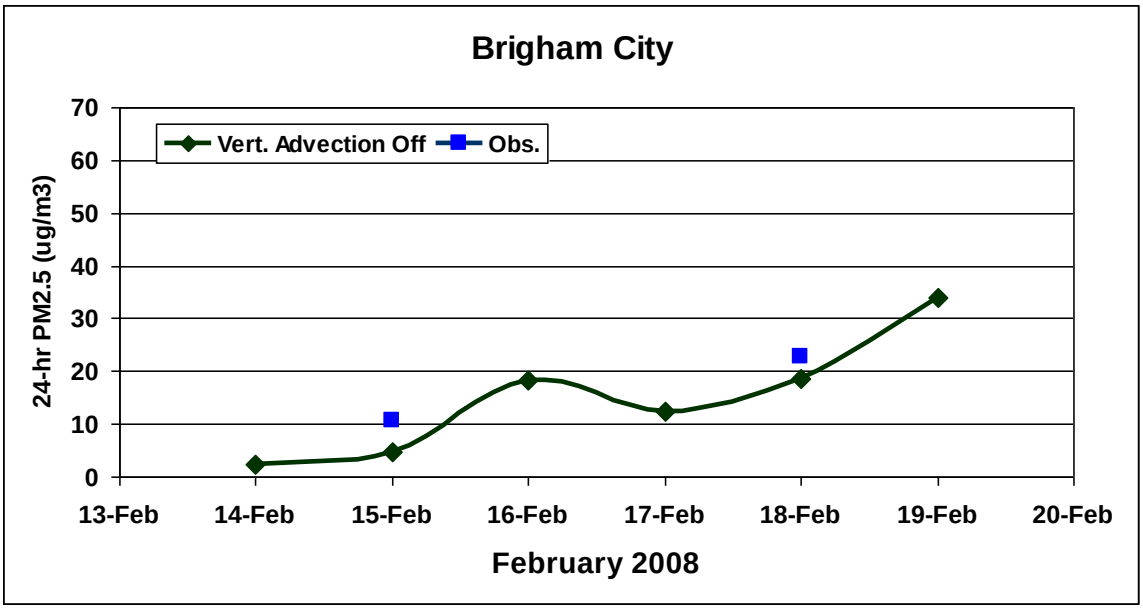

Figure C.12: 24-hr $PM_{2.5}$ time series for Brigham City. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

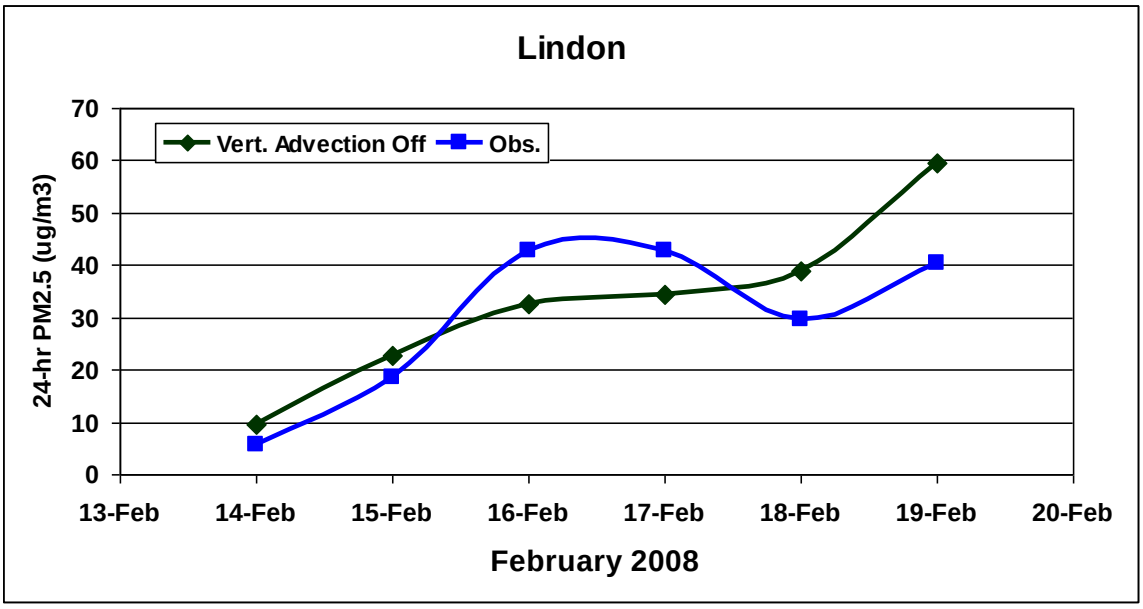

Figure C.13: 24-hr $PM_{2.5}$ time series for Lindon. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

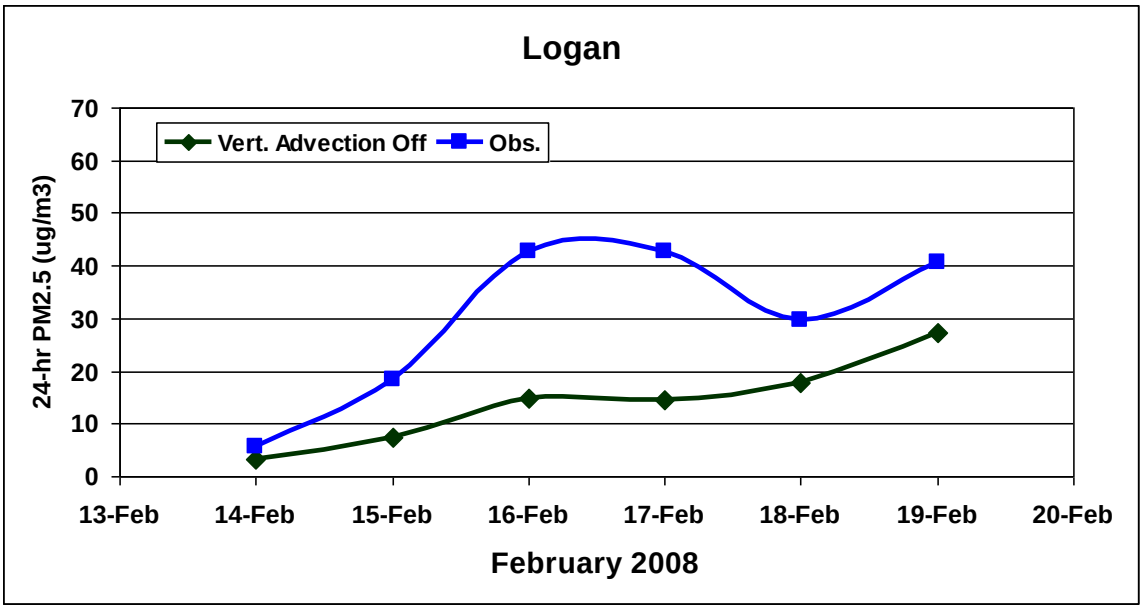

Figure C.14: 24-hr $PM_{2.5}$ time series for Logan. Observed $PM_{2.5}$ (blue trace), modeled with vertical advection deactivated (green trace).

Appendix D

Time Series of Observed vs. Predicted Speciation of PM2.5 at the Speciation Trends Network (STN) Sites

There are three Speciation Trends Network sites located in Northern Utah. They are located at the Hawthorne monitoring site in Salt Lake City, Lindon monitoring site in Utah County, and Bountiful monitoring site in Davis County. Speciated PM2.5 samples of numerous trace elements, ions (sulfate, nitrate, sodium, potassium, and ammonium), elemental carbon, and organic carbon are taken every three days at Hawthorne and every six days at Lindon and Bountiful. During January 2010, the Utah Division of Air Quality supplemented the STN sampling schedule and collected samples every other day at all three sites.

Time series plots for the Hawthorne STN are shown in Figures D.1 (Nitrate), D.2 (Ammonium), D.3 (Sulfate), D.4 (Organic Carbon), and D.5 (Elemental Carbon). Similar plots are presented for Lindon (Figures D.6 -D.10) and Bountiful (Figures D.11 – D.15).

The time series for organic carbon (Figures D.4, D.9, and D14) have two CMAQ predicted time series shown. The 2010 Baseline inventory (black trace) used updated emission factors for wood burning that effect the emissions of organic carbon. UDAQ applied an updated wood burning emission factor that increased organic carbon emissions in 2010 Baseline modeling inventory. This new wood burning inventory (fireplaces, woodstoves, etc.) comes from EPA's new Residential Wood Combustion estimation tool (released December 2012). The tool uses 2010 US Census Housing data as inputs. The use of the updated emission factors was predicated on a recent positive matrix factorization (PMF) analysis that indicated the 2009-2010 episodic emissions inventory was low for the estimates of wood burning emissions (Kelly et al, 2012). Using the updated emission factors helped to increase the model predicted organic carbon and improved the model performance.

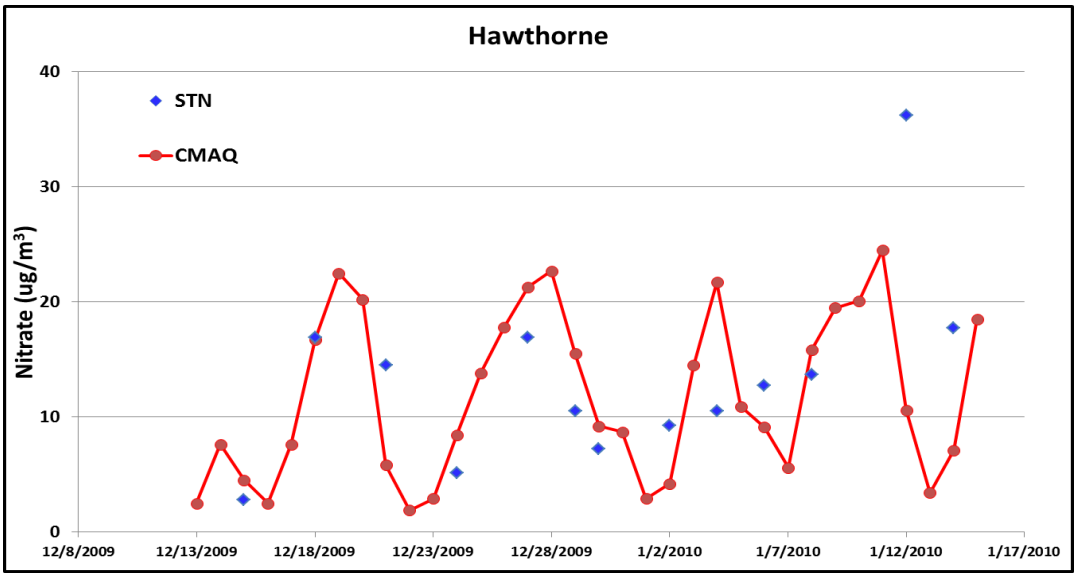

Figure D.1: Time Series of Observed vs. Predicted Nitrate (ug/m^3) of PM2.5 at the Hawthorne Speciation Trends Network site.

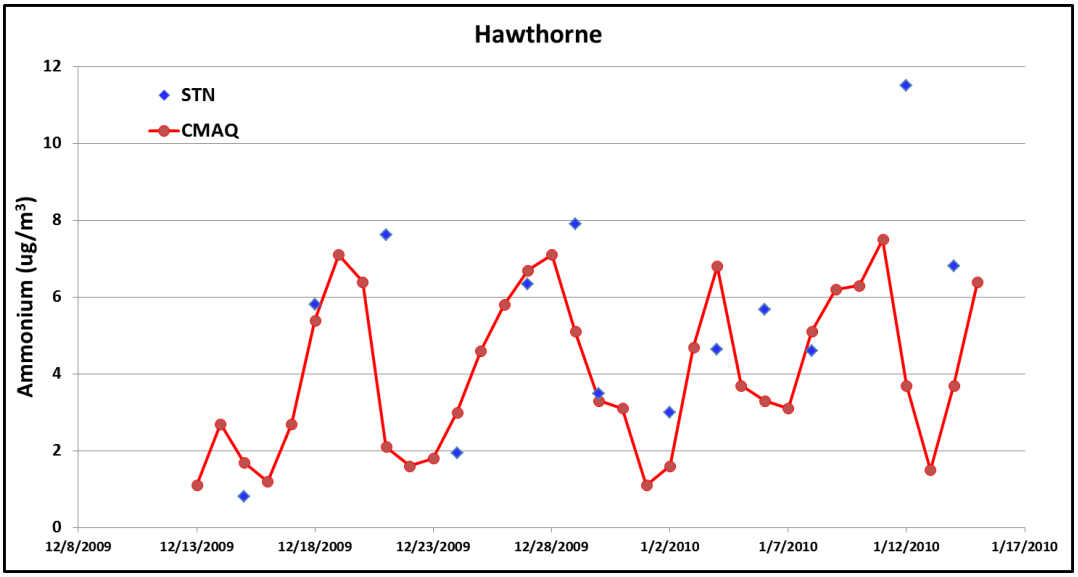

Figure D.2: Time Series of Observed vs. Predicted Ammonium (ug/m^3) of PM2.5 at the Hawthorne Speciation Trends Network site.

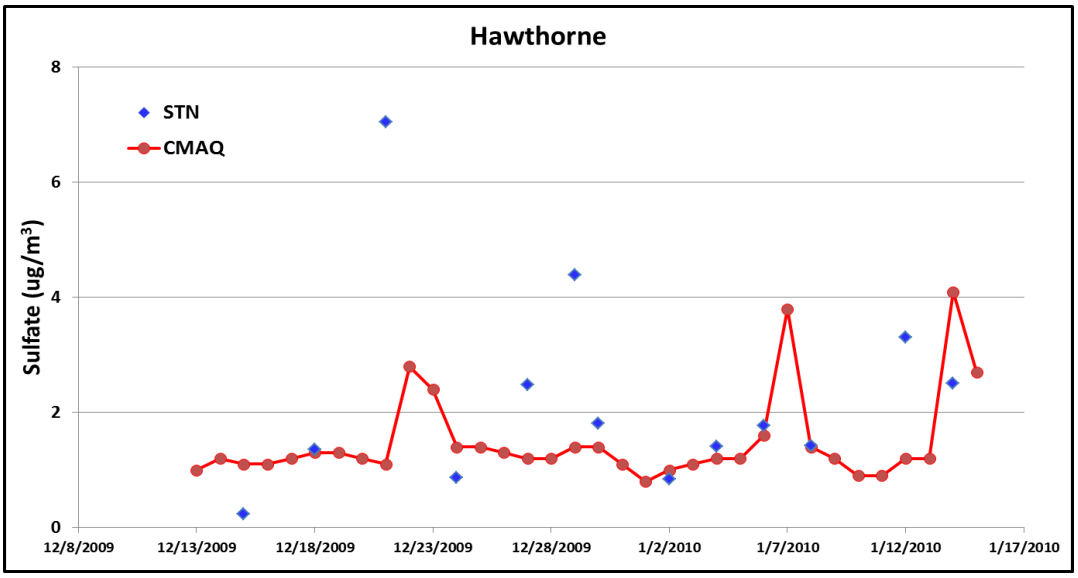

Figure D.3: Time Series of Observed vs. Predicted Sulfate (ug/m^3) of PM2.5 at the Hawthorne Speciation Trends Network site.

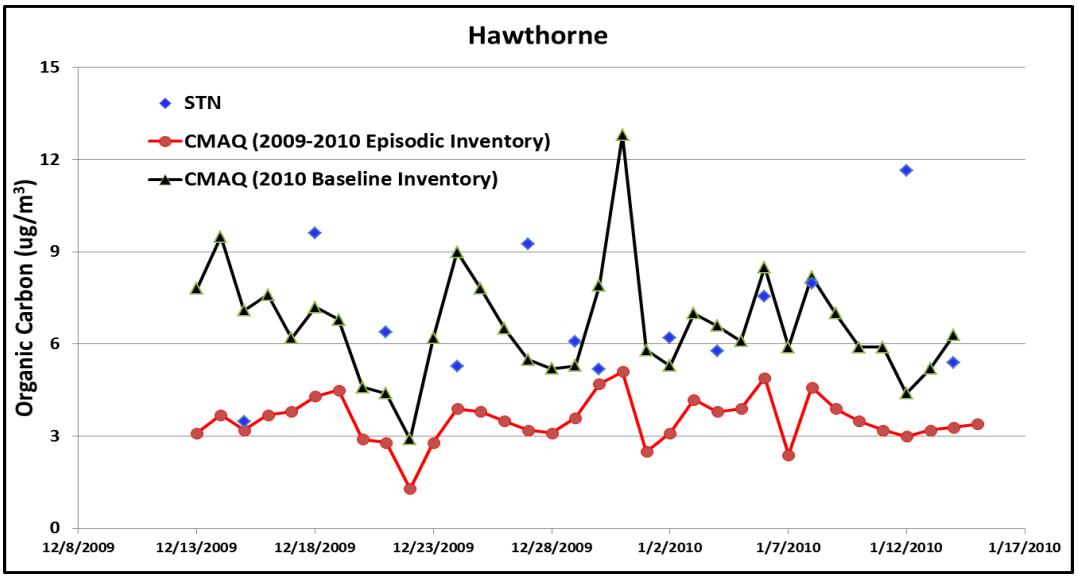

Figure D.4: Time Series of Observed vs. Predicted Organic Carbon (ug/m^3) of PM2.5 at the Hawthorne Speciation Trends Network site.

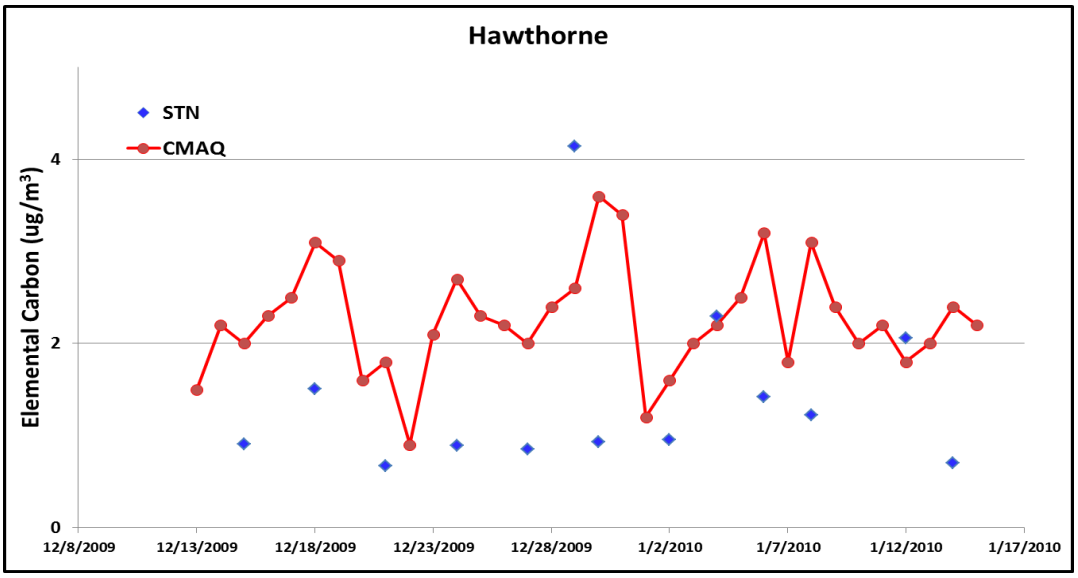

Figure D.5: Time Series of Observed vs. Predicted Elemental Carbon (ug/m^3) of PM2.5 at the Hawthorne Speciation Trends Network site.

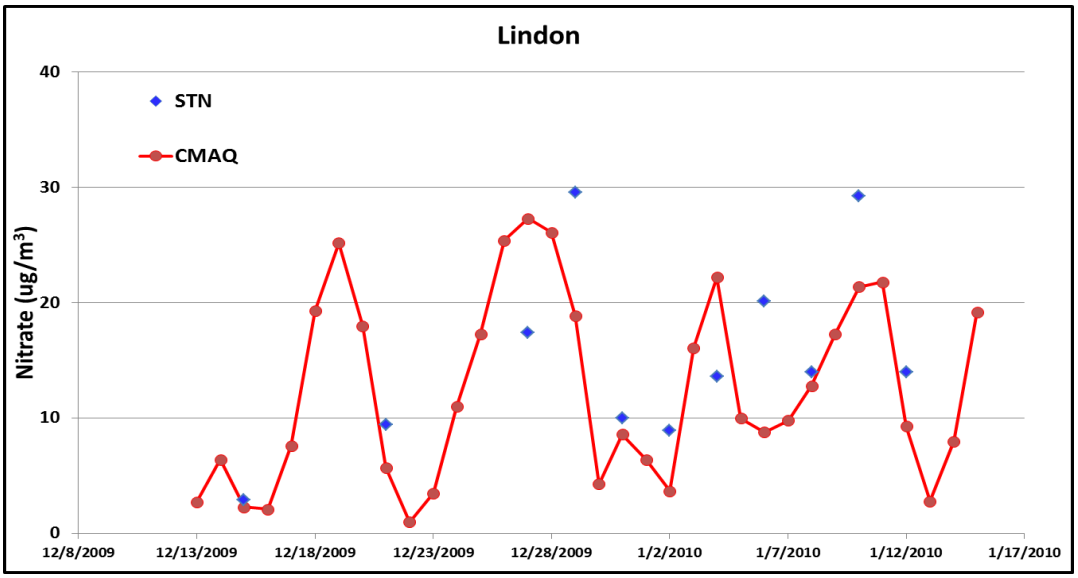

Figure D.6: Time Series of Observed vs. Predicted Nitrate (ug/m^3) of PM2.5 at the Lindon Speciation Trends Network site.

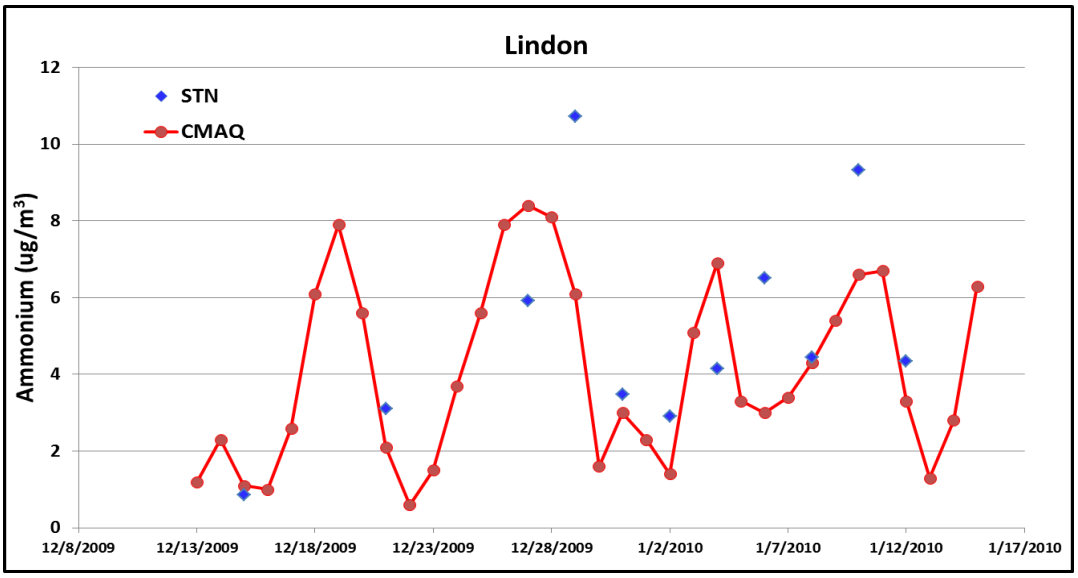

Figure D.7: Time Series of Observed vs. Predicted Ammonium (ug/m^3) of PM2.5 at the Lindon Speciation Trends Network site.

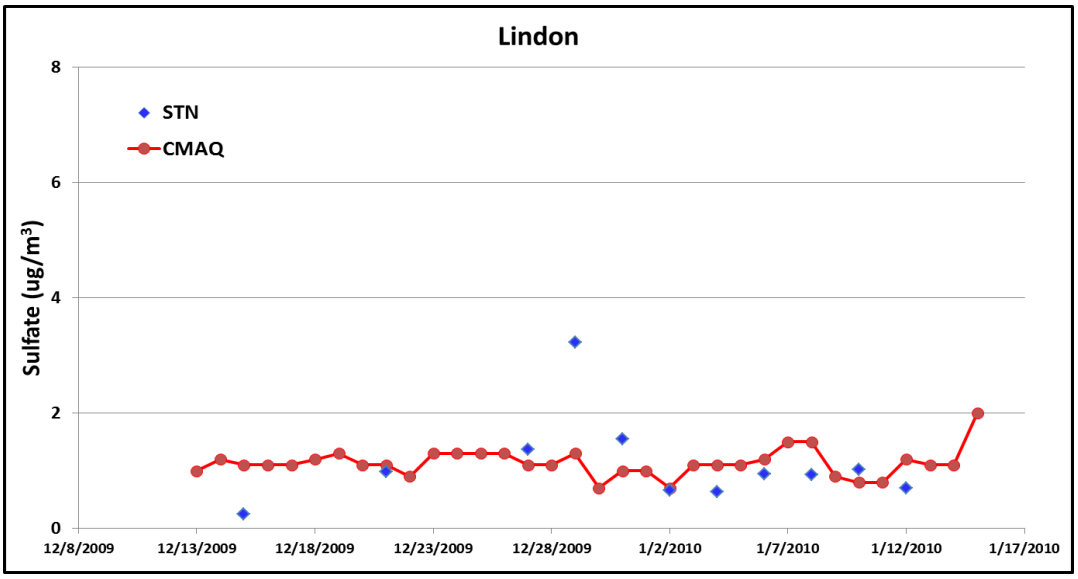

Figure D.8: Time Series of Observed vs. Predicted Sulfate (ug/m^3) of PM2.5 at the Lindon Speciation Trends Network site.

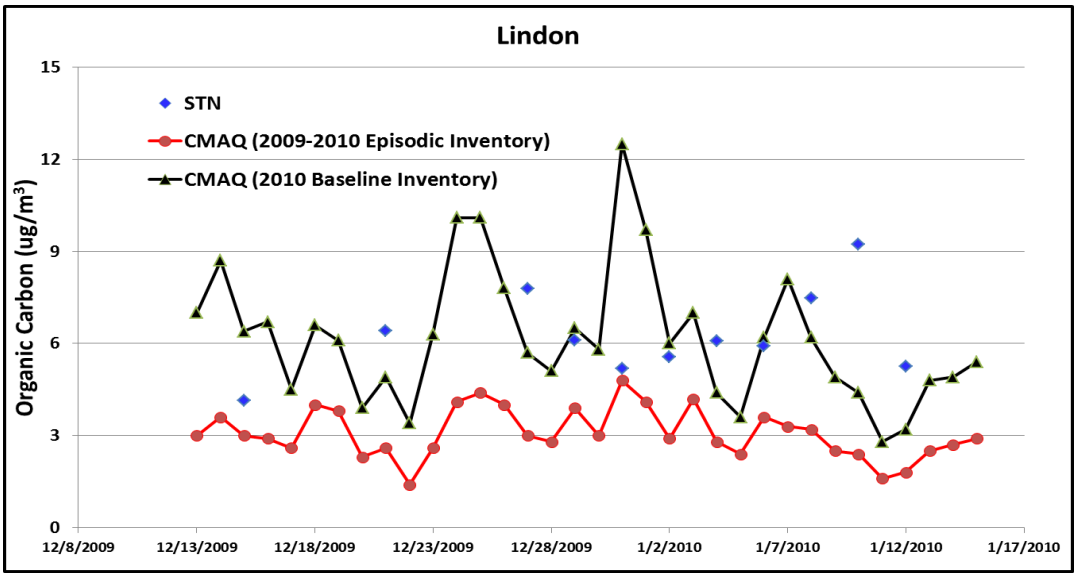

Figure D.9: Time Series of Observed vs. Predicted Organic Carbon (ug/m^3) of PM2.5 at the Lindon Speciation Trends Network site.

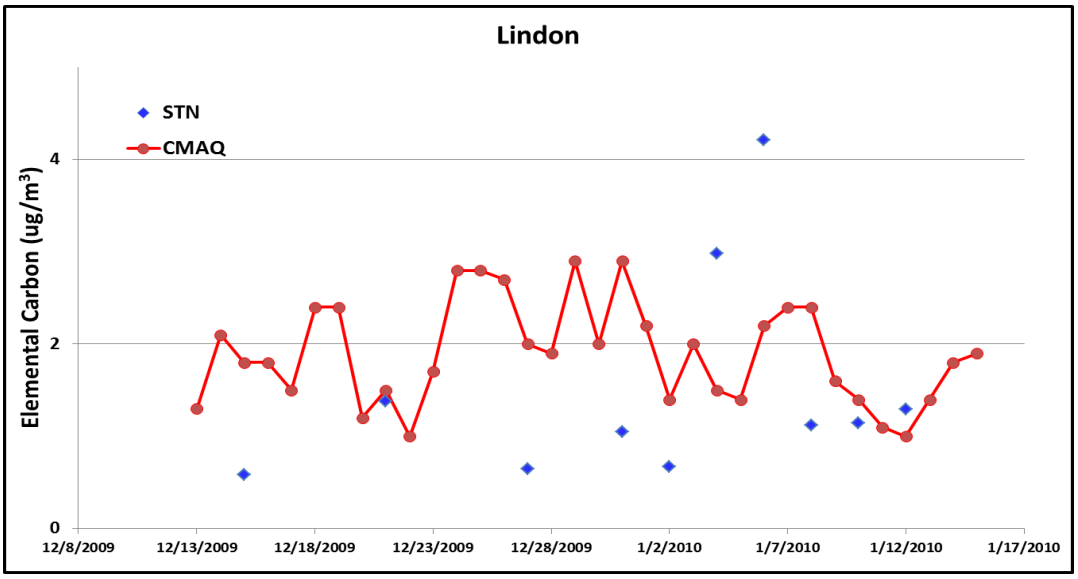

Figure D.10: Time Series of Observed vs. Predicted Elemental Carbon (ug/m^3) of PM2.5 at the Lindon Speciation Trends Network site.

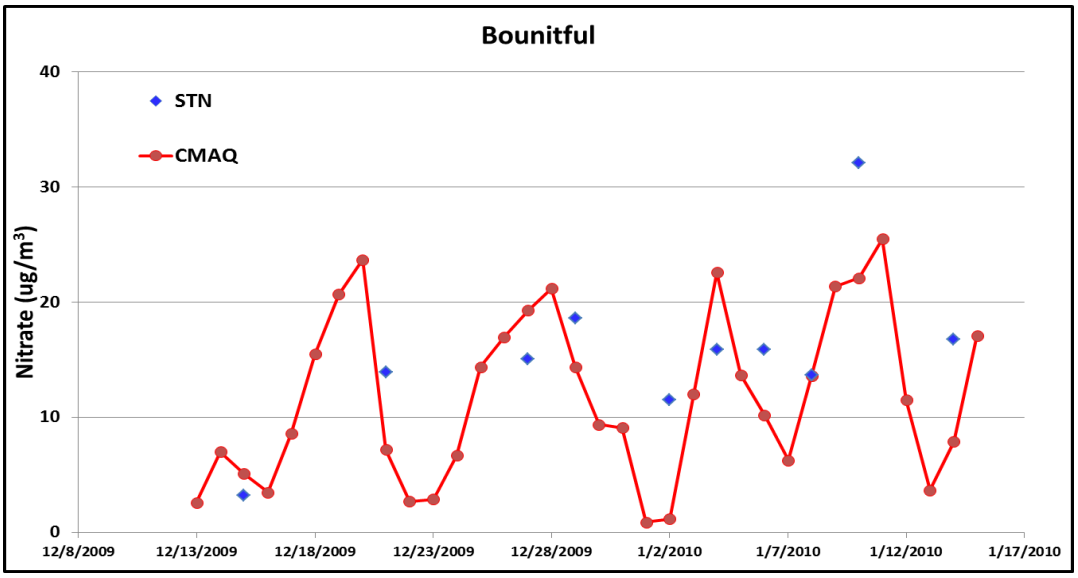

Figure D.11: Time Series of Observed vs. Predicted Nitrate (ug/m^3) of PM2.5 at the Bountiful Speciation Trends Network site.

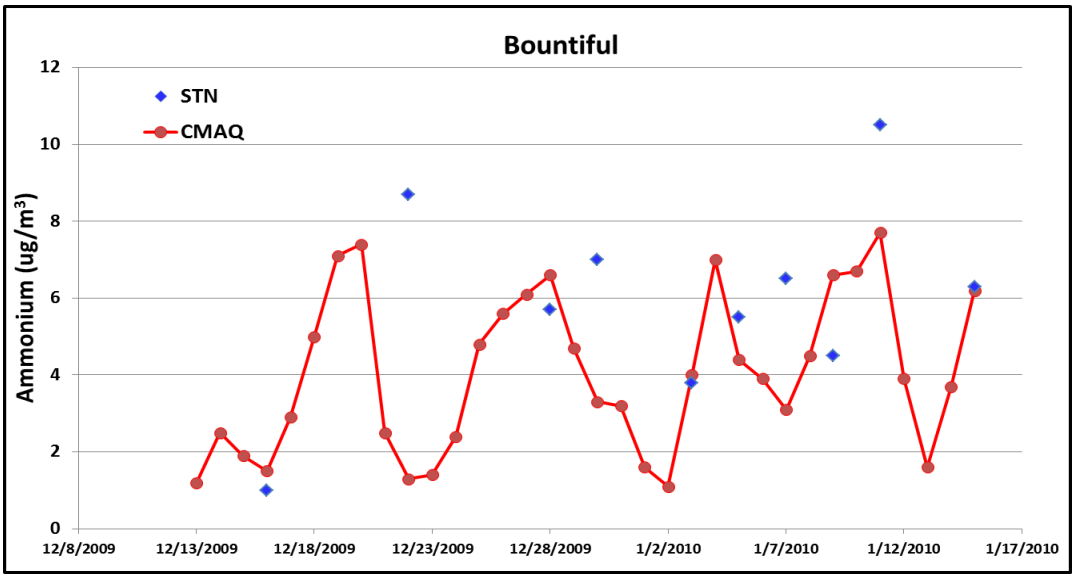

Figure D.12: Time Series of Observed vs. Predicted Ammonium (ug/m^3) of PM2.5 at the Bountiful Speciation Trends Network site.

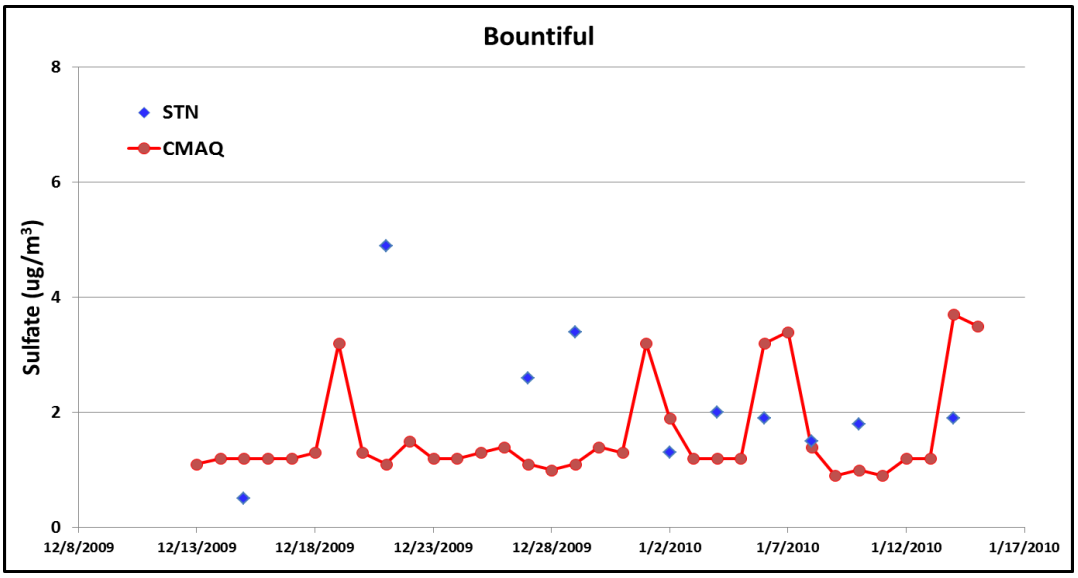

Figure D.13: Time Series of Observed vs. Predicted Sulfate (ug/m^3) of PM2.5 at the Bountiful Speciation Trends Network site.

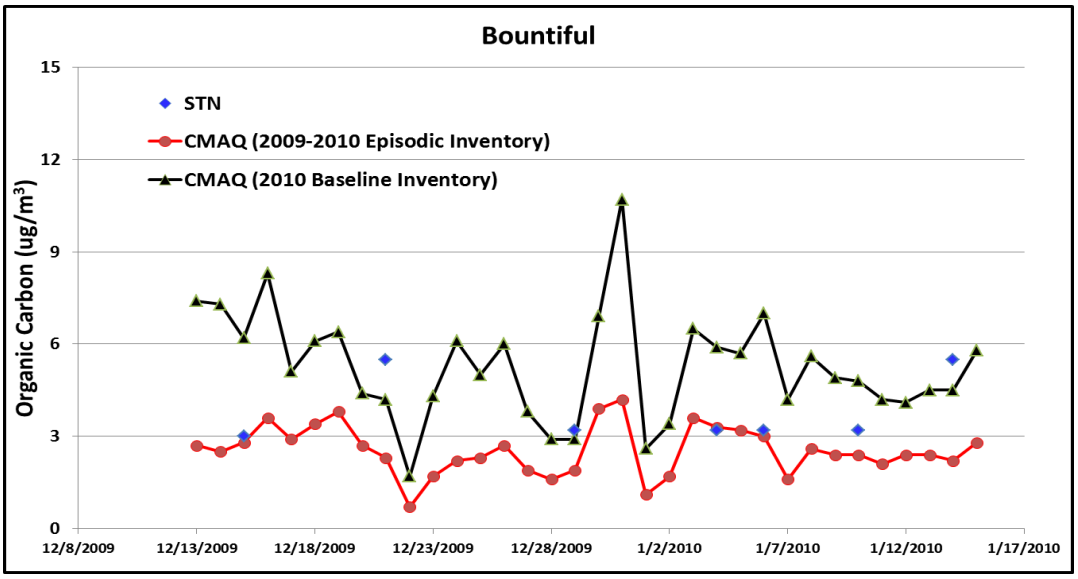

Figure D.14: Time Series of Observed vs. Predicted Organic Carbon (ug/m^3) of PM2.5 at the Bountiful Speciation Trends Network site.

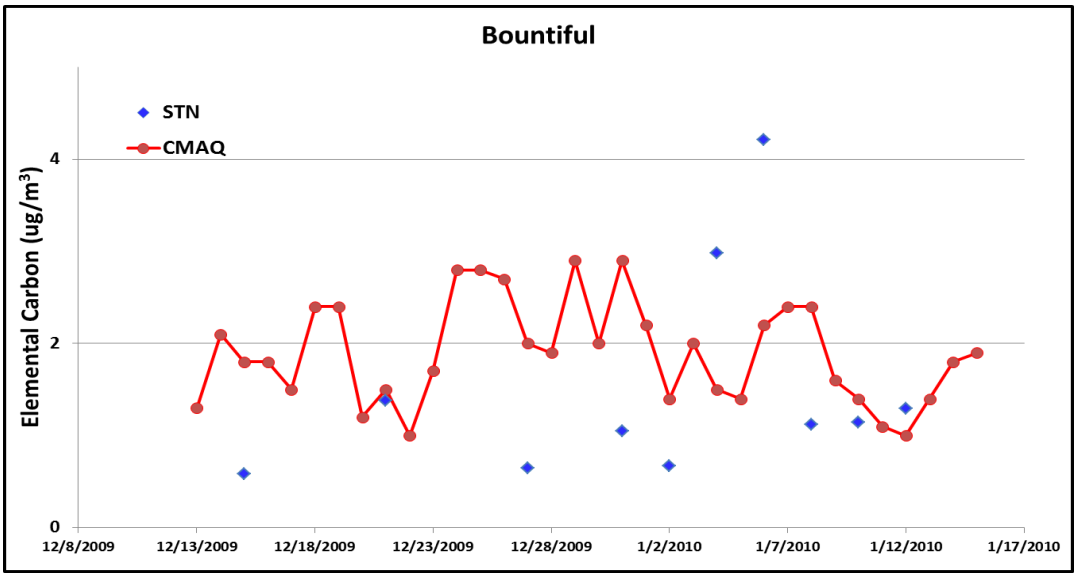

Figure D.15: Time Series of Observed vs. Predicted Elemental Carbon (ug/m^3) of PM2.5 at the Bountiful Speciation Trends Network site.