Photochemical Model Performance Evaluation

Utah Division of Air Quality

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1. Introduction

To assess how accurately the photochemical model predicts observed concentrations and to demonstrate that the model can reliably predict the change in pollution levels in response to changes in emissions, a model performance evaluation was conducted. This model performance evaluation also provides support for the model modifications that were implemented (ammonia injection, albedo, snow cover, ozone deposition velocity, cloud water content and vertical diffusion modifications) to more accurately reproduce winter-time inversion episodes. A detailed explanation of these model modifications was provided earlier.

Various statistical metrics and graphical displays with the objective to determine whether modeled variables are comparable to observations were considered for evaluating the model. These included:

- Time series plots of modeled and observed 24-hr PM2.5 concentrations.
- Scatter plots of modeled and observed 24-hr PM2.5 concentrations.
- Coefficient of determination, R^2, which shows the degree to which modeled and observed 24-hr PM2.5 concentrations are linearly related.
- Pie charts showing modeled and observed PM2.5 chemical species
- Soccer plots with purpose to visualize model performance of both bias and error on a single plot.
- Bugle plots that reflect the model's ability to predict concentrations. PM2.5 normalized mean error relative to performance goals and criteria is shown for this purpose. A model performance goal and criteria of 50% and 75% were selected, respectively.
- Mean bias, which is a metric that averages the model/observation residual paired in time and space.
- Normalized mean bias, which is a statistic of normalized mean bias to the average observed value.
- Normalized mean error, which is determined by normalizing the mean error by average observation.
- Mean fractional bias, which is determined by normalizing the mean bias by the average of observed and modeled concentrations.
- Mean fractional error, which is determined by normalizing the mean error by the average of observed and modeled concentrations.
- Mean gross error, which is a performance statistic that averages the absolute value of the model/observation residual paired in time and space.

Available ambient monitoring data was also used for this photochemical model performance evaluation. Data included ozone (O_3), nitrogen oxides ($NOx=NO+NO_2$), carbon monoxide (CO), 24-hr total PM2.5, and 24-hr chemically-speciated PM2.5 measurements collected at UDAQ's ambient air monitoring stations in the Salt Lake non-attainment area. Ammonia and volatile organic compounds (VOCs) measurements collected during special field studies carried out in winters of 2016 and 2017 were also used for this performance evaluation. These measurements were used since measurements of ammonia and VOCs were not available during 2011. The evaluation was based on the December 31-January 10 2011 episode, which will be used for model attainment test. 2011 emissions inventory was considered for this purpose. The evaluation was also overall focused on days with PM2.5 concentration exceeding the 24-hr national ambient air quality standard (> 35 µg/m^3). December 31, which is a spin-up day, was excluded from this evaluation.

2. Daily PM2.5 Concentrations

Figures 6.1a-h show 24-hr modeled and observed PM2.5 during January 1-10 2011 at all monitoring stations in the Salt Lake non-attainment area where 24-hr filter PM2.5 data was available. At Hawthorne monitoring station, the model overall captures well the temporal variation in PM2.5 (Figure 6.1a). The gradual increase in PM2.5 concentration and its transition back to low levels are generally well reproduced by the model. This overall good temporal agreement is further confirmed by the high temporal correlation between modeled and measured 24-hr PM2.5 over the modeling episode (Figure 6.2). The coefficient of determination (R^2) between modeled and measured 24-hr PM2.5 was 0.80, indicating their high temporal correlation.

It is noteworthy that the overestimation in PM2.5 on January 3rd at Hawthorne is related to the meteorological model performance on this day. While thin mid-level clouds were observed on January 3-4, these clouds were not simulated in the meteorological model, leading to an increasingly stable low-level boundary layer, particularly at night[1]. This limited the mixing of pollutants on January 3rd in the model, resulting in an over-prediction in PM2.5 levels. This over-prediction in PM2.5 on January 3rd at the Hawthorne monitor was also observed at Rose Park and Bountiful Viewmont stations (Figure 6.1b-c), located in the Salt Lake Valley. The underestimation in PM2.5 on January 5, 2011 at the Hawthorne station is also related to the meteorological model performance on this day. The meteorological model overestimated the wind shear near the mixing height, leading to increased vertical instability in the simulated temperature structure, which resulted in lower modeled PM2.5 concentrations[2].

[1] https://documents.deq.utah.gov/air-quality/planning/technical-analysis/research/model-improvements/3-wintertime-episodes/DAQ-2017-014342.pdf
[2] https://documents.deq.utah.gov/air-quality/planning/technical-analysis/research/model-improvements/3-wintertime-episodes/DAQ-2017-014342.pdf

Figure 6.1a-h: *Ten-day time series of measured (black) and modeled (red) mean 24-hour PM2.5 concentrations for January 1 - 10, 2011 (MDT) at monitoring sites within the Salt Lake non-attainment area. Dashed red line shows 24-hr PM2.5 NAAQS.*

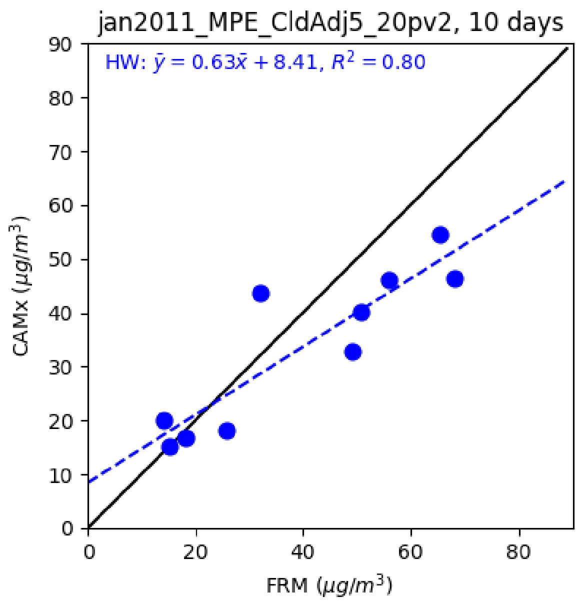

Figure 6.2: *Scatter plot showing mean 24-hour PM2.5 concentrations; modeled (vertical axis) compared to observed (horizontal axis) for Hawthorne (HW, blue dots). Linear regression line fit is also shown (dashed blue line).*

Similarly to its performance at Hawthorne, the photochemical model overall captured well the temporal variation in 24-hour PM2.5 at all other monitoring stations in the Salt Lake non-attainment area. The gradual increase in PM2.5 concentration and its transition back to low levels are generally well represented in the model. The overestimation in PM2.5 on January 3rd at Bountiful Viewmont and Rose Park stations is related to the meteorological model performance on this day, as aforementioned.

3. PM2.5 Chemical Speciation

To further investigate the photochemical model performance, UDAQ compared measured and modeled PM2.5 chemical species at Hawthorne and Bountiful Viewmont monitoring sites, which are part of EPA's Chemical Speciation Network (CSN). Figures 6.3a-d and 6.6a-d respectively show a comparison of the bulk chemical composition of measured and modeled PM2.5 at Hawthorne and Bountiful Viewmont sites on January 7 2011, which is the only PM2.5 exceedance day where measurement data is available. Chemical species, including nitrate (NO3), sulfate (SO4), ammonium (NH4), organic carbon (OC), elemental carbon (EC), chloride (Cl), sodium (Na), crustal material (CM) and other species (other mass), were considered in this analysis.

At Hawthorne, measured PM2.5 was 61.8 μg/m^3 while modeled PM2.5 was 54.5 μg/m^3 indicating that the model is biased low by an estimated 7.3 μg/m^3 or 11.8%. Model performance for NO3, which is the major PM2.5 component, was good, with modeled and measured particulate nitrate accounting for similar contributions to PM2.5 filter mass (about 40 and 41%, respectively). Modeled and observed nitrate concentrations were also comparable, with modeled concentration being biased low by about 15% (Figure 6.4). The model performance for particulate sulfate was also reasonably good, with measured and modeled concentrations accounting for 5.6 μg/m^3 and 4.2 μg/m^3 of total PM2.5 mass (Figures 6.3a and c), respectively, resulting in a low model bias of about 25% (Figure 6.4). Similarly to its performance for sulfate and nitrate, the model was also biased low for ammonium by about 33.5% (Figure 6.4). This low model bias in particulate ammonium can be attributed to an underestimation of ammonium chloride (NH4Cl) in the model. A previous source apportionment analysis showed that ammonium chloride accounts for 10-15% of total PM2.5 mass at Hawthorne during high wintertime PM2.5 pollution episodes[3]. This underestimation in modeled ammonium chloride can be related to an underestimation in modeled HCl emissions from US Magnesium plant, a large source of HCl emissions on the west side of the Great Salt Lake. Maximum hourly modeled values are about 12 and 35 ppb near US Magnesium (Figures 6.5a-b) on typical exceedance and non-exceedance days while values as high as 100 ppb were observed in the afternoon in the vicinity of US Magnesium during the 2017 Utah Winter Fine Particulate Study (UWFPS)[4]. The model was also biased low for sodium and chloride, possibly because major sources of chloride are not included in UDAQ's emissions inventory. Potential sources include the Great Salt Lake, road salt and playa dusts from dry salt beds. Aircraft measurements from the 2017 UWFPS showed that chloride mass fraction in PM2.5 is higher in the Great Salt Lake and Salt Lake region compared to other areas in the Salt Lake Valley[5]. Conversely, the model performance for OC was quite good for January 7. Modeled and observed concentrations were quite comparable, averaging 5.7 and 5.4 μg/m^3, respectively. During the winter, organic carbon is largely emitted by residential wood burning and commercial cooking. On January 7, the State of Utah issued a wood-burning ban in Salt Lake County. Utah DAQ modeled this ban on January 7 by reducing wood-smoke emissions by a factor derived from recent levoglucosan measurements[6]. The model overestimated EC on January 7 2011. This high model bias in EC is possibly due to an overestimation of EC in Utah's mobile emissions modeling using MOVES 2014a. Similarly, modeled crustal material was quite higher than measured for January 7 2011. In Utah's emissions inventory, re-suspended road dust accounts for nearly 90% of crustal material. It seems clear that the EPA tool used for calculating re-suspended road dust produced emissions estimates that are far too high, even when silt loading was reduced to the allowed minimum.

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[3] Kerry E. Kelly, Robert Kotchenruther, Roman Kuprov & Geoffrey D. Silcox (2013) Receptor model source attributions for Utah's 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

[4] https://www.esrl.noaa.gov/csd/groups/csd7/measurements/2017uwfps/finalreport.pdf

[5] https://www.esrl.noaa.gov/csd/groups/csd7/measurements/2017uwfps/finalreport.pdf

[6] https://deq.utah.gov/ProgramsServices/programs/air/research/projects/residential-wood-burning/wasatch-front-wood-smoke.htm

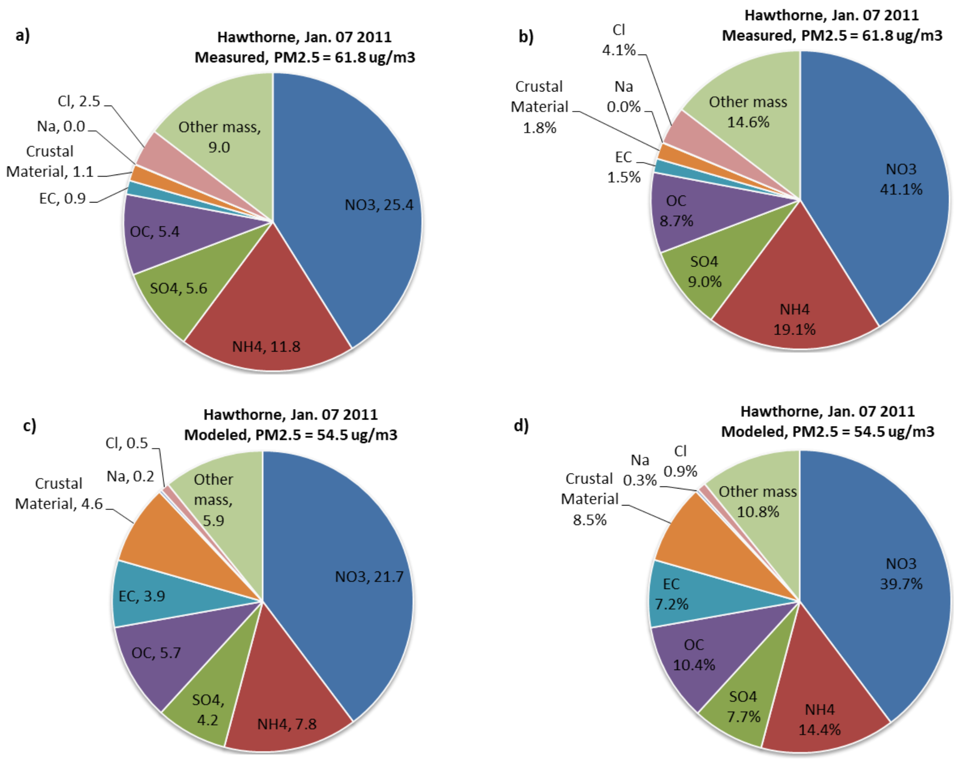

Figure 6.3a-d: *Measured (a,b) and modeled (c,d) mean 24-hour PM2.5 species for January 7, 2011 (MDT) at Hawthorne, Salt Lake County. Panels a and c show absolute concentrations (µg/m^3) of PM2.5 chemical species while panels b and d display their percent contributions to total PM2.5.*

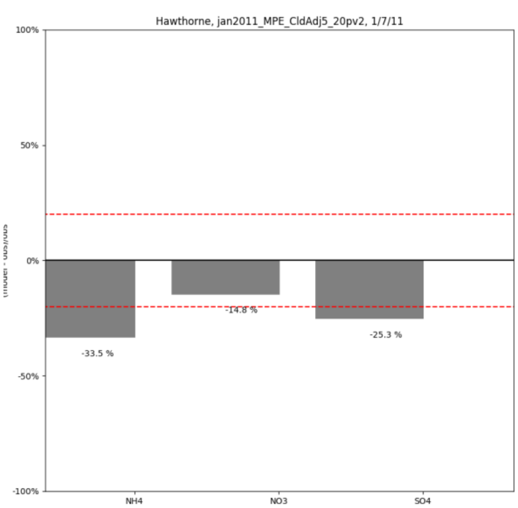

Figure 6.4: *24-hour mean secondary aerosol model performance for January 7, 2011 at Hawthorne, Salt Lake County. Dashed red lines depict +/- 20% levels. Positive percentages indicate high model bias.*

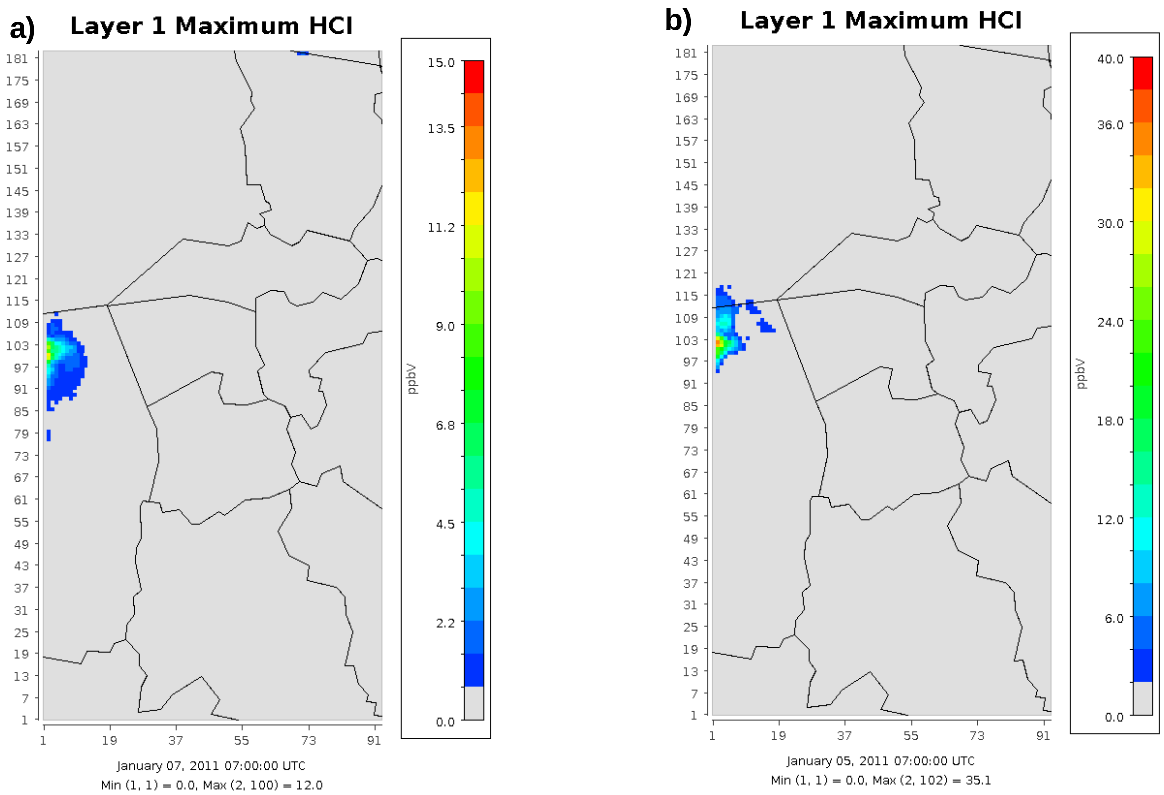

Figure 6.5a-b. Spatial distribution of maximum hourly HCl concentrations (in ppb) during a typical 24-hr PM2.5 a) exceedance day and b) non-exceedance day.

The model performance at Bountiful Viewmont site (Figure 6.6a-d) was generally similar to that at Hawthorne. Modeled and measured nitrate concentrations were quite similar (23.8 and 21.3 µg/m^3, respectively). The model was also biased low for sulfate and ammonium (43.8 and 41.1%, respectively, Figure 6.7). This bias for sulfate and ammonium was, however, more pronounced at Bountiful Viewmont compared to Hawthorne. The model was also biased low for chloride and organic carbon. On the other hand, the model overestimated EC and crustal material. The high bias in EC can also be attributed to an overestimation of EC in Utah's mobile emissions modeling using MOVES 2014a. The overestimation in crustal material can also be related to an overestimation in re-suspended road dust emissions estimates produced by the EPA tool used for these calculations.

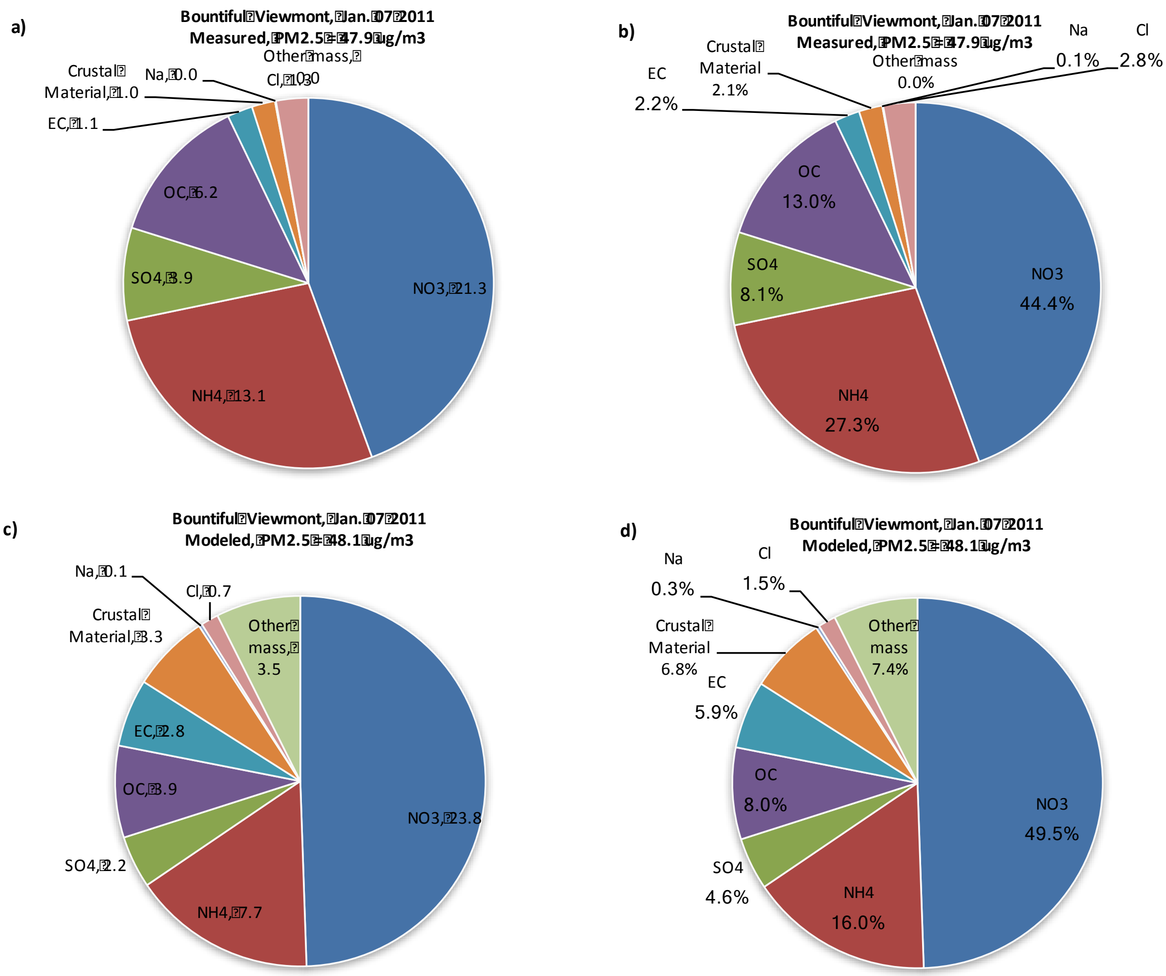

Figure 6.6a-d: *Measured (a,b) and modeled (c,d) mean 24-hour PM2.5 species for January 7, 2011 (MDT) at Bountiful Viewmont, Salt Lake County. Panels a and c show absolute concentrations (µg/m^3) of PM2.5 chemical species while panels b and d display their percent contributions to total PM2.5.*

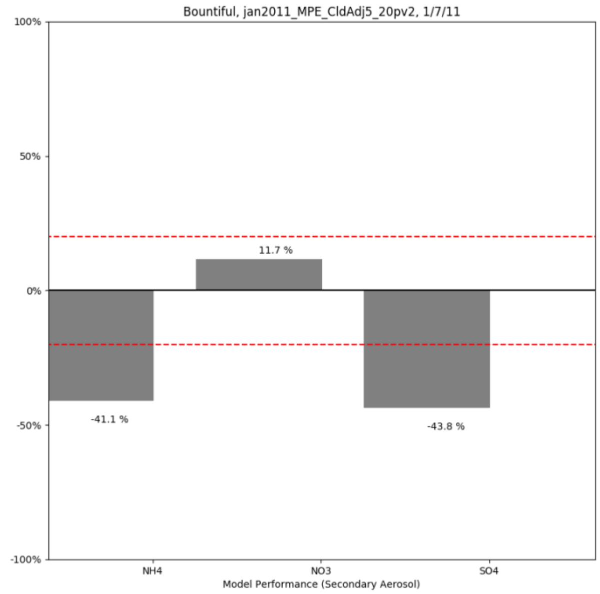

Figure 6.7: *24-hour mean secondary aerosol model performance for January 7, 2011 at Bountiful Viewmont, Salt Lake County. Dashed red lines depict +/- 20% levels. Positive percentages indicate high model bias.*

The model performance was also assessed at Rose Park monitoring station in Salt Lake Valley (Figures 6.8a-c). Given that measurements of PM2.5 chemical species were not available during 2011, this analysis is based on a comparison of the fraction of individual PM2.5 chemical species in total PM2.5 mass between model outputs and measurements. The latter correspond to FRM filter speciation data collected at Rose Park during an inversion event in 2017. While the 2017 filter measurements cannot be directly compared to day-specific 2011 model simulations, the measurements are useful to assess if the model predicts similar PM2.5 chemical composition during strong inversion conditions. While the concentration of individual PM2.5 chemical species may vary between inversion events, their relative contribution to total PM2.5 mass is expected to remain the same during typical inversion events. As can be seen, the chemical composition of modeled PM2.5 is similar to that of measured PM2.5. Modeled nitrate accounts for about 50% of PM2.5, in agreement with the contribution of measured nitrate to PM2.5 mass (about 49 and 50%). Measured and modeled sulfate and ammonium also have similar fractional contributions to PM2.5 mass.

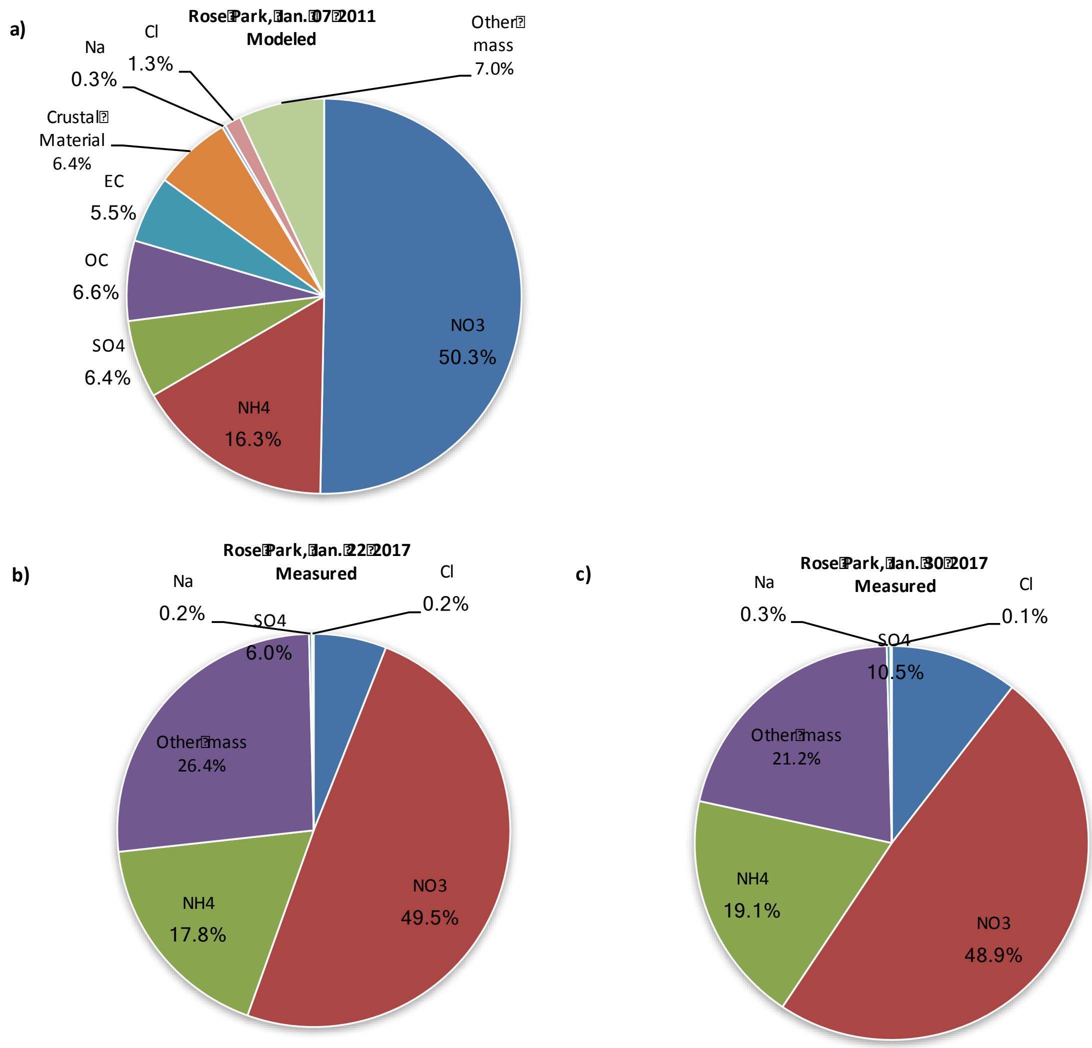

Figure 6.8: a) *Modeled and b-c) measured species contributions (in %) to PM2.5 at Rose Park, Salt Lake County during 24-hr PM2.5 exceedance days.*

The photochemical model performance was also evaluated for low 24-hr PM2.5 days (i.e. when PM2.5 was less than 35 μg/m^3). Figures 6.9a-d and 6.10a-d show a comparison between modeled and measured PM2.5 chemical species on low 24-hr PM2.5 days at Hawthorne and Bountiful Viewmont sites. This comparison was limited to January 1 and 9, which correspond to days when CSN measurements were available. Measurements were not available for other low PM2.5 days of the considered modeling episode. Similarly to the model performance on high PM2.5 days, the model overestimated primary PM2.5 species, particularly crustal material and EC. Organic carbon was also overestimated in the model at Hawthorne. There was no ban on residential wood burning in effect for January 1 and 9 in Salt Lake County. However, despite these biases, total 24-hour PM2.5 mass was overall comparable between modeled results and measurements.

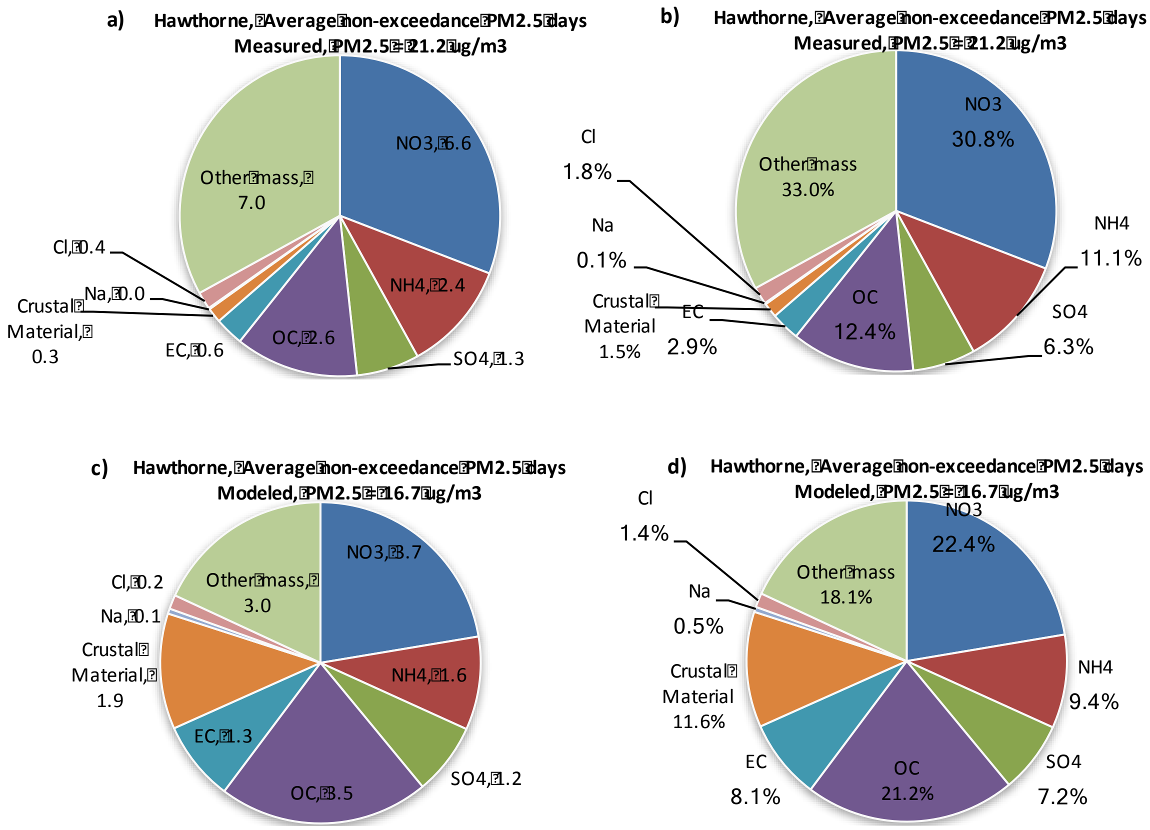

Figure 6.9a-d: *Average of measured (a,b) and modeled (c,d) mean 24-hour PM2.5 species over January 1 and 9, 2011 (MDT) at Hawthorne, Salt Lake County. Panels a and c show absolute concentrations (µg/m^3) of PM2.5 chemical species while panels b and d display their percent contributions to total PM2.5.*

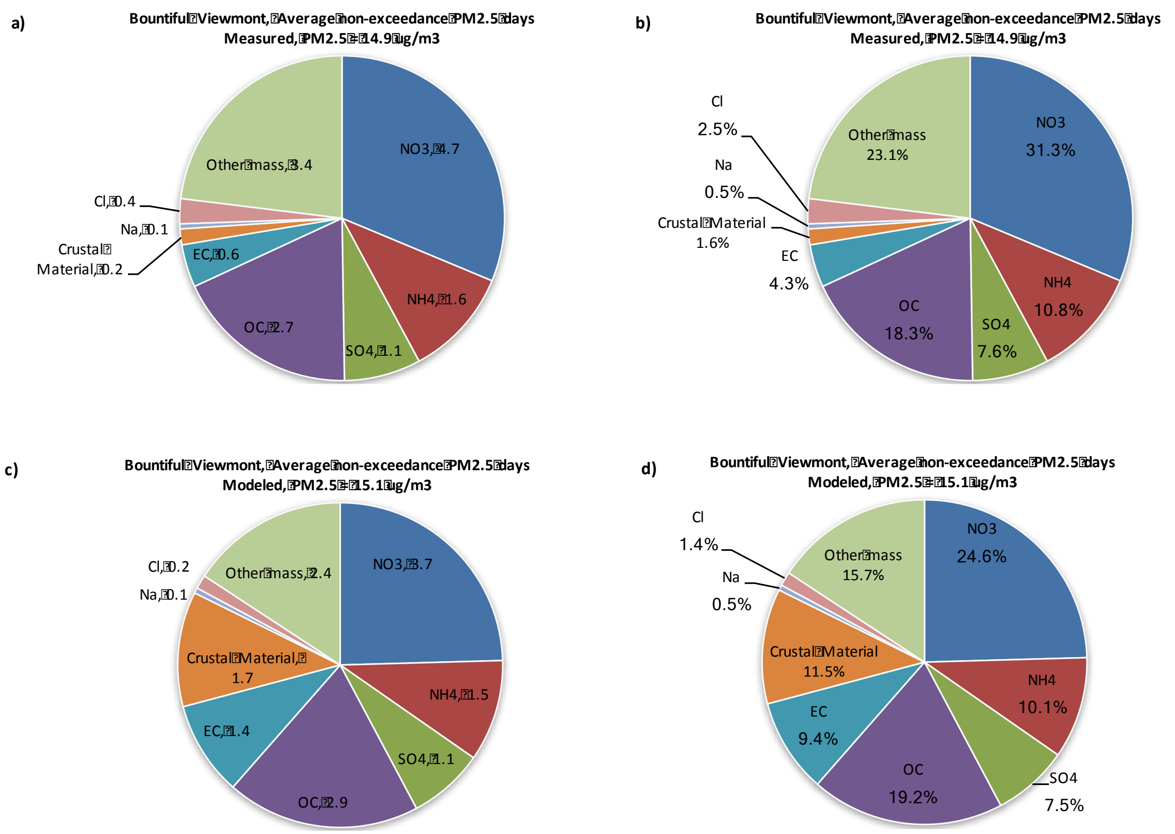

Figure 6.10a-d: Average of measured *(a,b) and modeled (c,d) mean 24-hour PM2.5 species over January 1 and 9, 2011 (MDT) at Bountiful Viewmont, Salt Lake County. Panels a and c show absolute concentrations (µg/m^3) of PM2.5 chemical species while panels b and d display their percent contributions to total PM2.5.*

4. Hourly Ambient Gaseous Compounds

The model performance was also evaluated for gaseous compounds, particularly precursor species to PM2.5 formation. Gaseous compounds considered in this analysis include carbon monoxide (CO), nitrogen oxides (NOx, defined as NO+NO2), ozone (O3), ammonia (NH3) and volatile organic compounds (VOCs).

Given that CO is a chemically inert compound and a non-PM2.5 precursor, examining modeled CO helps in delineating the causal effects of meteorology and air chemistry on model performance. As shown in figure 6.11, modeled CO performance is good for most of the January 2011 episode. The concentration of modeled CO is overall within the same range as that measured. During the earlier part of the episode (January 3 and 4), modeled CO concentration was greater than that measured. This is likely due to the absence of mid-level clouds in the meteorological model simulation during that time[7]. The modeled mixing height was lower than in reality, leading to a build-up of CO near the surface.

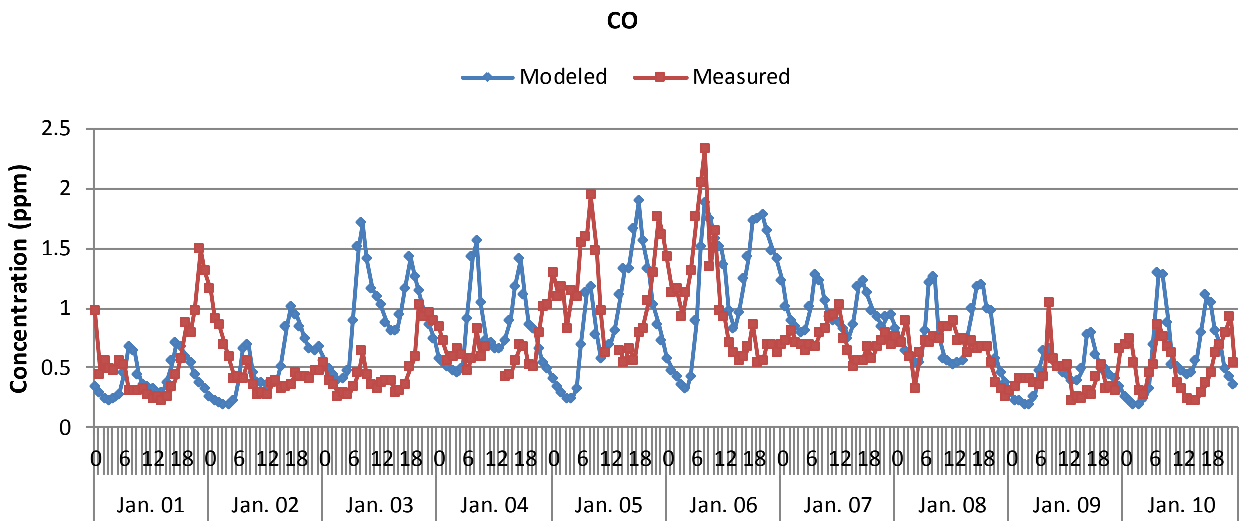

Figure 6.11: *Hourly time series of CO (ppm). Measured (red) compared to modeled (blue) for January 1 - 10, 2011 at Hawthorne, Salt Lake County.*

As a precursor to particulate nitrate, achieving good model performance for modeled NOx is important. Over the January 2011 episode, the magnitude of modeled NOx is generally on par with measurements at the Hawthorne monitoring site (Figure 6.12). There was a pronounced low model bias in NOx that occurred on January 5 and 6. This low bias is likely related to an overestimation in WRF of the wind shear that occurred aloft during that time[8].

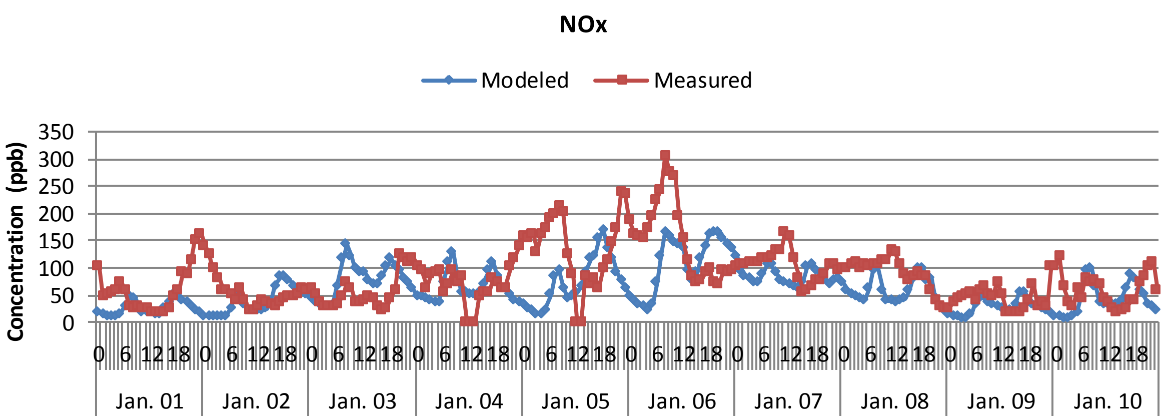

Figure 6.12: Hourly time series of NOx (NO + NO2, ppb). Measured (red) compared to modeled (blue) for January 1 - 10, 2011 at Hawthorne, Salt Lake County.

[7] https://documents.deq.utah.gov/air-quality/planning/technical-analysis/research/model-improvements/3-wintertime-episodes/DAQ-2017-014342.pdf

[8] https://documents.deq.utah.gov/air-quality/planning/technical-analysis/research/model-improvements/3-wintertime-episodes/DAQ-2017-014342.pdf

O3 is an important oxidant for secondary PM2.5 formation. As seen in figure 6.13, while not all early morning O3 peaks (e.g., 12 - 3 AM MDT during the early part of the episode) were well represented by the model, ozone was well simulated during the peak PM2.5 conditions of January 7. The temporal trend and magnitude of ozone concentration were well simulated on that day.

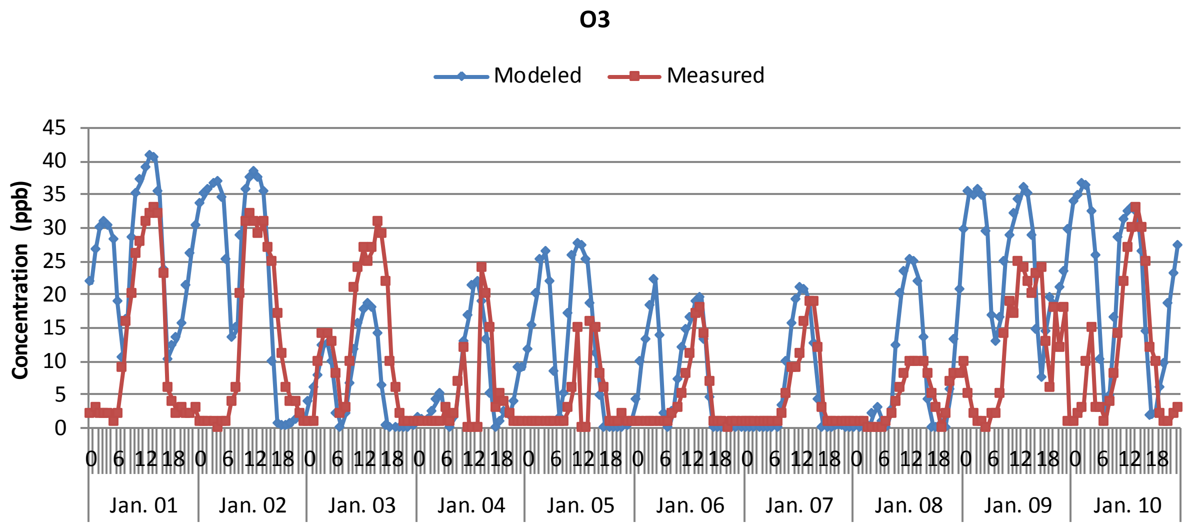

Figure 6.13: *Hourly time series of Ozone (ppb). Measured (red) compared to modeled (blue) for January 1 - 10, 2011 at Hawthorne, Salt Lake County.*

The model performance was also evaluated for NH3, which is an important precursor to the formation of ammonium nitrate, ammonium sulfate and ammonium chloride, all of which are important PM2.5 species accounting for over 50% of the PM2.5 mass during inversion events (Figure 6.3a-d).

Modeled ammonia (figure 6.14) was compared to hourly ammonia measurements (figure 6.15) conducted at Neil Armstrong Academy during a special field study in winter 2016. Measurements from 2016 were considered since measurements of ammonia were not available during 2011. Hourly measurements were also only available at Neil Armstrong Academy, located in West Valley City in the Salt Lake non-attainment area. However, while these 2016 field study measurements cannot be directly compared to day-specific 2011 model simulations, the measurements are qualitatively useful to assess if the model predicts similar levels of ammonia during strong inversion conditions.

A comparison of measured and modeled ammonia shows that modeled ammonia at Hawthorne and Neil Armstrong Academy is well within the range observed in 2016. It also displays a similar behavior to that of measured NH3, with NH3 concentration dropping during peak PM2.5 events during which the airshed is saturated and virtually all near-surface ambient ammonia has yielded to particulate ammonium.

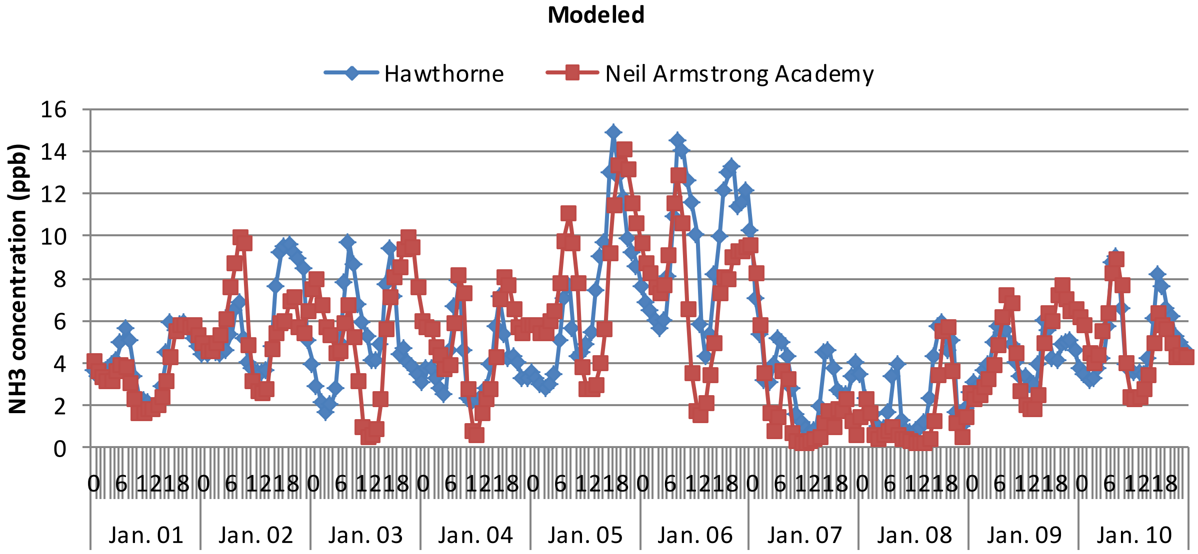

Figure 6.14: *Hourly time series of modeled ammonia (ppb) for January 1 - 10, 2011 at Hawthorne and Neil Armstrong Academy, Salt Lake County.*

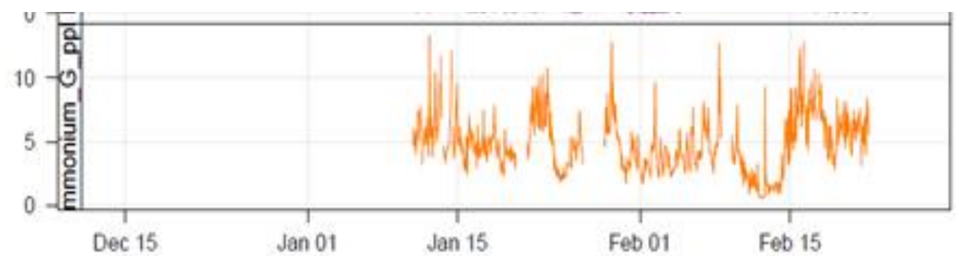

Figure 6.15: *Hourly ammonia measurements from Neil Armstrong Academy (West Valley City, Salt Lake County) during winter 2016. Note that ammonia drops during the persistent cold air pool period during Feb. 7 - 14 2016.*

The model performance was also evaluated for VOCs and carbonyls, which can act as radical sources important for the photochemical production of PM2.5 during wintertime inversion episodes in the Salt Lake Valley[9]. Given that measurements of VOCs species were not available during 2011, the modeling results were compared to observations conducted in winter 2017 at the University of Utah (2017 Utah Winter Fine Particulate Study (UWFPS)). While these field study measurements from 2017 cannot be directly compared to day-specific 2011 model simulations, they're qualitatively useful to assess if the model predicts similar levels of VOCs during strong inversion conditions.

A comparison of the modeling results and measurements showed that formaldehyde may be underrepresented in the model during mid-day hours. On average during peak PM2.5 exceedance days, measured formaldehyde peaked at about 3 ppb around 11 am (Figure 6.17) while modeled

[9] https://www.esrl.noaa.gov/csd/groups/csd7/measurements/2017uwfps/finalreport.pdf. Chapter 3.

formaldehyde peaked at 6 pm and displayed a concentration of 1.8 ppb at 11 am (figure 6.16). Modeled formaldehyde also displayed a temporal trend different from that of measured formaldehyde, with observations indicating direct emission as well as secondary production of formaldehyde. Similarly, modeled acetaldehyde exhibited a temporal trend different from that measured on peak PM2.5 days. This comparison suggests that acetaldehyde and formaldehyde, an important source of radicals, may be underestimated in the model during mid-day hours.

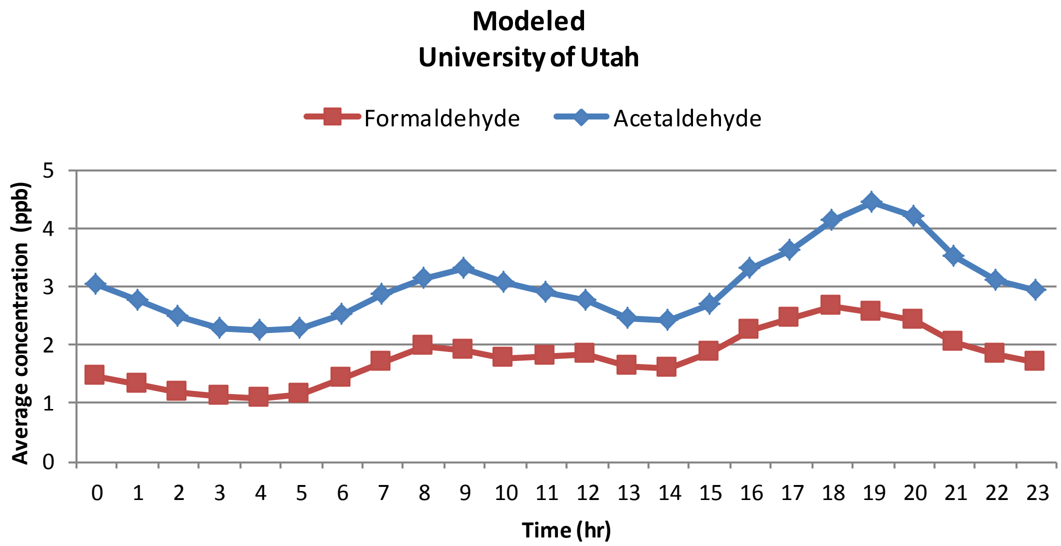

Figure 6.16: *Hourly time series of average modeled formaldehyde and acetaldehyde during January 6-8 2011 at the University of Utah.*

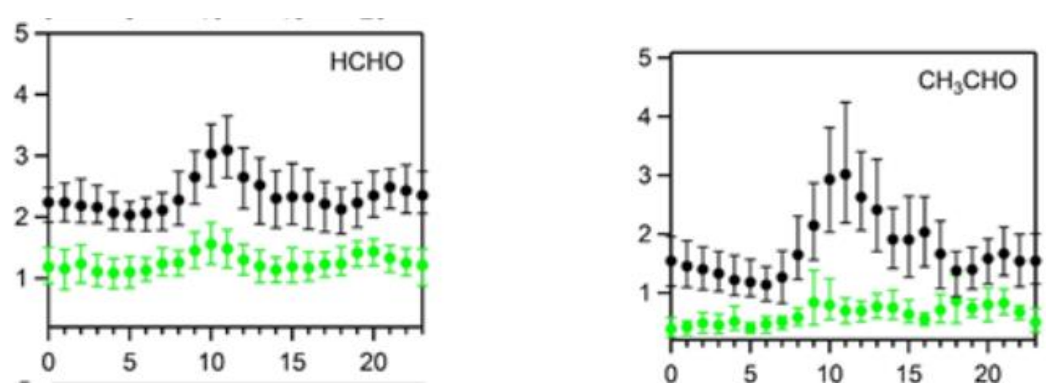

Figure 6.17: *Diurnal trend of hourly averaged formaldehyde (HCHO) and acetaldehyde (CH3CHO) measured at the University of Utah during polluted (black lines) and clean (green lines) conditions in winter 2017. Figure retrieved from the 2017 Utah Winter Fine Particulate Study, final report, Figure 3.59 (https://www.esrl.noaa.gov/csd/groups/csd7/measurements/2017uwfps/finalreport.pdf).*

5. Model Performance Evaluation Metrics

The model performance was further evaluated by examining various bias and error metrics. These were developed according to Boylan et al. 2008[10] and are discussed in "Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5, and Regional Haze" (EPA, April 2007).

Modeled 24-hour PM2.5 species were evaluated for January 1, 3, 5, 7, and 9 2011 at the Hawthorne monitoring site in the Salt Lake non-attainment area. Where EPA AQS data was not available for a given day, observed concentrations recorded during a special field study conducted by Utah DAQ in January 2011 were used.

Dataset used	**AQS**	**Special Study**
January 1, 2011	Hawthorne	
January 3, 2011		Hawthorne
January 5, 2011	Hawthorne	
January 7, 2011	Hawthorne	
January 9, 2011	Hawthorne	

Table 5.1: *Hawthorne speciated filter measurements retrieved from two sources: EPA AQS and Utah DAQ special study. Where measurements from both were available for a given day, AQS data was used.*

Soccer and bugle plots were first considered for the model performance evaluation, where two different thresholds were considered:

1. An upper threshold, below which model performance is considered acceptable for most modeling applications.
2. A lower threshold that suggests a level of accuracy that is as good as can possibly be expected from an air quality model.

Figure 6.18 shows soccer plots for Hawthorne for the January, 2011 episode. Two thresholds of +/-30% and +/-60% were used for the normalized mean bias (NMB) and fractional mean bias (FMB) while two thresholds of +50% and +75% were used for the normalized mean error (NME) and fractional mean error (FME).

[10] James W. Boylan, Armistead G. Russell (2006) PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models, Atmospheric Environment 40 (2006) 4946–4959, doi:10.1016/j.atmosenv.2005.09.087

As can be seen in figure 6.18, model performance for SO4 is exceptional at Hawthorne. Model performance for NO3 and NH4 is also acceptable. However, primary aerosol species (OC, EC, CM) fall outside of the performance threshold. This is likely due to the aforementioned problems with modeled overestimates of primary aerosol species during low 24-hour PM2.5 days; days when primary aerosol makes up most of the filter mass.

For the wintertime modeling of Wasatch Front air pollution events, achieving good model performance is more important for secondary aerosols which account for over 50% of total PM2.5 mass (Figures 6.3 and 6.6).

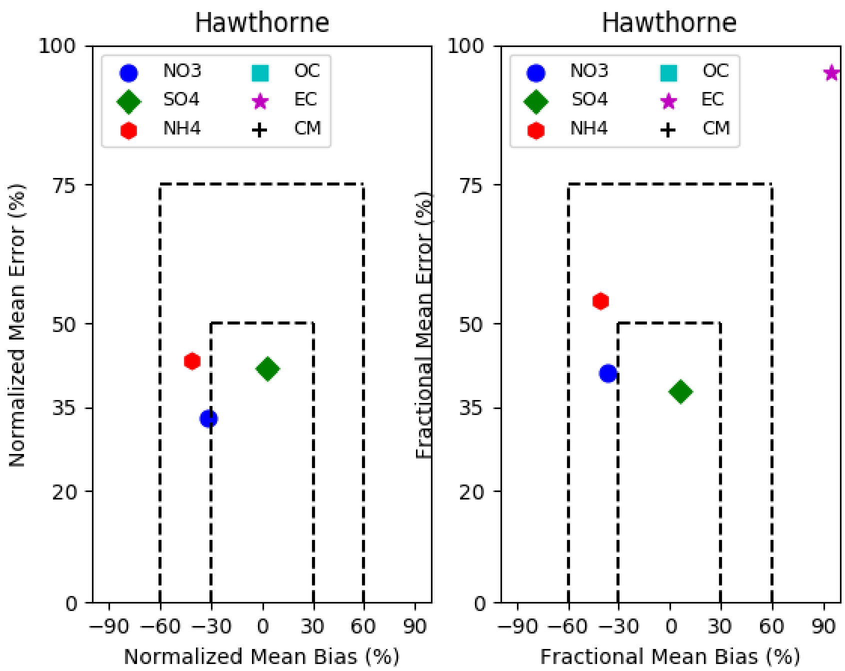

Figure 6.18: *Soccer plot depicting modeled PM2.5 species performance for five days when speciated PM2.5 filter data was available at Hawthorne, Salt Lake County. Note that OC, EC, and CM are outside of the plotting range.*

Figure 6.19 (left panels) shows bugle plots with the NMB/NME displayed on the vertical axis and the five-day average of absolute average concentrations of speciated PM2.5 mass displayed along the horizontal axis. Threshold values of +/-30%, +/-60% are used for evaluating the NMB, while threshold values of +50%, +75% were used for evaluating the NME.

Similarly, the right two panels (Figure 6.19) show bugle plots for mean fractional bias (MFB) and mean fractional error (MFE). Model performance is evaluated against the same thresholds for the MFB and MFE as the NMB and NME, respectively. Both metrics (MFB, MFE) suggest model performance for secondary aerosols (NO3, SO4, NH4) is quite good.

Good model performance for secondary aerosols is more important for wintertime modeling of inversion events, since secondary aerosol makes up most of the PM2.5 filter mass during highly elevated PM2.5 days.

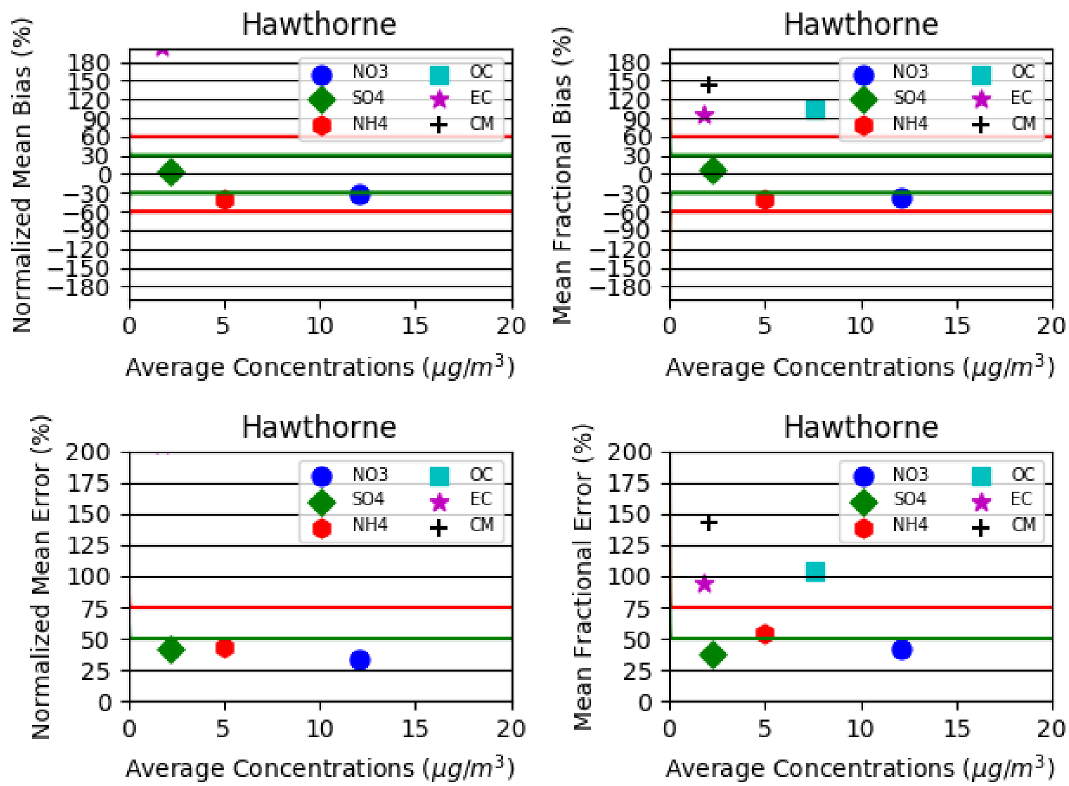

Figure 6.19: *Bugle plots depicting modeled PM2.5 species performance for five days when speciated PM2.5 filter data was available at Hawthorne, Salt Lake County.*

PM2.5 Species	**Mean (obs) ug/m3**	**Mean (modeled) ug/m3**	**Mean Bias ug/m3**	**Mean Error ug/m3**	**Normalized Mean Bias**	**Normalized Mean Error**	**Mean Fractional Bias**	**Mean Fractional Error**
FCRS	0.6	3.6	2.9	2.9	468	468	142	142
OC	3.7	11.6	7.9	7.9	218	218	104	104
PEC	0.89	2.7	1.8	1.8	205	205	95	95
PNH4	6.3	3.7	-2.6	2.7	-41	43	-41	54
PNO3	14.4	9.8	-4.6	4.7	-32	33	-36	41
PSO4	2.2	2.3	0.1	0.9	3.0	42	6.1	38

Table 6.1: *Model performance statistics for five days when speciated PM2.5 filter data was available for Hawthorne, Salt Lake County.*

Model performance was further evaluated by examining various model performance metrics for PM2.5 species as presented above in table 6.1 for the Hawthorne monitoring site during the January, 2011 episode. As can be seen, the model mean bias and error were generally low for secondary PM2.5 species.

6. Summary of Model Performance

The model performance replicating the buildup and clear out of $PM_{2.5}$ is good overall. The model captures well the temporal variation in $PM_{2.5}$. The gradual increase in $PM_{2.5}$ concentration and its transition back to low levels are generally well reproduced by the model. The model also predicts reasonably well $PM_{2.5}$ concentration on peak days. It also overall replicates well the composition of $PM_{2.5}$ on exceedance days, with good model performance for secondary nitrate and ammonium which account for over 50% of $PM_{2.5}$ mass. Simulated ammonia concentrations are also within the range of those observed, further indicating that the model overall performs well.