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Fine Particulate Matter Data Analysis and Modeling in the Bay Area

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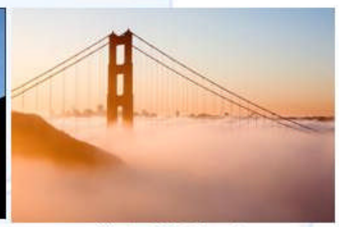

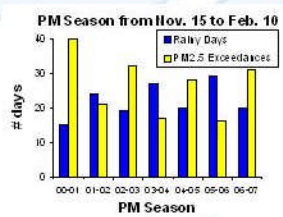

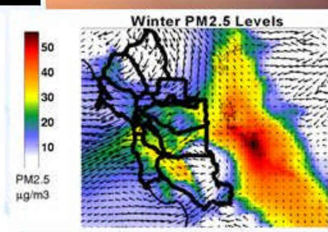

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Disclaimer

This report presents results from analyses of measurements and computer modeling performed by the District to study $PM_{2.5}$. The results presented should be viewed as preliminary because uncertainties may exist in emissions estimate, modeling and ambient measurements. This is the first attempt in analyzing ambient data and modeling $PM_{2.5}$. The District plans to refine and expand upon these preliminary results, and minimize uncertainties via its on-going research effort.

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Executive summary

This report presents preliminary findings of BAAQMD's on-going data analysis and modeling efforts to better understand fine particulate matter ($PM_{2.5}$) formation in the Bay Area. $PM_{2.5}$ is a complex mixture of suspended particles and liquid droplets having aerodynamic diameters of 2.5 μm or less. For the Bay Area, public health impacts from $PM_{2.5}$ may well exceed the combined impacts of all other currently regulated air pollutants. The body of knowledge contained in this report is an enhancement by BAAQMD investigations to supplement research performed under state and federal agencies. Research efforts include analyses of measurements and computer modeling. This document is the first in a series of periodic technical reports describing BAAQMD $PM_{2.5}$ research efforts.

E.1 Data analysis

Bay Area 24-hour $PM_{2.5}$ exceedances, almost entirely confined to winter months, occur under increased stable atmospheric conditions that trappe pollutants near the ground. Winters with frequent stagnant periods tend to have more 24-hour $PM_{2.5}$ exceedances than winters with more periods of windy and stormy conditions. Consecutive stagnant, clear winter days are typically requisite for $PM_{2.5}$ episodes to develop. $PM_{2.5}$ episodes are regional in nature and impact most Bay Area locations. Livermore, Concord, San Jose, and Vallejo have 24-hour $PM_{2.5}$ design values at or near the NAAQS exceedance threshold of 35 $\mu g/m^3$. Other populated locations exhibit design values around 25-30 $\mu g/m^3$. Near-background $PM_{2.5}$ levels were observed at Point Reyes, where annual-average $PM_{2.5}$ levels were about half that of other Bay Area monitoring locations. The Bay Area is expected to attain the NAAQS for annual-average $PM_{2.5}$ level.

The Chemical Mass Balance (CMB) analysis was applied for $PM_{2.5}$ source apportionment, using specialized measurements mostly obtained during the years 1999-2001. Primary combustion sources (both fossil fuels and biomass) were prevalent $PM_{2.5}$ contributors for all seasons. The biomass combustion contribution to peak $PM_{2.5}$ levels was about 3-4 times higher during winter than for the other seasons. Isotopic carbon (^{14}C) analysis confirmed this increased proportion of winter biomass combustion emissions. The increased winter biomass combustion sources reflected increased levels of wood burning during the winter season. Wood burning may have been the single largest contributing source to $PM_{2.5}$ under episodic conditions. Secondary $PM_{2.5}$ levels were only elevated during the winter months. Wintertime secondary $PM_{2.5}$ was mostly ammonium nitrate. This semi-volatile $PM_{2.5}$ component is stable in its solid form only during the cooler winter months. Secondary ammonium sulfate $PM_{2.5}$ levels were generally low (< 1-2 $\mu g/m^3$) but non-negligible. Sea salt, geological dust, and tire and brake wear contributed minimally to $PM_{2.5}$.

Meteorological cluster analysis, a data mining technique, was implemented by UC Davis to determine how weather patterns impact $PM_{2.5}$ levels. Clustering was applied to measurements from every winter day across more than 10 years. This method robustly established how the prevailing weather drives the development of $PM_{2.5}$ episodes. Episodes nearly always developed under: stable atmospheric conditions inhibiting vertical dispersion; clear and sunny skies favoring enhanced secondary $PM_{2.5}$ formation; and pronounced overnight drainage (downslope) flows off the Central Valley rims, causing low-level air in the Central Valley to empty through the Delta and into the Bay Area along its eastern boundary. Atmospheric transitions of aloft weather systems profoundly influenced the surface winds that determine $PM_{2.5}$ levels. Surface conditions stagnated whenever an upper-level high pressure system moved over Central California. Persisting high pressure conditions allowed $PM_{2.5}$ buildup, and Bay Area 24-hour $PM_{2.5}$ exceedances generally occurred after 2-4 days.

A refined cluster analysis further characterized the upwind Central Valley conditions during Bay Area episodes. Two distinct inter-regional air flow patterns were associated with different types of Bay Area episodes. The majority of exceedance days (around 60 percent) were associated with winds from the Sacramento Valley to the northeast entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred at San Jose for this type of episode. A minority of exceedance days (around 20 percent) were associated with winds from the San Joaquin Valley from the southeast entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred in the East Bay (at Livermore, Concord, or Vallejo) for this type of episode. The remaining relatively moderate episodes (around 20 percent) could not be associated with any distinct inter-regional transport pattern linking the Bay Area and surrounding air basins.

E.2 Computer modeling

Computer modeling efforts were initially based on data from the California Regional Particulate Air Quality Study (CRPAQS) and provided by the California Air Resources Board (ARB). BAAQMD staff and its contractors have since contributed to a custom computer model developed to address Bay Area $PM_{2.5}$ exceedances. $PM_{2.5}$ simulations were performed for the core PM season months of December-January for both the 2000-01 and 2006-07 periods. Wood smoke simulations covered most of the 2008-09 winter.

$PM_{2.5}$ base case simulations were performed using the most historically accurate winter emissions inventory available. This inventory comprised various data compiled by the ARB, BAAQMD, and Sonoma Technology, Inc. The base case simulation was validated against measurements to adequately represent PM levels in the Bay Area and Delta regions. Figure E-1 shows the spatial distribution of simulated primary and secondary $PM_{2.5}$ components averaged across the 52 simulated days for which measured Bay Area 24-hour $PM_{2.5}$ level (FRM or BAM) exceeded 35 $\mu g/m^3$. For these episodic days, light winds flowed through the Bay Area from the east, and Central Valley conditions were near calm. Primary $PM_{2.5}$ levels were elevated primarily near centers of commerce around the bay; over the Central Valley major cities and to a lesser extent its rural areas; near industrial facilities along Carquinez Straight; and somewhat at Travis, Santa Rosa, and Santa Cruz. Secondary $PM_{2.5}$, present mostly as ammonium nitrate, was not localized near the sources of its precursor emissions

NO_x and ammonia. Rather, secondary $PM_{2.5}$ was regionally elevated. A sharp gradient existed with very high secondary $PM_{2.5}$ levels in the Central Valley decreasing westward through the Bay Area to reach background levels over the Pacific Ocean. The model suggested that regional ammonium nitrate buildup is limited by nitric acid, a product of NO_x emissions photochemical aging, and not by ammonia. In the Central Valley, $PM_{2.5}$ levels were dominated by secondary components which could alone build to the exceedance level. Around San Francisco and San Jose, $PM_{2.5}$ levels were dominated by primary components which could alone build to the exceedance level. For other areas affected by PM episodes, such as the eastern and northern Bay Area and the Delta, primary and secondary $PM_{2.5}$ levels were comparable. Both primary and secondary buildup was required for exceedances to occur in these locations.

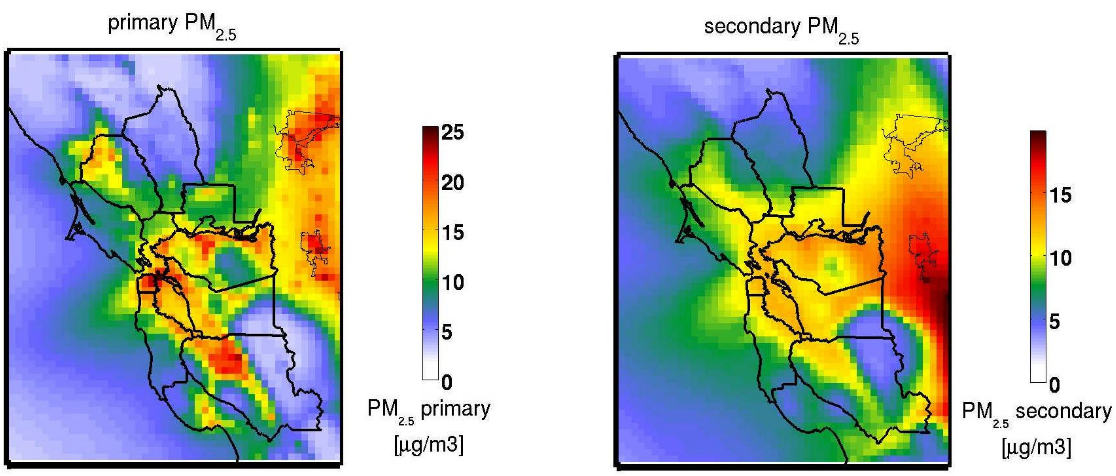


Figure E-1. Spatial distribution of simulated primary and secondary $PM_{2.5}$ levels, averaged across the 52 simulated days for which measured Bay Area 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento and Stockton are drawn using thin black lines.

$PM_{2.5}$ sensitivity simulations were performed by reducing Bay Area emissions relative to the base case. Across-the-board Bay Area emissions reductions of 20 percent were simulated for the following five classes of chemical species: NO_x and VOC combined; gaseous sulfur species; ammonia; directly emitted PM; and these four classes combined, comprising all anthropogenic emissions. These across-the-board reductions were simulated for one episode each from 2000-01 and 2006-07. Reducing the directly emitted PM reduced peak $PM_{2.5}$ levels nearly ten times more efficiently than reducing the secondary PM precursors. Reducing primary PM emissions by 20 percent (around 18 tons/day eliminated) typically reduced primary $PM_{2.5}$ levels by 12-20 percent, depending on location, with an average around 16 percent. Reductions of directly emitted PM were most effective near the PM emissions sources where primary $PM_{2.5}$ levels were highest (see Figure E-1). The largest benefits of around 4-6 $\mu g/m^3$ occurred near San Jose. Reducing ammonia emissions by 20 percent (around 15 tons/day) was the most effective of the precursor emissions reductions. Secondary $PM_{2.5}$ levels were typically reduced 0-4 percent, depending on location, with an average around 2 percent. Ammonia emissions reductions were less effective near ammonia sources, where the secondary PM forming chemistry was limited by lack of nitric acid. Reducing NO_x and VOC emissions by 20 percent (around 250 tons/day total) was relatively ineffective. Reducing sulfur-containing PM precursor emissions by 20 percent (around 16 tons/day) typically had a small impact on Bay Area $PM_{2.5}$ levels under episodic conditions. On certain days with the offshore shipping lanes upwind of the Bay Area, however, the 20 percent sulfur emissions reductions produced over 1 $\mu g/m^3$ benefit.

$PM_{2.5}$ transport simulations were performed by zeroing out anthropogenic emissions for various air basins. Transport impacts were evaluated for 55 days from 2000-01 and 2006-07 having simulated base case 24-hour $PM_{2.5}$ levels 35 $\mu g/m^3$ or higher. Anthropogenic Bay Area emissions were eliminated to estimate the cumulative transport impacts from all sources outside of the Bay Area. On average, transported primary $PM_{2.5}$ levels were around 2-8 $\mu g/m^3$. Transport impacts were highest through the Carquinez Straight and Altamont Pass, which connect the Bay Area with the Central Valley. Transport impacts of secondary ammonium nitrate were as high as 13 $\mu g/m^3$ along the Bay Area eastern boundary, 8 $\mu g/m^3$ through the Carquinez Strait and Altamont Pass, and 5 $\mu g/m^3$ around the bay. Transported ammonium sulfate levels of around 1 $\mu g/m^3$ were present uniformly throughout the Bay Area. Ammonium sulfate appeared to be transported mostly from regions outside of the Central Valley. Central Valley $PM_{2.5}$ levels were relatively unaffected by eliminating the Bay Area emissions.

A second pair of $PM_{2.5}$ transport simulations was conducted by zeroing out anthropogenic emissions for the Sacramento area and San Joaquin Valley separately. Reductions in simulated $PM_{2.5}$ levels relative to the base case reflected transport impacts from the respective air basin for which emissions were eliminated. Eliminating the Sacramento area emissions reduced primary $PM_{2.5}$ levels by around 5 $\mu g/m^3$ through Carquinez Strait, by less than 2 $\mu g/m^3$ in the northern half of the Bay Area, and had little effect elsewhere in the Bay Area. Secondary $PM_{2.5}$ levels transported from the Sacramento area were 2.5 $\mu g/m^3$ through Carquinez Strait and Altamont Pass and around 1.5 $\mu g/m^3$ elsewhere in the Bay Area. Eliminating the San Joaquin Valley emissions reduced primary $PM_{2.5}$ levels by around 4 $\mu g/m^3$ through Carquinez Strait and Altamont Pass, by around 3 $\mu g/m^3$ through Pacheco Pass and into southern Santa Clara Valley, and had little impact farther into the Bay Area. Secondary $PM_{2.5}$ levels transported from the San Joaquin Valley were up to 8 $\mu g/m^3$ through Pacheco Pass and into southern Santa Clara Valley, around 6 $\mu g/m^3$ through Altamont Pass and into eastern Contra Costa County, and around 5 $\mu g/m^3$ elsewhere in the Bay Area.

The above transport simulation results were based on average episodic conditions. During the more severe episodes, transport impacts were often greater than for the average episodic conditions. Transport impacts were tabulated for the six days each 2000-01 and 2006-07 winter period with the highest measured $PM_{2.5}$ levels, for 12 days total. Total transported $PM_{2.5}$ levels averaged 19, 19, 11, and 12 $\mu g/m^3$ at the Livermore, Vallejo, San Jose, and San Francisco monitoring locations, respectively. Maximum total transported $PM_{2.5}$ levels were 33, 37, 24, and 24 $\mu g/m^3$ for these stations, respectively. Thus, 24-hour

$PM_{2.5}$ exceedances could have occurred in the Bay Area without any Bay Area anthropogenic emissions. Transported secondary $PM_{2.5}$ levels averaged around 40-80 percent more than transported primary $PM_{2.5}$ levels, depending upon location. Total transported $PM_{2.5}$ levels from the Sacramento area averaged 4, 5, 2, and 3 $\mu g/m^3$ for these stations, respectively. At Vallejo, transported $PM_{2.5}$ from the Sacramento area had a somewhat higher proportion of primary components. At the other three locations, transported $PM_{2.5}$ from the Sacramento area had a somewhat higher proportion of secondary components. Total transported $PM_{2.5}$ levels from the San Joaquin Valley averaged 13, 10, 7, and 7 $\mu g/m^3$ for these stations, respectively. Transported secondary $PM_{2.5}$ from San Joaquin Valley were 2.5-4 times higher than transported primary $PM_{2.5}$ levels.

Simulated transport impacts were also compared across two different transport scenarios identified by the measurements-based meteorological cluster analysis (described above). There were 41 episodic days classified as having transport from the Sacramento area and 5 episodic days classified as having transport from the San Joaquin Valley. Zeroing out the Sacramento area emissions provided greater benefit in the Bay Area when transport occurred from the Sacramento area. Transported $PM_{2.5}$ from the Sacramento area was about half primary and half secondary. It mostly impacted the central and northern portions of the Bay Area. Zeroing out the San Joaquin Valley emissions provided greater benefit in the Bay Area when transport occurred from the San Joaquin Valley. Transported $PM_{2.5}$ from the San Joaquin Valley was about one-third primary and two-thirds secondary. It mostly impacted the central and southern portions of the Bay Area.

Wood smoke $PM_{2.5}$ levels were simulated for the 2008-09 winter. The simulation period contained 8 of the 11 Spare the Air days during the 2008-09 winter. Two different model runs were performed. Bay Area wood smoke levels were simulated without and with wood burning restrictions during the Spare the Air periods. Without burning restrictions on the Spare the Air days, peak wood smoke levels of up to 10-20 $\mu g/m^3$ were simulated over the areas having high wood burning emissions. Calculated wood smoke levels were around 5 $\mu g/m^3$ or more for many of the remaining populated locations within the Bay Area. For the run with burning restrictions, wood burning emissions were eliminated from the simulation only for noon of each Spare the Air day through noon of the following day. Peak benefits of the wood burning restrictions were around 10 $\mu g/m^3$ of reduced wood smoke. The 24-hour wood smoke levels (averaged midnight to midnight) were not reduced to zero because the burning restrictions did not begin until noon of the Spare the Air days. Also, carried over wood smoke from previous days may have impacted the Bay Area during the Spare the Air days. Simulated peak wood smoke levels and maximum benefits of burning restrictions sometimes occurred away from the monitoring locations. Modeling results suggested that reductions of population exposure to wood smoke were considerably greater than indicated by the monitoring data alone. Without the burning restrictions, wood smoke levels for the eight simulated Spare the Air days were averaged to be 11, 7, 5, 3, and 3 $\mu g/m^3$ for the Concord, San Jose, San Francisco, Vallejo, and Livermore monitoring locations, respectively. Assuming 100 percent compliance, the burning restrictions were estimated to reduce these wood smoke levels by about 50-75 percent, depending on location. Because the burning restrictions reduced carry over, enhanced benefits may be achieved for multiple, consecutive Spare the Air calls.

E.3 Conclusions

This report summarizes a wealth of knowledge generated from BAAQMD in-house $PM_{2.5}$ research efforts that builds on the U.S. EPA (EPA) and ARB efforts. Various analyses of measurements were conducted to identify major sources and important weather patterns contributing to $PM_{2.5}$ buildup. Extensive simulations covered the bulk of three winter seasons. The custom computer model adequately reproduced the various phenomena represented in the measurements. The high degree of corroboration between the measurements- and modeling-based results provides a high level of confidence that the findings presented herein are both accurate and representative.

Primary and secondary $PM_{2.5}$ impact the Bay Area differently by location and across a range of typical meteorological conditions. The model suggests that reducing direct $PM_{2.5}$ emissions within the Bay Area is the most effective means of reducing Bay Area primary $PM_{2.5}$ levels. These reductions, however, are most effective near direct $PM_{2.5}$ emission sources. These are the areas in which Bay Area total $PM_{2.5}$ levels are highest. The model also suggests that significant amounts of $PM_{2.5}$, especially secondary $PM_{2.5}$, are transported from the Central Valley. Secondary $PM_{2.5}$ exhibits a fairly regionally uniform influence throughout the Bay Area. Analysis of measurements identified separate transport patterns occurring on different days from either the Sacramento Valley or San Joaquin Valley. During 1999-2007, around 60 percent of Bay Area 24-hour $PM_{2.5}$ exceedance days occurred with transport from Sacramento area, and 20 percent with transport from San Joaquin Valley.

Model results indicated that Bay Area wood smoke levels during 2008-09 episodic conditions would have averaged 3-11 $\mu g/m^3$ without wood burning restrictions, depending on location. Spare the Air burning restrictions were estimated to have reduced wood smoke levels by around 50-75 percent, assuming 100 percent compliance. Spare the Air calls on consecutive days had the added benefit of reducing carried over wood smoke, in addition to reducing fresh burning emissions.

Further research results and refinements to existing findings will be reported as new information becomes available. More measurements, including those from recently commissioned monitoring stations, will be added to the analyzed databases. Longer records of measurements will be especially useful for evaluating the effectiveness of wood burning restrictions. Modeling results will be enhanced by the development of more accurate emissions inventories. Additional winter seasons will be selected for both $PM_{2.5}$ and wood smoke simulations. Newer version models having enhanced physics and chemistry will be implemented for all simulations.

Fine Particulate Matter Data Analysis and Modeling in the Bay Area

1. Introduction

This report provides technical details of data analysis and modeling efforts to better understand fine particulate matter ($PM_{2.5}$) formation in the Bay Area. This is the first significant published report describing Bay Area Air Quality Management District (BAAQMD) scientific investigations into $PM_{2.5}$. The report includes a history of BAAQMD's activities and describes key results from a number of important studies.

1.1 Background Information

$PM_{2.5}$ is a complex mixture of suspended particles and liquid droplets in the atmosphere having aerodynamic diameters of 2.5 μm or less. An individual particle typically begins as a core or nucleus of carbonaceous material, often containing trace metals. These *primary* (directly emitted) particles usually originate from incomplete combustion of fossil fuels or biomass. Layers of organic and inorganic compounds are then deposited onto a particle, causing it to grow in size. These layers are largely comprised of *secondary* material that is not emitted directly. Secondary PM instead forms from chemical reactions of precursor gasses released from combustion, agriculture, household activities, industry, vegetation, and other sources. As a particle grows larger, gravity eventually causes it to be deposited onto a surface. Naturally emitted dust particles mostly have diameters too large to be classified as $PM_{2.5}$.

Numerous studies have demonstrated $PM_{2.5}$ to be deleterious to human health. Major human health outcomes resulting from $PM_{2.5}$ exposure include: aggravation of asthma, bronchitis, and other respiratory problems, leading to increased hospital admissions; cardiovascular symptoms, including chronic hardening of arteries and acute triggering of heart attacks; and decreased life expectancy, potentially on the order of years. Smaller particles have increasingly more severe impacts on human health as compared to larger particles. This occurs in part because smaller particles are able to penetrate more deeply into the human body. For the Bay Area, public health impacts from $PM_{2.5}$ may well exceed the combined impacts of all other currently regulated air pollutants.

Bay Area $PM_{2.5}$ levels are elevated during the winter months. Elevated winter $PM_{2.5}$ levels result from a combination of conducive weather patterns and increased wood burning emissions.

1.2 Regulatory history

Regulation of airborne particles started with total suspended particulates (TSP) in the original 1970 federal Clean Air Act. TSP is effectively a measure of particles with aerodynamic diameters of 100 μm or less. In 1987, TSP was replaced by PM_{10}, or particles with aerodynamic diameters of 10 μm or less. In 1997, the federal $PM_{2.5}$ standard was created in addition to the PM_{10} standard, which was retained. Since then, California has established standards for $PM_{2.5}$ and PM_{10} that are more stringent than required under federal regulations. Both the California and federal standards have tightened as more is learned about the consequences of PM exposure. This trend is expected to continue.

Under federally mandated programs, the BAAQMD began measuring ambient $PM_{2.5}$ levels in 1999. $PM_{2.5}$ is a subset of PM_{10}, measured in the Bay Area since 1985. Prior to that, measurements for coefficient of haze reflected ambient levels of carbonaceous particles.

In 2008, the United States Environmental Protection Agency (USEPA) proposed the first attainment designations for $PM_{2.5}$ under the National Ambient Air Quality Standards (NAAQS) of the Clean Air Act. Attainment status has two components: daily (24-hour) and annual average ambient $PM_{2.5}$ levels. The Bay Area currently attains the annual standard, but does not attain the 24-hour standard. As a result, the District will be required to develop a State Implementation Plan (SIP), tentatively scheduled for 2013. This SIP development process will largely be guided by scientific information summarized in this document and refined as research progresses.

1.3 BAAQMD research efforts

A tremendous effort to advance the scientific understanding of $PM_{2.5}$ has been carried out in recent years at the federal, state, and local levels. Much of the work that will ultimately drive the Bay Area SIP process has been performed in-house by the BAAQMD Research and Modeling Section. This undertaking has been necessary because $PM_{2.5}$ is a complex mixture of individual pollutants that can vary considerably from one region to the next. As such, research performed at the state and federal levels cannot be expected to sufficiently address the relevant intricacies of the Bay Area $PM_{2.5}$ problem.

Research into the Bay Area $PM_{2.5}$ problem began with a review and evaluation of monitoring stations and an analysis of ambient measurements. Simple data analyses were first applied to understand when, where, and to what extent elevated $PM_{2.5}$ levels occurred. Increasingly sophisticated statistical analyses were subsequently applied to understand the sources of $PM_{2.5}$ and how this pollutant is affected by the prevailing weather. These analyses of measurements have been instructive; however, measurement campaigns alone are insufficient to fully characterize the Bay Area $PM_{2.5}$ problem. As such, computer simulations were performed to characterize $PM_{2.5}$ at times and locations for which measurements were not feasible. These modeling efforts were initially based on data resulting from the California Regional Particulate Air Quality Study (CRPAQS), provided by the California Air Resources Board (ARB). BAAQMD staff and contractors have since contributed to improve and expand upon these initial simulations. As a result, a custom computer model was utilized to explain many of the intricacies of the Bay Area $PM_{2.5}$ problem.

District efforts for data analysis and computer modeling of $PM_{2.5}$ are ongoing and will continue through the SIP development process and beyond. These efforts include dedicated field measurement campaigns, advanced statistical analyses of expanding volumes of historical records, development of increasingly accurate and contemporary emissions inventories, and development and implementation of meteorological and photochemical computer models. These studies are expected to continue to expand and refine the scientific understanding of $PM_{2.5}$ in the Bay Area and its surrounding regions. This scientific knowledge is critical for the development of effective regulatory strategies. This document will be the first in a series of technical reports that will be periodically published. These reports are intended to convey information about $PM_{2.5}$ that is necessary for bringing the Bay Area into attainment for this pollutant.

2. Measurements and available data

Measurements of both $PM_{2.5}$ levels and meteorological conditions are necessary for better understanding $PM_{2.5}$. Networks of instruments are continuously operated to provide data for key Bay Area locations. Locations of PM monitors (FRM and BAM) and weather stations are shown in Figure 1. A large number of additional instruments are not included for brevity such as NO_x, ozone, precipitation, etc. The map denotes instruments positioned within the Bay Area, as well as selected proximal sampling locations in the Central Valley to the east. Measurements performed at each of these locations are described in Table 1. The air quality monitoring network plan published by BAAQMD (2009) provides additional details for the PM monitors. Soundings launched twice daily from Oakland, and Wind

Table 1. Surface monitoring locations for PM and meteorology. Check marks indicate type of measurements performed at each location. PM may be monitored using FRM or BAM instrument.

Monitoring Location	*Agency*	*FRM*	*BAM*	*Meteorology*
San Francisco Bay Area				
Bethel Island	BAAQMD			x
Concord	BAAQMD	x		x
Fort Funston	BAAQMD			x
Fremont	BAAQMD	x		
Kregor Peak	BAAQMD			x
Livermore	BAAQMD	x	x	
Mt Tamalpais	BAAQMD			x
NUMMI	BAAQMD			x
Oakland	BAAQMD		x	
Pleasanton STP	BAAQMD			x
Pt. San Pablo	BAAQMD			x
Redwood City	BAAQMD	x	x	
Rio Vista	BAAQMD			x
San Carlos	BAAQMD			x
San Francisco	BAAQMD	x	x	
San Jose	BAAQMD	x	x	
San Martin APT	BAAQMD			x
Santa Rosa	BAAQMD	x		x
Suisun STP	BAAQMD			x
Vallejo	BAAQMD	x	x	
Outside the San Francisco Bay Area				
Davis	ARB			x
Modesto	ARB	x	x	x
Roseville	ARB			x
Sacramento	SMAQMD/ARB	x	x	
Stockton	ARB	x	x	x
Woodland	YSAQMD	x	x	

Profiler and RASS systems, operated continuously at Livermore and Burkeville, provide aloft weather data.

Data obtained from these monitoring stations undergo rigorous evaluation for quality assurance and quality control, and are regularly archived by staff of the BAAQMD before they are used for scientific studies.

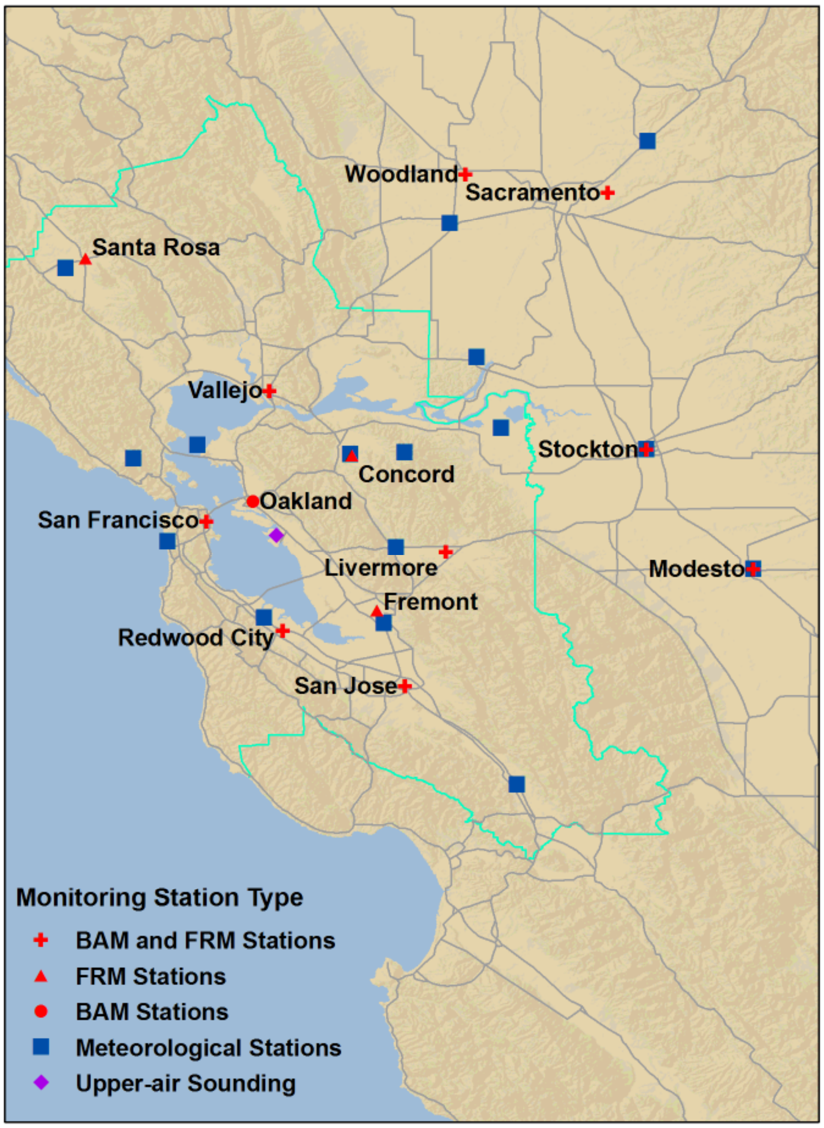


Figure 1. Map of Bay Area domain showing locations of key PM monitors, weather stations, and sounding launch point. A large number of sampling locations have been excluded for brevity. Named locations refer to PM monitors.

3. Emissions inventory preparation

An emissions inventory was prepared to establish source-receptor relationships, identify major sources contributing to primary PM and releasing precursors of secondary PM (TOG, NO_x, SO_2, NH_3), and provide inputs for modeling. The inventory prepared for this study covers an area extending from Redding in the north to Bakersfield in the south and from the Pacific Ocean in the west to the Sierra Nevada in the east. This domain is essentially the same as the California Regional Particulate Air Quality Study (CRPAQS) domain (Figure 2).

Initially, the 2000 CRPAQS inventory was utilized for modeling. Subsequently, the Bay Area portion of the CRPAQS inventory was replaced with local information, as these local data were assumed to be more accurate and up to date. In addition, new inventories were developed for Bay Area emissions of ammonia and wood smoke, as it was determined that the CRPAQS emissions were not representative of local sources.

Both District and ARB emissions data were manipulated and reformatted by Sonoma Technology, Inc. for use in the EPA's Sparse Matrix Operator Kernel Emissions (SMOKE) model. District staff then prepared the CMAQ inputs for both winter 2000-01 and 2006-07 PM simulations. Several different versions of these inventories were prepared for PM sensitivity simulations, transport analyses, future year modeling, and wood smoke analyses.

Below are summarized some notable features and special handling requirements of the BAAQMD and ARB emissions data, respectively. BAAQMD emissions associated with some non-road diesel sources were halved to reflect staff's belief that these emissions were overestimated by ARB's OFFROAD model. Also, Bay Area wood burning emissions were estimated using information from several winter season surveys conducted by the District. For areas outside the Bay Area, ARB provided emissions data that were pre-gridded according to the California statewide 4-km grid (Figure 2). SMOKE processing retained the pre-existing spatial distribution for these emissions. Temporal distribution information embedded in the ARB data were also retained.

Modeling was performed for both the 2000-01 and 2006-07 winter seasons. Therefore, the 2000 ARB data had to be projected forward to 2006, while the 2005 District data were backcasted to 2000. Projection factors for criteria pollutants were developed using information in ARB's Emissions Almanac. Bay Area ammonia emissions were projected using activity indicators from ARB's EMFAC model (for on-road) and EPA's Economic Growth and Analysis System (EGAS 5.0) for the remaining source categories. Ammonia emissions outside the Bay Area as well as biogenic emissions were not projected because of insufficient data.

Table 2 summarizes the emissions input to SMOKE as obtained through the processes described above. Figure 3 shows the resulting spatial distribution of the model-ready wood burning emissions for the Bay Area. Figure 4 shows the spatial distribution of the model-ready ammonia emissions for the entire modeling domain. For further reference, Appendix A provides detailed summaries as well as SMOKE-related information.

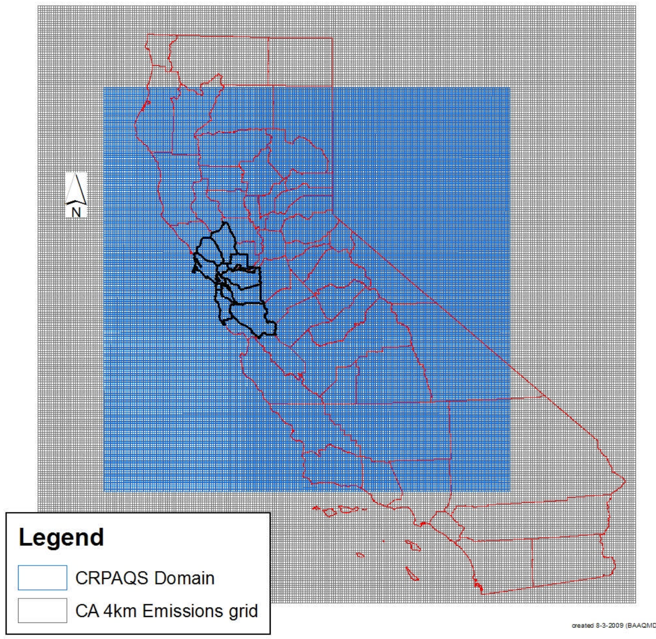


Figure 2. Emissions modeling domains. Gray shows ARB 4-km statewide domain. Blue is the CRPAQS domain for which emissions were prepared for District PM modeling.

Table 2. Summary of emissions input to SMOKE (tons/day). Biogenic emissions are excluded.

	2000		2006	
	BAAQMD[a]	Remainder of Domain[b]	BAAQMD[a]	Remainder of Domain[b]
TOG	751	3877	620	3670
NO_x	609	1785	508	1595
SO_2	89	130	66	129
$PM_{2.5}$	88	653	87	640
NH_3	72	299	82	299

[a] Annual average daily
[b] December weekday

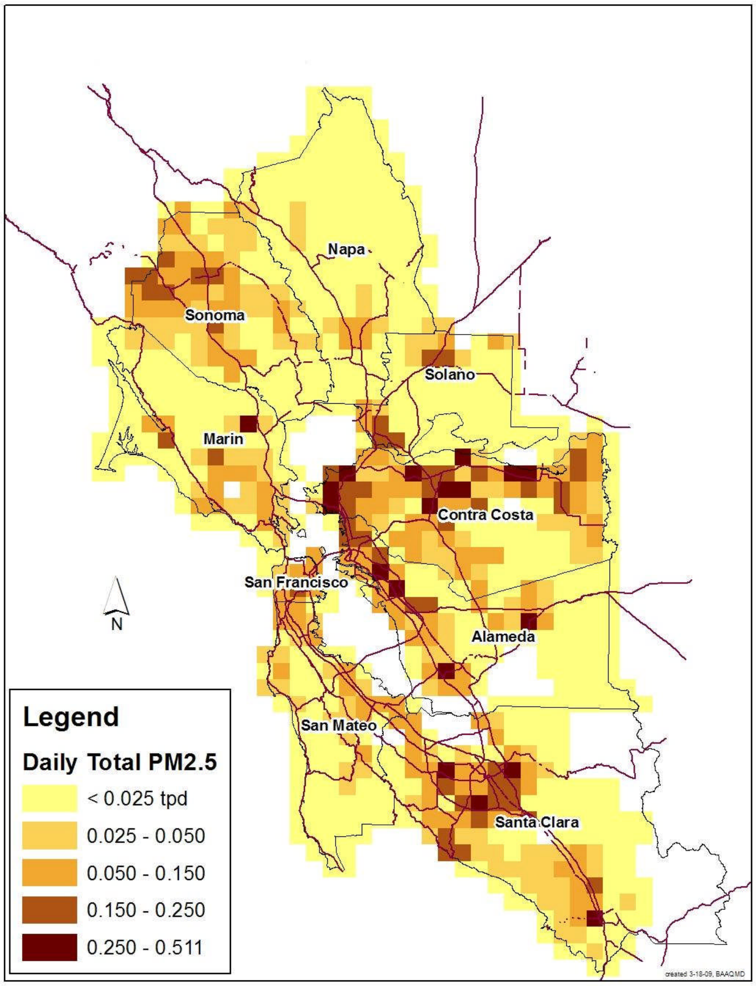


Figure 3. Emissions inventory for winter wood burning within Bay Area.

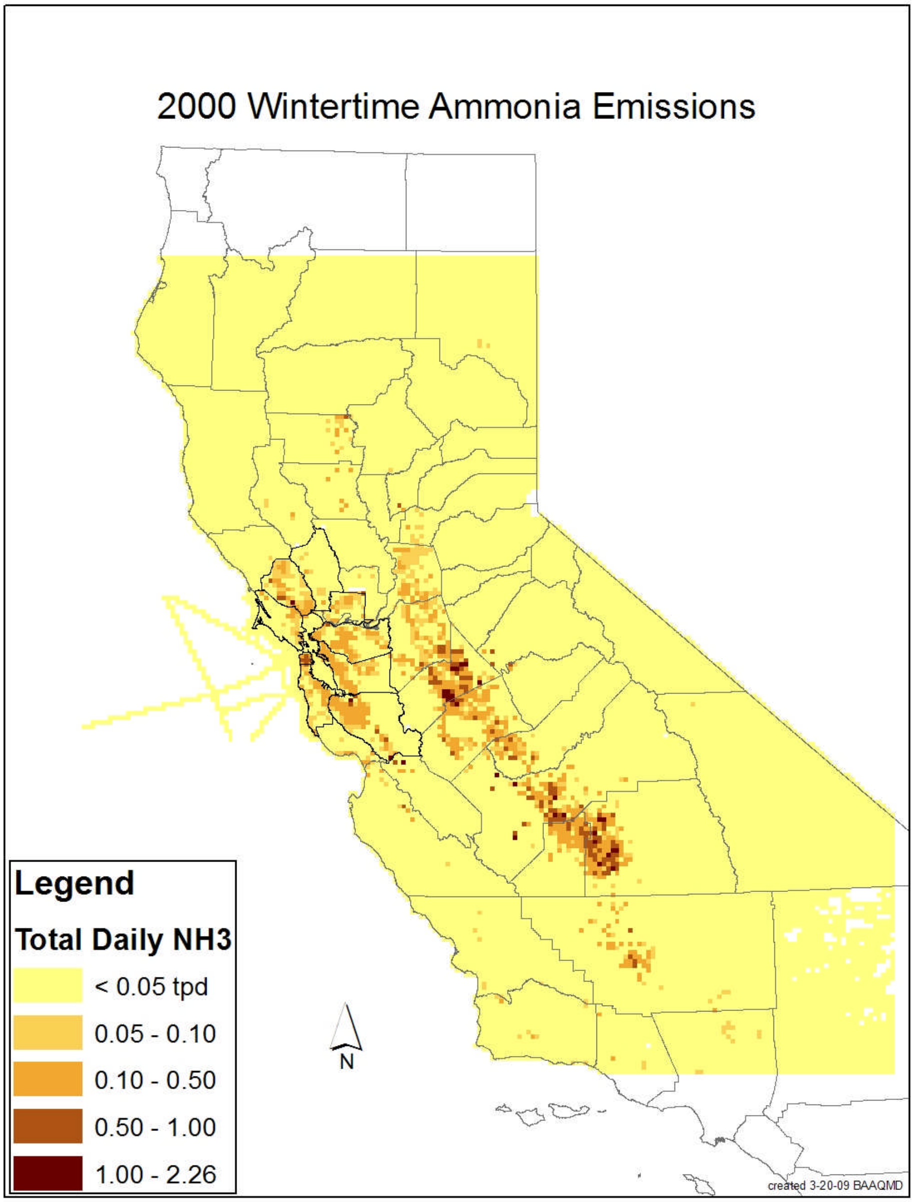


Figure 4. Emissions inventory for ammonia within modeling domain.

4. Data analysis

A variety of data analyses have been performed to better understand Bay Area $PM_{2.5}$ formation. They can be summarized in three main categories: characteristics of measured $PM_{2.5}$, Chemical Mass Balance (CMB) analysis, and statistical methods including cluster analysis to infer how $PM_{2.5}$ is affected by weather patterns. Details of these analyses and findings are reported in various District papers or reports. Key findings are briefly summarized in this report.

4.1 Analysis of PM measurements

4.1.1 Seasonal patterns

Analyses were performed to characterize when, where, and to what extent elevated $PM_{2.5}$ levels occurred. Figure 5 shows the percentage of 24-hour NAAQS exceedance days for $PM_{2.5}$ by calendar month. An exceedance day is defined as any day for which $PM_{2.5}$ levels at one or more sites exceeds 35 $\mu g/m^3$. Most exceedances occur during the winter months from November through February. The bulk of the exceedances, however, occur during the core winter PM season of December and January.

Several reasons explain the pronounced seasonality for $PM_{2.5}$. First, the winter months favor the development of stable air masses over the Bay Area. Such conditions exhibit a layer of relatively warm air aloft and cool air at surface, creating negative buoyancy. Thus, vertical mixing of pollutants are limited and pollutants are trapped near the surface. Second, the cooler winter temperatures favor partitioning of ammonium nitrate, a major $PM_{2.5}$ component, into the solid particulate phase. Higher temperatures for other seasons favor the evaporation of particulate ammonium nitrate into its gaseous (non-particle) constituents ammonia and nitric acid. Third, household wood burning during the winter season is a significant source of $PM_{2.5}$.

$PM_{2.5}$ concentrations exceed the federal 24-hour standard from 5 to 40 times a year, depending on meteorological conditions. Typical elevated exceedances range from 36 to 55 ug/m3.

4.1.2 Annual trends

Attainment status for PM is based on the calendar year; however, it is instructive to examine the number of 24-hour $PM_{2.5}$ exceedances for each winter season. Figure 6 shows the number of 24-hour exceedance days by winter season (November 15 through February 10), and also the number of rainy days for each corresponding season. There is a general alternating trend with every other winter having relatively high then moderate numbers of exceedances. An opposite trend occurs for the number of rainy days per winter season.

Winters with relatively high numbers of rainy days have fewer PM exceedances. This trend occurs because rainy conditions are associated with strong, (vertically) deep, turbulent air flow patterns that allow ventilation of emitted PM and its precursors away from the ground level. Thus, the relative severity of a given winter PM season is largely governed by global circulation patterns determining the proportion of stormy days during a given winter. The 2000-01 winter had a particularly high proportion of stagnant days. This period exhibited extreme $PM_{2.5}$ levels and had the most exceedances of any winter on record $PM_{2.5}$ was measured.

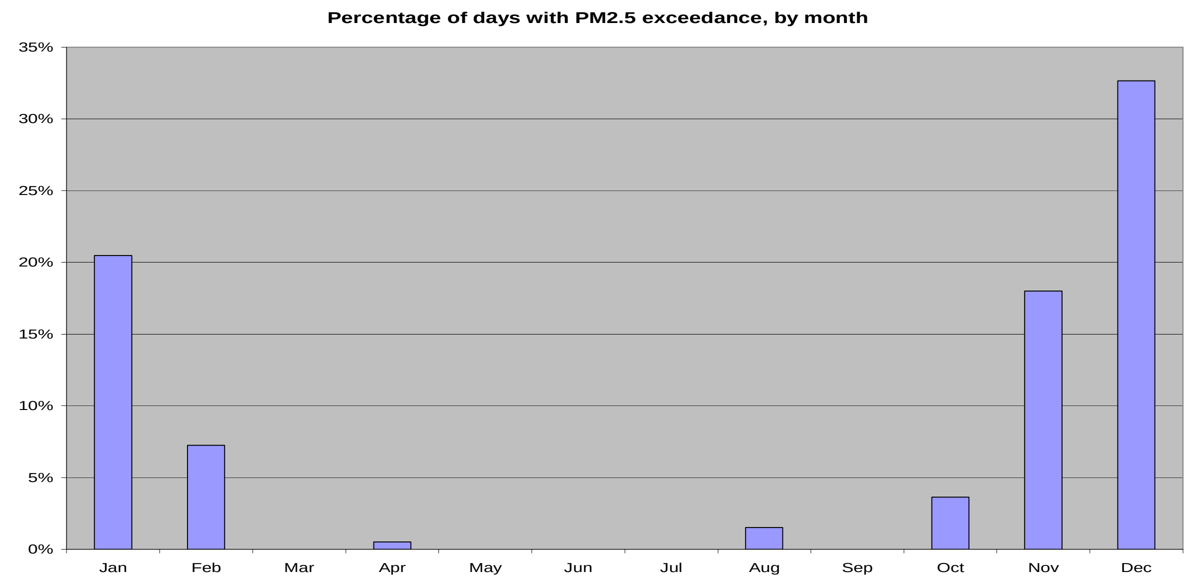


Figure 5. Percentage of 24-hour $PM_{2.5}$ NAAQS exceedances by calendar month.

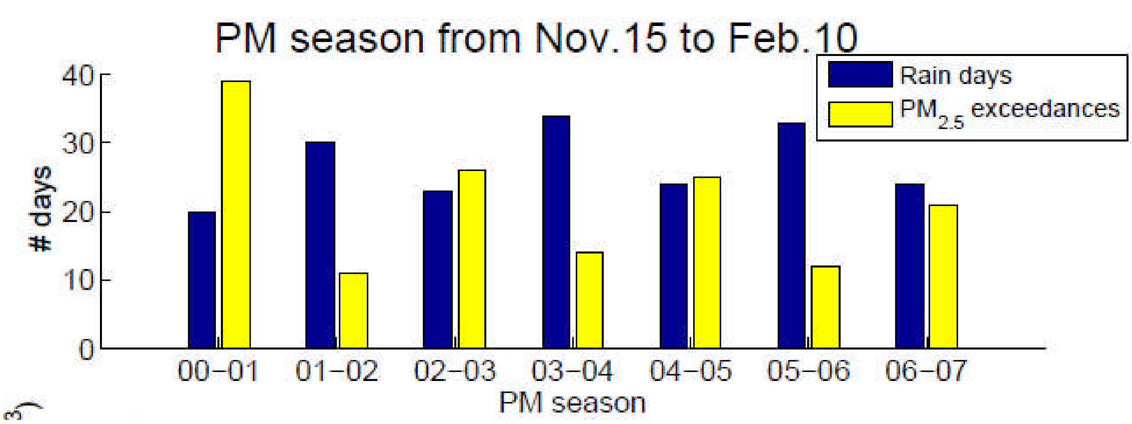


Figure 6. Bar plots showing number of 24-hour $PM_{2.5}$ exceedance days and number of rainy days for each winter season from November 15 through February 10. $PM_{2.5}$ exceedance days occurred when at least one Bay Area monitor recorded 24-hour $PM_{2.5}$ level of 35 $\mu g/m^3$ or greater. Rainy days occurred when at least 0.1 in. of rain was reported in the Bay Area.

Trend analyses have been performed for both $PM_{2.5}$ and PM_{10} levels using historical measurements. Time series for the annual average levels are shown in Figure 7. $PM_{2.5}$ measurements are only available since 1999. The data appears to indicate a decreasing trend for $PM_{2.5}$ and PM_{10} levels. Since the late 1980s, PM_{10} levels have decreased nearly 50 percent. Decrease in $PM_{2.5}$ concentrations is not certain because there are fewer data points to confirm this conclusion. Significant year-to-year variability in weather patterns (as evidenced in Figure 6) may confound the interpretation of pollutant long-term trends over periods of less than about 10 years.

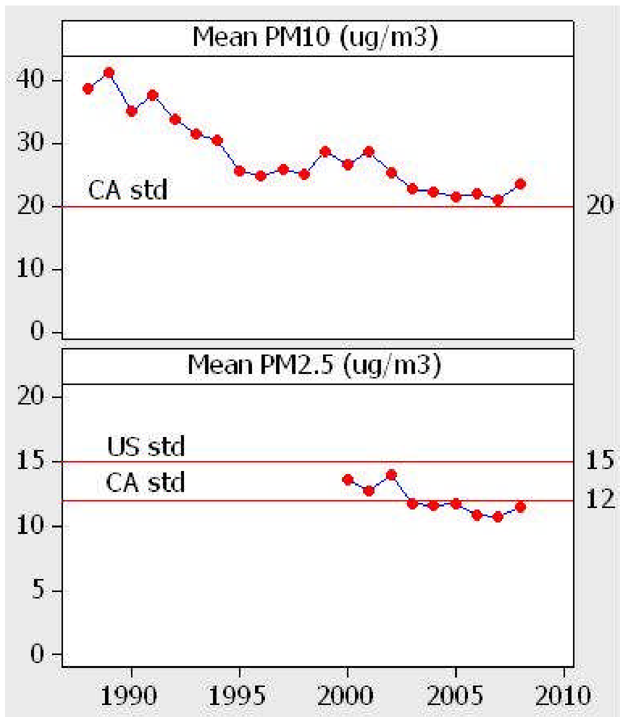


Figure 7. Trends for annual average PM_{10} and $PM_{2.5}$ levels, with annual standards shown for reference. $PM_{2.5}$ data were not available before 1999. There is no annual component of the federal PM_{10} standard.

4.1.3 Spatial patterns

$PM_{2.5}$ is a regional pollutant. Its concentrations within the Bay Area are relatively uniform as compared to locations outside of the District. $PM_{2.5}$ measurements for all Bay Area monitoring locations are strongly correlated. This correlation implies that $PM_{2.5}$ levels generally rise and fall with similar timing for all locations throughout the District. $PM_{2.5}$ episodes develop under conducive meteorological conditions, when levels throughout the District increase and may eventually level off well above the background concentration. Typically, $PM_{2.5}$ levels must build for 2-4 days before a 24-hour exceedance occurs. Episodes commonly last a few days, but they may persist 1-2 weeks or longer.

Despite its regional nature, there is significant spatial variability for $PM_{2.5}$ levels within the Bay Area. It is important to understand how the spatial distribution of PM impacts attainment for both the daily and annual components of the $PM_{2.5}$ standards. These levels are calculated using a 3-year period to be consistent with how attainment status is defined. The 3-year period was selected as 2006-08.

Annual average $PM_{2.5}$ levels for 9 Bay Area locations are shown in Figure 8. Point Reyes, largely reflecting the background, has annual $PM_{2.5}$ levels around half that of other sites. San Jose and Vallejo have somewhat higher annual average levels than the other sites. These two sites appear to be the most important in terms of attainment of annual standards. The remaining sites have roughly uniform annual $PM_{2.5}$ levels around 9-10 $\mu g/m^3$.

Design values are estimated as a 3-yr average of the quarterly 98^{th} percentiles for measured 24-hour $PM_{2.5}$ levels. They are shown in Figure 9 for the period 2006-08. There is considerably more site-to-site variability than for the annual averages (Figure 8) because the design values are based on peak $PM_{2.5}$ levels. Four stations are at or near the exceedance threshold: Livermore, Concord, San Jose, and Vallejo. The design value for the remote Point Reyes location is around half that of the other sites. Design values for the remaining sites are around 25-30 $\mu g/m^3$.

The composition of $PM_{2.5}$ also varies throughout the Bay Area. Chemical speciation of $PM_{2.5}$ samples was performed at six locations during the 2000-01 winter as part of CRPAQS. Results are shown in Figure 10. Levels for sulfate, nitrate, and ammonium are relatively uniform throughout the Bay Area. They reflect the secondary particulate compounds ammonium nitrate and ammonium sulfate. These secondary $PM_{2.5}$ components may require a few days of air mass aging to reach appreciable levels. During this aging process, the secondary PM and its precursors can be transported and dispersed uniformly throughout the Bay Area. Elemental carbon (EC), and to a lesser extent organic carbon (OC), reflect primary $PM_{2.5}$. These compounds are more concentrated near their sources around the Bay such as San Francisco and San Jose. In terms of percentages, more urban locations around the bay have relatively higher proportions of primary $PM_{2.5}$, whereas more rural locations further inland have relatively higher proportions of secondary $PM_{2.5}$. Sodium and chloride levels reflect the presence of sodium chloride from suspended sea salt. This natural $PM_{2.5}$ component represents a small fraction of the overall particulate mass. As expected, sodium chloride levels are much higher at San Francisco and Point Reyes than at the other non-coastal sites.

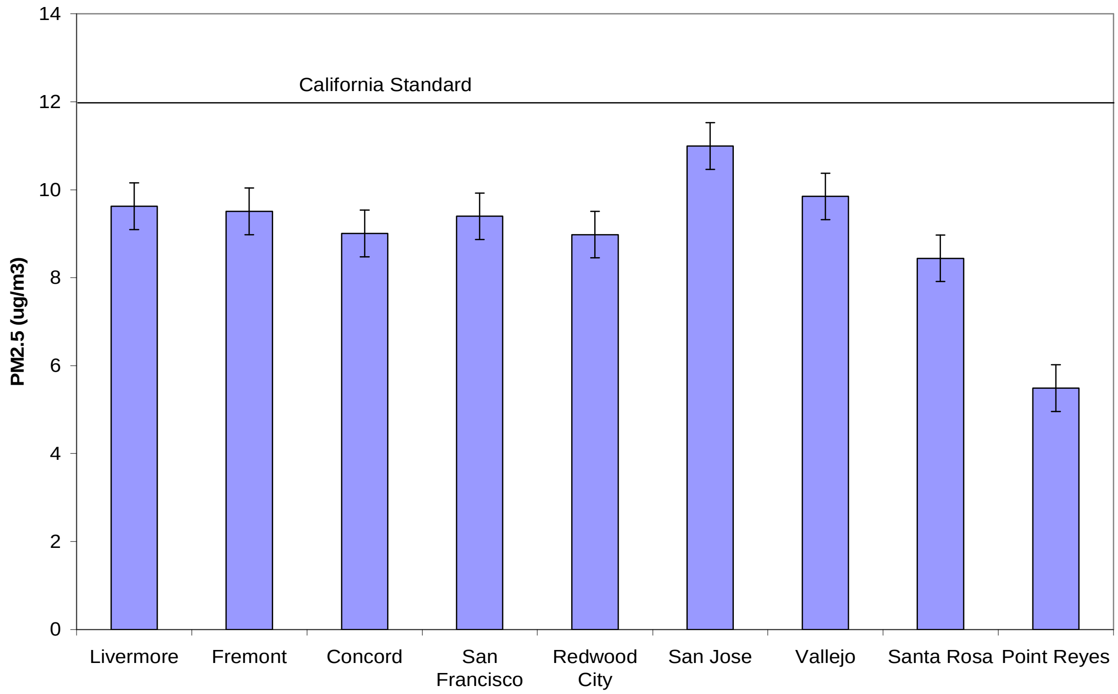


Figure 8. Annual average $PM_{2.5}$ levels by site for 3-yr period 2006-08. Error bars represent 95% confidence intervals.

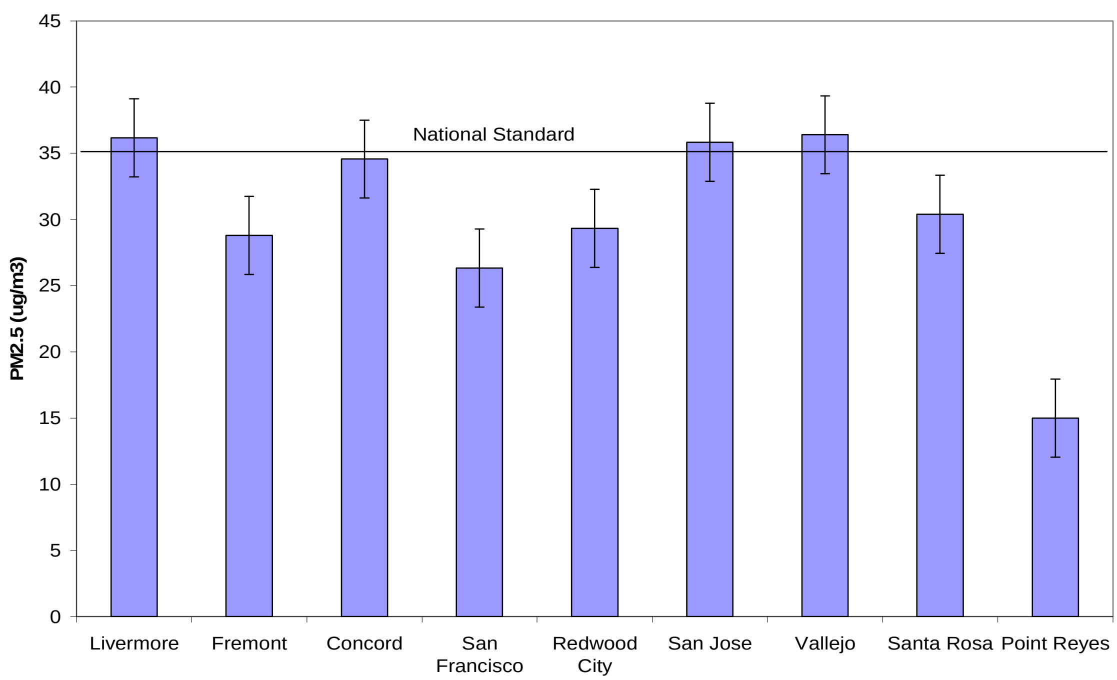


Figure 9. Average 98^{th} percentile 24-hour $PM_{2.5}$ levels (design values) by site for 3-yr period 2006-08. Error bars represent 95% confidence intervals.

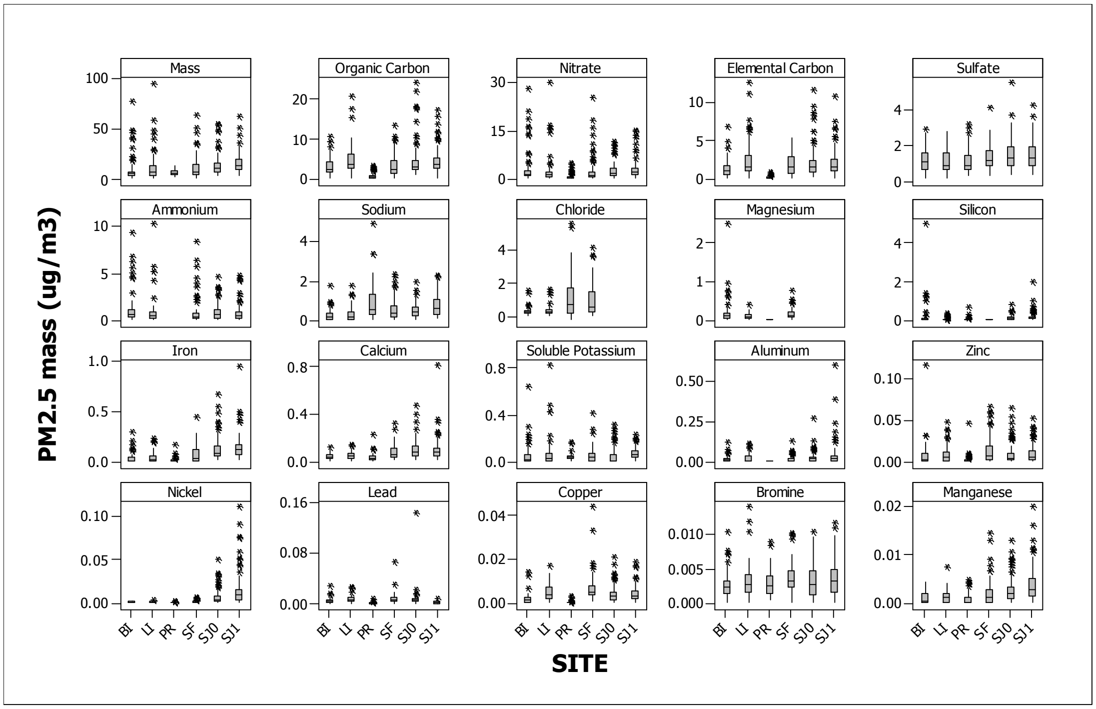


Figure 10. Levels for $PM_{2.5}$ major components at 6 Bay Area monitoring locations.

4.2 Chemical Mass Balance (CMB) analysis

Chemical Mass Balance (CMB) is a statistical receptor model used for source apportionment. It requires speciated PM measurements and also experimentally determined source profiles for the source categories of interest. CMB then determines the contribution (strength) of each source category that best accounts for the observed PM composition on a given day. Detailed results of CMB analysis have been presented in a separate report by Fairley et al. (2008).

CMB was applied to speciated $PM_{2.5}$ measurements from five locations obtained as part of CRPAQS. These sampling locations accounted for the spatial variability in $PM_{2.5}$ composition throughout the Bay Area. The San Francisco and San Jose locations represented urban conditions. Livermore was suburban. Bethel Island was a rural location between the Bay Area and heavily polluted Central Valley. Point Reyes was a remote coastal location, presumably sampling near-background pollution levels. Speciated $PM_{2.5}$ measurements were obtained for these locations every third day from late 1999 through early 2001.

Two separate CMB analyses were applied to determine source contributions to annual average and peak $PM_{2.5}$ levels. Annual average contributions were estimated by averaging CMB results from year-round records. Peak contributions were estimated by averaging CMB results for the ten winter days having the highest 24-hour $PM_{2.5}$ levels for each monitoring location.

For each analysis, the same six known source categories were used: ammonium nitrate; ammonium sulfate; marine (sea salt) aerosol; geological and road dust; fossil fuels combustion; and biomass combustion. The fossil category included combustion of fuels from on-road and off-road vehicles, construction equipment, aircraft, heavy industry, and power generation. The biomass category included combustion products of wood burning, commercial cooking, fires, tobacco smoke, and waste incineration. Isotopic carbon (C^{14}) analysis was used to adjust the raw CMB results to distinguish between combustion of fossil and non-fossil (biomass) materials.

4.2.1 Source contributions to peak $PM_{2.5}$ levels

The ten samples with the highest 24-hour $PM_{2.5}$ levels were all obtained during winter. Most of these measurements occurred on days exceeding the 24-hour $PM_{2.5}$ standard of 35 $\mu g/m^3$. Figure 11 shows the percentage contribution of each source category for each location. These results do not reflect differences in total $PM_{2.5}$ levels between the stations.

The urban and suburban locations (San Francisco, San Jose, and Livermore) exhibited comparable source contributions. Primary combustion sources (fossil and biomass) and secondary ammonium nitrate accounted for the bulk of $PM_{2.5}$. San Jose had a somewhat lower contribution of ammonium nitrate than the other heavily populated locations. It was more distant from the concentrated ammonia sources in rural North Bay and Central Valley locations. San Francisco had a somewhat lower contribution of biomass burning than the other urbanized locations. Household wood burning was less common in this densely populated city that has many apartments lacking fireplaces. Fossil fuel combustion contributions were very comparable for these three locations impacted by vehicular and construction emissions related to commerce.

For the rural Bethel Island location, over half of the $PM_{2.5}$ was ammonium nitrate. This location is closest to the Central Valley where intense ammonia emissions and meteorologically conducive conditions enhanced ammonium nitrate formation. Due to the lack of substantial commercial activity, fossil fuel combustion contribution was about half that of the more populated locations. Biomass burning contribution was comparable to the more populated locations. Likely, wood burning occurred in a higher proportion of households, but population density was considerably lower for this rural location.

Point Reyes was quite different from the other locations. The strongest contributing source was naturally occurring marine aerosols at over 30 percent. Ammonium sulfate contribution was also significant at nearly 20 percent. This was the only location with an elevated proportion of ammonium sulfate. The site was proximal to offshore shipping lanes and lacked other local sources. Secondary ammonium nitrate contribution was lowest for this location most distant from concentrated ammonia sources. Fossil fuel combustion contribution was also low for this remote location with negligible commercial activity.

Overall, primary combustion particles and secondary ammonium nitrate were the main drivers for Bay Area $PM_{2.5}$ episodes impacting populated areas. Wood burning may have been the single largest $PM_{2.5}$ source contribution for the Bay Area during episodes. Geological dust, tire and break wear, and marine sources contributed near-negligible amounts to $PM_{2.5}$ exceedances.

4.2.2 Source contributions to annual average $PM_{2.5}$ levels

Many $PM_{2.5}$ measurements made were during non-winter months when $PM_{2.5}$ levels are generally low. Annual averages were computed from quarterly averages to avoid over-weighting seasons for which more measurements were performed. Figure 12 shows the percentage contribution of each source category for each location. These results do not reflect differences in total $PM_{2.5}$ levels between the stations.

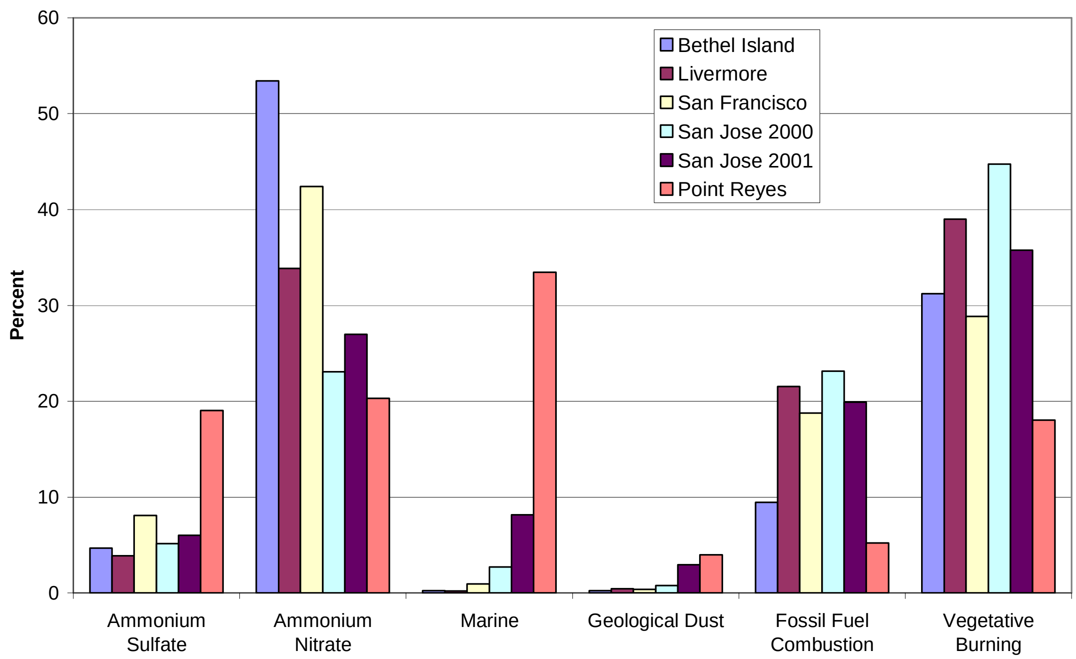
The urban and suburban locations exhibited comparable source contributions. Primary combustion sources dominated. These locations were impacted by vehicular and construction emissions related to commerce and also household activities. As with peak $PM_{2.5}$, biomass contributions were somewhat lower for San Francisco as compared to the other heavily populated locations. The contributions of ammonium nitrate, ammonium sulfate, and marine particulates were similar and are about half that of the combustion sources.

The rural Bethel Island location had higher secondary and lower primary contributions as compared with the more populated locations. This location was relatively distant from the intense primary PM sources around the bay. It was most strongly impacted by regional secondary $PM_{2.5}$. The marine contribution was relatively weak for this inland location.

The remote coastal location at Point Reyes was affected most strongly by marine particulate. Marine percentage contributions were 2-3 times greater than for the other locations. Ammonium sulfate percentage contribution was around twice that of the other locations because of proximity to offshore shipping lanes. In terms of mass contributions, however, marine and ammonium sulfate contributions were not very different from the other locations. This is because anthropogenic emissions had little impact at Point Reyes, and thus total $PM_{2.5}$ levels here were low.

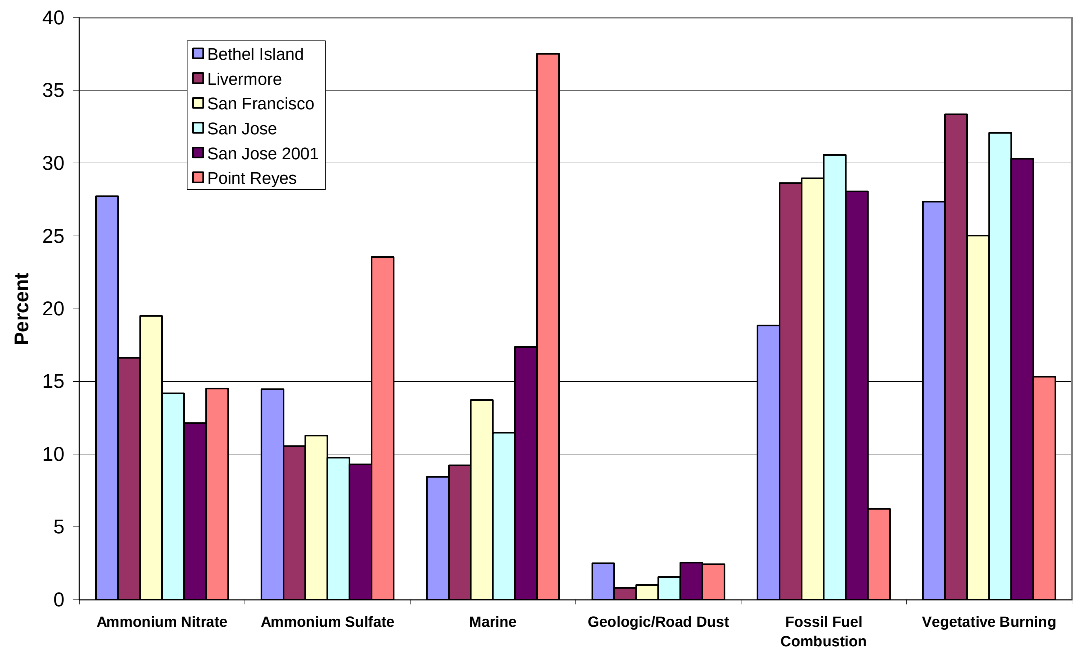
Overall, primary combustion particles accounted for the bulk of annual average $PM_{2.5}$ levels. Ammonium nitrate contributed somewhat more than ammonium sulfate and marine influences, which were comparable. Geological dust and tire and break wear contributed negligible amounts.

Figure 13 shows the quarterly CMB results for Bethel Island. It demonstrates the pronounced impacts of ammonium nitrate and biomass burning during the winter season. Ammonium nitrate formation was favored by low winter temperatures. This season also exhibited increased wood burning emissions. Similar results were obtained for other locations; however, the more urbanized locations may not have been as strongly affected by winter wood burning.



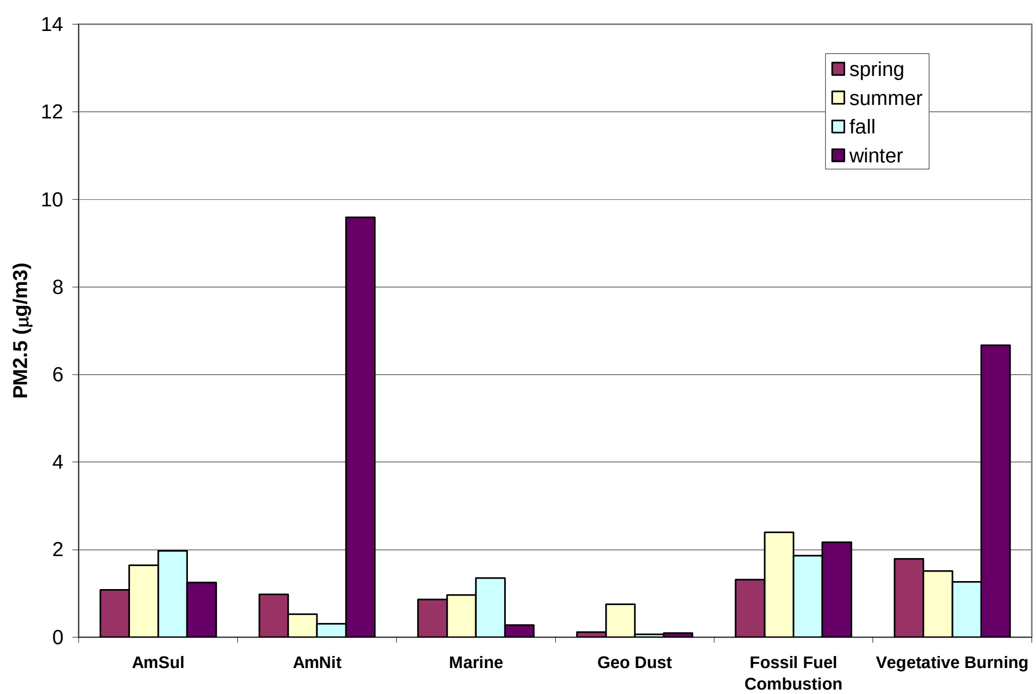
Note: Estimated annual percentage contributions from various source categories to the 10 highest PM2.5 days, based on CMB analysis adjusted for Carbon-14. The values shown are the masses from individual source categories as a percentage of the total estimated mass.

Figure 11. CMB results for CRPAQS period. Results for exceedance days only.



Note: Estimated annual percentage contributions to Bay Area ambient PM2.5 for 2000 and San Jose 2001. Values are percentages of total quarterly averaged PM2.5 from individual CMB results with fossil fuel combustion and vegetative burning adjusted for Carbon-14 results.

Figure 12. CMB results for CRPAQS period. Annual results.



Note: Bethel Island PM2.5 source contributions by season. Values represent averages for the 4 pm seasons.

Figure 13. CMB results for CRPAQS period. Seasonal results for Bethel Island location used to compute the annual averages shown in Figure 12.

4.3 Relationship between weather patterns and PM

Air monitoring showed that, along with elevated $PM_{2.5}$ levels during the winter season, there was a considerable day-to-day variability for PM levels. A number of analyses were performed to identify weather patterns associated with high PM episodes.

4.3.1 Comparing and contrasting direct measurements

Meteorological characteristics associated with PM episodes were identified by comparing weather station observations between episodic and non-episodic winter days. It was possible that different types of PM episodes could occur under different weather patterns. Pooling meteorological observations according to whether or not an exceedance occurred could not possibly resolve such intricacies.

Common meteorological characteristics associated with elevated Bay Area PM levels were light winds from the east throughout much of the Bay Area and no rain. Specifically, 24-hour average winds at San Carlos in the South Bay, Pleasanton in the Livermore Valley, and Bethel Island in the East Bay had speeds less then 0.5 mph and an easterly (from the east) directional component. Also, no appreciable precipitation was measured at San Jose. Such days generally exhibited cool temperatures; however, temperature itself was not a strong indicator of elevated PM levels.

Exceedances of the 24-hour $PM_{2.5}$ standard in the Bay Area typically occur as PM levels build over time upon three or more consecutive days having the above conditions. Thus, the exceedances appear to exhibit considerable carryover of PM from previous days. This effect is demonstrated in Figure 14 which shows the mean Bay Area $PM_{2.5}$ level as a function of the number of consecutive days having the above described characteristics. The increase in $PM_{2.5}$ levels over time is mathematically consistent with exponential decay. Physically, this model corresponds to new PM being added on to existing, carried over PM on each additional day, with atmospheric loss of PM proportional to PM level.

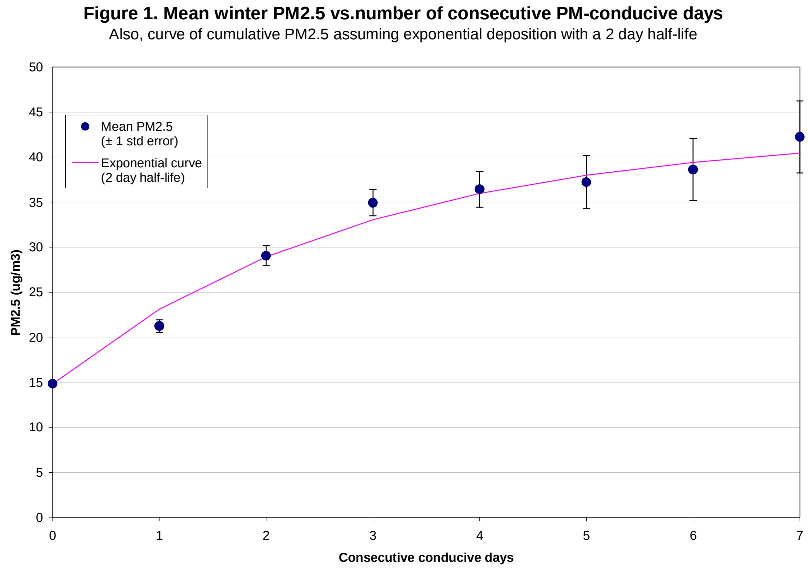


Figure 14. Mean observed Bay Area $PM_{2.5}$ level in response to number of consecutive days with favorable conditions. Curve is fit for exponential decay with 2-day time constant.

4.3.2 Cluster analysis for Bay Area weather patterns

Cluster analysis is a data mining technique that can identify recurring patterns among historical observations. A rigorous approach to characterizing episodic meteorological conditions can be achieved through cluster analysis of weather station measurements. Disregarding PM levels, cluster analysis was applied solely to meteorological measurements for each winter day of an extended study period. "Clusters," or homogeneous groups, of days are identified that share similar meteorological characteristics. The average meteorological conditions associated with each cluster constitute a distinct weather pattern. Then, average pollutant levels are tabulated for each cluster (weather pattern) to determine its propensity to result in elevated PM levels. This framework allows identification of different weather patterns that may result in PM exceedances.

A cluster analysis of Bay Area conditions was performed at the University of California, Davis. Detailed results are provided in a report by Palazoglu (2009). This study analyzed each winter day (November through March) of the years 1996-2007, for a total of 1754 days. This large sample size ensured robust identification of weather patterns influencing PM in the Bay Area. Also, the decade-long study period allowed characterization of year-to-year variability in global weather patterns affecting the Bay Area. Meteorological observations input to the cluster analysis were obtained from 12 weather stations positioned at key locations throughout the Bay Area (stations in Figure 1 within the District boundaries).

The cluster analysis revealed five dominant winter weather patterns prevailing over the Bay Area. Three of the clusters are conducive to elevated Bay Area PM levels. All three exhibit winds entering the Bay Area from the east. Two of the three clusters exhibit near-calm conditions in the Central Valley, where PM levels are considerably higher than in the Bay Area. These two clusters account for around 80 percent and 15 percent of all Bay Area 24-hour $PM_{2.5}$ exceedances, respectively. The cluster accounting for 80 percent of the Bay Area exceedances exhibits persistent easterly winds into the Bay Area throughout the day. The cluster accounting for 15 percent of the Bay Area exceedances exhibits easterly winds into the Bay Area during the overnight and morning hours. Winds may reverse to enter the Bay Area from the west during the afternoon. The third cluster with easterly flow into the Bay Area has high winds in the Central Valley and correspondingly increased dispersion rates. PM levels are higher than average; however, Bay Area exceedances are uncommon. The remaining two clusters exhibit marine winds entering the Bay Area from the west. Both of these clusters represent stormy conditions, and PM levels are low.

The pair of episodic clusters exhibits considerable buildup of secondary PM, particularly ammonium nitrate. For these two episodic weather patterns, PM levels in the Central Valley can be about 2-3 times higher than in the Bay Area. This is largely because of meteorological conditions, especially for the most episode-prone cluster. Conditions are more conducive to the transformation of NO_x to nitric acid (needed for the formation of ammonium nitrate) in the Central Valley than for coastal locations. These conditions include low wind speeds combined with high amounts of sunlight during the day and high humidity at night. These settings enhance daytime and nighttime conversion of NO_x to nitric acid. Nitric acid then rapidly reacts with ammonia emissions, mostly from dairy activities, which are especially concentrated in the northern San Joaquin Valley, to form ammonium nitrate.

The clusters, based solely on surface meteorological conditions, correspond well with aloft weather systems influencing much of the West Coast and/or southwestern United States. A developing or approaching upper-level high pressure center over Central California causes a transition from a high wind pattern into a low wind pattern for the region, resulting in increasing PM levels. Typically, PM builds to the exceedance level in 2-4 days upon a transition into an episodic weather pattern. Thereafter, PM levels remain approximately constant while the high pressure system persists over Central California. A transition from an episodic weather pattern into one of the non-episodic patterns marks the onset of high surface winds that terminate the episodic conditions. Episodes often terminate abruptly when a migrating storm (cyclone) passes over the Bay Area. Strong, deep, turbulent winds associated with the storm, but not the precipitation itself, is the key factor resulting in a sudden decrease of elevated PM levels. Transitions from an episodic weather pattern into a non-episodic pattern lacking rain are often associated with PM levels that decrease gradually over a few days.

A single cluster accounted for over 80 percent of all Bay Area exceedances; however, only around one in three days belonging to this cluster resulted in an exceedance. Therefore, this weather pattern constitutes a necessary but insufficient condition for an exceedance to occur. Days belonging to this lone cluster were further explored to distinguish between exceedances and non-exceedances. Exceedance days could be defined in terms of a number of simultaneous meteorological characteristics: a ridge of high pressure aloft moving over SFBA and providing a weak surface pressure gradient over Central California; persistent easterly flows through SFBA extending vertically from the surface to around the 925-hPa pressure level; orographically channeled winds resulting from strongly stable conditions; enhanced nocturnal cooling under clear-sky conditions providing for enhanced overnight drainage flows off the Central California slopes; and at least two consecutive days of these listed conditions.

Year-to-year differences in global weather patterns strongly influence the number of 24-hour $PM_{2.5}$ exceedances. Winters with more rainy days tended to have fewer exceedances. This is because winters frequently affected by stormy conditions tended to have fewer days with the light easterly winds and other above listed conditions that are associated with PM episodes.

4.3.3 Cluster analysis for inter-regional transport patterns

The cluster analysis of Bay Area weather patterns described above suggests that transport from the Central Valley occurs during many Bay Area exceedances. That study, however, was unable to resolve the upwind source regions from which PM and its precursors may have originated. It was suspected that sources in the Sacramento Valley and/or San Joaquin Valley may contribute to Bay Area exceedances, depending upon prevailing atmospheric conditions.

A second set of cluster analysis was conducted at the University of California, Davis to investigate these potential transport patterns. This study applied the clustering technique described above to an expanded spatial domain. In addition to Bay Area weather stations, measurements were also taken from stations in the Delta region (all stations shown in Figure 1). In this manner, the clustering reflects Bay Area conditions as well as upwind conditions where the Sacramento and San Joaquin Valleys directly connect to the Bay Area. High quality weather station observations were not available in the Delta region for the entire 1996-2007 period used in the previous Bay Area clustering. Also, the weather stations in the Delta region exhibited considerable gaps in their records which resulted in days being excluded from the cluster analysis. In total, 1001 days from the years 1999-2007 had sufficient observations to be included in this transport cluster analysis. Though smaller than the above Bay Area clustering, this sample size was still sufficiently large enough for robust identification of inter-regional transport patterns.

The transport cluster analysis reveals six dominant winter weather patterns prevailing over the Bay Area. Together, two of these clusters largely correspond with the single pattern from the Bay Area clustering that accounted for over 80 percent of all Bay Area exceedances. Both of these episodic transport patterns exhibit air flows entering the Bay Area from the east. This pair of patterns is distinguished by upwind conditions in the Delta and beyond. Average surface air flows for this pair of clusters are shown in Figure 15. One cluster has winds entering the Bay Area from the Sacramento Valley and accounts for around 60 percent of the Bay Area exceedances. The highest Bay Area $PM_{2.5}$ levels are usually observed in San Jose. The other cluster has winds entering the Bay Area from the San Joaquin Valley and accounts for around 20 percent of the Bay Area exceedances. The highest Bay Area $PM_{2.5}$ levels are usually observed in East Bay locations such as Concord, Livermore, or Vallejo.

These transport patterns will be further used for evaluating transport simulation results in section 6.2.3.

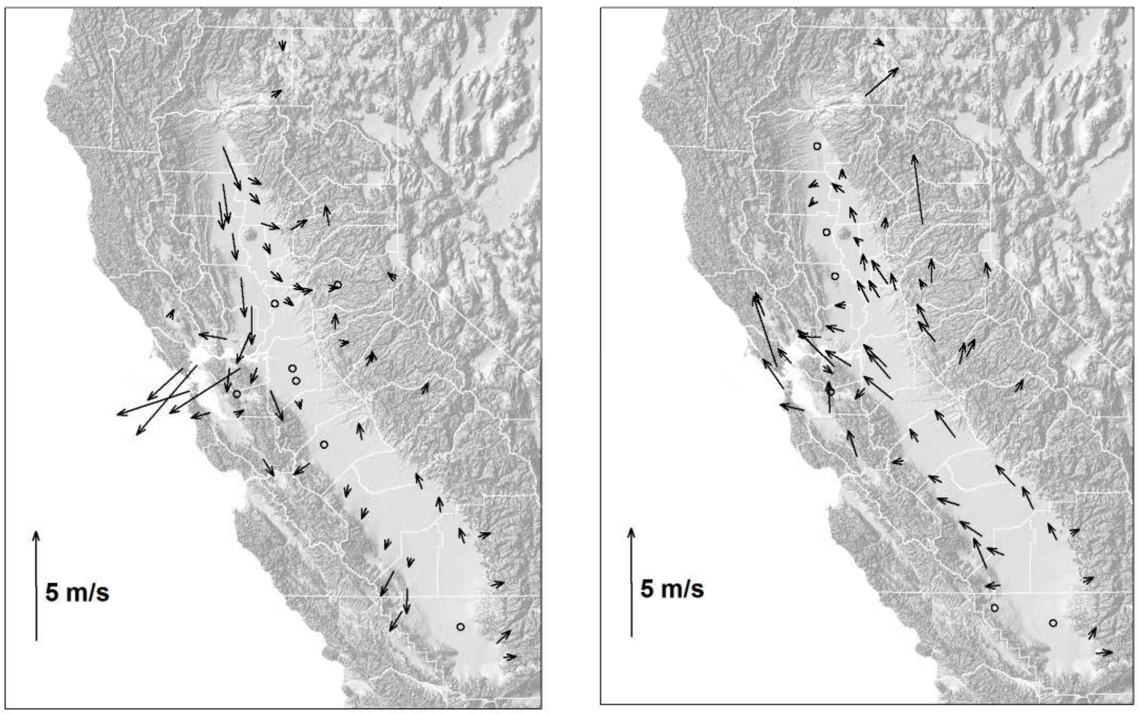


Figure 15. Pair of episodic transport clusters in which air flow into the Bay Area occurs from the Sacramento Valley (left, 60% of Bay Area exceedances) and from the San Joaquin Valley (right, 20% of Bay Area exceedances).

5. Computer simulations

A number of different simulations were performed to better understand the formation of $PM_{2.5}$ in the Bay Area. In section 5.1, the computer models and their configurations are briefly described. In section 5.2, base case simulation results are presented. The models were applied to estimate the sensitivity of $PM_{2.5}$ levels to reductions of Bay Area emissions (section 5.4) and transport impacts on the Bay Area (section 5.5).

Three winter seasons were simulated. All PM and precursor sources were modeled for the winters of 2000-01 and 2006-07. The 2000-01 winter was simulated because extensive measurements were available from CRPAQS; however, this was a severe PM season with the highest PM levels on record. The 2006-07 winter exhibited moderate conditions that may be more representative for air quality planning purposes. In total, $PM_{2.5}$ was simulated for 128 days. This large sample size ensured that all representative meteorological conditions under which elevated PM levels occurred were modeled. The third modeled winter was 2008-09. For this winter, only directly emitted PM from wood burning was simulated. This winter was simulated to evaluate the effectiveness of wood burning restrictions first enacted for the 2008-09 winter.

5.1 Description of models

Computer modeling of PM required two types of simulations to be performed. First, meteorological fields were simulated. These meteorological fields were then used as inputs to an air quality model to simulate PM levels.

5.1.1 Meteorological modeling

Meteorological modeling used the Fifth-Generation National Center for Atmospheric Research (NCAR)/Pennsylvania State University Mesoscale Model (MM5). Separate MM5 configurations were used for PM modeling and wood smoke modeling.

For PM modeling, three nested modeling domains were used. The outer domain covered the entire western United States with 36-km horizontal grid resolution to capture synoptic (large-scale) flow features and the impact of these features on local meteorology. The second domain covered California and portions of Nevada with 12-km horizontal resolution to capture mesoscale (sub-regional) flow features and their impacts on local meteorology. The third domain covered Central California with 4-km resolution to capture localized air flow features. The 4-km domain included the Bay Area, San Joaquin Valley, and Sacramento Valley, as well as portions of the Pacific Ocean and the Sierra Nevada mountains. This innermost domain had 189 grid cells in both the east-west and north-south directions.

All three domains employed 30 vertical layers with thicknesses expanded with height from the surface to the top of the modeling domain (about 15 km). Meteorological variables are estimated at the middle of the layers in MM5. The thickness of the lowest layer nearest the surface was about 30 m. Thus, meteorological variables near the surface were estimated around 15 m above ground level.

The model configuration was tested using a number of available physics options. The final choice of options that proved to be the best for characterizing meteorology in the domain were similar to those used by the National Oceanic and Atmospheric Administration (NOAA) for the Central California Ozone Study simulations. An exception is that the Pleim-Xiu Land Surface Model and PBL Scheme were used to provide additional fields to feed the CMAQ model.

Simulation periods were 12/1-2/2 of both 2000-01 and 2006-07. The resulting meteorological fields showed reasonable agreement with observations archived at the National Center for Atmospheric Research (NCAR). Details of the validation of the simulated meteorological fields against measurements are presented in Appendix B.

A different MM5 configuration was used for wood smoke modeling for 11/15/2008-2/15/2009. The inner 4-km modeling domain had 79 grid cells in both the east-west and north-south directions. This domain covered the Bay Area and surrounding regions, but not the rest of Central California that was included in the PM modeling MM5 configuration. There were 50 vertical layers. Physics options were the same as for the PM modeling runs. The resulting meteorological fields compared well against observations. Details of the validation of the simulated meteorological fields against measurements are presented in Appendix B.

5.1.2 PM modeling

PM modeling used the EPA Community Multiscale Air Quality (CMAQ) modeling system version 4.6. CMAQ simulates six individual $PM_{2.5}$ components which are combined to estimate total $PM_{2.5}$ levels: ammonium, sulfate, nitrate, OC, EC, and other unresolved components. The model distinguishes between primary and secondary OC, which is not possible from measurements. The simulated “other” components account for inert particulates including dust, marine aerosol, brake and tire wear, and trace metals.

The PM modeling domain had 185×185 horizontal grid cells and 4-km grid resolution. It was centered in the innermost meteorological modeling domain. The meteorological fields from 2 grid cells along each edge of the meteorological modeling domain were not used in order to minimize the impact of boundary conditions on PM modeling within the 4-km modeling domain. This resulting modeling domain matches the 4-km CRPAQS modeling domain shown in Figure 2. Some upper-level meteorological model layers were collapsed while preparing meteorological inputs for CMAQ to reduce computational time. This is a common practice in air quality modeling, as pollutant levels in layers aloft are relatively low and do not significantly impact levels at the surface. The resulting number of vertical layers in CMAQ was 16, with layer thicknesses expanding with height from the surface to the top of the modeling domain (about 16 km). The thickness of the first layer of CMAQ was kept the same as in MM5 (about 30 m), estimating pollutant concentrations at around 15 m above the surface.

Secondary PM formation was dependent upon ozone photochemistry. The ozone chemistry used in CMAQ was the Statewide Air Pollution Research Center version 1999 chemistry mechanism (SAPRC99). Secondary PM gas to particle conversion chemistry was simulated using in the Models-3 AE3 aerosol module in conjunction with the Regional Acid Deposition Model (RADM) aqueous-phase chemistry model.

As described in section 3, base case emissions inventories were developed for one week each for the years 2000 and 2006. These one-week inventories were replicated such that identical emissions were simulated for each week of the 2000-01 and 2006-07 winters, respectively. The replicated weeks were taken from near the middle of each winter simulation period. The inventories are believed to be representative of their respective winter simulation periods; however, specific emissions events such as increased wood burning were not reflected in the replicated inventories. The simple replication also ignored differences in plume rise that may have resulted under different meteorological conditions occurring during different weeks of a given winter. This approximation is believed to have negligible impact on simulated PM levels.

The boundary and initial conditions for the simulations were taken from CRPAQS. The only particulates included in the boundary conditions were dust and sulfur species, both set to low levels. Boundary conditions were also supplied for nitrogen species, VOCs, and ozone to drive the ozone photochemistry upon which PM depends. Initial conditions were set for the same set of species as present in the boundary conditions. Initial conditions were uniform in the horizontal dimension, but changed vertically. Initial conditions for pollutant levels were set to small values to avoid numerical instabilities. Each model run was initialized during a period of low PM levels to avoid excessive model spin-up time.

5.1.3 Wood smoke modeling

Wood smoke modeling used the ENVIRON International Corporation Comprehensive Air quality Model with extensions (CAMx) version 4.50. CAMx was used to simulated wood burning emissions during the winters of 2000-01 and 2008-09. The wood burning emissions inventory is described in section 3. The wood smoke modeling used an emissions inventory for a single day that was replicated over the winters of 2000-01 and 2008-09. As such, the emissions inventory represents average levels of winter wood burning. It does not reflect specific, intensified wood burning events expected during periods with colder temperatures or holidays. The directly emitted, nonreactive wood smoke components were simulated without any chemistry to reduce computational burden. Initial and boundary conditions had small amounts of wood smoke particles.

5.2 *Base case PM modeling results*

CMAQ was run with the base case emissions inventory for 12/2-2/2 of both 2000-01 and 2006-07. These base case simulations were intended to reconstruct actual pollutant levels that occurred during these periods. The simulated surface $PM_{2.5}$ fields compared favorably against $PM_{2.5}$ measurements. Certain limitations of the model were noted, however, such as a tendency to underestimate very high $PM_{2.5}$ levels. This shortcoming was primarily due to the overestimation of winds within the boundary layer by the meteorological model during extremely stable atmospheric conditions. When the atmosphere is stable, air aloft decouples from the surface and the model tends to generate local low-level jets that subsequently cause underestimation of PM in the air quality model. A separate research project is considered as part of the CRPAQS program to improve the meteorological model performance for such conditions. Details of the validation of the simulated $PM_{2.5}$ levels against measurements are presented in Appendix C.

5.2.1 *Individual $PM_{2.5}$ components*

A key benefit of modeling is the ability to estimate levels of the major $PM_{2.5}$ components throughout the Bay Area. This information helps fill the large gaps in the speciated $PM_{2.5}$ measurements that are only available for a limited number of days at a few locations. Simulated episodic 24-hour levels for the $PM_{2.5}$ components are shown in Figure 16. These results are averaged across the 55 days for which simulated Bay Area 24-hour $PM_{2.5}$ exceeded 35 $\mu g/m^3$. For these episodic days, light winds flowed through the Bay Area from the east, and Central Valley conditions were near calm.

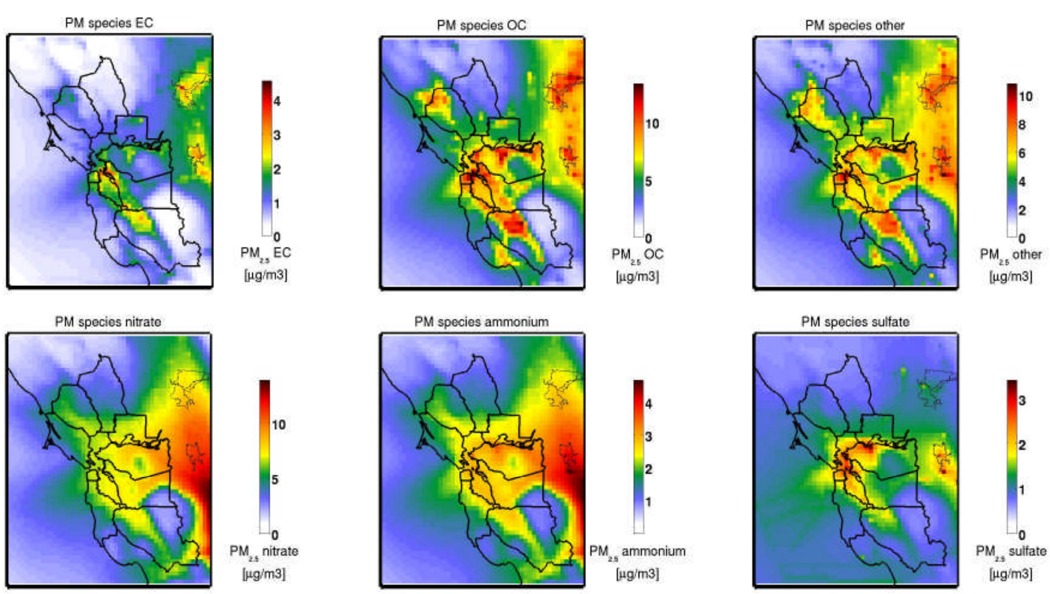


Figure 16. Surface plots of simulated 24-hour levels for the six $PM_{2.5}$ components, averaged across the 55 days for which simulated base case Bay Area maximum 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento and Stockton are drawn using thin black lines.

EC and most of the OC result from primary emissions. EC levels are elevated primarily at and near centers of commerce around the bay; over the Central Valley major cities and, to a lesser extent, rural areas. The highest Bay Area EC levels occur over West Oakland, reflecting Port of Oakland diesel sources. Aside from the rural Central Valley locations, EC accumulates only near its sources. OC levels are elevated for the same locations as EC, as well as other moderately populated areas. OC is associated with both commerce and household activities. Also, OC may be proportionally higher than EC over populated areas as compared to over highways and centers of commerce and industry. Likely, this reflects impacts of household wood burning and cooking in residential areas. Accumulated EC and OC in the rural Central Valley locations demonstrate the lack of ventilation in the Valley. During an episode, a stable, stagnating air mass is trapped between the Valley's rims.

The "other" $PM_{2.5}$ component presented in Figure 16 also results from primary emissions only. It is elevated near highways and populated areas. It reflects trace metals from mobile and stationary combustion sources, suspended road dust, and also small amounts of tire and brake wear particles. As with carbonaceous components, the other primary $PM_{2.5}$ components are trapped in the Central Valley and accumulate in its rural areas. Geological dust would not appear to be a major contributor to elevated $PM_{2.5}$ levels under relatively calm conditions or during the winter rainy season.

Figure 16 shows that ammonium nitrate is the dominant component of secondary $PM_{2.5}$. During episodic conditions, nearly all of the nitrate and most of the ammonium are present as the compound ammonium nitrate. (Nitrate with molar mass 62 g/mol and ammonium with molar mass 18 g/mol would appear with the mass ratio of 3.4 g nitrate/g ammonium if they contributed solely to ammonium nitrate. This is very close to the ratio visually apparent for most of the plotted domain in Figure 16.) Notable exceptions include near Richmond and Carquinez Strait where excess ammonium is present. The ammonium nitrate is not localized near ammonia or NO_x sources. It is diffuse. This is because ammonium nitrate forms by chemical reactions occurring over the course of several days and nights, as fresh emissions are aged in a relatively calm air mass. Ammonium nitrate levels are highest in the Central Valley. There is a general gradient with levels decreasing from east to west through the Bay Area.

Ammonium sulfate is a minor component of secondary $PM_{2.5}$ during episodic conditions. Presence of this compound is reflected by the sulfate levels shown in Figure 16. Appreciable levels of ammonium sulfate in the Bay Area appear only around the ports, industrial plants, and refineries near Oakland, Richmond, and Carquinez Straight. (Hence the excess ammonia here that does not neutralize nitrate, as noted above.) These areas represent the only significant land-based sulfur sources in the Bay Area. Ammonium sulfate also forms over the offshore shipping lanes from combustion of sulfur-laden bunker fuel. Because winds are from the east during episodes, these offshore sulfur sources do not strongly impact the Bay Area.

Ammonium sulfate can occasionally account for a moderate proportion of $PM_{2.5}$. This situation may occur under non-episodic conditions when winds are from the west and the shipping lanes are upwind of the Bay Area (not shown). Under such conditions, $PM_{2.5}$ levels are generally low, and ammonium sulfate mass loading is still typically not much more than a few micrograms per cubic meter..

5.2.2 Ammonium nitrate limitation

Ammonium nitrate particulate forms upon the reaction of gaseous compounds ammonia and nitric acid. Ammonia is directly emitted, whereas nitric acid forms through the photochemical aging of NO_x emissions. Lack of availability of either ammonia or nitric acid can be the limiting factor in ammonium nitrate formation. Figure 17 shows levels for these gases averaged across the 55 days for which simulated Bay Area 24-hour $PM_{2.5}$ exceeded 35 $\mu g/m^3$.

Under episodic conditions, ammonia accumulated in the atmosphere only near intense ammonia sources. (Compare ambient ammonia levels of Figure 17 with ammonia emissions levels of Figure 4.) Ammonia was especially concentrated in the Central Valley, but its levels also increased for some Bay Area source locations. Near the ammonia sources, nitric acid was consumed to near-zero levels. Also, ammonium nitrate levels were elevated over the ammonia sources (see Figure 16), indicating locations of significant secondary particulate formation. Nitric acid was only able to accumulate for remote locations over the Coast Range and the Pacific Ocean, and to a lesser extent rural locations near the Central Valley rims. There were no major NO_x emissions sources near the locations where nitric acid accumulated. These findings suggested that ammonium nitrate formation was limited by nitric acid, and not by ammonia. It is cautioned, however, that these results could be misleading because of the preliminary ammonia emissions inventory used for modeling.

Nitric acid limited chemistry means that nitric acid availability ultimately limited the total tonnage of secondary ammonium nitrate that formed. It does not imply that reductions of nitric acid levels would be the most efficient means for reducing ammonium nitrate levels. Ammonia emissions reductions could still reduce ammonium nitrate levels under nitric limited chemistry; however, ammonia emissions reductions could not impede ammonium nitrate formation for regions in which all nitric acid has been consumed.

5.2.3 Spatial distribution of $PM_{2.5}$

The base case simulation results demonstrate how primary $PM_{2.5}$ accumulates near its sources, whereas secondary $PM_{2.5}$ is spread out through the Bay Area. To analyze the spatial gradients in finer detail, it is constructive to divide the Bay Area into a number of subregions sharing distinct $PM_{2.5}$ characteristics. To objectively identify the relevant subregions, a cluster analysis was performed on the simulated $PM_{2.5}$ levels. (This is a different type of cluster analysis than applied to meteorological measurements in section 4.3. The term “cluster analysis” applies to a variety of data mining techniques having different mechanics and goals.) The cluster analysis was performed to group model grid cells having strongly correlated $PM_{2.5}$ levels. By definition, correlated grid cells exhibit $PM_{2.5}$ levels that rise and fall with the same timings. This type of clustering naturally identifies contiguous domains, because adjacent grid cells directly interact via the wind and the terrain. The clustering was applied only to days with simulated PM levels exceeding 30 $\mu g/m^3$ so that the identified subregions reflect episodic conditions. Eight subdomains were identified within the Bay Area (Figure 18). Other subdomains of interest in the Central Valley (not shown) include the Modesto area and the Delta region immediately east of Carquinez Straight. Plots of secondary versus primary $PM_{2.5}$ levels were constructed for each identified subregion. Results for selected subregions are shown in Figure 19.

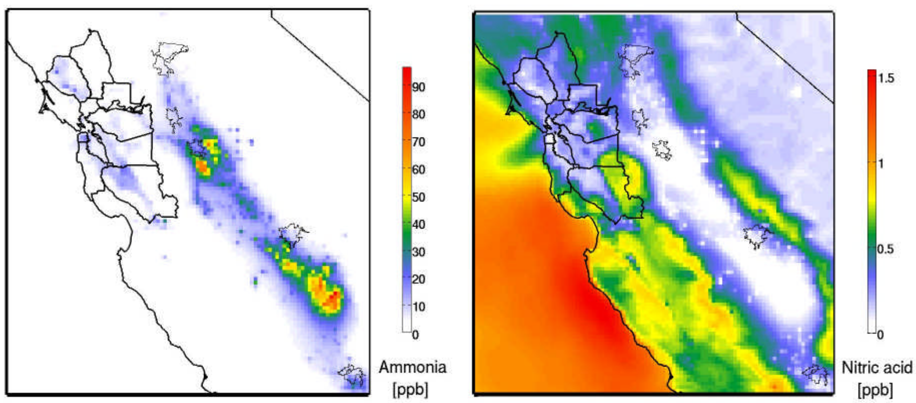


Figure 17. Aerial plots of simulated 24-hour levels for gas phase ammonia and nitric acid, averaged across the 55 days for which simulated Bay Area maximum 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento, Stockton, Modesto, Fresno, and Bakersfield (listed north to south) are drawn using thin black lines.

Around Modesto, $PM_{2.5}$ is composed of approximately equal portions of primary and secondary components, up to about 50 $\mu g/m^3$ of total $PM_{2.5}$. This distribution demonstrates the typical buildup of secondary $PM_{2.5}$ in the Central Valley to levels as high as primary $PM_{2.5}$ around a major urban source area for primary particles. Secondary $PM_{2.5}$ levels occasionally exceed 35 $\mu g/m^3$, indicating that an exceedance could occur in the Central Valley even without any primary PM emissions. For high levels of primary $PM_{2.5}$ (beyond 25 $\mu g/m^3$), additional buildup of secondary $PM_{2.5}$ does not occur. Likely, this indicates a limit for air mass aging to progress. Conditions in the Central Valley are near-stagnant, yet not stagnant enough to allow for indefinite secondary PM accumulation.

In the Delta subregion, $PM_{2.5}$ characteristics are similar to Modesto; however, there is slightly more primary than secondary contribution. Primary levels are similar to Modesto, but secondary levels are slightly decreased outside of the Central Valley proper. A similar effect is observed through the Altamont Pass and into the Livermore Valley. Here, however, total $PM_{2.5}$ levels are lower than in the Central Valley or Delta. Livermore Valley is buffered from the heavily polluted Central Valley by the Coast Range. Significant contributions of both primary and secondary $PM_{2.5}$ are required for an exceedance to occur in the eastern portion of the Bay Area.

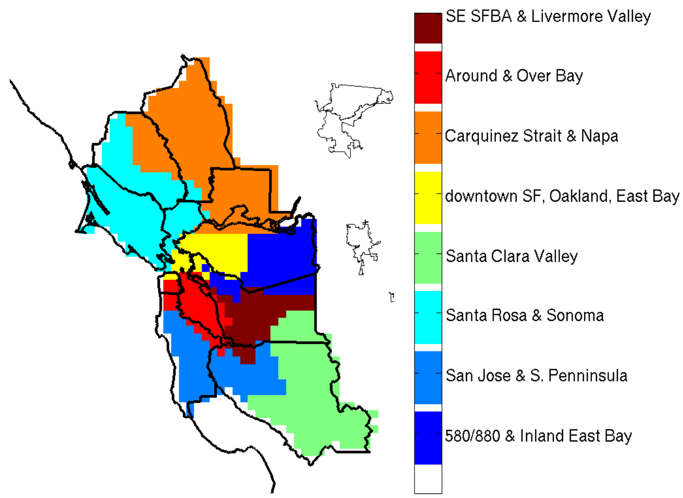


Figure 18. Eight Bay Area subdomains sharing similar air quality characteristics when PM levels are elevated. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento and Stockton are drawn using thin black lines.

In the San Francisco Peninsula and San Jose, $PM_{2.5}$ is dominated by primary PM emissions. These urban areas have intense primary sources, and also are distant from the main locus of secondary formation in the Central Valley. Secondary levels are around 5 $\mu g/m^3$ lower than in the Delta or Livermore Valley. In the San Francisco Peninsula and San Jose, $PM_{2.5}$ exceedances can occur from primary contributions alone.

North of San Francisco, in the Petaluma Valley, $PM_{2.5}$ is more primary than secondary; however, primary components do not dominate as in the urban areas. Secondary $PM_{2.5}$ levels are similar as in the urban areas, reflecting the regional nature of secondary PM. Primary $PM_{2.5}$ levels are around half that of San Francisco and San Jose, reflecting the smaller source strength of Santa Rosa. Significant contributions of both primary and secondary $PM_{2.5}$ are required for an exceedance to occur in the North Bay.

5.3 Development of a typical Bay Area PM episode

Simulations depicted how a typical PM episode developed in the Bay Area over time. Figure 20 shows simulation results for the four-day period January 21-24, 2007. On January 21, a high pressure system was approaching the northern California coast from the west. The offshore clockwise rotating high pressure system created strong winds entering the Sacramento Valley from the north. The winds blew down through the Sacramento Valley and split at its southern end to enter the Bay Area and San Joaquin Valley. The low-level winds remained strong through the Bay Area and exited over the Pacific Ocean. PM levels were low for the Bay Area, Delta region, and Sacramento Valley because of the strong winds and associated dispersion. Deeper into the San Joaquin Valley, however, the winds became weaker and PM was accumulated to high levels. On the next day, January 22, the center of the high pressure system reached land and winds became weaker throughout Central California. Light winds entered the Bay Area from the east as the Central Valley air mass emptied toward the Pacific Ocean. In the San Joaquin Valley, secondary PM levels were regionally elevated. In the Bay Area and around Sacramento, primary PM levels were elevated near their sources. On January 23, Central Valley winds were near calm and light flow continued through the Bay Area from east to west. The entire Central Valley, the Bay Area, and offshore locations immediately west of the Bay Area were impacted by regionally accumulated secondary PM. As the high pressure system gained strength and its west to east motion was slowed down by the Sierras, $PM_{2.5}$ levels were especially elevated for around the San Francisco bay, through Carquinez Straight, and near the Central Valley cities. For these source areas, localized primary PM in addition to regional secondary PM allowed for high $PM_{2.5}$ levels. Similar meteorological conditions persisted through January 24. $PM_{2.5}$ levels were similarly elevated as in the previous day. The plume of regional PM expanded somewhat to more strongly affect outlying areas such as Santa Rosa and Santa Cruz. This episode continued for several more days as meteorological conditions persisted (not shown).

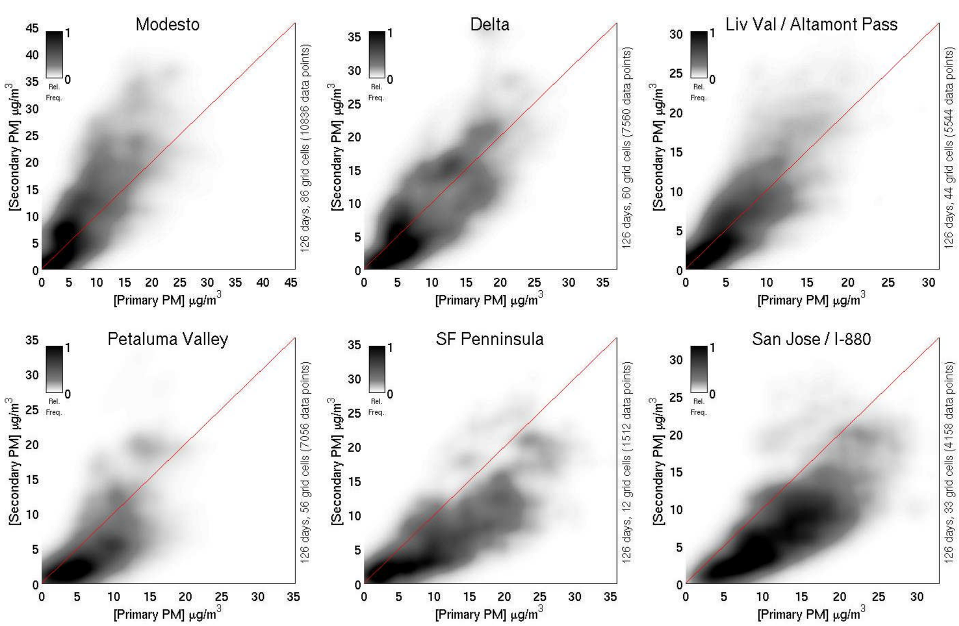


Figure 19. Simulated secondary versus primary $PM_{2.5}$ levels for four selected subdomains shown in Figure 18, plus Modesto and the Delta. Grayscale indicates relative frequency at which combinations of primary and secondary $PM_{2.5}$ levels occurred. Diagonal 1:1 lines indicate equal proportions of primary and secondary components.

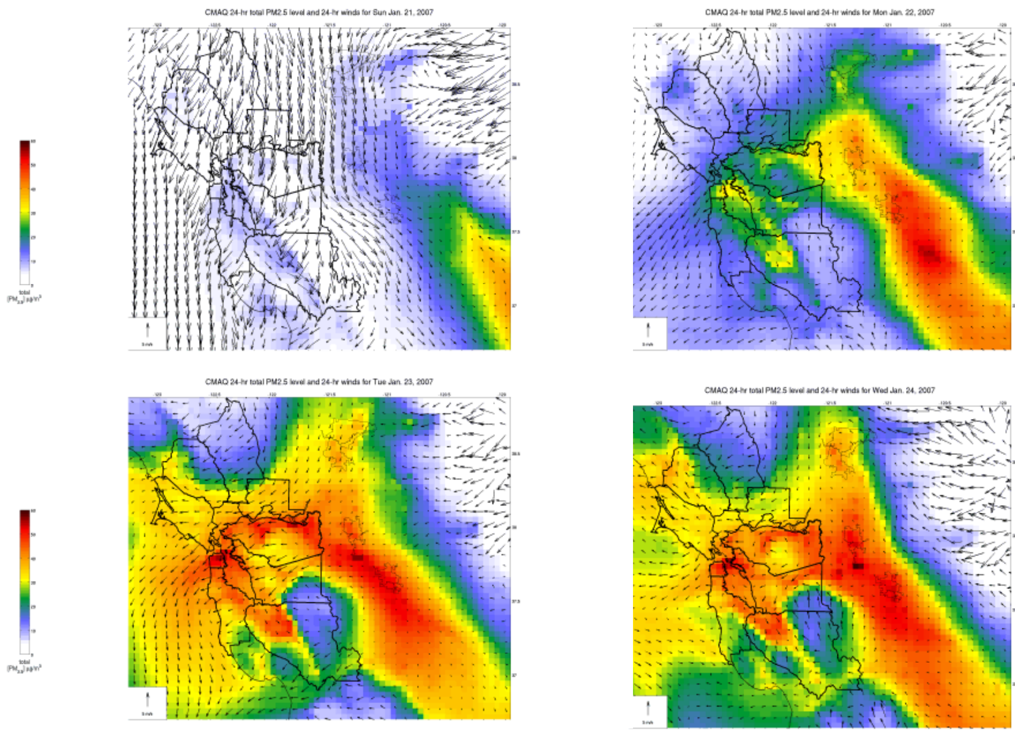


Figure 20. Simulation results for four consecutive days showing the development of a relatively severe PM episode in the Bay Area. Aerial plots of CMAQ-simulated 24-hour $PM_{2.5}$ levels with superimposed 24-hour averaged wind field simulated with MM5. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento, Stockton, and Modesto are drawn using thin black lines.

5.4 PM sensitivities to Bay Area emissions reductions

The sensitivities of $PM_{2.5}$ levels to various reductions of Bay Area emissions were estimated by simulation. This approach required implementing a "sensitivity run" of the air quality model using a modified base case inventory. Typically, the modified inventory has emissions reductions for one or more important source categories relative to the base case. Differences in simulated PM levels between the base case and the sensitivity run reflect the modeled impact of the reduced emissions. Two types of sensitivity runs were performed: across-the-board emissions reductions for classes of chemical species and reductions of wood smoke emissions only.

The first type of simulation explored the sensitivity of PM levels to 20 percent across-the-board reductions of classes of chemical species emitted by anthropogenic sources within the Bay Area: NO_x and VOC combined; gaseous sulfur species; ammonia; directly emitted PM; and these four classes combined, comprising all anthropogenic emissions. Simultaneous NO_x and VOC emissions reductions were simulated because historical controls for ozone have targeted both of these emissions classes. Ammonia, sulfur, and direct PM emissions reductions were simulated independently. This type of sensitivity run based on classes of chemical species did not distinguish between specific source categories (e.g. mobile and stationary sources).

Additional sensitivity simulations explored the impact of Bay Area wood burning on $PM_{2.5}$ levels. Model runs were performed with 100 percent, 50 percent, and 0 percent simulated compliance rate with the District wood burning restriction enacted for the 2008-09 winter. Reductions of wood smoke emissions were simulated only for actual Spare the Air days during which wood burning was restricted. The simulated emissions reductions were implemented from noon of the Spare the Air day through noon of the following day. This timing was consistent with the no-burn period specified in the regulation. This type of sensitivity run was intended to estimate how much higher $PM_{2.5}$ levels would have been without wood burning control measures for the 2008-09 winter.

5.4.1 Across-the-board emissions reductions

Across-the-board emission reductions were simulated for 12/18/2000-1/6/2001 and 12/27/2006-1/11/2007, for a total of 36 days when PM levels were elevated in the Bay Area. Differences in $PM_{2.5}$ levels ($\Delta PM_{2.5}$ equals base case $PM_{2.5}$ level minus sensitivity run $PM_{2.5}$ level) were computed for each model grid cell. $\Delta PM_{2.5}$ is defined such that positive values reflect a decrease in PM levels when emissions are reduced. $\Delta PM_{2.5}$ values at each grid cell were averaged across the 20 days in the 36-day study period having simulated base case Bay Area $PM_{2.5}$ levels exceeding 35 $\mu g/m^3$. These sensitivities under episodic conditions are shown in Figure 21.

Reducing 20 percent of the directly emitted PM (around 18 tons/day eliminated, see Table 2) was approximately an order of magnitude more effective in reducing peak $PM_{2.5}$ levels than reducing 20 percent of the secondary PM precursors. In Figure 21, $\Delta PM_{2.5}$ achieved from direct PM emissions reductions is only slightly below than that achieved from reducing all emissions. Correspondingly, $\Delta PM_{2.5}$ achieved from 20 percent reductions in precursor gas emissions (NO_x and VOC; ammonia; and sulfur-containing species) was about 10 times lower than for 20 percent reductions of directly emitted PM. Reductions of directly emitted PM, however, were most effective near the PM emissions sources.

Reducing 20 percent of the ammonia emissions (around 15 tons/day eliminated, see Table 2) was the most effective of the precursor emissions reductions simulated. The $\Delta PM_{2.5}$ achieved mostly reflects reduced particulate ammonium nitrate levels. The ammonia emissions reductions also reduced ammonium sulfate levels by up to 0.1 $\mu g/m^3$ near sulfur sources around Richmond and through Carquinez Strait (not shown). The effectiveness of the 20 percent ammonia emissions reductions was roughly uniform throughout the Bay Area. This contrasts markedly with reductions of primary PM emissions, which were most effective near primary PM source areas. Ammonia emissions reductions were less effective near ammonia sources, where the secondary PM forming chemistry was limited by lack of nitric acid. (See Figure 17 and also the discussion of the implications of nitric acid limited chemistry in the last paragraph of section 5.2.2.). This effect was most notable in the Bay Area around San Francisco, San Jose, and Santa Rosa.

Reducing a combined 20 percent of the NO_x and VOC emissions (around 110 tons/day NO_x and 140 tons/day VOC eliminated, see Table 2) was relatively ineffective. These precursors contribute primarily to ammonium nitrate formation. Benefits from these emissions reductions occurred primarily around Santa Rosa. The benefit here was around 0.25 $\mu g/m^3$. For other locations, $\Delta PM_{2.5}$ was small in magnitude. The negative $\Delta PM_{2.5}$ values may be mathematical artifacts from the model.

Reducing 20 percent of the sulfur-containing PM precursor emissions (around 16 tons/day eliminated, see Table 2) had a relatively small impact on Bay Area $PM_{2.5}$ levels. Benefits of these emissions reductions occurred primarily near sulfur sources around the bay. Maximum $\Delta PM_{2.5}$ of around 0.25 $\mu g/m^3$ was comparable with that of the combined 20 percent NO_x and VOC emissions reductions. Tonnage reductions of sulfur (16 tons/day), however, were an order of magnitude lower than for the NO_x and VOC reductions (around 250 tons/day) required to achieve a similar effect.

Under episodic conditions with winds from the east, sulfur emissions from the offshore shipping lanes were downwind of the Bay Area. Offshore sulfur emissions reductions under winds from the east likely had little impact around the bay where ammonium sulfate reductions occurred. Reductions of sulfur emissions may have been more effective under non-episodic conditions having winds from the west. Under such conditions, the offshore shipping lanes were upwind of the Bay Area. $\Delta PM_{2.5}$ resulting from the 20 percent sulfur emissions reductions were over 1 $\mu g/m^3$ in some cases with winds from the west (not shown).

Emissions reductions benefits were tabulated for the Bay Area subdomains shown in Figure 18. Benefits were tabulated only for directly emitted PM and ammonia emissions reductions, the most effective reductions for controlling primary and secondary $PM_{2.5}$, respectively. For each subdomain, $\Delta PM_{2.5}$ values were tabulated only for the grid cell with the highest simulated $PM_{2.5}$ levels on each episodic day. Pooling the model results in this manner reflects how emissions reductions impact attainment of 24-hour PM standards, which is likewise based on peak PM levels. Results are shown in Figure 22.

Directly emitted PM reductions of 20 percent impacted ambient $PM_{2.5}$ levels differently for different Bay Area subdomains. The directly emitted PM reductions were most effective around San Jose, where primary $PM_{2.5}$ levels were high over a relatively large area. Benefits ranged about 4-6 $\mu g/m^3$. Directly emitted PM reductions were less effective for some days at locations distant from PM sources, such as the eastern extremity of the Bay Area, Santa Rosa, and Livermore Valley. Otherwise, $\Delta PM_{2.5}$ values were generally in the range 3-5 $\mu g/m^3$. In terms of percentage reductions of primary $PM_{2.5}$, there was much less spatial variability. This is because reductions of directly emitted PM more strongly impact primary $PM_{2.5}$ levels near PM sources where primary levels are higher. Primary $PM_{2.5}$ levels were typically reduced 12-20 percent, with an average around 16 percent. Secondary PM levels were not significantly affected by reductions of directly emitted PM.

Ammonia emissions reductions of 20 percent impacted ambient $PM_{2.5}$ levels relatively uniformly across the Bay Area subdomains. An exception was the extreme eastern portion of the Bay Area, where $PM_{2.5}$ levels were somewhat less sensitive to the ammonia emissions reductions. This subdomain adjacent to the Delta was mostly affected by transported secondary PM under episodic conditions having winds from the east. $\Delta PM_{2.5}$ values were generally in the range 0.1-0.5 $\mu g/m^3$. Secondary $PM_{2.5}$ levels were typically reduced 0-4 percent, with an average around 2 percent. Primary PM levels were not significantly affected by reductions of ammonia emissions.

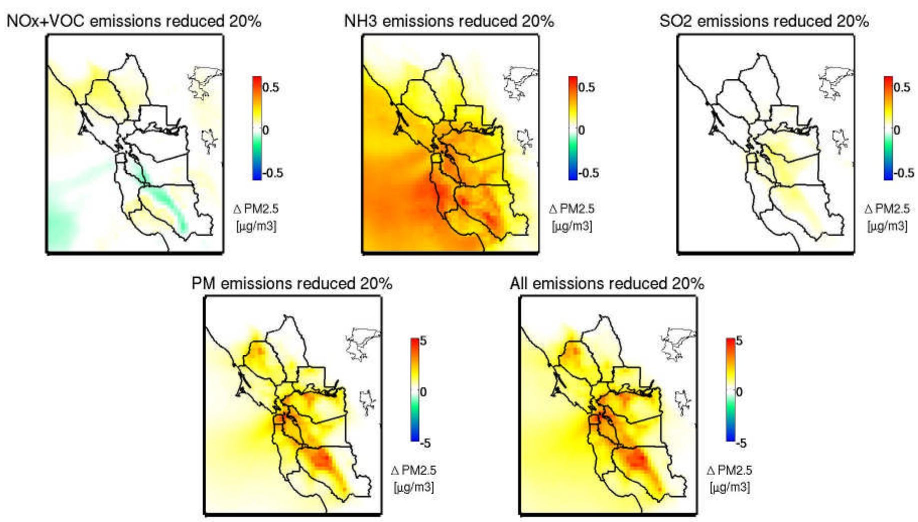


Figure 21. Surface plots of simulated sensitivities of $PM_{2.5}$ for five 20% emissions reductions, averaged across the 20 days for which simulated Bay Area maximum 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$. Bay Area counties and the California coastline are drawn using thick black lines. City limits for Sacramento and Stockton are drawn using thin black lines. Positive $\Delta PM_{2.5}$ values indicate that ambient PM levels decrease with emissions reductions. Same scale is used for top and bottom tiles.

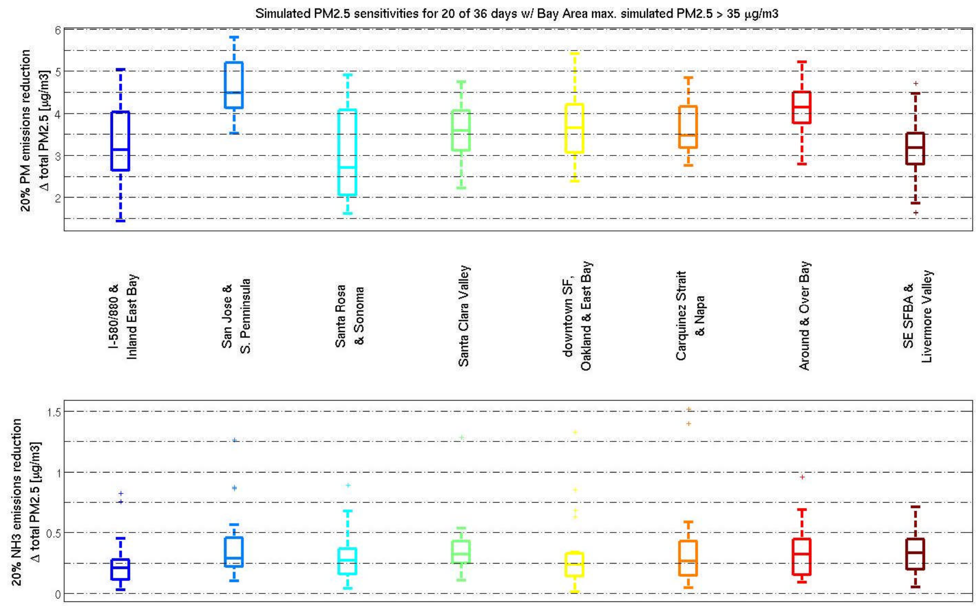


Figure 22. Tabulated $\Delta PM_{2.5}$ values for grid cell with highest simulated $PM_{2.5}$ level for eight subdomains depicted in Figure 18, for 20 exceedance days only. Top plot shows sensitivity to 20% direct PM emissions reductions. Bottom plot shows sensitivity to 20% ammonia reductions. Horizontal lines on boxes indicate 25^{th}, 50^{th} (median), and 75^{th} percentiles for $\Delta PM_{2.5}$ values. Remaining values are contained within whiskers, except for outliers plotted using a plus signs.

5.4.2 Wood smoke impacts

Wood smoke $PM_{2.5}$ levels were simulated for 11/15/2008-1/31/2009. This was the first winter for which BAAQMD wood burning restrictions were in effect. The simulation period contained 8 of the 11 Spare the Air days during the 2008-09 winter (Table 3). Two different model runs were performed. Bay Area wood smoke levels were simulated with and without wood burning restrictions during the Spare the Air periods. For the run without burning restrictions, full wood burning emissions were simulated for the entire winter period. For the run with burning restrictions, wood burning emissions were eliminated from the simulation only for noon of each Spare the Air day through noon of the following day. This timing reflects 100 percent compliance with the actual periods of wood burning restriction. For all other periods, full wood burning emissions were simulated. The only difference between the pair of model runs was the presence or absence of wood burning during the eight 24-hour Spare the Air periods.

Examples of the wood smoke simulations are shown in Figure 23 for Spare the Air days 12/10/2008 and 1/18/2009. Without burning restrictions, peak wood smoke levels of 10-20 $\mu g/m^3$ would have occurred over the areas having high wood burning emissions (see Figure 3). Wood smoke levels would have been around 5 $\mu g/m^3$ or more for many of the remaining populated locations within the Bay Area. Without wood burning restrictions on 12/10/2008, wood smoke levels would have been comparably high in the South Bay and East Bay. Wood smoke levels also would have been elevated around the bay and Santa Rosa. Without wood burning restrictions on 1/18/2009, wood smoke levels would have been highest in the

South Bay. Other locations would have been less strongly impacted by wood smoke. With burning restrictions on these Spare the Air days, considerable reductions in wood smoke levels occurred for most Bay Area locations near concentrated wood burning source areas. Peak benefits were around 10 $\mu g/m^3$ of reduced wood smoke. On 12/10/2008 greater benefit was obtained in the East Bay, whereas on 1/18/2008 greater benefit was obtained in the South Bay. Wood smoke levels were not reduced to zero because the burning restrictions did not begin until noon of these days. Also, carried over wood smoke from previous days may have impacted the Bay Area during the Spare the Air days. These results were representative of the 2008-09 winter. The burning restrictions had a significant effect which varied by location depending on the prevailing weather.

Figure 24 shows the effect of the wood burning ban for the 2008-09 winter at the Concord and San Jose monitoring locations. These data are representative of the other Bay Area sites. Blue bars indicate the observed $PM_{2.5}$ level. It is assumed that measurements during these Spare the Air periods reflected the effects of 100 percent compliance with the wood burning ban (i.e. no wood burning emissions). Green bars indicate the simulated additional concentration of wood smoke that would have resulted without the burning restrictions. These simulated wood smoke levels were averaged across the 3×3 array of model grid cells surrounding each respective monitoring location. The sum of the blue and green bars reflect the total $PM_{2.5}$ levels that would have resulted without burning restrictions. Thus, the green bars reflect the effect of the restrictions.

On Spare the Air day 12/10/2008, observed Concord $PM_{2.5}$ level was 17 $\mu g/m^3$. Without burning restrictions, more than 14 $\mu g/m^3$ additional wood smoke would have been present, for a total $PM_{2.5}$ level of over 31 $\mu g/m^3$. This was the largest benefit of the wood burning restrictions to have occurred at Concord. At San Jose, $PM_{2.5}$ level was 30 $\mu g/m^3$ with burning restrictions, but would have been nearly 34 $\mu g/m^3$ without the restrictions. This benefit at the San Jose monitoring location was far smaller than the maximum South Bay benefit (10 $\mu g/m^3$) indicated in the surface plot (Figure 23). This discrepancy arises because the San Jose monitor was not located at the area of peak simulated wood smoke level in the South Bay. For Spare the Air day 1/18/2009, benefits of the burning restriction were roughly equal (3-4 $\mu g/m^3$) for both the Concord and San Jose monitoring locations; however, greater reductions of peak wood smoke levels (Figure 23) occurred in the South Bay (10 $\mu g/m^3$) than in the East Bay (7 $\mu g/m^3$). These modeling results suggest that reductions of population exposure to wood smoke were considerably greater than indicated by the monitoring data alone.

Without the burning restrictions, wood smoke levels for the eight Spare the Air days would have averaged around 11, 7, 5, 3, and 3 $\mu g/m^3$ for the Concord, San Jose, San Francisco, Vallejo, and Livermore monitoring locations, respectively. Assuming 100 percent compliance, the burning restrictions were estimated to reduce these wood smoke levels by about 50-75 percent, depending on location. The 24-hour (midnight to midnight) wood smoke levels were never reduced to zero because of both the timing (noon to noon) of the burning restrictions and also carried over wood smoke. The burning restrictions had the added benefit of reducing carried over wood smoke into the days following burning restrictions. Because the burning restrictions reduced carry over, enhanced benefits may be achieved for multiple, consecutive Spare the Air calls. For most locations, the two consecutive Spare the Air calls on 11/24-25/2008 provided the largest reductions of $PM_{2.5}$ levels simulated for the 2008-09 winter.

Table 3. Spare the Air days for 2008-09 winter during which wood burning ban was in effect from noon through noon the following day.

11/19/2008	12/7/2008	1/15/2009	2/3/2009
11/24/2008	12/10/2008	1/18/2009	2/4/2009
11/25/2008	1/4/2009	1/30/2009	

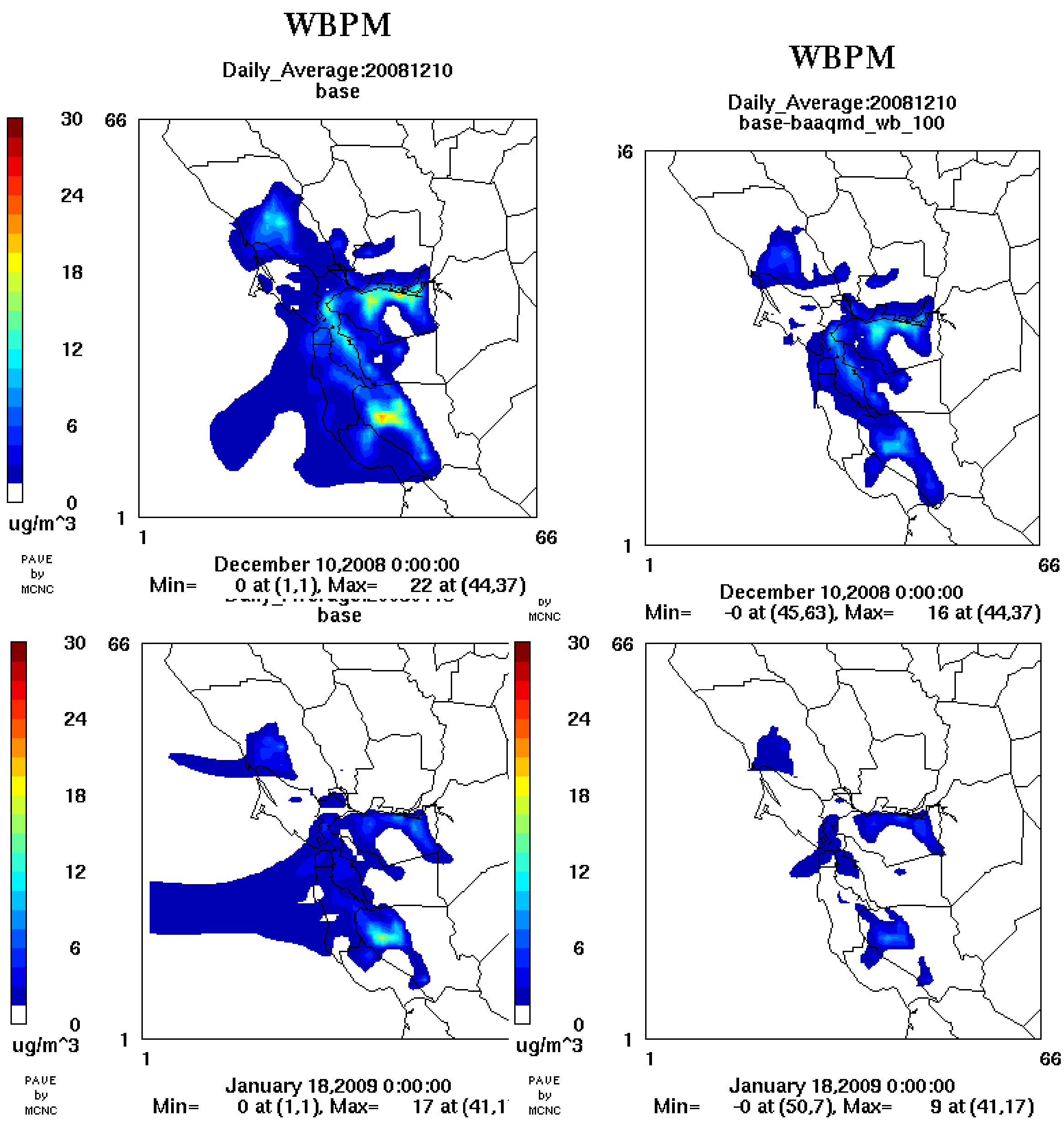
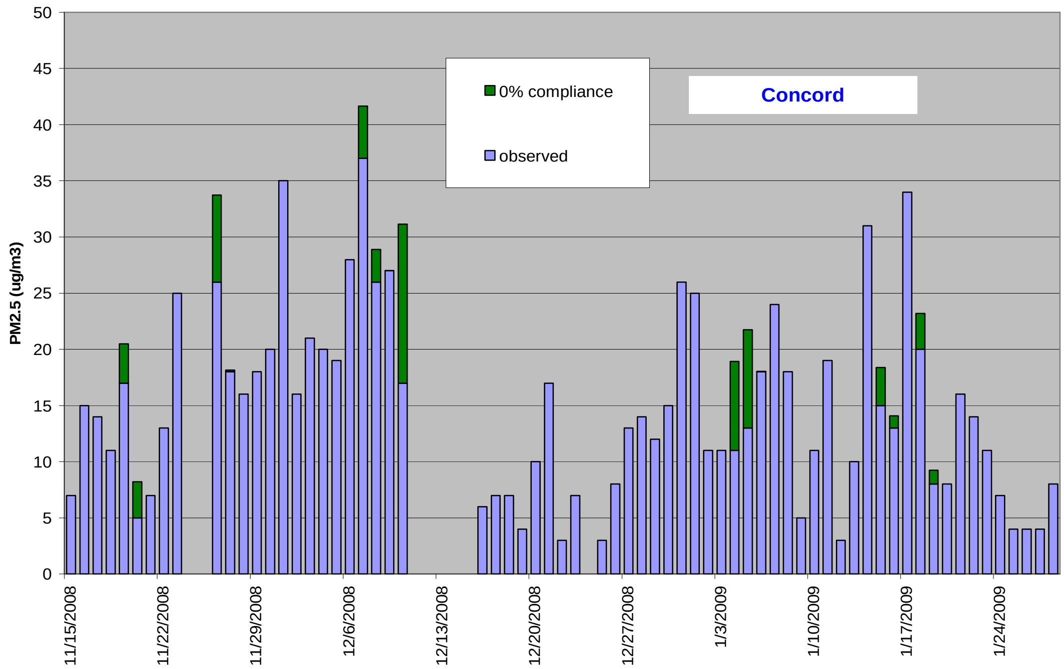


Figure 23. Wood smoke simulation results for Spare the Air days 12/10/2008 (top row) and 1/18/2009 (bottom row). Simulation with wood burning emissions (left column) shows estimated Bay Area wood smoke

levels assuming full wood burning. Simulation without wood burning emissions (right column) shows estimated benefit (reduction) of wood smoke levels resulting from the burning restrictions.



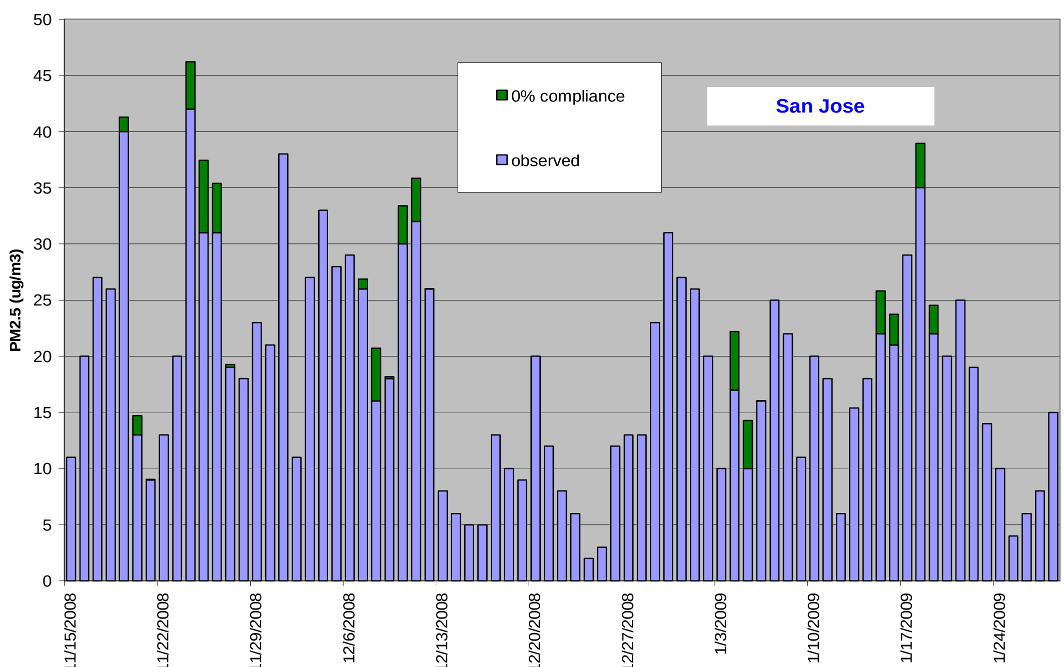


Figure 24. Simulated effect of wood burning restrictions during 2008-09 winter at Concord and San Jose monitoring locations. Blue bars are observed $PM_{2.5}$ levels. For Spare the Air days, the observed $PM_{2.5}$ levels are assumed to result from 100% compliance with the burning restrictions. Green bars indicate simulated wood smoke that would have additionally been present without the burning restrictions. They represent the benefit of the burning restrictions.

5.5 Transport impacts on Bay Area

$PM_{2.5}$ transport impacts on the Bay Area were explored by simulation. The approach implemented “transport runs” of the air quality model similar to the sensitivity runs described in section 5.4. Two types of transport runs were performed: zeroing out of Bay Area anthropogenic emissions and reducing upwind areas’ anthropogenic emissions. Zeroing out the Bay Area emissions provided an estimate of the cumulative transport impacts from all sources outside of the Bay Area. Reducing upwind area emissions provided an estimate of how Bay Area air quality may benefit from reduced upwind emissions sources. This latter approach was applied to estimate transport impacts separately from the Sacramento area and San Joaquin Valley. The model results indicated differences in transported primary and secondary $PM_{2.5}$ from these Central Valley areas.

The transport analyses in which emissions were zeroed out were unrealistic. Such simulations only provided qualitative information regarding the relative contributions of sources within and outside of the Bay Area. Moreover, they did not account for potential interactions of emissions from different air basins.

5.5.1 Bay Area emissions zeroed out

CMAQ was run with zero Bay Area anthropogenic emissions for 12/2-2/2 of both 2000-01 and 2006-07. Simulated 24-hour levels for the six $PM_{2.5}$ components are shown in Figure 25. These results are averages across the same 55 days as shown in Figure 16, for which Bay Area maximum 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$ in the base case simulation. PM levels shown in Figure 25 resulted from emissions outside of the Bay Area, as well as biogenic emissions within the Bay Area. Bay Area biogenic emissions contributed to OC and “other” primary PM only. Differences in PM levels between Figure 16 and Figure 25 represent the contribution of Bay Area anthropogenic emissions to $PM_{2.5}$ levels.

Without Bay Area anthropogenic emissions, primary $PM_{2.5}$ levels (EC, most of OC, and other) in the Bay Area were markedly reduced. This effect was most pronounced near the Bay Area sources, where base case levels were locally elevated (see Figure 16). Transported EC levels were as high as 1 $\mu g/m^3$ in the eastern portion of the Carquinez Straight and through the Altamont Pass. These corridors directly connect with the Central Valley, where EC levels were higher. For the rest of the Bay Area, EC levels were 0.5 $\mu g/m^3$ or lower. Similar spatial distributions were observed for OC and other $PM_{2.5}$. Higher levels were observed nearer the mountain passes connecting to the Central Valley. In the Bay Area, OC levels ranged about 1-4 $\mu g/m^3$, and other $PM_{2.5}$ levels ranged about 0.5-3 $\mu g/m^3$.

Transport impacts of secondary ammonium nitrate were generally greater than for the primary $PM_{2.5}$ components combined. Ammonium nitrate levels along the eastern boundary of the Bay Area were as high as13 $\mu g/m^3$. Plumes of ammonium nitrate with levels around 8 $\mu g/m^3$ were present through the Carquinez Strait and Altamont Pass. Areas around the bay had about 5 $\mu g/m^3$ transported ammonium nitrate.

Ammonium sulfate levels in the Bay Area were spatially uniform at around 1 $\mu g/m^3$. This regional ammonium sulfate did not appear to be strongly transported from the Central Valley.

Central Valley levels for all PM components were nearly the same with and without Bay Area emissions. Therefore, it is unlikely that PM and its precursors were transported from the Bay Area into the Central Valley when Bay Area episodes occurred.

Figure 25 indicates average transport impacts that occurred under episodic Bay Area conditions. During the more severe episodes, transport impacts were often greater. Transport impacts were tabulated for the six days with highest measured $PM_{2.5}$ levels for both 2000-01 and 2006-07, for 12 days total. Total transported $PM_{2.5}$ levels averaged 19, 19, 11, and 12 $\mu g/m^3$ at the Livermore, Vallejo, San Jose, and San Francisco monitoring locations, respectively. Maximum total transported $PM_{2.5}$ levels were 33, 37, 24, and 24 $\mu g/m^3$ for these stations, respectively. Thus, 24-hour $PM_{2.5}$ exceedances could have occurred in the Bay Area without any Bay Area anthropogenic emissions. For these 12 days, transported primary $PM_{2.5}$ averaged 7, 8, 4, and 5 $\mu g/m^3$ and transported secondary $PM_{2.5}$ averaged 12, 11, 7, and 7 $\mu g/m^3$ for these four stations, respectively. Transported secondary $PM_{2.5}$ levels averaged around 40-80 percent more than transported primary $PM_{2.5}$ levels, depending upon location.

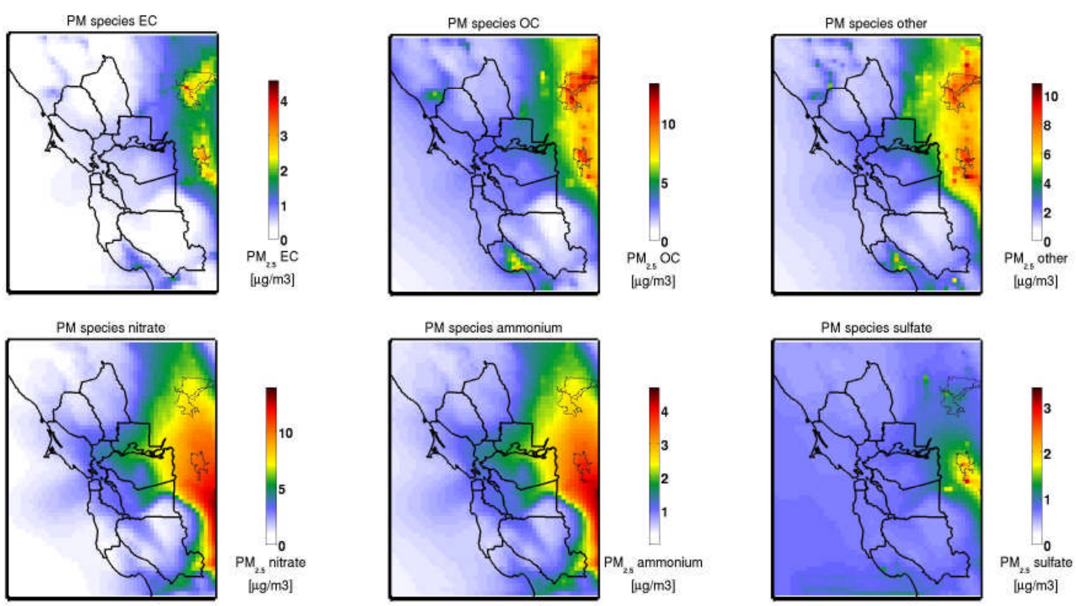


Figure 25. Same as Figure 16, except simulated with Bay Area anthropogenic emissions zeroed out. Scales are same as in Figure 16 to facilitate comparison.

5.5.2 Upwind emissions zeroed out

CMAQ was run separately with zero Sacramento area and San Joaquin Valley anthropogenic emissions for 12/2-2/2 of both 2000-01 and 2006-07. Simulated differences in 24-hour

$PM_{2.5}$ component levels between the base case and each transport run ($\Delta PM_{2.5}$, as defined in section 5.4.1) indicated how the Bay Area benefits from eliminating emissions in these upwind regions. The results were averaged across the same 55 days as shown in Figure 16 for which Bay Area maximum 24-hour $PM_{2.5}$ level exceeded 35 $\mu g/m^3$ in the base case simulation. $\Delta PM_{2.5}$ values for eliminating Sacramento area and San Joaquin Valley emissions are shown in Figure 26 and Figure 27, respectively.

Eliminating the primary PM emissions from the Sacramento area reduced levels of primary $PM_{2.5}$ (EC, OC, and other) through Carquinez Strait and into the northern portion of the Bay Area. Benefits of around 5 $\mu g/m^3$ primary $PM_{2.5}$ were achieved through Carquinez Strait. Benefits of reducing Sacramento area EC and OC emissions were primarily localized through Carquinez Strait. For the "other" $PM_{2.5}$ component, benefits additionally extended over the northern San Francisco peninsula and Santa Rosa. Benefits of reducing the other PM components extended farther into the Bay Area because these emissions occurred in the rural southwestern portion of the Sacramento Valley adjacent to the Bay Area. Sacramento area EC and OC emissions, on the other hand, were concentrated only around Sacramento. EC and OC were less strongly transported into the Bay Area because of the increased transport distance relative to the other primary PM components.

Eliminating the PM precursor emissions from the Sacramento area reduced levels of secondary ammonium nitrate $PM_{2.5}$ throughout the Bay Area. The benefits were largest and approximately equal in magnitude through both Carquinez Straight and Altamont Pass. The Sacramento area precursors contributed to regionally elevated Central Valley secondary $PM_{2.5}$ levels. This regional secondary $PM_{2.5}$ was then transported into the Bay Area through mountain passes connecting with the Central Valley. Through these passes, reductions in ammonium nitrate of around 2.5 $\mu g/m^3$ resulted from elimination of the Sacramento area emissions. Elsewhere throughout the Bay Area, the benefit was around 1.5 $\mu g/m^3$. These benefits may have been underestimated because the model sometimes produced overly strong winds throughout the Sacramento Valley during Bay Area episodes. This bias resulted in an underestimation of secondary PM levels away from the Sacramento source area.

Eliminating sulfur emissions from the Sacramento area had little impact on the Bay Area. Benefits of up to 0.1 $\mu g/m^3$ occurred for Solano County only.

Figure 26 indicates average transport impacts from the Sacramento area that occurred under episodic Bay Area conditions. During the more severe episodes, transport impacts were often greater. Transport impacts were tabulated for the six days with highest measured $PM_{2.5}$ levels for both 2000-01 and 2006-07, for 12 days total. Total transported $PM_{2.5}$ levels averaged 4, 5, 2, and 3 $\mu g/m^3$ at the Livermore, Vallejo, San Jose, and San Francisco monitoring locations, respectively. For these 12 days, transported primary $PM_{2.5}$ averaged 2, 3, 1, and 1 $\mu g/m^3$ and transported secondary $PM_{2.5}$ averaged 2, 2, 1, and 2 $\mu g/m^3$ for these four stations, respectively. Transported primary $PM_{2.5}$ levels were somewhat higher at Vallejo, and transported secondary $PM_{2.5}$ levels were somewhat higher for the other three monitoring locations.

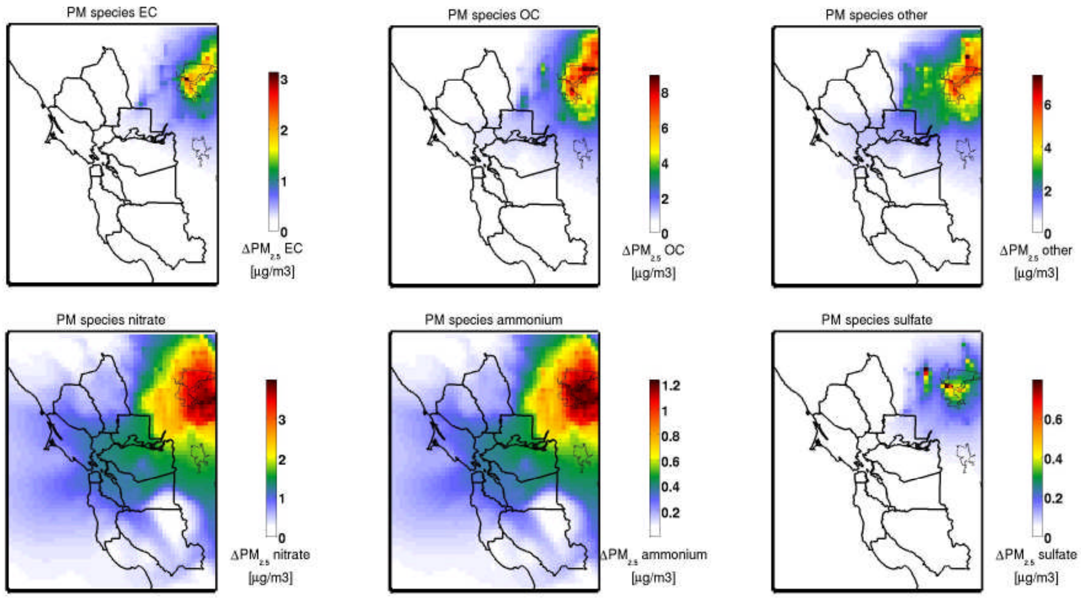


Figure 26. Benefit ($\Delta PM_{2.5}$) upon eliminating anthropogenic emissions for the Sacramento area. Averaged across same 55 days as for Figure 16 having base case simulated Bay Area PM levels exceeding 35 $\mu g/m^3$.

Elimination of the primary PM emissions from the San Joaquin Valley reduced levels of primary $PM_{2.5}$ (EC, most of the OC, and other) through Carquinez Strait and Altamont Pass. Benefits of around 4 $\mu g/m^3$ primary $PM_{2.5}$ were achieved through these mountain passes. Slightly lower benefits of around 3 $\mu g/m^3$ primary $PM_{2.5}$ were achieved through the Pacheco Pass and into southernmost Santa Clara County. Transported EC, OC, and other $PM_{2.5}$ affected the same locations within the Bay Area.

Eliminating the PM precursor emissions from the San Joaquin Valley reduced levels of secondary ammonium nitrate $PM_{2.5}$ throughout the Bay Area. The benefits were largest (up to 8 $\mu g/m^3$) through Pacheco Pass and into southernmost Santa Clara County. The benefits were enhanced and approximately equal in magnitude (up to 6 $\mu g/m^3$) over easternmost Contra Costa County and into Altamont Pass. Transport impacts were increased for the more southern mountain passes because secondary $PM_{2.5}$ levels generally increased further south into San Joaquin Valley. Elsewhere throughout the Bay Area, the benefit was around 5 $\mu g/m^3$.

Eliminating sulfur emissions from the San Joaquin Valley provided less than 0.5 $\mu g/m^3$ benefit through Carquinez Strait and Altamont Pass only.

Figure 27 indicates average transport impacts from the San Joaquin Valley that occurred under episodic Bay Area conditions. During the more severe episodes, transport impacts were often greater. Transport impacts were tabulated for the six days with highest measured $PM_{2.5}$ levels for both 2000-01 and 2006-07, for 12 days total. Total transported $PM_{2.5}$ levels averaged 13, 10, 7, and 7 $\mu g/m^3$ at the Livermore, Vallejo, San Jose, and San

Francisco monitoring locations, respectively. For these 12 days, transported primary $PM_{2.5}$ averaged 4, 2, 2, and 1 $\mu g/m^3$ and transported secondary $PM_{2.5}$ averaged 9, 7, 6, and 6 $\mu g/m^3$ for these four stations, respectively. Transported secondary $PM_{2.5}$ levels were 2.5-4 times higher than transported primary $PM_{2.5}$ levels.

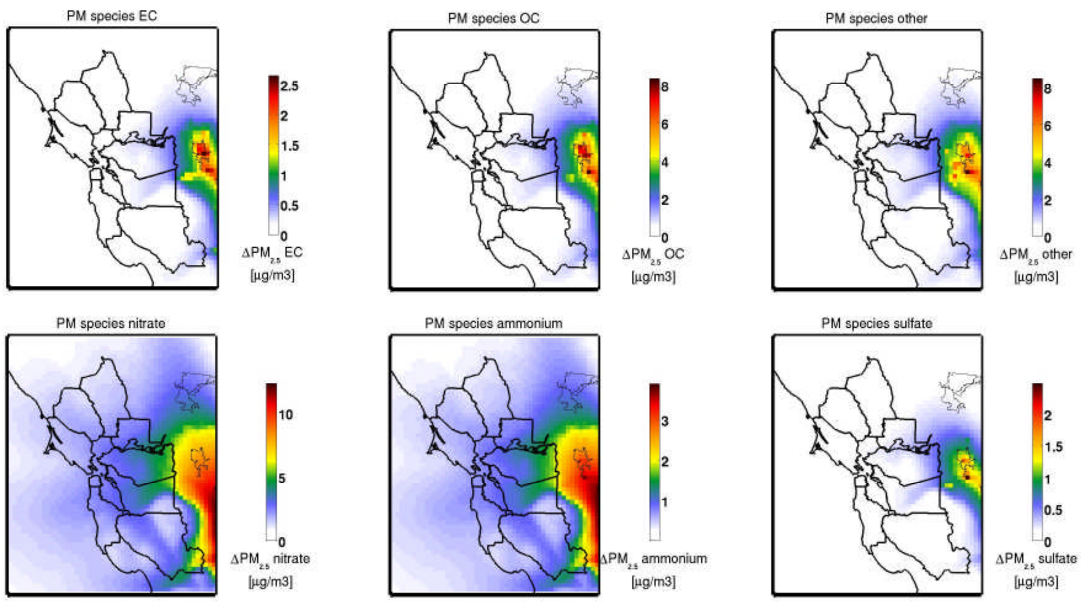


Figure 27. Benefit ($\Delta PM_{2.5}$) upon eliminating anthropogenic emissions for the San Joaquin Valley. Averaged across same 55 days as for Figure 16 having base case simulated Bay Area PM levels exceeding 35 $\mu g/m^3$.

The transport cluster analysis of section 4.3.3 identified two distinct weather patterns under which transport is believed to occur. One pattern exhibited bulk air flow into the Bay Area (through Carquinez Strait) from the Sacramento Valley (Figure 15, left panel), while the other pattern exhibited bulk flow from the San Joaquin Valley (Figure 15, right panel). Transport impacts were assessed by averaging $\Delta PM_{2.5}$ values across days associated with each transport pattern. Only days for which Bay Area maximum 24-hour $PM_{2.5}$ level exceeded the 30 $\mu g/m^3$ in the base case simulation were included in the averages. Transport impacts under each transport pattern were assessed separately for Sacramento area and San Joaquin Valley emissions zeroed out. During the transport simulation period, there were 41 days classified as having transport from the Sacramento area and 5 days classified as having transport from the San Joaquin Valley. Results are shown in Figure 28.

Zeroing out the Sacramento area emissions provided the greatest benefit to the Bay Area under the transport pattern with bulk air flow arriving from the Sacramento Valley. The benefit was around 5 $\mu g/m^3$ throughout the central portion of the Bay Area. This transported $PM_{2.5}$ was about half primary and half secondary. With bulk air flow arriving from the San Joaquin Valley, benefits of eliminating the Sacramento area emissions were smaller and limited to adjacent portions of the Bay Area.

Zeroing out the San Joaquin Valley emissions provided the greatest benefit to the Bay Area under the transport pattern with bulk air flow arriving from the San Joaquin Valley. The benefit was around 5-15 $\mu g/m^3$ throughout the northern portion of the Bay Area. Transport impacts were highest through the Carquinez Strait. This transported $PM_{2.5}$ was about one-third primary and two-thirds secondary. With bulk air flow arriving from the Sacramento Valley, benefits of eliminating the San Joaquin Valley emissions were smaller. Under these conditions, the central and southern portions of the Bay Area benefited the most, around 5-10 $\mu g/m^3$. Transported $PM_{2.5}$ levels through both the Altamont and Pacheco Passes were higher than through Carquinez Strait.

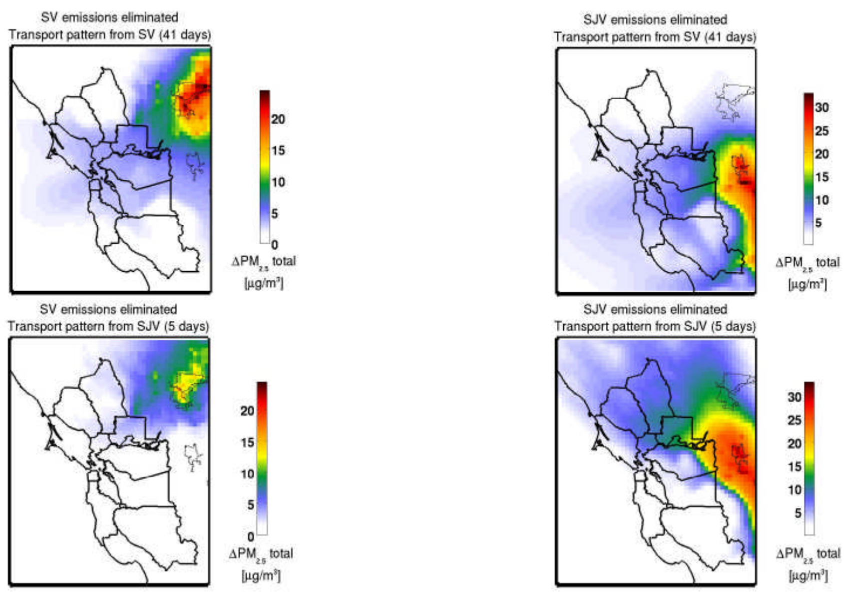


Figure 28. $\Delta PM_{2.5}$ values averaged across 41 days with transport from the Sacramento Valley (top panels) and 5 days with transport from the San Joaquin Valley (bottom panels). Transport simulations were conducted with Sacramento area anthropogenic emissions zeroed out (left panels) and with San Joaquin Valley anthropogenic emissions zeroed out (right panels).

6. Conclusions and further study

This report provided interim technical details of research efforts to better understand fine particulate matter ($PM_{2.5}$) formation in the Bay Area. The body of knowledge contained in this report was an enhancement by BAAQMD investigations to supplement research performed under state and federal agencies. This document provided a history of BAAQMD $PM_{2.5}$ research activities and described key results from a number of important studies. Research efforts included analyses of measurements as well as computer modeling.

6.1 Data analysis

6.1.1 Analysis of PM measurements

The Bay Area 24-hour $PM_{2.5}$ exceedances were almost entirely confined to the winter months. This season exhibited increased atmospheric stability that trapped pollutants near the ground. Consecutive stagnant, clear, and cool winter days were typically requisite for $PM_{2.5}$ episodes to develop. Stagnant conditions prevented dispersion of $PM_{2.5}$. Clear skies favored photochemical production of secondary $PM_{2.5}$, especially ammonium nitrate. Cool temperatures favored secondary ammonium nitrate particulate buildup by decreasing its tendency to evaporate. Typically, $PM_{2.5}$ levels would build for 2-4 days before a 24-hour exceedance occurred. Episodes commonly lasted a few days, but some persisted 1-2 weeks or longer. More stagnant winters tended to have more 24-hour $PM_{2.5}$ exceedances than those with more windy and stormy conditions.

$PM_{2.5}$ episodes were regional in nature and impacted most Bay Area locations. Livermore, Concord, San Jose, and Vallejo had 24-hour $PM_{2.5}$ design values at or near the NAAQS exceedance threshold of 35 $\mu g/m^3$. Other populated locations exhibited design values around 25-30 $\mu g/m^3$. Near-background $PM_{2.5}$ levels were observed at Point Reyes, where annual-average $PM_{2.5}$ levels were about half that of other Bay Area monitoring locations. The Bay Area is expected to attain the NAAQS for annual-average $PM_{2.5}$ level.

The composition of $PM_{2.5}$ varied throughout the Bay Area. Carbonaceous $PM_{2.5}$ (EC and OC) was mostly concentrated near its sources around the bay. Levels for secondary components sulfate, nitrate, and ammonium were relatively spatially uniform throughout the Bay Area. The secondary $PM_{2.5}$ components required a few days of air mass aging to reach appreciable levels, during which they were dispersed throughout the Bay Area. Bay Area secondary $PM_{2.5}$ was mostly ammonium nitrate. In terms of percentages, more urban locations around the bay had relatively higher proportions of primary $PM_{2.5}$, whereas more rural locations further inland had relatively higher proportions of secondary $PM_{2.5}$. Natural sea salt (sodium and chloride) levels were generally low, and were somewhat higher nearer the coast.

6.1.2 Chemical Mass Balance (CMB) for source apportionment

The Chemical Mass Balance (CMB) analysis was applied for source apportionment. CMB estimates the contributions (strengths) of predefined source categories to best account for the observed PM composition on a given day. Six source categories were used in the analysis: ammonium nitrate, ammonium sulfate, marine (sea salt) aerosol, geological and road dust, fossil fuels combustion, and biomass combustion. CMB analysis was performed on speciated $PM_{2.5}$ measurements from 5 locations mostly obtained during 1999-2001. Separate CMB analyses were performed to determine source contributions to peak 24-hour and annual average $PM_{2.5}$ levels. Isotopic carbon (^{14}C) analysis was used to adjust the raw CMB results to distinguish between combustion of fossil and non-fossil (biomass) materials. Source contributions were expressed as percentages to allow comparisons between sites having different $PM_{2.5}$ levels.

Source contributions to peak 24-hour $PM_{2.5}$ levels were based on measurements during episodic winter conditions. The urban and suburban locations (San Francisco, San Jose, and Livermore) exhibited comparable source contributions. Primary combustion sources (fossil and biomass) and secondary ammonium nitrate accounted for the bulk of $PM_{2.5}$. San Jose had a somewhat lower contribution of ammonium nitrate than the other heavily populated locations. San Francisco had a somewhat lower contribution of biomass burning than the other urbanized locations. The rural Bethel Island location had increased ammonium nitrate contribution and decreased fossil fuel combustion source strength relative to the more urbanized locations. Point Reyes was quite different from the other locations. The strongest contributing sources were naturally occurring marine aerosols (over 30 percent) and ammonium sulfate (20 percent). Ammonium nitrate contribution was lower at Point Reyes than for the other Bay Area monitoring locations. Overall, primary combustion particles and secondary ammonium nitrate were the main drivers for Bay Area $PM_{2.5}$ episodes impacting populated areas. Wood burning may have been the single largest $PM_{2.5}$ source contribution for the Bay Area during episodes. Geological dust, tire and break wear, and marine sources contributed near-negligible amounts to $PM_{2.5}$ exceedances.

Source contributions to annual average $PM_{2.5}$ levels were based on year-round measurements. The urban and suburban locations exhibited comparable source contributions. Primary combustion sources dominated. As with peak $PM_{2.5}$, biomass contributions were somewhat lower for San Francisco as compared to the other heavily populated locations. The rural Bethel Island location had higher secondary and lower primary contributions as compared with the more populated locations. It was most strongly impacted by regional secondary $PM_{2.5}$. The remote coastal location at Point Reyes was affected most strongly by marine and ammonium sulfate particulate. Overall, primary combustion particles accounted for the bulk of annual average $PM_{2.5}$ levels. Ammonium nitrate contributed somewhat more than ammonium sulfate and marine influences, which are comparable. Geological dust and tire and break wear contributed negligible amounts. Ammonium nitrate and biomass burning sources were much stronger during the winter than for the other seasons.

6.1.3 Relationships between weather patterns and PM

Meteorological characteristics associated with PM episodes were identified by comparing weather station observations between episodic and non-episodic winter days. Common meteorological characteristics associated with elevated Bay Area PM levels were light winds from the east throughout much of the Bay Area and also no rain. Such days generally exhibited cool temperatures; however, temperature itself was not a strong indicator of elevated PM levels. Exceedances of the 24-hour $PM_{2.5}$ standard in the Bay Area typically occurred as PM levels built over time upon three or more consecutive days having the above conditions.

Clustering of measurements from every winter day across more than 10 years robustly established how weather patterns impact Bay Area $PM_{2.5}$ levels. The cluster analysis revealed five dominant winter weather patterns prevailing over the Bay Area. Three of the clusters were conducive to elevated Bay Area PM levels. All three exhibited winds entering the Bay Area from the east. Two of these three clusters exhibited near-calm conditions in the Central Valley, where PM levels were considerably higher than in the Bay Area. These two clusters accounted for around 80 percent and 15 percent of all Bay Area 24-hour $PM_{2.5}$ exceedances, respectively. The cluster accounting for 80 percent of the Bay Area exceedances exhibited persistent easterly winds (arriving from the east) into the Bay Area throughout the day. The cluster accounting for 15 percent of the Bay Area exceedances exhibited easterly winds into the Bay Area during the overnight and morning hours. Winds often reversed to enter the Bay Area from the west during the afternoon. The third cluster with easterly flow into the Bay Area had high winds in the Central Valley and correspondingly increased dispersion rates. PM levels were higher than average; however, Bay Area exceedances were uncommon. The remaining two clusters exhibited marine winds entering the Bay Area from the west. Both of these clusters represented stormy conditions, and PM levels were low.

Atmospheric transitions of weather systems aloft profoundly influenced the surface winds that determine $PM_{2.5}$ levels. A developing or approaching upper-level high pressure center over Central California caused a transition from a high wind pattern into a low wind pattern for the region, resulting in increasing PM levels. Typically, PM would build to the exceedance level in 2-4 days upon a transition into an episodic weather pattern. Thereafter, PM levels remained approximately constant while the high pressure system persisted over Central California. A transition from an episodic weather pattern into one of the non-episodic patterns marked the onset of high surface winds that terminate the episodic conditions. Episodes often terminated abruptly when a migrating storm (cyclone) passed over the Bay Area. Transitions from an episodic weather pattern into a non-episodic pattern lacking rain were often associated with PM levels that decreased gradually over a few days.

Exceedances nearly always developed under: stable atmospheric conditions inhibiting vertical dispersion; clear and sunny skies favoring enhanced secondary $PM_{2.5}$ formation; and pronounced overnight drainage (downslope) flows off the Central Valley rims, causing low-level air in the Central Valley to empty through the Delta and into the Bay Area from its eastern boundary. Episodes exhibited considerable buildup of secondary PM, particularly ammonium nitrate. Ammonium nitrate levels in the Central Valley could be about 2-3 times higher than in the Bay Area. Central Valley conditions were more conducive to the transformation of NO_x to nitric acid (needed for the formation of ammonium nitrate) in the Central Valley than for coastal locations. Nitric acid then rapidly reacted with ammonia emissions, which were especially concentrated in the northern San Joaquin Valley, to form ammonium nitrate.

A refined cluster analysis further characterized the upwind Central Valley conditions during Bay Area episodes. Two distinct inter-regional air flow patterns were associated with different types of Bay Area episodes. The majority of exceedance days (around 60 percent) were associated with winds from the Sacramento Valley to the north entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred at San Jose for this type of episode. A minority of exceedance days (around 20 percent) were associated with winds from the San Joaquin Valley from the south entering the Bay Area through the Delta. Peak $PM_{2.5}$ levels typically occurred in the East Bay (at Livermore, Concord, or Vallejo) for this type of episode. The remaining relatively moderate episodes (around 20 percent) could not be associated with any distinct inter-regional transport pattern linking the Bay Area and surrounding air basins.

6.2 Computer modeling

A number of different simulations were performed to better understand $PM_{2.5}$ formation in the Bay Area. Three winter seasons were simulated. All PM and precursor sources were modeled for the winters of 2000-01 and 2006-07. The 2000-01 winter was simulated because extensive measurements were available from CRPAQS; however, this was a severe PM season with the highest PM levels on record. The 2006-07 winter exhibited moderate conditions that may have been more representative for air quality planning purposes. The third modeled winter was 2008-09. For this winter, only directly emitted PM from wood burning was simulated. This winter was simulated to evaluate the effectiveness of wood burning restrictions first enacted for the 2008-09 winter.

Meteorology for all three winters was simulated using MM5. $PM_{2.5}$ was simulated using CMAQ for 2000-01 and 2006-07, and wood smoke was simulated using CAMx for 2008-09. Emissions inventories comprised various data compiled by the ARB, BAAQMD, and Sonoma Technology, Inc. All meteorology and air quality model results were validated against measurements to be reasonably accurate.

6.2.1 Base-case PM modeling

CMAQ simulated six individual $PM_{2.5}$ components which were combined to estimate total $PM_{2.5}$ levels: ammonium, sulfate, nitrate, OC, EC, and other unresolved components. The simulated “other” component accounted for inert particulates including dust, marine aerosol, brake and tire wear, and trace metals.

EC and most of the OC resulted from primary emissions. The highest Bay Area EC levels occurred over West Oakland, reflecting Port of Oakland diesel sources. Aside from the rural Central Valley locations, EC accumulated only near its sources. OC levels were elevated for the same locations as EC, as well as other moderately populated areas. OC was associated with both commerce and household activities. OC levels over West Oakland, the EC hot spot, were lower than other areas having elevated OC levels. Also, OC may have been proportionally higher than EC over populated areas as compared to over highways and centers of commerce and industry. Accumulated EC and OC in the rural Central Valley locations demonstrated the lack of ventilation for this polluted valley. The "other" $PM_{2.5}$ component resulted from primary emissions only. It was elevated near highways and populated areas. It reflected trace metals from mobile and stationary combustion sources, suspended road dust, and small amounts of tire and brake wear particles. Geological dust did not appear to be a major contributor to elevated $PM_{2.5}$ levels under relatively calm conditions during the winter rainy season.

Ammonium nitrate was the dominant component of secondary $PM_{2.5}$. Ammonium nitrate levels were highest in the Central Valley. There was a general gradient with levels decreasing with distance from the Delta deeper into the Bay Area. The model results suggested that ammonium nitrate formation is limited by nitric acid, and not by ammonia. Ammonium sulfate was a minor component of secondary $PM_{2.5}$ during episodic conditions. Appreciable levels of ammonium sulfate in the Bay Area appeared only around the ports, industrial plants, and refineries near Oakland, Richmond, and Carquinez Straight. Ammonium sulfate also formed over the offshore shipping lanes from combustion of sulfur-laden bunker fuel. Because winds were from the east during episodes, these offshore sulfur sources did not strongly impact the Bay Area. Ammonium sulfate occasionally accounted for a moderate proportion of $PM_{2.5}$. This situation sometimes occurred under non-episodic conditions when winds were from the west and the shipping lanes were upwind of the Bay Area.

There was a distinct spatial gradient in the fraction of primary versus secondary $PM_{2.5}$ over Central California. In the Central Valley, at Modesto, $PM_{2.5}$ was composed of approximately equal portions of primary and secondary components, up to about 25 $\mu g/m^3$ of primary $PM_{2.5}$. Secondary $PM_{2.5}$ levels occasionally exceeded 35 $\mu g/m^3$, indicating that an exceedance could have occurred in the Central Valley even without any primary PM emissions. For high levels of primary $PM_{2.5}$ (beyond 25 $\mu g/m^3$), additional buildup of secondary $PM_{2.5}$ did not occur. In the Delta subregion, $PM_{2.5}$ characteristics were similar to Modesto; however, there was slightly more primary than secondary contribution. A similar effect was observed through the Altamont Pass and into the Livermore Valley. Here, however, total $PM_{2.5}$ levels were lower than in the Central Valley or Delta. Significant contributions of both primary and secondary $PM_{2.5}$ were required for an exceedance to occur in the eastern portion of the Bay Area. For the San Francisco and San Jose urban areas, $PM_{2.5}$ was dominated by primary contribution. Near these cities, $PM_{2.5}$ exceedances could have occurred from primary contributions alone. North of San Francisco, in the Petaluma Valley, $PM_{2.5}$ was more primary than secondary; however, primary components did not dominate as in the urban areas. Significant contributions of both primary and secondary $PM_{2.5}$ were required for an exceedance to occur in the North Bay.

6.2.2 PM sensitivities to Bay Area emissions reductions

Across-the-board Bay Area emissions reductions of 20 percent were simulated for the following five classes of chemical species: NO_x and VOC combined, gaseous sulfur species, ammonia, directly emitted PM, and these four classes combined, comprising all anthropogenic emissions. These across-the-board reductions were simulated for one episode each from 2000-01 and 2006-07.

Reducing the directly emitted PM reduced peak $PM_{2.5}$ levels nearly ten times more efficiently than reducing the secondary PM precursors. Benefits achieved from direct PM emissions reductions were only slightly below than that achieved from reducing all emissions. Reducing primary PM emissions by 20 percent (around 18 tons/day eliminated) typically reduced primary $PM_{2.5}$ levels by 12-20 percent, depending on location, with an average around 16 percent. Reductions of directly emitted PM were most effective near the PM emissions sources where primary $PM_{2.5}$ levels were highest (see Figure E-1). The largest benefits of around 4-6 $\mu g/m^3$ occurred near San Jose. Directly emitted PM reductions were less effective for some days at locations distant from PM sources, such as the eastern extremity of the Bay Area, Santa Rosa, and Livermore Valley.

Reducing ammonia emissions by 20 percent (around 15 tons/day) was the most effective of the precursor emissions reductions. The effectiveness of the 20 percent ammonia emissions reductions was roughly uniform throughout the Bay Area. Secondary $PM_{2.5}$ levels were typically reduced 0-4 percent, depending on location, with an average around 2 percent. Ammonia emissions reductions were less effective near ammonia sources, where the secondary PM forming chemistry was limited by lack of nitric acid. Ammonia reductions were also relatively ineffective for the extreme eastern portion of the Bay Area. This area adjacent to the Delta was mostly affected by transported secondary PM under episodic conditions having winds from the east.

Reducing NO_x and VOC emissions by 20 percent (around 250 tons/day total) was relatively ineffective. Small benefits from these emissions reductions occurred primarily around Santa Rosa.

Reducing sulfur-containing PM precursor emissions by 20 percent (around 16 tons/day) typically had a small impact on Bay Area $PM_{2.5}$ levels under episodic conditions. Benefits were similar as for the NO_x and VOC reductions. Tonnage reductions of sulfur (16 T/day), however, were around 15 times lower than for the combined NO_x and VOC reductions (250 T/day) required to achieve a similar effect. On certain days with the offshore shipping lanes upwind of the Bay Area, the 20 percent sulfur emissions reductions produced over 1 μg/m^3 benefit.

6.2.3 Transport impacts on Bay Area

Transport $PM_{2.5}$ simulations were performed by zeroing out anthropogenic emissions for various air basins. Transport impacts were evaluated for 55 days from 2000-01 and 2006-07 having simulated base case $PM_{2.5}$ levels 35 μg/m^3 or higher. Anthropogenic Bay Area emissions were eliminated to estimate the cumulative transport impacts from all sources outside of the Bay Area. Transported primary $PM_{2.5}$ levels were around 2-8 μg/m^3. Transport impacts were highest through Carquinez Straight and Altamont Pass which connect the Bay Area with the Central Valley. Transport impacts of secondary ammonium nitrate were as high as 13 μg/m^3 along the Bay Area eastern boundary, 8 μg/m^3 through the Carquinez Strait and Altamont Pass, and 5 μg/m^3 around the bay. Transported ammonium sulfate levels of around 1 μg/m^3 were present uniformly throughout the Bay Area. Ammonium sulfate appeared to be transported mostly from regions outside of the Central Valley. Central Valley $PM_{2.5}$ levels were relatively unaffected by eliminating the Bay Area emissions.

A second pair of $PM_{2.5}$ transport simulations was conducted by zeroing out anthropogenic emissions for the Sacramento area and San Joaquin Valley separately. Reductions in simulated $PM_{2.5}$ levels relative to the base case reflected transport impacts from the respective air basin for which emissions were eliminated. Eliminating the Sacramento area emissions reduced primary $PM_{2.5}$ levels around 5 μg/m^3 through Carquinez Strait, less than 2 μg/m^3 in the northern half of the Bay Area, and had little effect elsewhere in the Bay Area. Secondary $PM_{2.5}$ levels transported from the Sacramento area were 2.5 μg/m^3 through Carquinez Strait and Altamont Pass and around 1.5 μg/m^3 elsewhere in the Bay Area. Eliminating the San Joaquin Valley emissions reduced primary $PM_{2.5}$ levels around 4 μg/m^3 through Carquinez Strait and Altamont Pass, around 3 μg/m^3 through Pacheco Pass and into southern Santa Clara Valley, and had little impact farther into the Bay Area. Secondary $PM_{2.5}$ levels transported from the San Joaquin Valley were up to 8 μg/m^3 through Pacheco Pass and into southern Santa Clara Valley, around 6 μg/m^3 through Altamont Pass and into eastern Contra Costa County, and around 5 μg/m^3 elsewhere in the Bay Area.

During the more severe episodes, transport impacts were often greater than for the average episodic conditions. Transport impacts were tabulated for the six days with highest measured $PM_{2.5}$ levels for both 2000-01 and 2006-07, for 12 days total. Total transported $PM_{2.5}$ levels averaged 19, 19, 11, and 12 μg/m^3 at the Livermore, Vallejo, San Jose, and San Francisco monitoring locations, respectively. Maximum total transported $PM_{2.5}$ levels were 33, 37, 24, and 24 μg/m^3 for these stations, respectively. Thus, 24-hour $PM_{2.5}$ exceedances could have occurred in the Bay Area without any Bay Area anthropogenic emissions. Transported secondary $PM_{2.5}$ levels averaged around 40-80 percent more than transported primary $PM_{2.5}$ levels, depending upon location. Total transported $PM_{2.5}$ levels from the

Sacramento area averaged 4, 5, 2, and 3 $\mu g/m^3$ for these stations, respectively. At Vallejo, transported $PM_{2.5}$ from the Sacramento area had a somewhat higher proportion of primary components. At the other three locations, transported $PM_{2.5}$ from the Sacramento area had a somewhat higher proportion of secondary components. Total transported $PM_{2.5}$ levels from the San Joaquin Valley averaged 13, 10, 7, and 7 $\mu g/m^3$ for these stations, respectively. Transported secondary $PM_{2.5}$ from San Joaquin Valley were 2.5-4 times higher than transported primary $PM_{2.5}$ levels.

Simulated transport impacts were also compared across two different transport scenarios identified by the measurements-based meteorological cluster analysis (described above). There were 41 episodic days classified as having transport from the Sacramento area and 5 episodic days classified as having transport from the San Joaquin Valley. Zeroing out the Sacramento area emissions provided greater benefit in the Bay Area when transport occurred from the Sacramento area. Transported $PM_{2.5}$ from the Sacramento area was about half primary and half secondary. It mostly impacted the central and northern portions of the Bay Area. Zeroing out the San Joaquin Valley emissions provided greater benefit in the Bay Area when transport occurred from the San Joaquin Valley. Transported $PM_{2.5}$ from the San Joaquin Valley was about one-third primary and two-thirds secondary. It mostly impacted the central and southern portions of the Bay Area.

6.2.4 Wood smoke modeling

Wood smoke $PM_{2.5}$ levels were simulated for the 2008-09 winter. The simulation period contained 8 of the 11 Spare the Air days during the 2008-09 winter. Two different model runs were performed. Bay Area wood smoke levels were simulated with and without wood burning restrictions during the Spare the Air periods. For the run without burning restrictions, full wood burning emissions were simulated for the entire winter period. For the run with burning restrictions, wood burning emissions were eliminated from the simulation only for noon of each Spare the Air day through noon of the following day. This timing reflected 100 percent compliance with the actual periods of wood burning restriction. For all other periods, full wood burning emissions were simulated.

Without burning restrictions on the Spare the Air days, peak wood smoke levels of up to 10-20 $\mu g/m^3$ would have occurred over the areas having high wood burning emissions. Wood smoke levels would have been around 5 $\mu g/m^3$ or more for many of the remaining populated locations within the Bay Area. Peak benefits of the wood burning restrictions were around 10 $\mu g/m^3$ of reduced wood smoke. The 24-hour wood smoke levels (averaged midnight to midnight) were not reduced to zero because the burning restrictions did not begin until noon of the Spare the Air days. Also, carried over wood smoke from previous days may have impacted the Bay Area during the Spare the Air days. Simulated peak wood smoke levels and maximum benefits of burning restrictions sometimes occurred away from the monitoring locations. Modeling results suggested that reductions of population exposure to wood smoke were considerably greater than indicated by the monitoring data alone.

Without the burning restrictions, wood smoke levels for the eight simulated Spare the Air days would have averaged around 11, 7, 5, 3, and 3 $\mu g/m^3$ for the Concord, San Jose, San Francisco, Vallejo, and Livermore monitoring locations, respectively. Assuming 100 percent compliance, the burning restrictions were estimated to reduce these wood smoke levels by about 50-75 percent, depending on location. The burning restrictions had the added benefit of reducing carried over wood smoke into the days following burning restrictions. Because the burning restrictions reduced carry over, enhanced benefits may be achieved for multiple, consecutive Spare the Air calls. Two consecutive Spare the Air calls during 2008-09 provided the largest reductions of wood smoke levels simulated.

6.3 Overall conclusions

This report summarized a wealth of knowledge generated from BAAQMD in-house $PM_{2.5}$ research efforts that build on the EPA and ARB efforts. Various analyses of measurements were conducted to identify major sources and important weather patterns contributing to $PM_{2.5}$ buildup. Extensive simulations covered the bulk of three winter seasons. This custom computer model adequately reproduced the various phenomena represented in the measurements. The high degree of corroboration between the measurements- and modeling-based results provides a high level of confidence that the findings presented herein are both accurate and representative.

Primary and secondary $PM_{2.5}$ impact the Bay Area differently for both various locations and across a range of typical meteorological conditions. The model suggests that reducing direct $PM_{2.5}$ emissions within the Bay Area is the most effective means of reducing Bay Area primary $PM_{2.5}$ levels. These reductions, however, are most effective only near direct $PM_{2.5}$ emissions sources. These are the areas in which Bay Area total $PM_{2.5}$ levels are highest. The model also suggests that significant amounts of $PM_{2.5}$, especially secondary $PM_{2.5}$, are transported from the Central Valley. Secondary $PM_{2.5}$ exhibits a fairly regionally uniform influence throughout the Bay Area. Analysis of measurements identified separate transport patterns occurring on different days from either the Sacramento Valley or San Joaquin Valley. During 1999-2007, around 60 percent of Bay Area 24-hour $PM_{2.5}$ exceedance days occurred with transport from Sacramento area, and 20 percent with transport from San Joaquin Valley.

Model results indicated that Bay Area wood smoke levels during 2008-09 episodic conditions would have averaged 3-11 $\mu g/m^3$ without wood burning restrictions, depending on location. Spare the Air burning restrictions were estimated to have reduced wood smoke levels by around 50-75 percent assuming 100 percent compliance. Spare the Air calls on consecutive days had the added benefit of reducing carried over wood smoke, in addition to reducing fresh burning emissions.

Further research results and refinements to existing findings will be reported as new information becomes available. More measurements, including those from recently commissioned monitoring stations, will be added to the analyzed databases. Longer records of measurements will be especially useful for evaluating the effectiveness of wood burning restrictions. Modeling results will be enhanced by the development of more accurate emissions inventories. Additional winter seasons will be selected for both $PM_{2.5}$ and wood smoke simulations. Newer version models having enhanced physics and chemistry will be implemented for all simulations.

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Appendix A. PM modeling emissions inventory preparation

This appendix provides additional information on the magnitudes as well as the spatial and temporal distributions of both directly-emitted $PM_{2.5}$ and key secondary $PM_{2.5}$ precursors (TOG, NO_x, SO_2, and NH_3) used for modeling. Because much of the modeling effort was for wintertime 24-hour PM, the focus here is on wintertime emission levels rather than annual average levels. This will facilitate direct interpretation of PM modeling results as they are influenced by emissions. The modeling domain includes much of northern and central California.

The anthropogenic emissions inventory for the Bay Area portion of the modeling domain was developed from local information and assumptions. For the rest of the domain outside the Bay Area, inventories were taken from the ARB. Therefore, emissions are summarized below under two subheadings: BAAQMD emissions and emissions outside of BAAQMD. Modeling was conducted for two separate winters (2000-01 and 2006-07). Emissions were summarized for winter 2005 for the Bay Area portion and for winter 2006 for the rest of the modeling domain; i.e., tables below show base year emissions for BAAQMD and CARB data adjusted from 2000 to 2006.

The ARB provided a biogenic emissions inventory for the entire modeling domain from December 16, 2000 to January 7, 2001, the California Regional Particulate Matter Air Quality Study modeling period. For winter 2000-01 modeling, ARB's biogenic emissions inventory was used for the period coinciding with the above dates. For 2000-01 modeling periods outside of the above dates and for the entire 2006-07 winter, biogenic emissions were used from December 19, 2000. This day had an average winter temperature.

A.1 BAAQMD emissions

Table A-1 summarizes BAAQMD 2005 wintertime $PM_{2.5}$ emissions by county and major source category. These emissions were obtained by adjusting annual average daily emissions to reflect a winter scenario. The adjustments were based upon seasonal adjustment factors used in SMOKE. Overall, area source emissions dominated, with Santa Clara and Contra Costa Counties showing the two highest estimates. These two counties were followed by Alameda and Sonoma. The remaining counties had appreciably less emissions.

Table A-2 shows source contributions to the 2005 area source fine PM emissions shown above. Together, these two tables indicate that wood burning was the largest source of $PM_{2.5}$ for all but San Francisco and San Mateo Counties, where non-road sources (such as commercial marine and construction equipment) were larger.

Table A-1. 2005 wintertime $PM_{2.5}$ emissions by Bay Area county and major source category. (tons/day)

	2005				
County	Area	Nonroad	Onroad	Point	Total
Alameda	10.8	2.2	2.3	1.3	16.6
Contra Costa	14.9	0.9	1.1	3.4	20.3
Marin	4.2	0.6	0.2	0.1	5.1
Napa	3.3	0.2	0.2	0.1	3.8
San Francisco	4.0	1.3	0.5	0.2	6.0
San Mateo	5.3	2.1	0.6	0.5	8.5
Santa Clara	15.2	1.0	1.7	1.0	18.9
Solano	3.5	0.5	0.4	0.9	5.3
Sonoma	8.8	0.3	0.4	0.1	9.6
Total	70.0	9.1	7.4	7.6	94.1

Table A-2. 2005 wintertime BAAQMD $PM_{2.5}$ emissions from area source categories. (tons/day)

Source category	Alameda	Contra Costa	Marin	Napa	S.F.	San Mateo	Santa Clara	Solano	Sonoma	Total
Residential Wood Combustion	4.67	10.15	2.57	1.38	0.63	2.07	7.47	1.70	4.95	35.59
All Paved Roads	2.28	1.62	0.39	0.26	0.80	1.20	2.59	0.46	0.66	10.25
Charbroiling	0.92	0.46	0.14	0.09	0.87	0.46	1.05	0.28	0.32	4.59
Res./Com. Natural Gas Comb.	0.60	1.05	0.11	0.05	0.29	0.36	0.77	0.14	0.15	3.52
Misc. Food & Kindred Products	0.69	0.35	0.10	0.07	0.66	0.35	0.80	0.21	0.24	3.47
Poultry Waste Emissions	0.17	0.00	0.28	0.94	0.00	0.00	0.35	0.00	1.54	3.28
Domestic Animal Wastes	0.46	0.41	0.11	0.08	0.26	0.32	0.54	0.13	0.17	2.48
Industrial/Commercial/Institutional	0.22	0.15	0.03	0.07	0.20	0.11	0.28	0.16	0.07	1.29
All Unpaved Roads	0.04	0.06	0.08	0.02	0.00	0.11	0.45	0.03	0.03	0.82
Concrete/Gypsum/Plaster Prods	0.16	0.10	0.04	0.02	0.10	0.09	0.16	0.03	0.05	0.75
All Others	0.61	0.59	0.37	0.27	0.14	0.23	0.70	0.35	0.63	3.89
Total	10.82	14.94	4.22	3.25	3.95	5.30	15.16	3.49	8.81	69.94

Tables A-3 through A-6 show 2005 wintertime county-level emissions of total organic gases (TOG), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and ammonia (NH_3), respectively. Emissions are broken out by major source category. Solano and Sonoma County emissions only included those portions which lie inside the District boundaries.

Table A-3. 2005 wintertime TOG emissions by Bay Area county and major source category. (tons/day)

	2005				
County	Area	Nonroad	Onroad	Point	Total
Alameda	61.9	15.8	37.4	2.9	118.0
Contra Costa	77.9	10.9	25.2	9.5	123.5
Marin	21.4	5.8	7.0	0.2	34.4
Napa	16.9	3.5	5.5	0.3	26.2
San Francisco	23.7	8.5	13.5	1.0	46.7
San Mateo	25.6	9.3	17.7	1.1	53.7
Santa Clara	86.7	15.0	41.1	13.6	156.4
Solano	14.3	6.7	7.1	2.1	30.2
Sonoma	38.3	4.6	13.6	0.6	57.1
Total	366.8	80.1	168.1	31.3	646.2

Table A-4. 2005 wintertime NO_x emissions by Bay Area county and major source category. (tons/day)

	2005				
County	Area	Nonroad	Onroad	Point	Total
Alameda	5.6	45.3	78.5	0.9	130.3
Contra Costa	7.4	17.3	40.1	21.8	86.6
Marin	1.3	5.7	9.8	0.0	16.8
Napa	0.8	2.8	8.0	0.0	11.6
San Francisco	3.0	20.3	19.5	0.1	42.9
San Mateo	3.3	37.4	23.2	0.1	64.0
Santa Clara	7.6	24.2	60.8	1.0	93.6
Solano	1.3	9.5	14.1	17.8	42.7
Sonoma	2.0	5.5	17.3	0.0	24.8
Total	32.3	168.0	271.3	41.7	513.3

Wintertime TOG emissions were dominated by area sources, with solvent utilization leading the way, followed by livestock, waste disposal/treatment, and industrial processes.

The largest NO_x contribution came from on-road vehicles, with slightly more than half attributable to gasoline vehicles and the remainder from heavy-duty diesel trucks. NO_x emissions from commercial marine and construction equipment comprised roughly 70 percent of the non-road source contribution.

Table A-5. 2005 wintertime SO_2 emissions by Bay Area county and major source category. (tons/day)

	2005				
County	Area	Nonroad	Onroad	Point	Total
Alameda	0.2	2.2	0.6	4.0	7.0
Contra Costa	0.3	1.2	0.3	17.8	19.6
Marin	0.1	1.8	0.1	0.2	2.2
Napa	0.0	0.1	0.0	0.3	0.4
San Francisco	0.1	4.9	0.2	2.0	7.2
San Mateo	0.1	11.7	0.2	0.7	12.7
Santa Clara	0.3	0.4	0.4	7.4	8.5
Solano	0.0	0.7	0.1	5.9	6.7
Sonoma	0.1	0.2	0.1	0.4	0.8
Total	1.2	23.2	2.0	38.7	65.1

Table A-6. 2006 wintertime NH_3 emissions by Bay Area county and major source category. (tons/day)

	2006					
County	Area	Nonroad	Onroad	Point	Biogenic	Total
Alameda	7.49	0.02	2.52	0.62	0.49	11.14
Contra Costa	6.50	0.02	1.76	1.79	0.70	10.77
Marin	3.34	0.01	0.46	0.25	0.62	4.68
Napa	1.09	0.00	0.27	0.28	0.83	2.47
San Francisco	3.81	0.03	0.98	0.13	0.01	4.96
San Mateo	4.14	0.02	1.57	0.67	0.30	6.70
Santa Clara	8.23	0.02	3.13	5.84	0.43	17.65
Solano	2.05	0.00	0.46	1.53	1.20	5.24
Sonoma	6.29	0.01	0.73	1.01	2.47	10.51
Total	42.94	0.13	11.88	12.12	7.05	74.12

Bay Area ammonia emissions were predominantly from area sources. A breakdown of these area sources is shown in Figure A-1. By far, the largest area sources were animal wastes, both domestic and livestock. Human perspiration and respiration and residential fuel combustion rounded out the top 90 percent of area source emissions. For point sources, composting facilities/landfills contributed two-thirds of emissions, and the remainder came from miscellaneous industrial processes including wastewater treatment facilities and refineries.

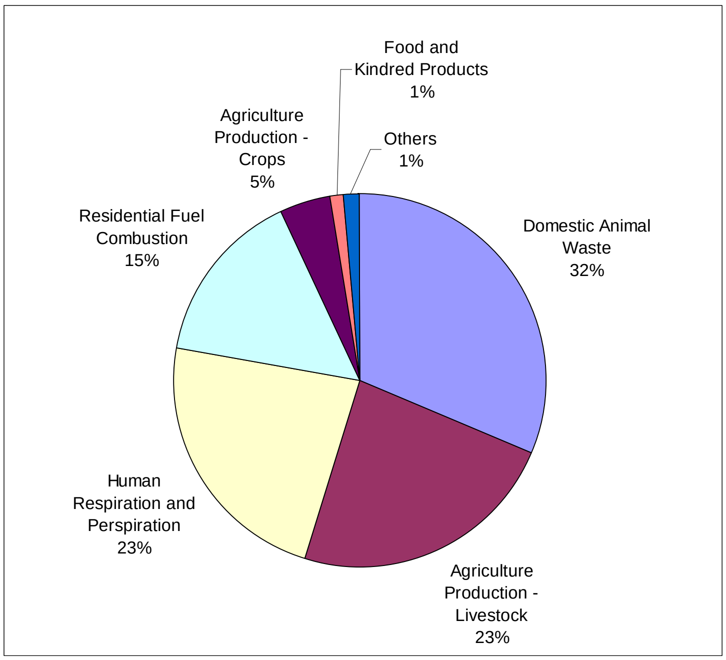


Figure A-1. Distribution of ammonia area source emissions for winter 2006.

Figures A-2 through A-6 illustrate the spatial distributions of BAAQMD wintertime $PM_{2.5}$, TOG, NO_x, SO_2 and NH_3 emissions, respectively.

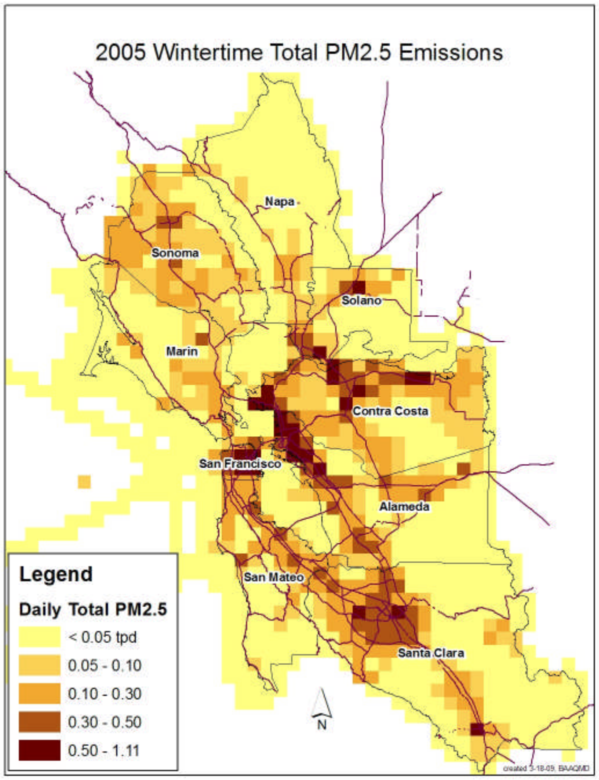


Figure A-2. Spatial distribution of $PM_{2.5}$ emissions.

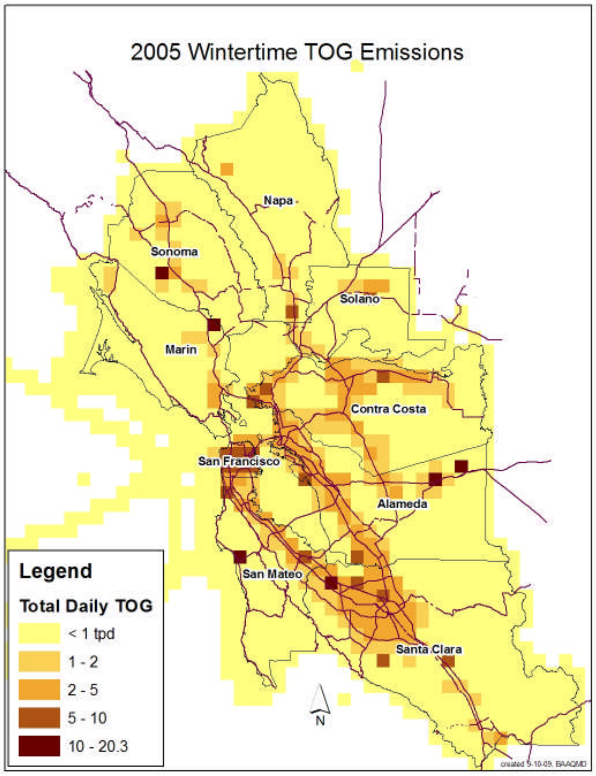


Figure A-3. Spatial distribution of TOG emissions.

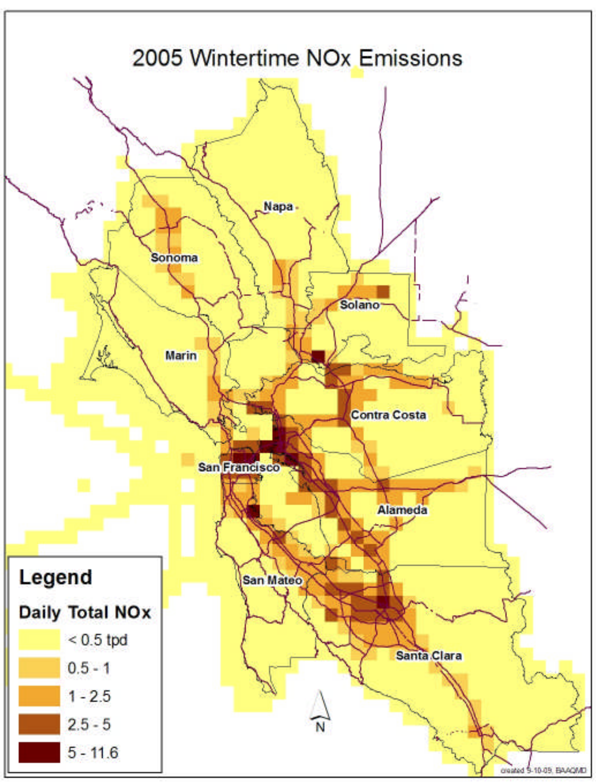


Figure A-4. Spatial distribution of NO_x emissions.

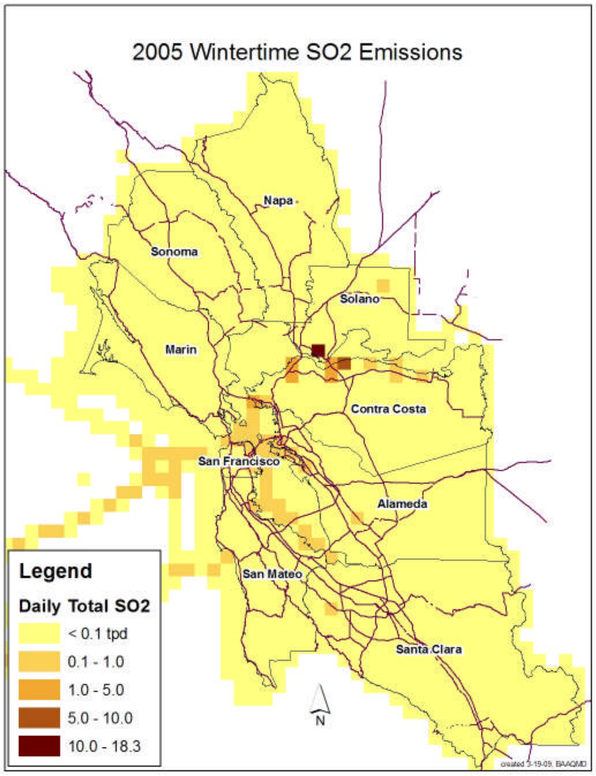


Figure A-5. Spatial distribution of SO_2 emissions.

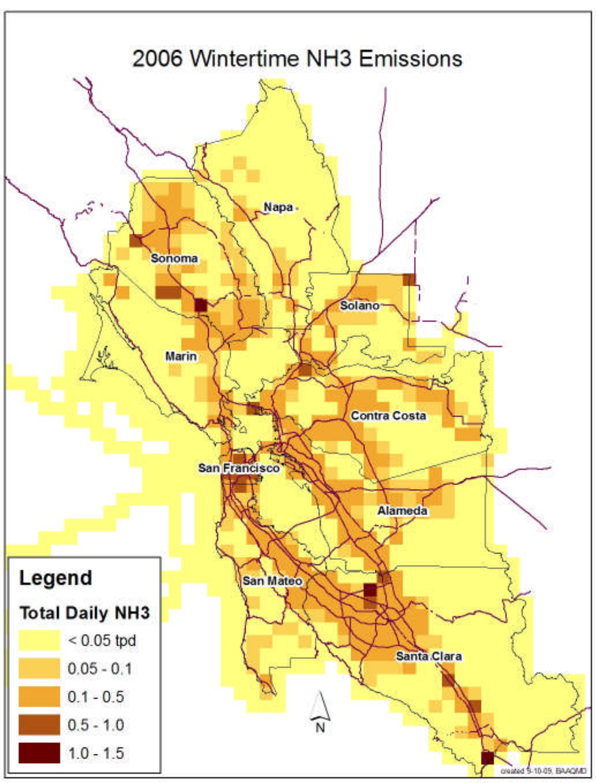


Figure A-6. Spatial distribution of NH_3 emissions.

With the exception of SO_2, emissions of these pollutants were generally found in populated places and/or nearby major arterials and highways. SO_2 emissions arose from commercial ships and stationary sources; therefore, their spatial distribution fell on major shipping lanes as well as centers of industry such as northern Contra Costa County.

With regards to temporal distributions of emissions, some source categories were assumed to follow a relatively "flat" diurnal distribution. This was particularly true of major stationary point sources, animal wastes, human perspiration and respiration, and commercial marine. Other categories followed distinctive hourly profiles for which data were available to construct the distributions. Some of the more significant of these sources are shown in Figure A-7.

Light-duty on-road vehicles had morning and afternoon peaks on weekdays, corresponding to the commute pattern. The morning peak was decidedly sharper than the evening peak. Heavy-duty vehicles, on the other hand, showed a single broad peak during the middle of the day and a much smaller late-night rise in activity. These profiles were based upon data from the ARB's EMFAC model. Wood burning had a bimodal distribution similar to light-duty vehicles, except that the evening peak was much later in the night, presumably after residents returned from work. The profile used to distribute construction equipment emissions concentrated activity in the afternoon and early evening hours. This allocation was questionable given anecdotal evidence and noise considerations and will undergo review. Also under review is the use of weekday profiles for weekend days for which local data were lacking.

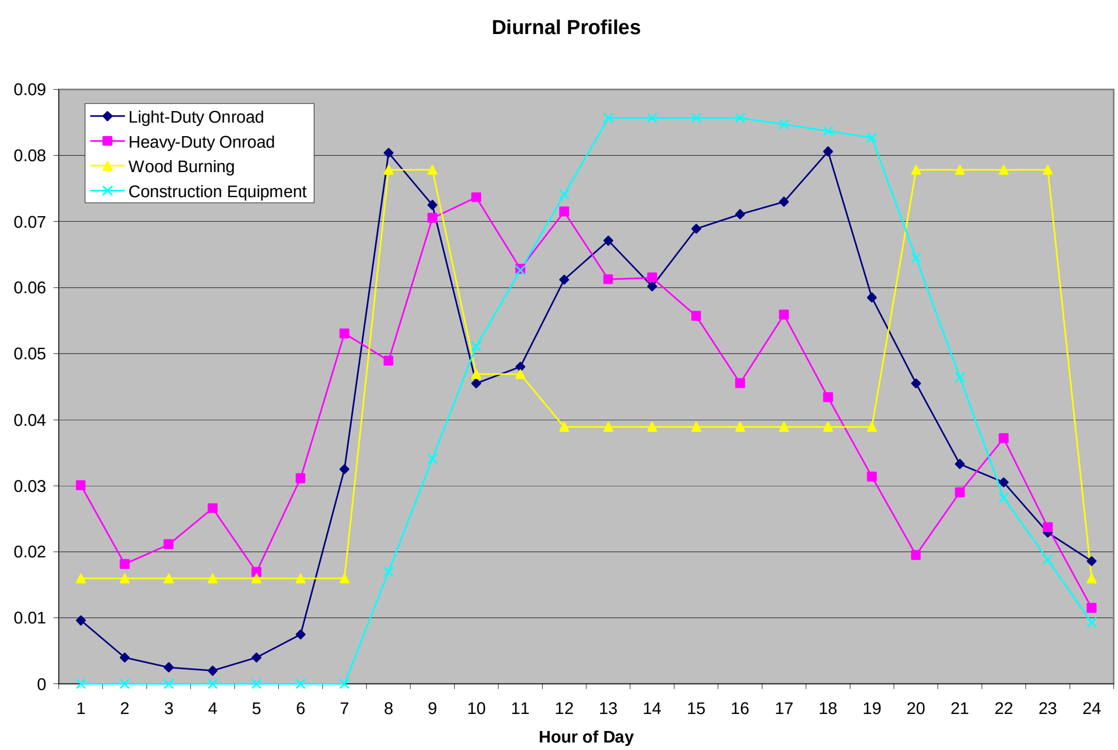


Figure A-7. Weekday diurnal profiles assumed for emissions from select key Bay Area $PM_{2.5}$ sources.

A.2 Emissions outside the BAAQMD

Table A-7 shows 2006 wintertime emissions by major source category for California areas outside of the BAAQMD but within the CRPAQS modeling domain (see Figure 2 in the main report). These emissions included the portions of Solano and Sonoma Counties which lie outside the Bay Area District. A total of 45 counties were included, though some only in part.

Table A-7. 2006 wintertime weekday emissions for areas of the modeling domain outside the BAAQMD (tons/day).

Source Category	SO_2	NO_x	TOG	$PM_{2.5}$
Area	18	158	2935	374
Non-road	49	412	124	25
Heavy-duty On-road	3	414	49	20
Light-duty On-road	2	393	223	6
Point	56	207	318	40
Total	128	1584	3649	465

Area source TOG emissions in the table above were dominated by livestock operations and landfills. For $PM_{2.5}$, emissions were from residential fuel combustion, road dust, crops production (tilling), and prescribed burning.

The total winter daily average ammonia emissions for portions of the modeling domain which lie outside the BAAQMD were about 300 tons. This was about four times the amount in the Bay Area.

Biogenic TOG emissions over the entire modeling domain, including the Bay Area, ranged from 490 to 668 tons per day during the winter simulation period. These values represented the sum of methyl butenol, isoprene, monoterpenes and other volatile organic compounds (OVOC). Much of these emissions were outside the BAAQMD, as shown in Figure A-8.

Biogenic emissions were strongly influenced by both temperature and photosynthetically-active radiation (PAR). These two factors dictated the diurnal distribution of these emissions. Due to the day-to-day variation of temperture and PAR, the magnitude and temporal profile of biogenic emissions changed each day. In general, biogenic emissions peaked during daylight hours and returned to a baseline value for the overnight hours. This timing is illustrated in Figure A-9.

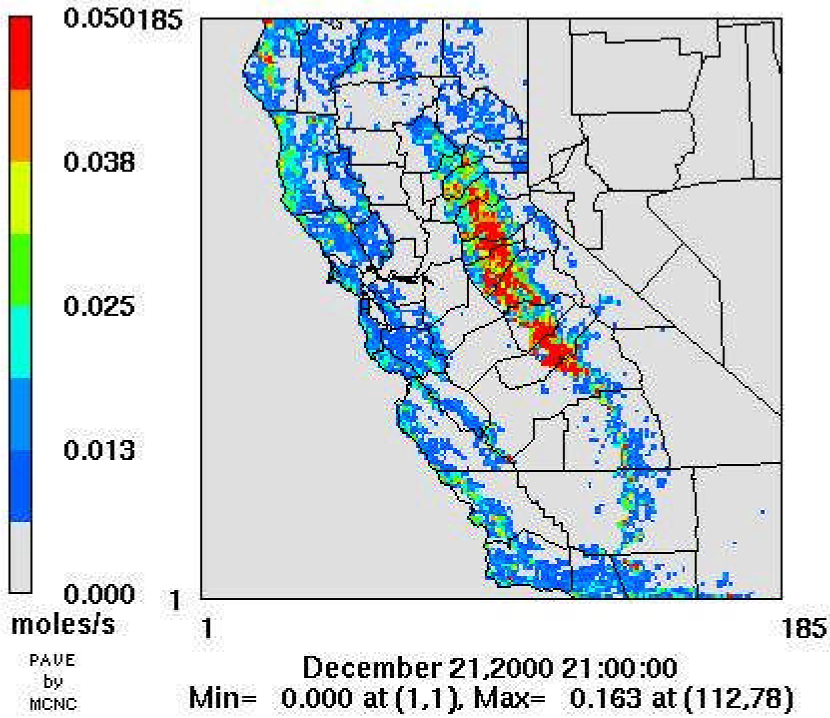


Figure A-8. Representative spatial distribution of biogenic TOG emissions.

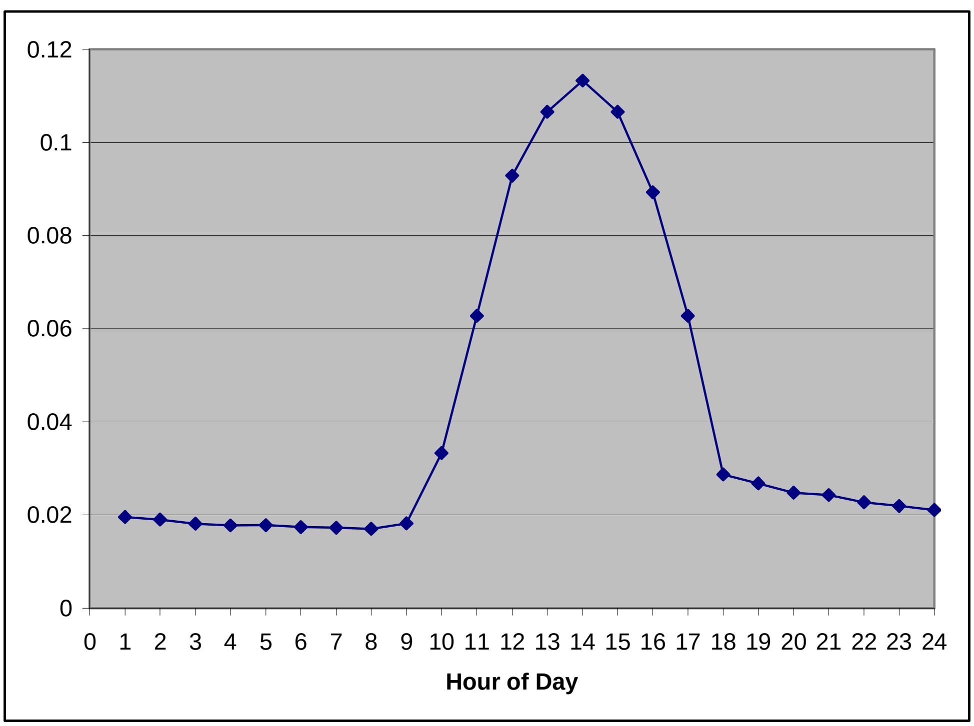


Figure A-9. Diurnal profile for biogenic TOG emissions throughout the modeling domain on December 19, 2000.

Appendix B. Meteorological model validation

The ENVIRON METSTAT program (Emery et al., 2001) was used to compare the MM5 generated meteorological fields against hourly surface observations archived at NCAR. METSTAT is a statistical analysis software package that calculates and graphically presents statistics such as mean observation, mean simulation, bias error, gross error, index of agreement (IOA), etc. Locations of the weather stations used for the validation are shown in Figure 1.

Hourly time series of observed and simulated surface-layer wind and temperature are presented to evaluate the model performance. Statistics are defined as follows:

Mean observation (M_o): calculated from all sites with valid data within a given analysis region and for a given time period (hourly or daily):

$$M_o = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I} O_j^i$$

where O_j^i is the individual observed quantity at site *i* and time *j*, and the summations are over all sites (*I*) and over time periods (*J*).

Mean prediction (M_p): calculated from simulation results that are interpolated to each observation used to calculate the mean observation (hourly or daily):

$$M_p = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I} P_j^i$$

where P_j^i is the individual simulated quantity at site *i* and time *j*. Note that mean observed and simulated winds are vector-averaged (for east-west component *u* and north-south component *v*), from which the mean wind speed and mean resultant direction are derived.

Bias error (*B*): calculated as the mean difference in prediction-observation pairings with valid data within a given analysis region and for a given time period (hourly or daily):

$$B = \frac{1}{IJ}\sum_{j=1}^{J}\sum_{i=1}^{I}\left(P_j^i - O_j^i\right)$$

B.1 MM5 validation for PM simulation periods

The hourly time series of regionally averaged observed and simulated surface-layer wind, temperature, and humidity for December-January of 2000-01 and 2006-07 are shown in Figures B-1 through B-16. The MM5 model results were averaged over the 4-km CRPAQS

MM5 domain. The figures show that the MM5 simulations are in good agreement with the observations.

BAAQMD 4km 2000 MM5 -- December

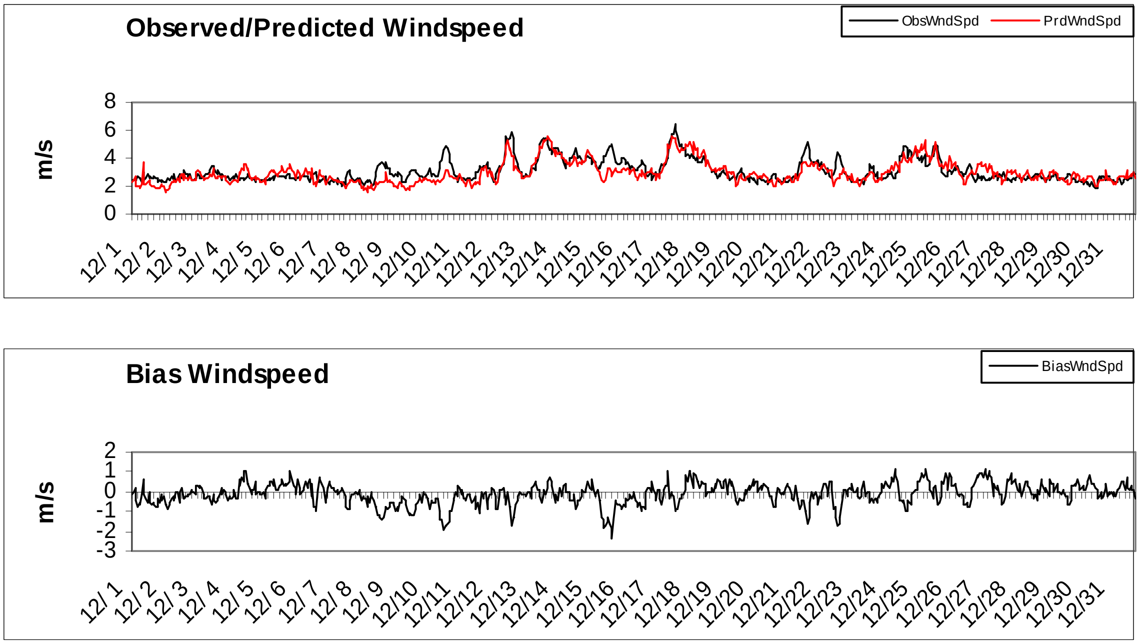


Figure B-1. Hourly time series of region-average observed and predicted surface-layer wind speed and performance statistics in the 4-km MM5 domain for December 2000.

BAAQMD 4km 2000 MM5 – December

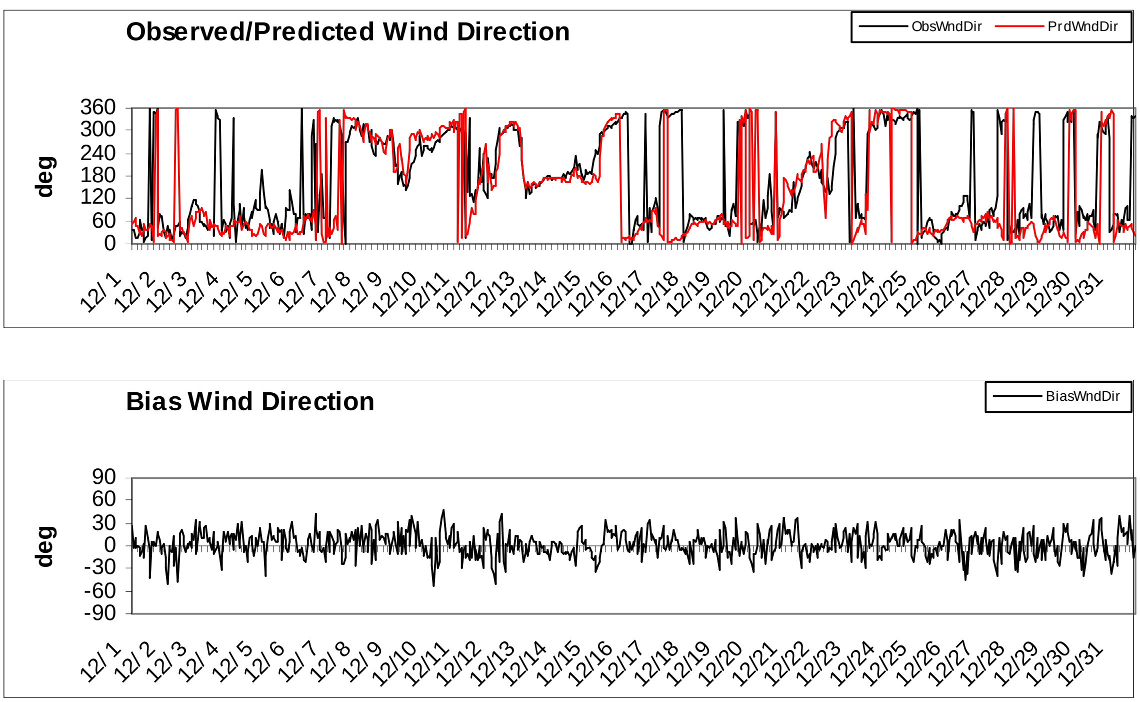


Figure B-2. Hourly time series of region-average observed and predicted surface-layer wind direction and performance statistics in the 4-km MM5 domain for December 2000.

BAAQMD 4km 2000 MM5 – December

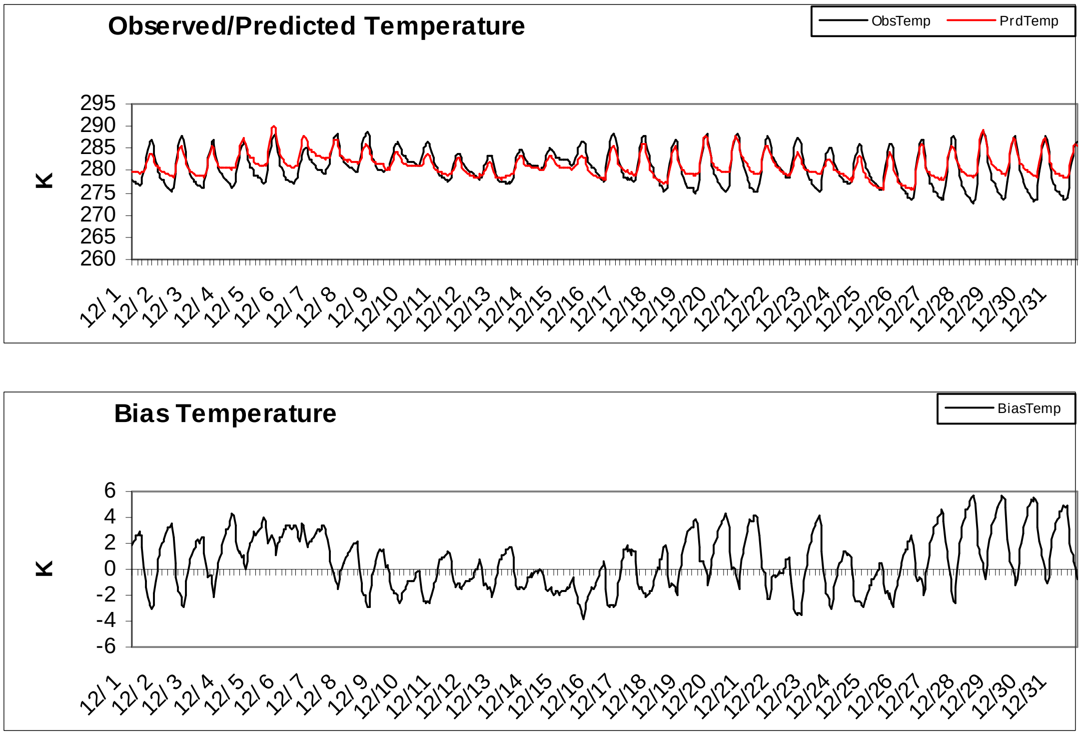


Figure B-3. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for December 2000.

BAAQMD 4km 2000 MM5 – December

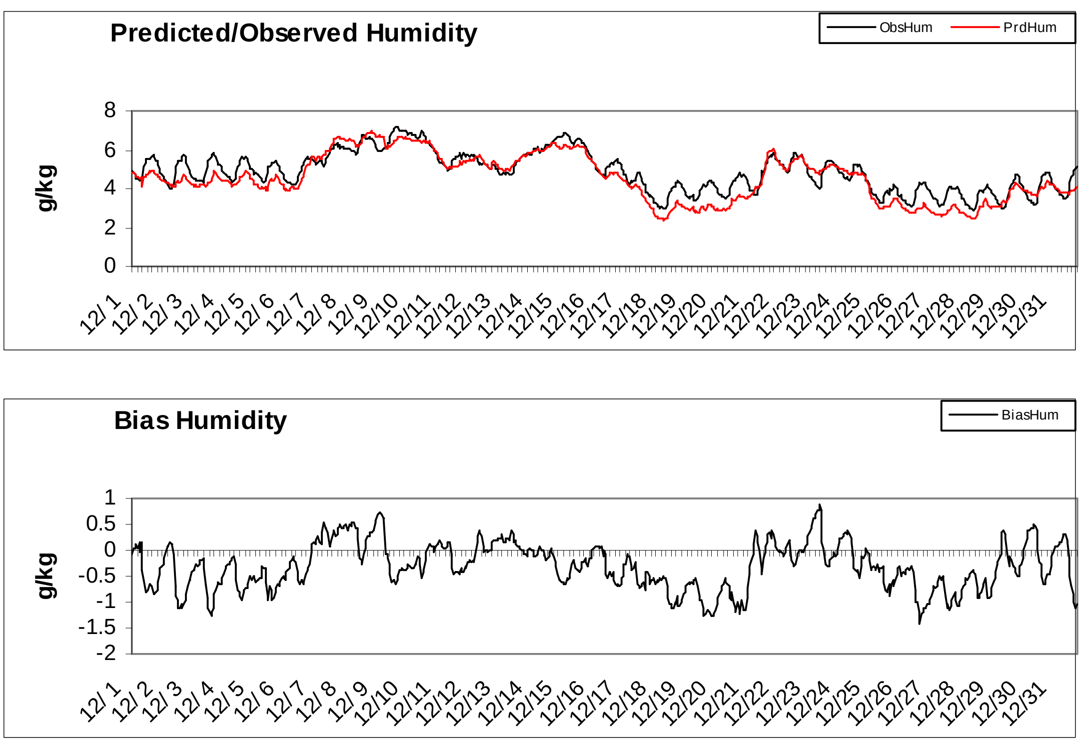


Figure B-4. Hourly time series of region-average observed and predicted surface-layer humidity and performance statistics in the 4-km MM5 domain for December 2000.

BAAQMD 4km 2001 MM5 -- January

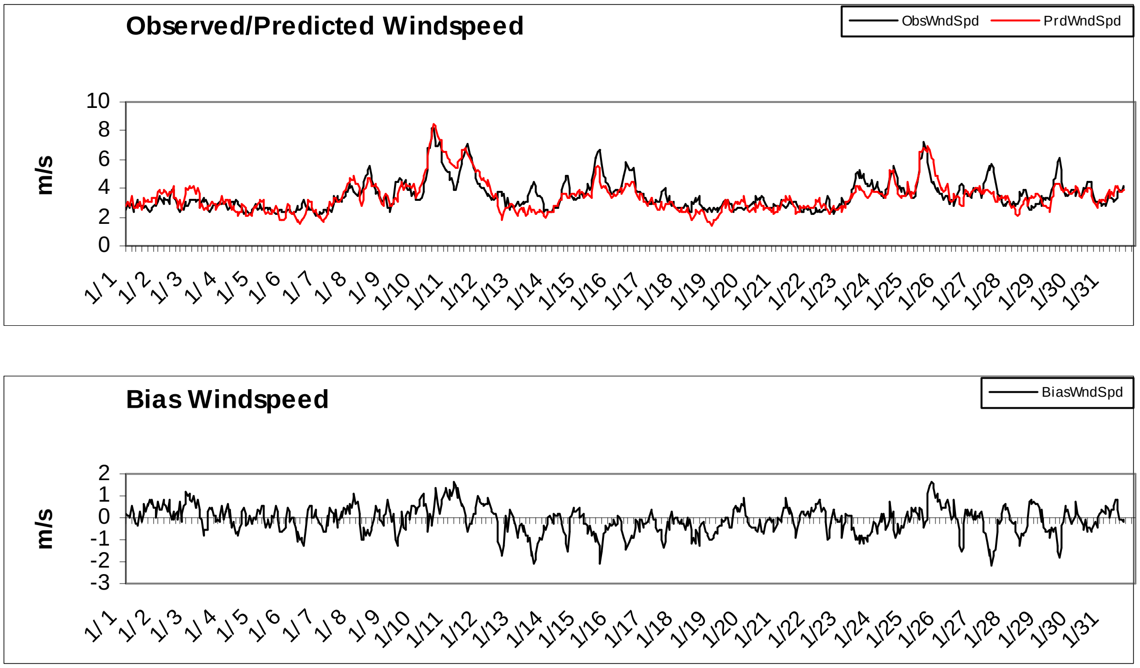


Figure B-5. Hourly time series of region-average observed and predicted surface-layer wind speed and performance statistics in the 4-km MM5 domain for January 2001.

BAAQMD 4km 2001 MM5 – January

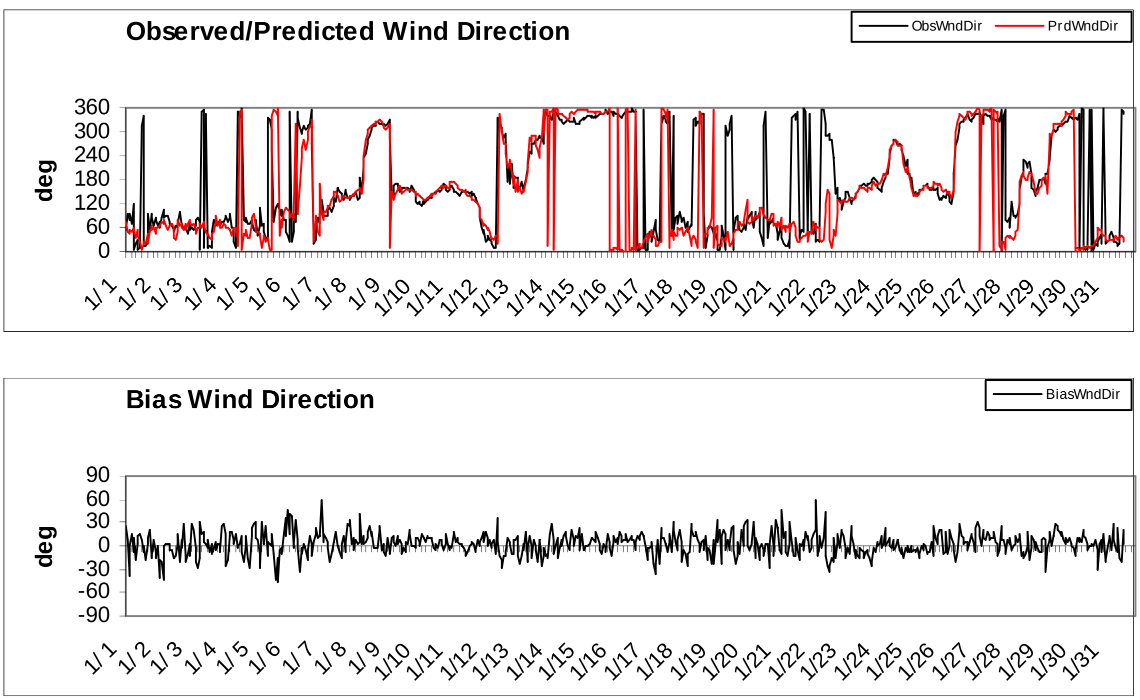


Figure B-6. Hourly time series of region-average observed and predicted surface-layer wind direction and performance statistics in the 4-km MM5 domain for January 2001.

BAAQMD 4km 2001 MM5 -- January

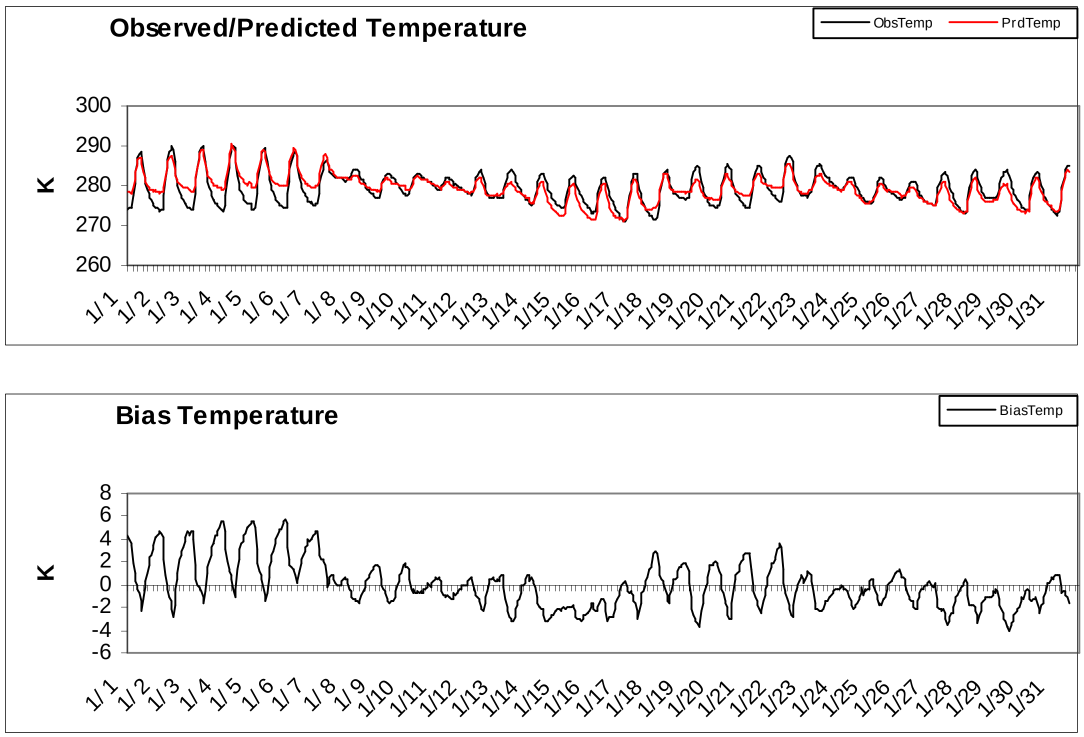


Figure B-7. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for January 2001.

BAAQMD 4km 2001 MM5 – January

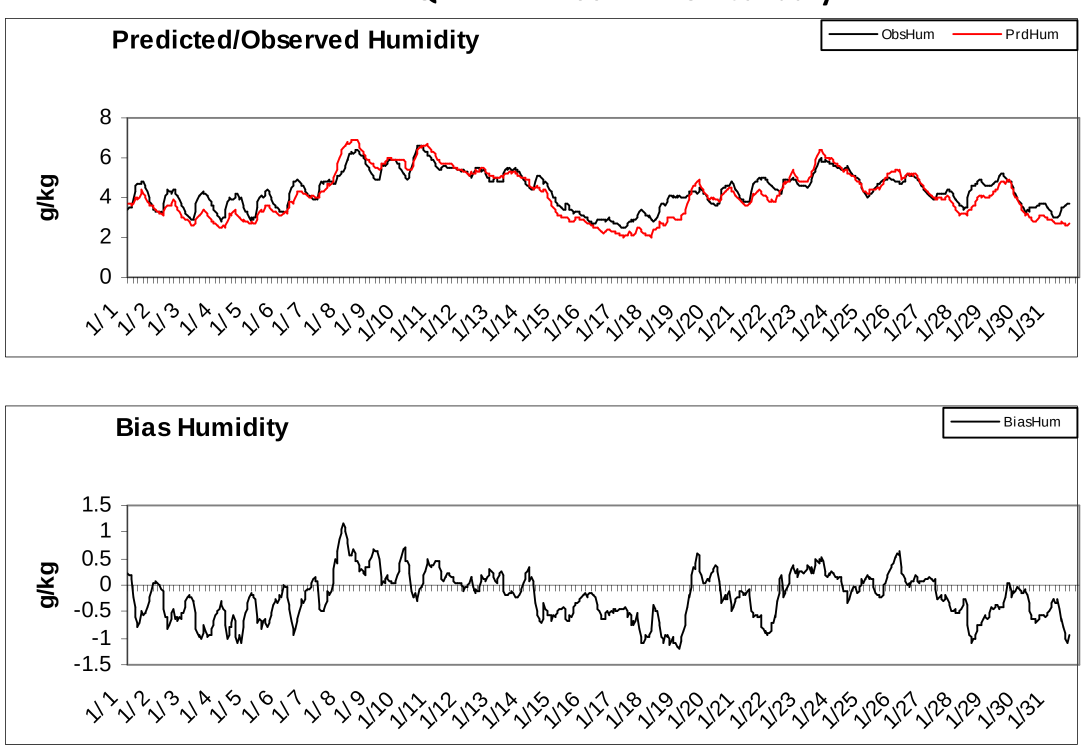


Figure B-8. Hourly time series of region-average observed and predicted surface-layer humidity and performance statistics in the 4-km MM5 domain for January 2001.

BAAQMD 4km 2006 MM5 – December

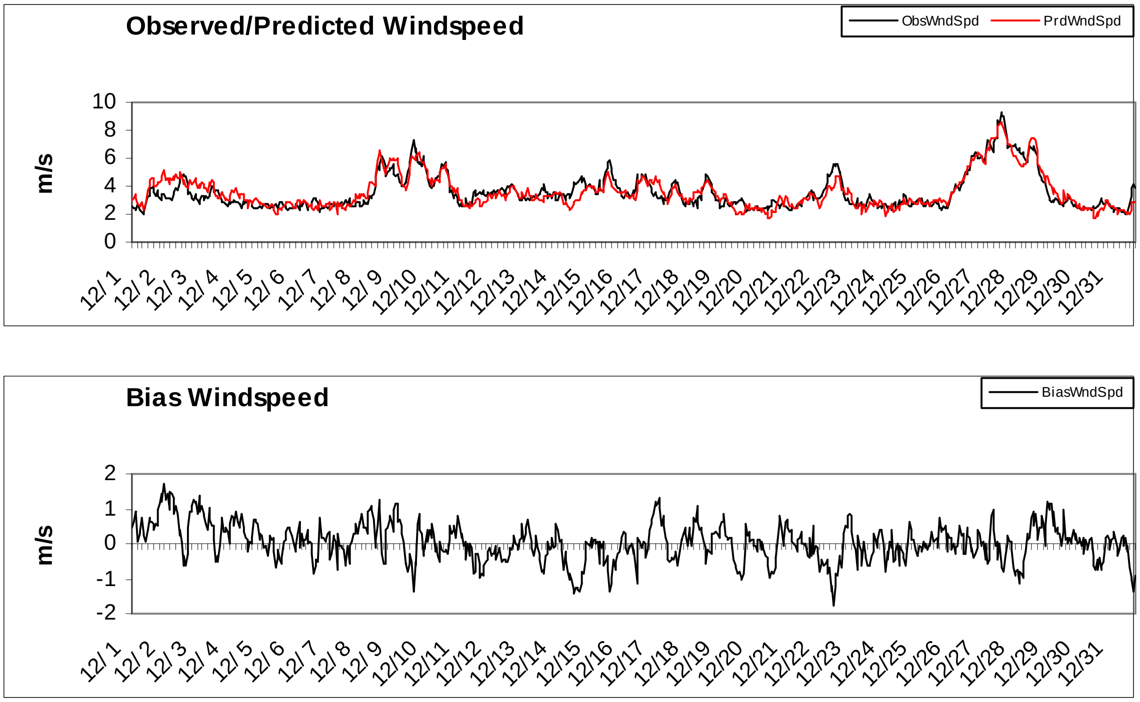


Figure B-9. Hourly time series of region-average observed and predicted surface-layer wind speed and performance statistics in the 4-km MM5 domain for December 2006.

BAAQMD 4km 2006 MM5 – December

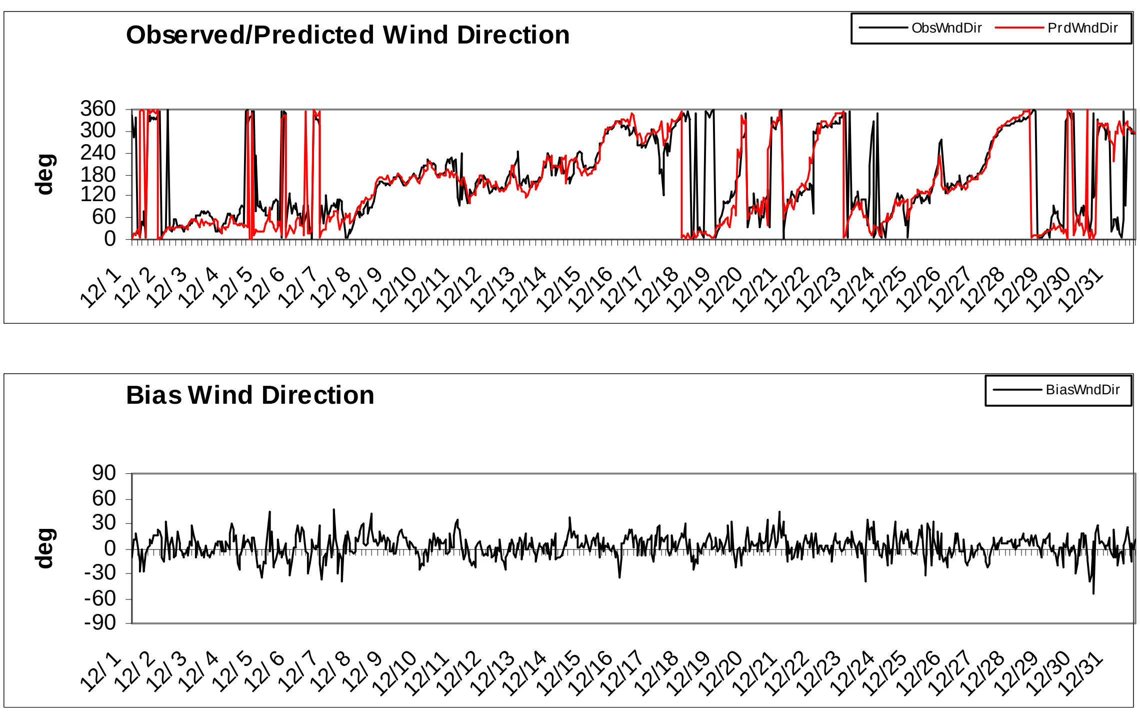


Figure B-10. Hourly time series of region-average observed and predicted surface-layer wind direction and performance statistics in the 4-km MM5 domain for December 2006.

BAAQMD 4km 2006 MM5 – December

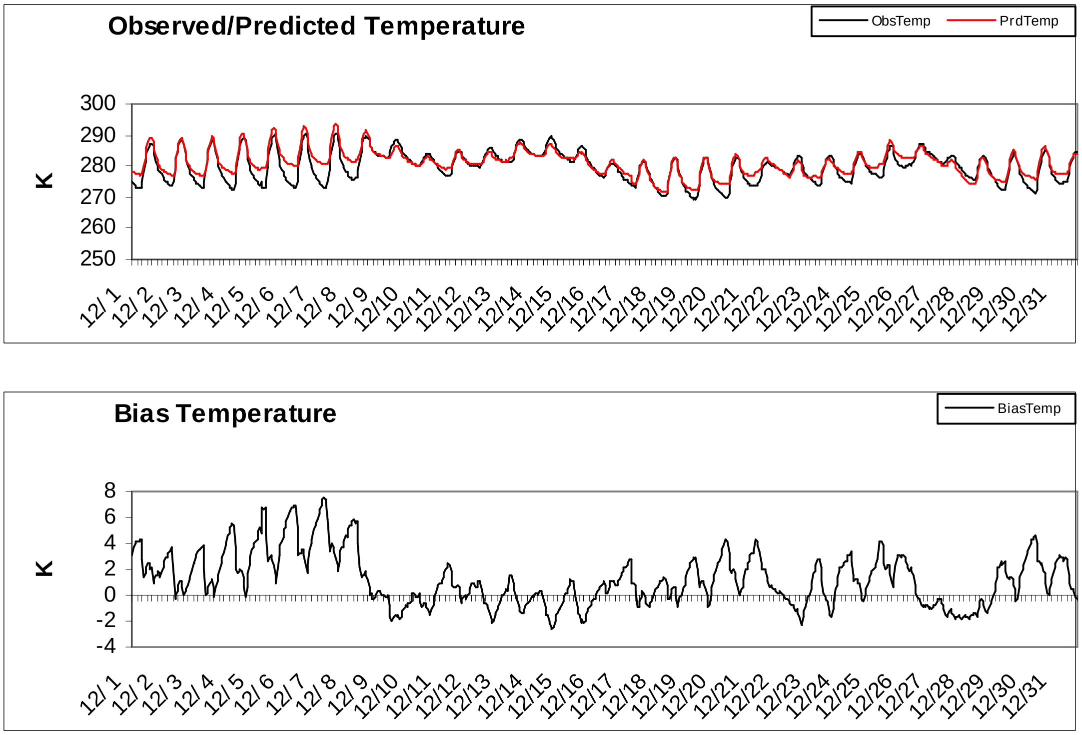


Figure B-11. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for December 2006.

BAAQMD 4km 2006 MM5 – December

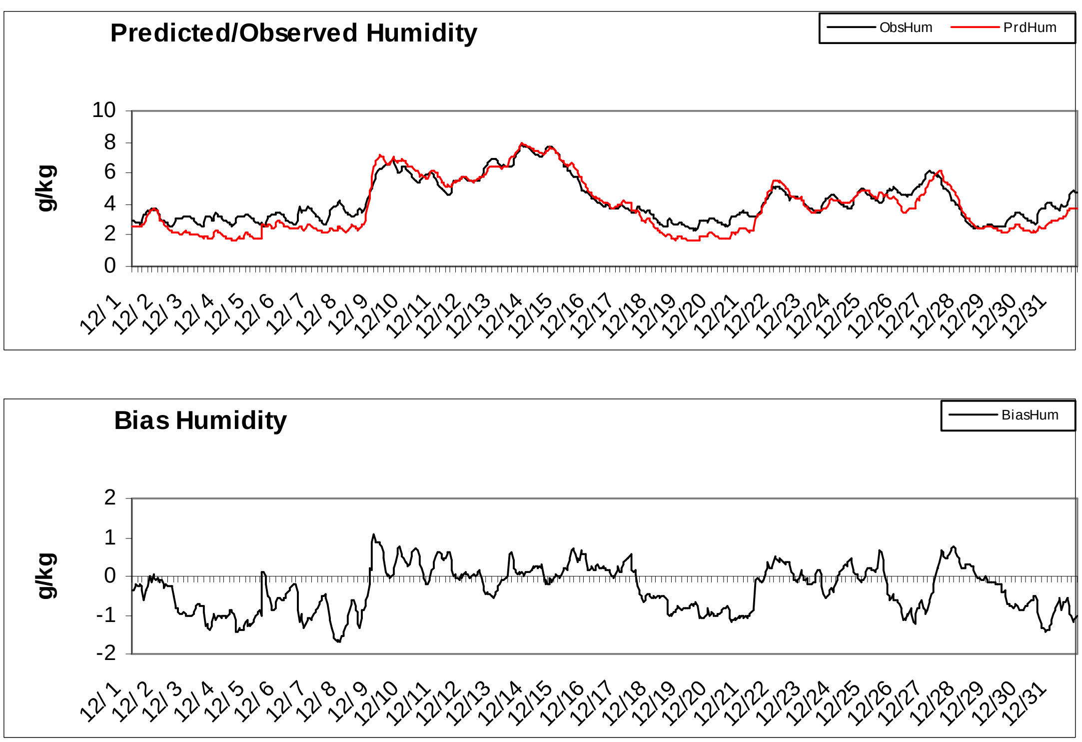


Figure B-12. Hourly time series of region-average observed and predicted surface-layer humidity and performance statistics in the 4-km MM5 domain for December 2006.

BAAQMD 4km 2007 MM5 -- January

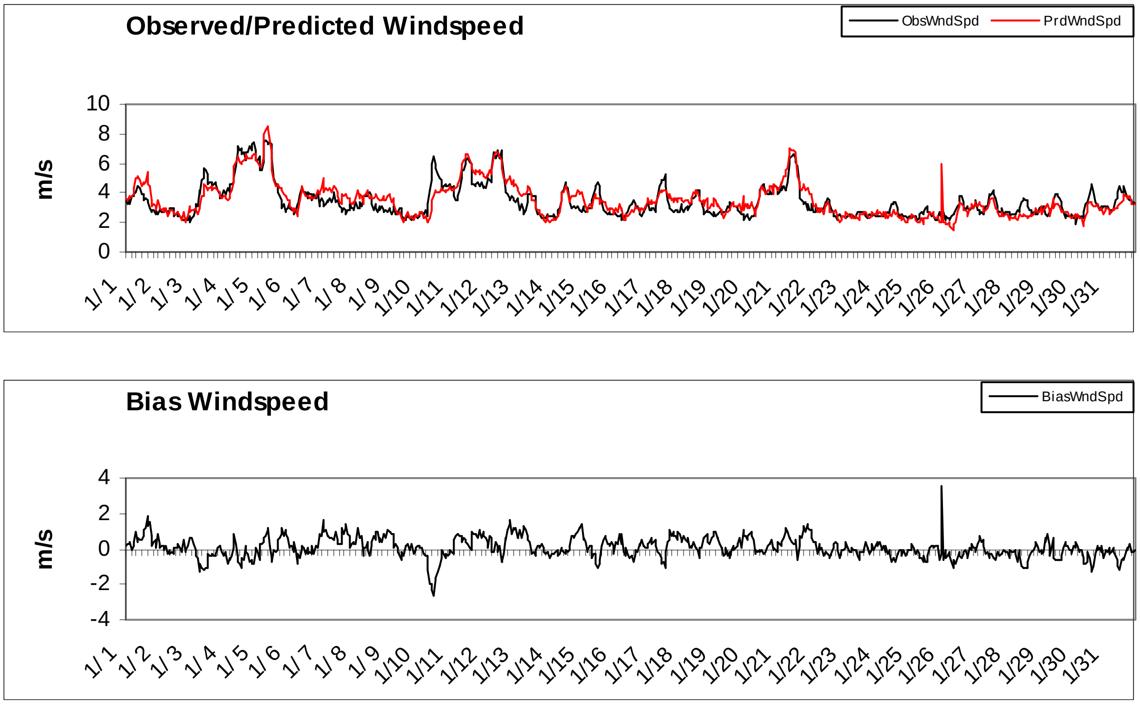


Figure B-13. Hourly time series of region-average observed and predicted surface-layer wind speed and performance statistics in the 4-km MM5 domain for January 2007.

BAAQMD 4km 2007 MM5 – January

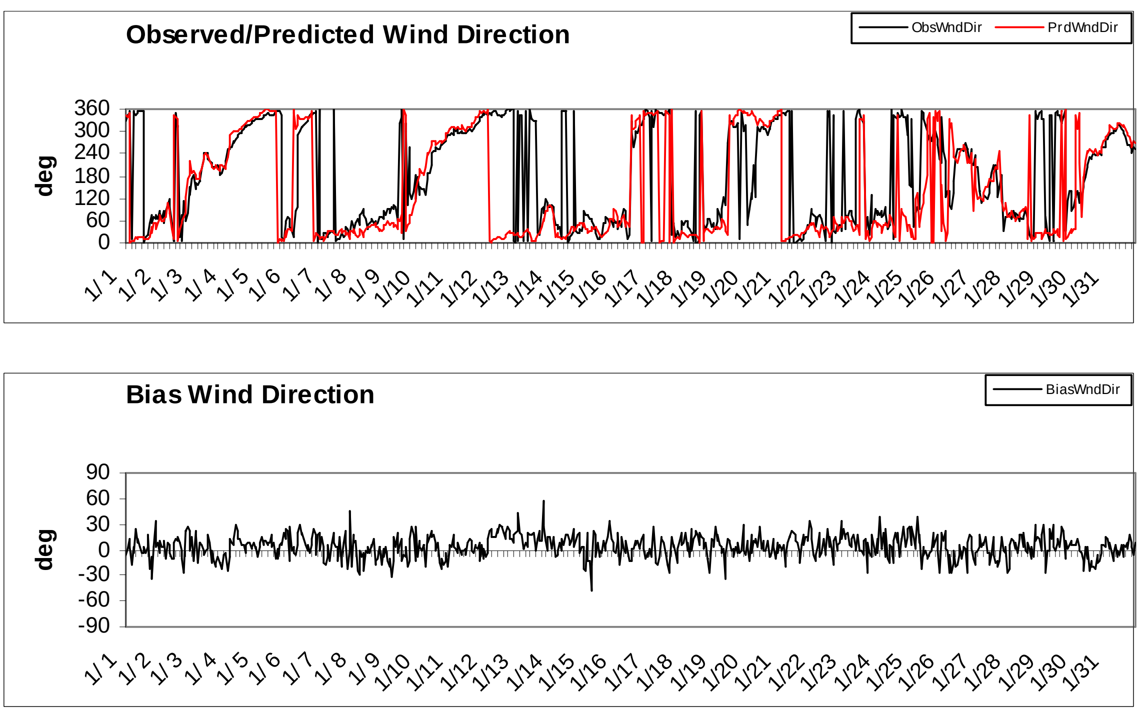


Figure B-14. Hourly time series of region-average observed and predicted surface-layer wind direction and performance statistics in the 4-km MM5 domain for January 2007.

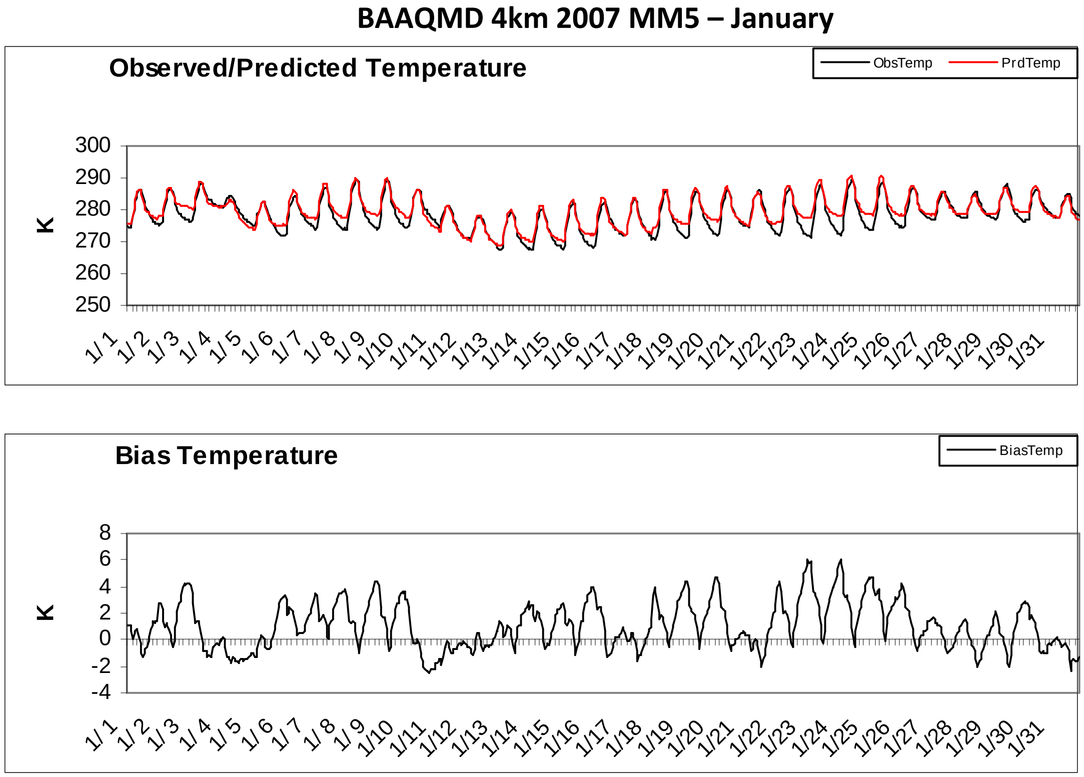


Figure B-15. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for January 2007.

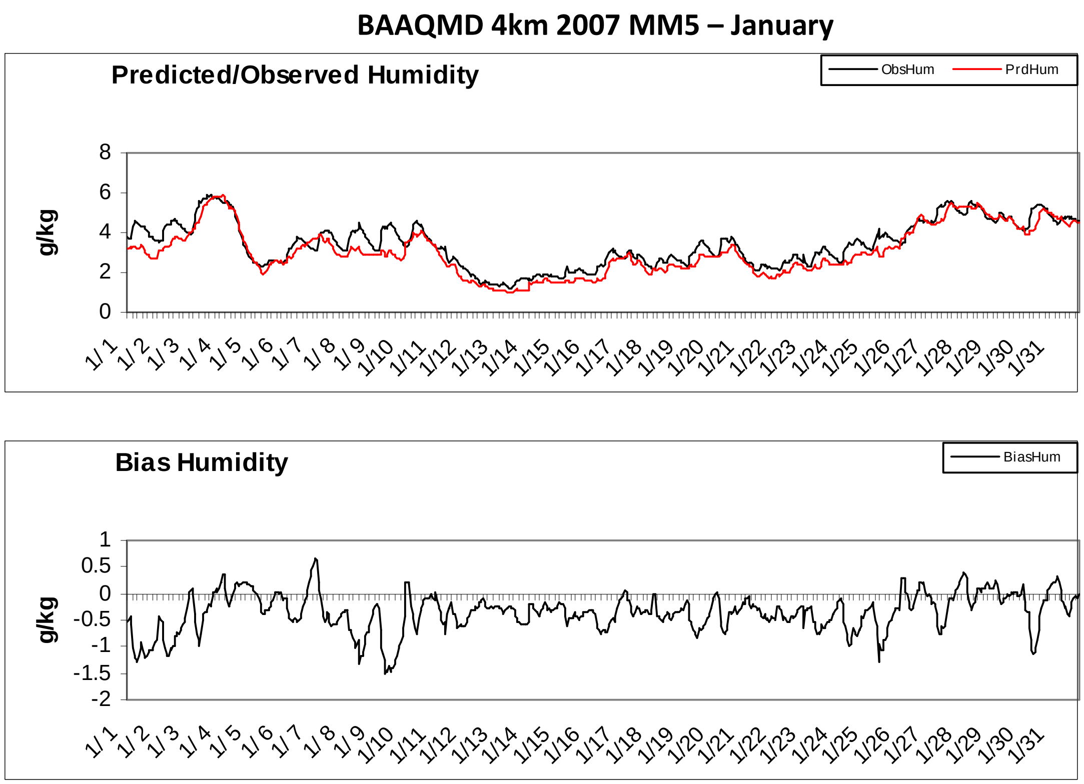


Figure B-16. Hourly time series of region-average observed and predicted surface-layer humidity and performance statistics in the 4-km MM5 domain for January 2007.

B.2 MM5 validation for wood smoke simulation periods

The hourly time series of regionally averaged observed and predicted surface-layer wind and temperature for November-February of 2008-09 are shown in Figures B-17 to B-24. The MM5 model results were averaged over the 4-km Bay Area MM5 domain. The MM5 simulations showed reasonably good agreement with the observations.

BAAQMD 4km 2008 MM5 – November

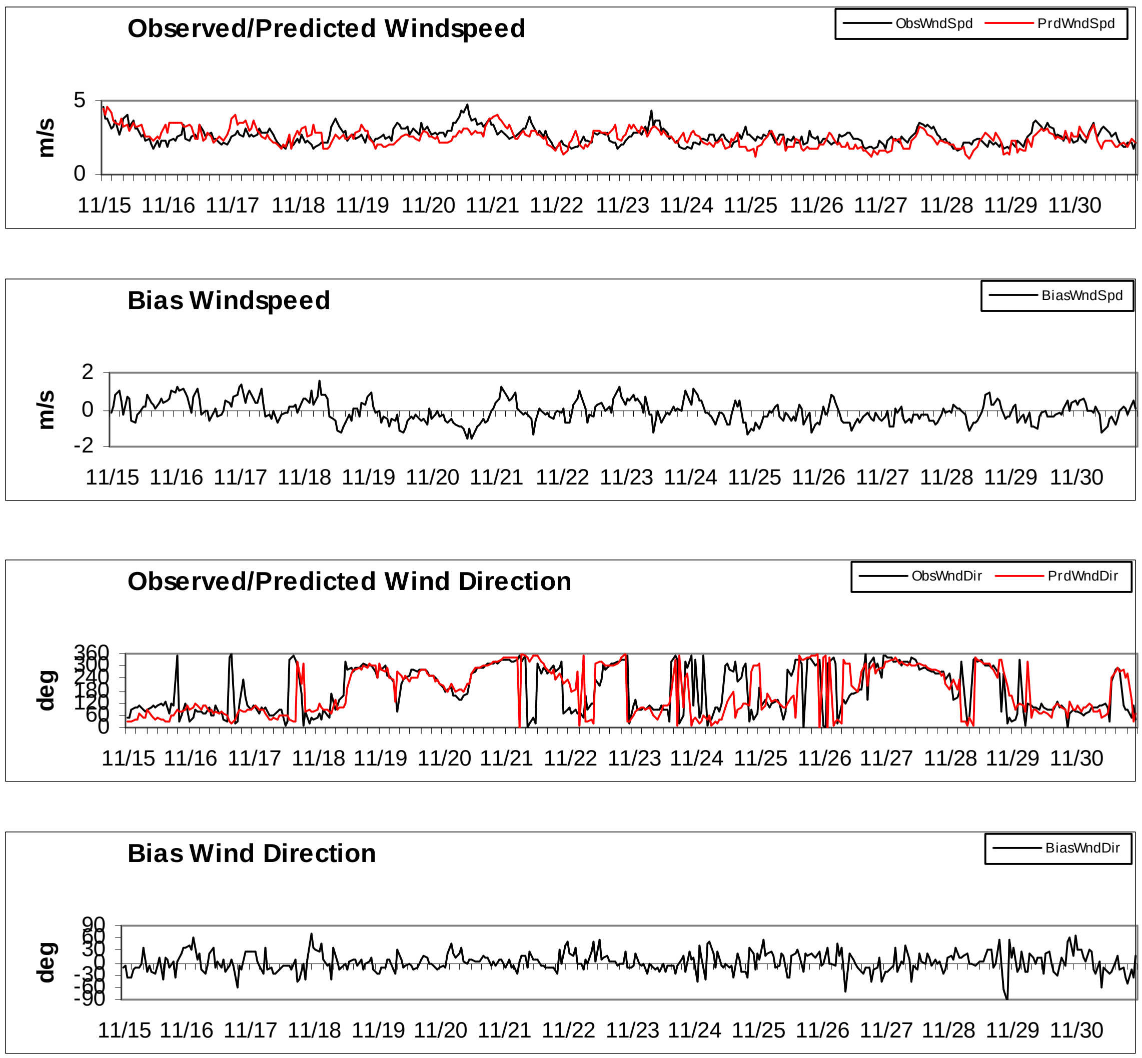
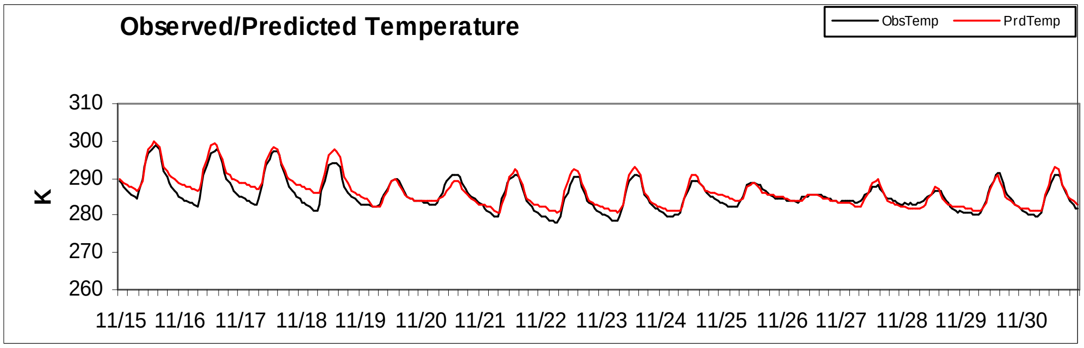


Figure B-17. Hourly time series of region-average observed and predicted surface-layer wind speed and direction and performance statistics in the 4-km MM5 domain for November 2008.

BAAQMD 4km 2008 MM5 – November



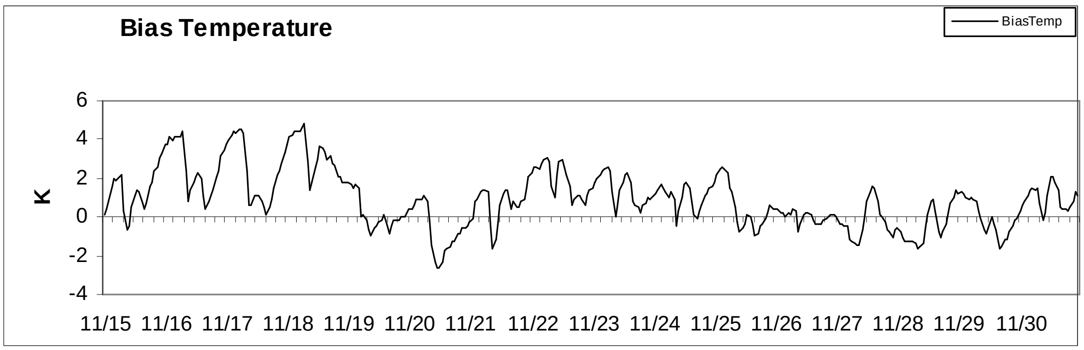


Figure B-18. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for November 2008.

BAAQMD 4km 2008 MM5 – December

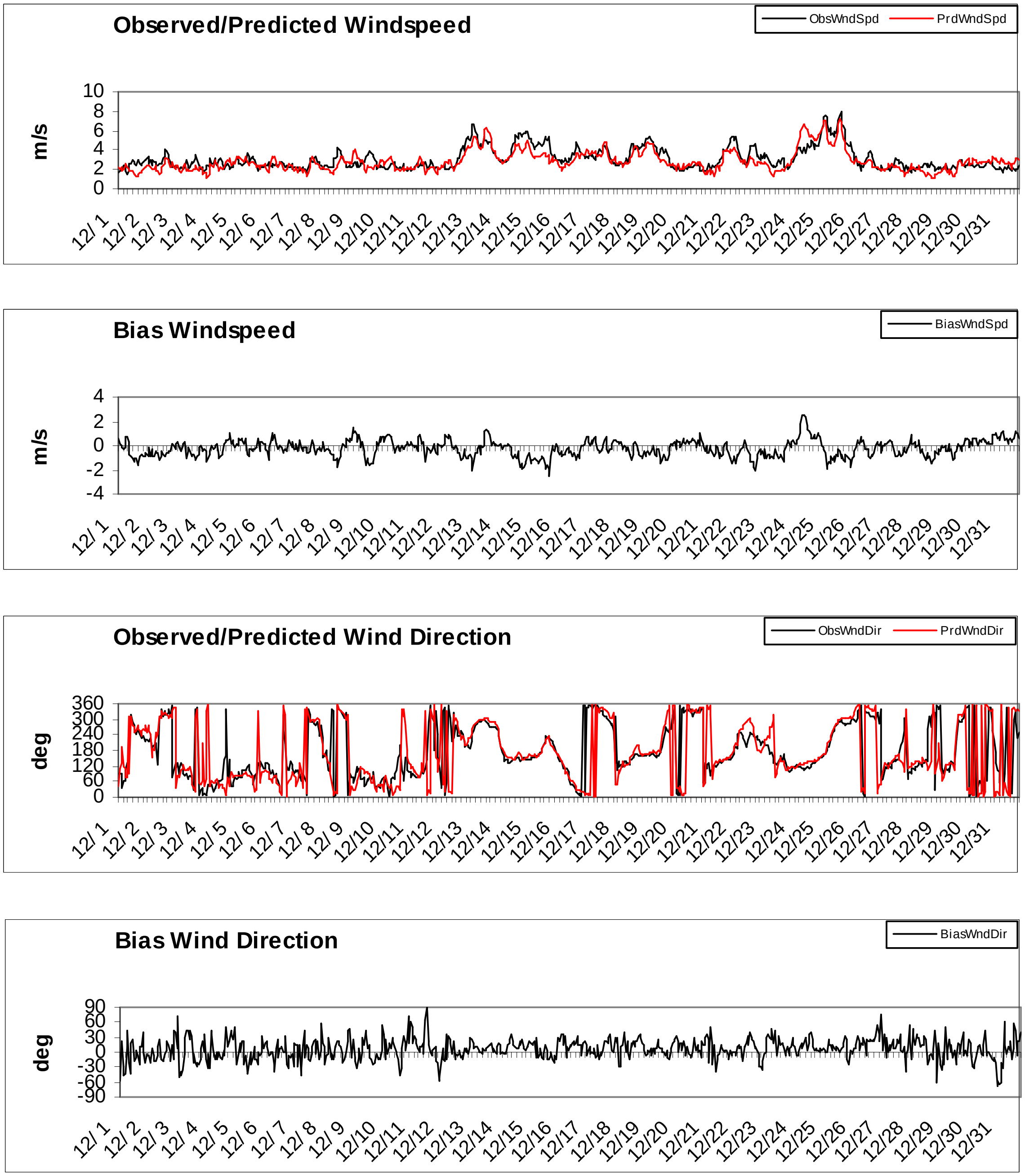


Figure B-19. Hourly time series of region-average observed and predicted surface-layer wind speed and direction and performance statistics in the 4-km MM5 domain for December 2008.

BAAQMD 4km 2008 MM5 – December

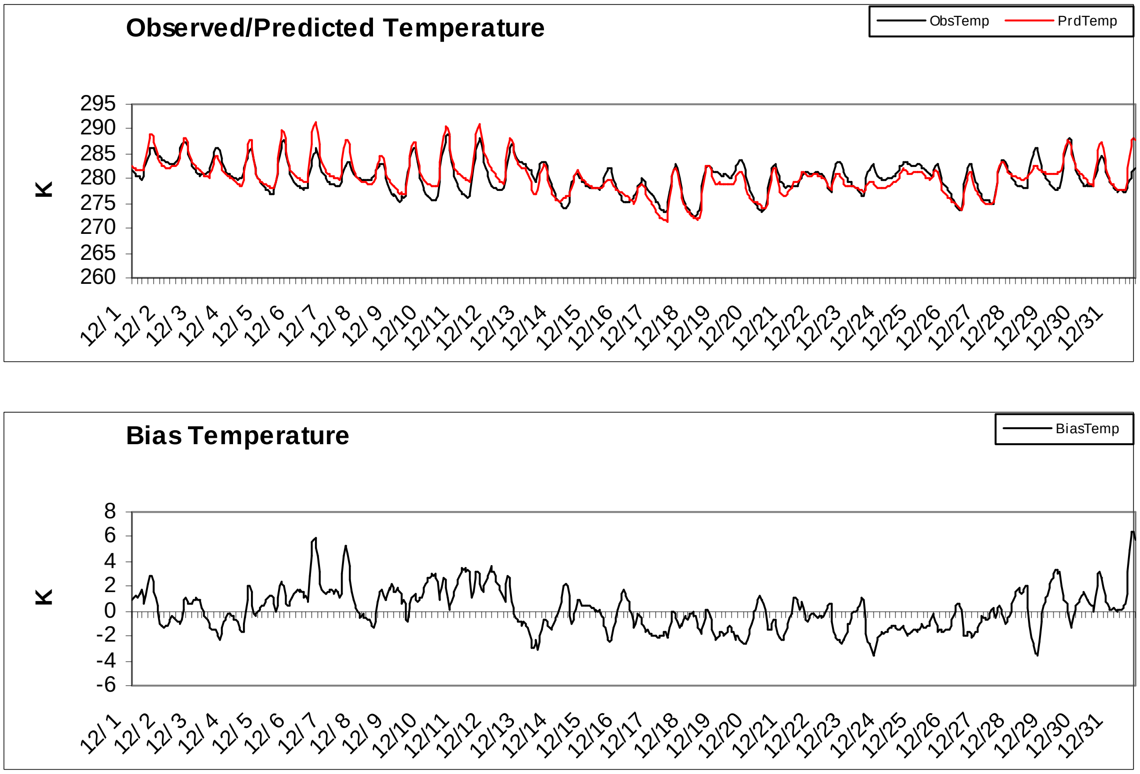


Figure B-20. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for December 2008.

BAAQMD 4km 2009 MM5 – January

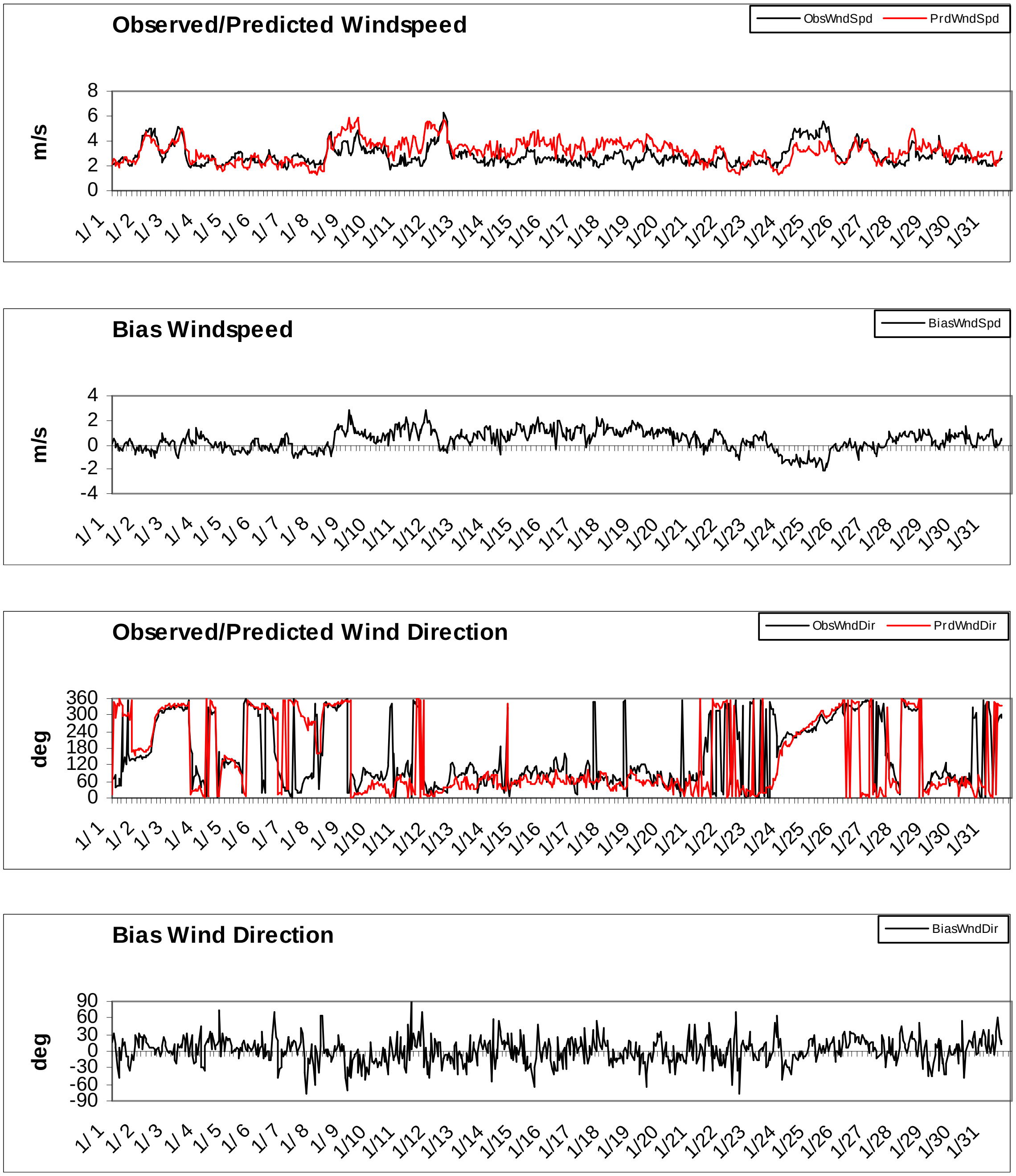


Figure B-21. Hourly time series of region-average observed and predicted surface-layer wind speed and direction and performance statistics in the 4-km MM5 domain for January 2009.

BAAQMD 4km 2009 MM5 – January

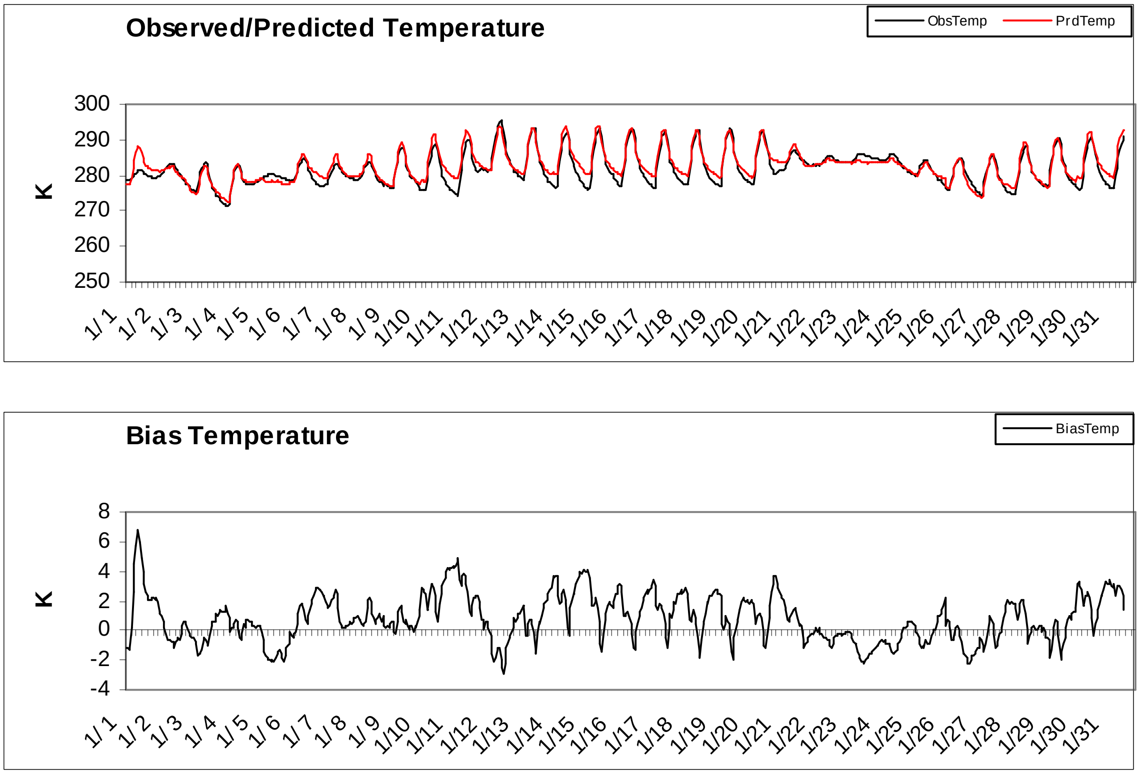


Figure B-22. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for January 2009.

BAAQMD 4km 2009 MM5 – February

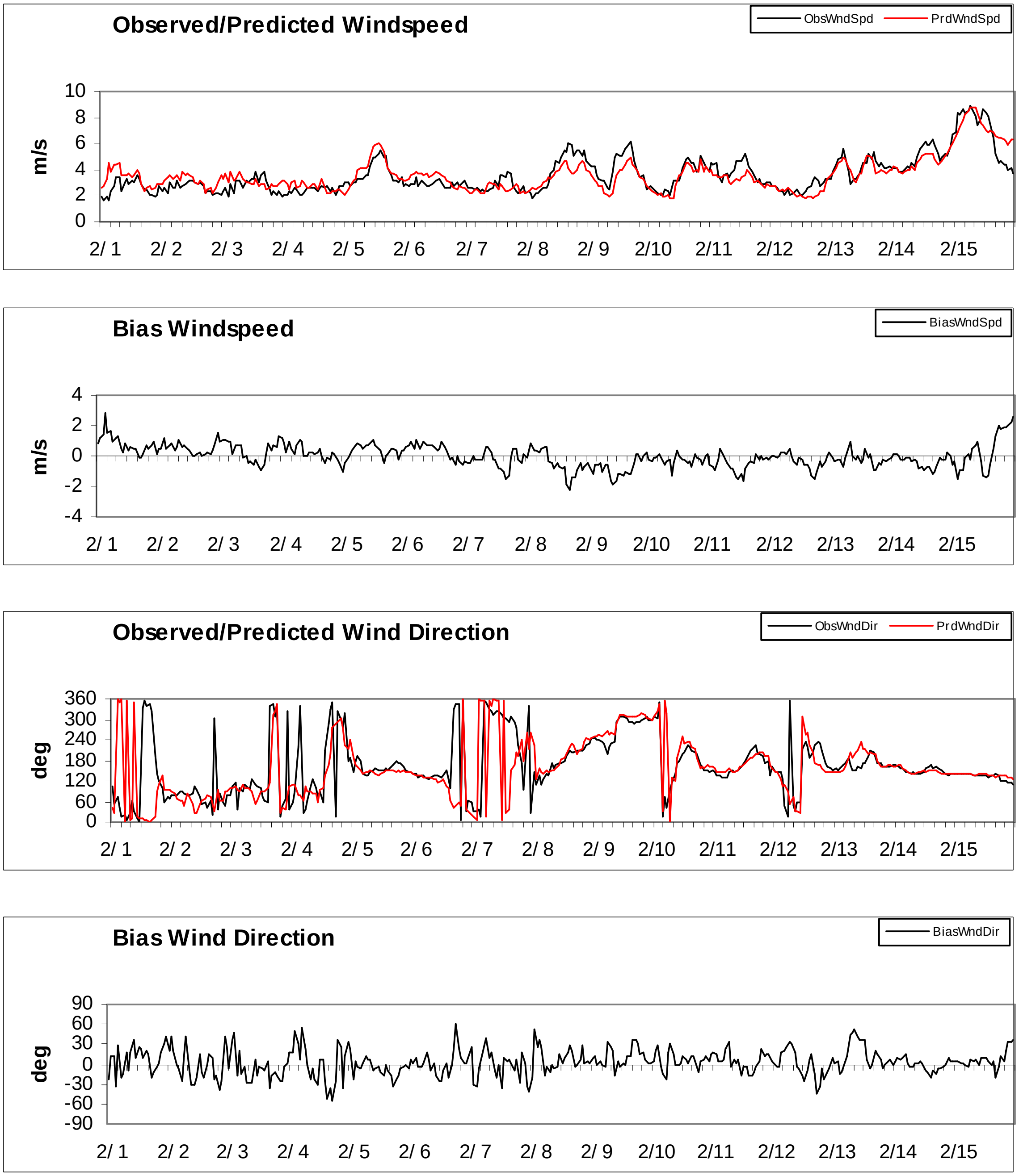


Figure B-23. Hourly time series of region-average observed and predicted surface-layer wind speed and direction and performance statistics in the 4-km MM5 domain for February 2009.

BAAQMD 4km 2009 MM5 – February

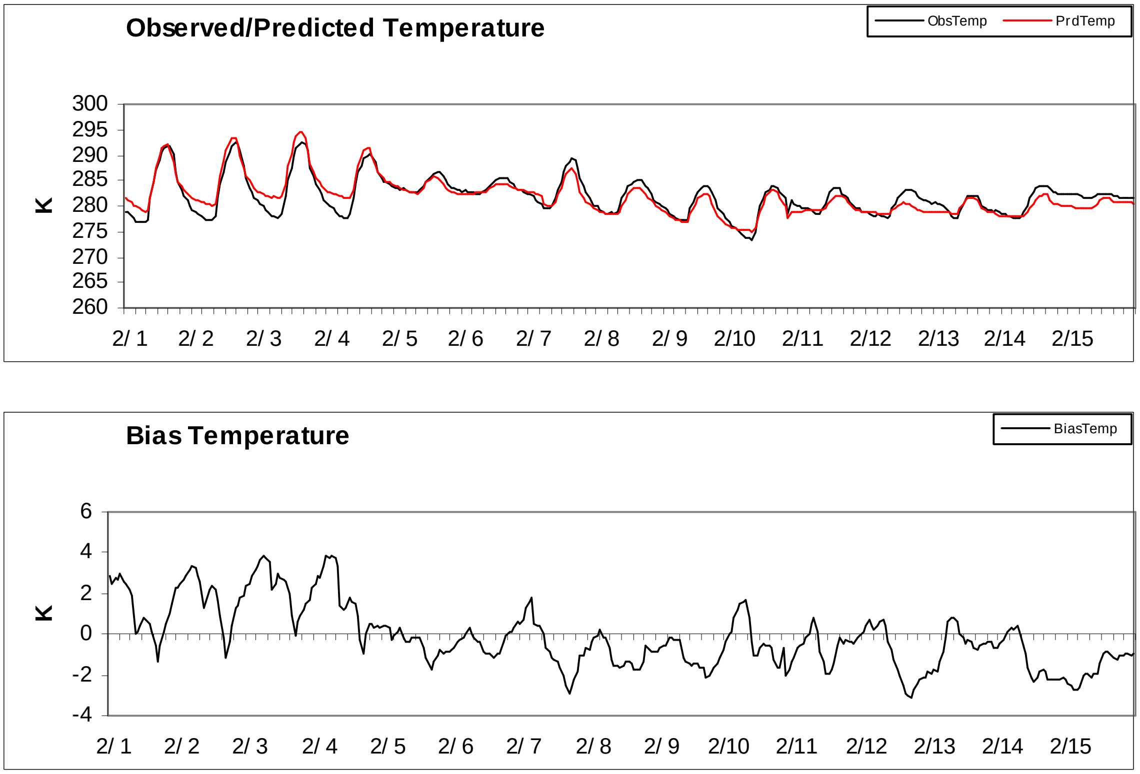


Figure B-24. Hourly time series of region-average observed and predicted surface-layer temperature and performance statistics in the 4-km MM5 domain for February 2009.

Appendix C. Air quality model validation

Air quality model performance was evaluated consistent with guidelines established by EPA (2007). A number of individual analyses were performed to validate the model outputs against available measurements. They included statistical (quantitative) as well as visual (qualitative) methods. Measurements were paired against their corresponding simulated values extracted from model grid cells nearest the respective monitoring locations. The performance evaluation was based on 24-hour averages (midnight to midnight) for measured and simulated PM levels.

Statistics are defined follows:

Mean observed PM level (PM_o^i): calculated for a single monitoring location *i* using all valid data available during the simulation period:

$$PM_o^i = \frac{1}{J}\sum_{j=1}^{J} O_j^i$$

where O_j^i is the individual observed PM level (μg/m^3) at site *i* for day *j*, and the summations are over all days (*J*). O_j^i may reflect total PM levels or individual PM components such as EC, OC, nitrate, or sulfate.

Mean model estimated PM level (PM_p^i): calculated from simulation results averaged for the model grid cell(s) nearest site *i* using the entire simulation period:

$$PM_p^i = \frac{1}{J}\sum_{j=1}^{J} P_j^i$$

where P_j^i is the individual model estimated PM level (μg/m^3) at site *i* for day *j*, and the summations are over all days (*J*). P_j^i may reflect total PM levels or individual PM components such as EC, OC, nitrate, or sulfate.

Bias error (B^i): calculated as the mean difference in simulation-observation pairings for the same PM type (total, EC, OC, nitrate, or sulfate) with valid data at site *i*:

$$B^i = PM_p^i - PM_o^i$$

Large, positive values for B^i indicate that the model is overestimating PM levels. Large, negative values for B^i indicate that the model is underestimating PM levels.

C.1 Validation of total PM levels

Validation of simulated total $PM_{2.5}$ levels was performed separately for each monitoring location. Generally, the model was able to reproduce the observed spatial distribution of PM. The model reasonably estimated total $PM_{2.5}$ levels throughout the Bay Area and, to a lesser extent, around the Delta. Realistically, simulated PM levels in the Delta were important as this region is immediately upwind of the Bay Area under episodic conditions.

Mean observed and simulated total $PM_{2.5}$ levels are shown in Figure C-1. Simulated $PM_{2.5}$ levels for most Bay Area locations were in good agreement with measurements. $PM_{2.5}$ levels were overestimated at San Francisco. This overestimation is believed to have resulted from an over-allocation of emissions for downtown San Francisco. Emissions from trucks and construction equipment that did not actually operate within San Francisco may have been placed into this city's inventory because they were linked to business addresses there. $PM_{2.5}$ levels were underestimated at the inland northern Bay Area sites Napa and Vallejo. Underestimations there likely resulted from underestimations around the Delta. $PM_{2.5}$ levels were also underestimated in Sacramento. This underestimation is believed to have resulted from an underestimation of regional secondary $PM_{2.5}$ levels in the Sacramento Valley.

Figure C-2 demonstrates the validity of the model across the range of historical PM levels that occurred for the 2006-07 winter. The 1:1 line on the scatter plots of paired observed and simulated total $PM_{2.5}$ levels indicates ideal model performance. For only a single outlier day, occurring on Christmas Day, the model performed poorly. This day is believed to have exhibited unusual emissions characteristics that were not properly represented in the model inventory that reflected average winter emissions. Otherwise, the data points on the scatter plots generally fell around the 1:1 line. One exception was San Francisco, where the data points fell below the 1:1 line. This reflects the general overestimation of San Francisco PM levels also indicated in Figure C-1. Observed and simulated total $PM_{2.5}$ levels correlated well here. This correlation suggests that PM buildup mechanisms were simulated realistically, but emissions levels were overestimated. Other exceptions were for Napa, Vallejo, and Sacramento. For these locations, total $PM_{2.5}$ levels were accurately estimated when PM levels were low. Higher PM levels, however, were significantly underestimated by the model. This discrepancy suggests shortcomings of the simulated chemistry to produce sufficient levels of secondary $PM_{2.5}$. The nature of the $PM_{2.5}$ level underestimation at Modesto was quite different than at Sacramento. At Modesto, simulated and observed total $PM_{2.5}$ levels correlated well, but the data points fell above the 1:1 line. This correlation suggests that PM buildup mechanisms were simulated realistically, but emissions levels impacting Modesto were underestimated.

Another reason for underestimation of higher PM levels was due to overestimated wind speed in MM5. Analysis of meteorological model outputs showed that the model tended to overestimate winds when the atmosphere was strongly stable, generating local low level jets. This short coming of the model is being investigated and is planned to be corrected soon.

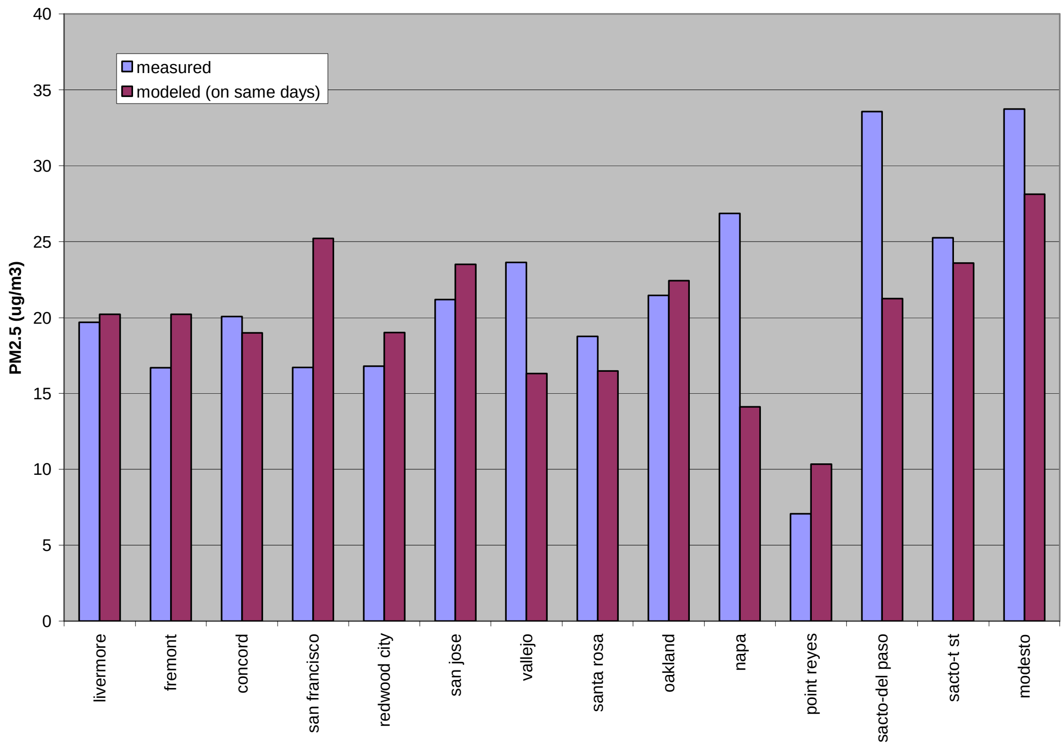


Figure C-1. Mean observed and model estimated total $PM_{2.5}$ levels at 11 Bay Area and 2 Delta region monitoring locations. Statistics are averaged across both the 2000-01 and 2006-07 winter simulation periods.

C.2 Validation of PM component levels

The model was validated to realistically simulate the major individual PM components EC, OC, nitrate, and sulfate. This verification is necessary to ensure that total $PM_{2.5}$ was estimated accurately from the accurate simulations of various PM components. Such behavior would indicate that the model produced the right answers for the right reasons and would therefore be reliable for planning purposes.

Scatter plots for carbonaceous $PM_{2.5}$ components EC and OC are shown in Figures C-3 and C-4, respectively. Generally, the data points fell along the 1:1 line for most stations. Exceptions included Napa and Vallejo for both EC and OC, and also San Jose for EC. Carbonaceous PM levels at Napa were particularly underestimated by the model, often by a factor of 2-3. However, simulation results did correlate well with the observations. This finding suggested that carbonaceous emissions in the Napa Valley, perhaps wood burning, may have been strongly underrepresented in the inventory. The underestimation of San Jose EC levels may have reflected an underestimation of vehicular and/or construction related emissions around this urban area. The degraded model performance at Vallejo was more difficult to attribute to a special cause. This is a complex area, which can be impacted by transport from the Central Valley and/or local industrial emissions, depending on the prevailing wind conditions.

Scatter plots for $PM_{2.5}$ component nitrate are shown in Figure C-5. This figure demonstrates the model’s ability to simulate secondary $PM_{2.5}$ ammonium nitrate levels. Nitrate levels were overestimated slightly (below the 1:1 line) at the remote Point Reyes location. For other locations, especially in the Central Valley, nitrate levels were underestimated. The model particularly had difficulty simulating high ammonium nitrate levels in the Sacramento Valley.

Scatter plots for $PM_{2.5}$ component sulfate are shown in Figure C-6. This figure demonstrates the model’s ability to simulate secondary $PM_{2.5}$ ammonium sulfate levels. The model simulated ammonium sulfate levels with higher accuracy than for any other $PM_{2.5}$ component. This may have resulted from the relatively simple emissions patterns for sulfur-containing substances as compared to other types of emissions. Sulfur emissions were highly localized around both the offshore shipping lanes and industrial facilities through Carquinez Straight. These results indicated the model's ability to capture source-receptor relationships for sulfur compounds under both easterly and westerly air flow patterns.

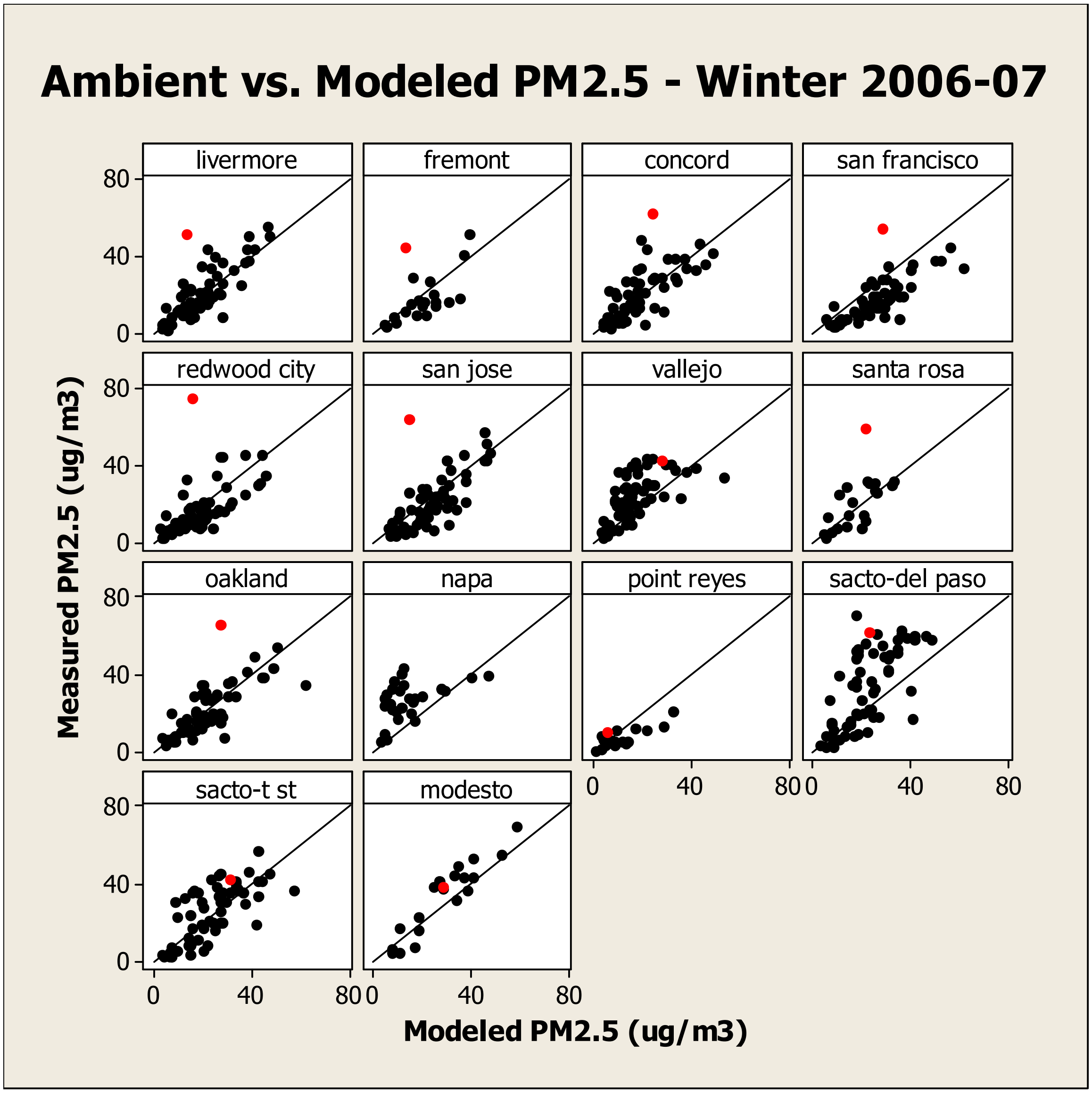


Figure C-2. Scatter plots for measured versus simulated total $PM_{2.5}$ levels at 11 Bay Area and 2 Delta region monitoring locations. Each data point represents an individual day for the 2006-07 winter simulation period. An outlier plotted in red occurred on Christmas Day. Diagonal 1:1 lines indicate ideal model performance.

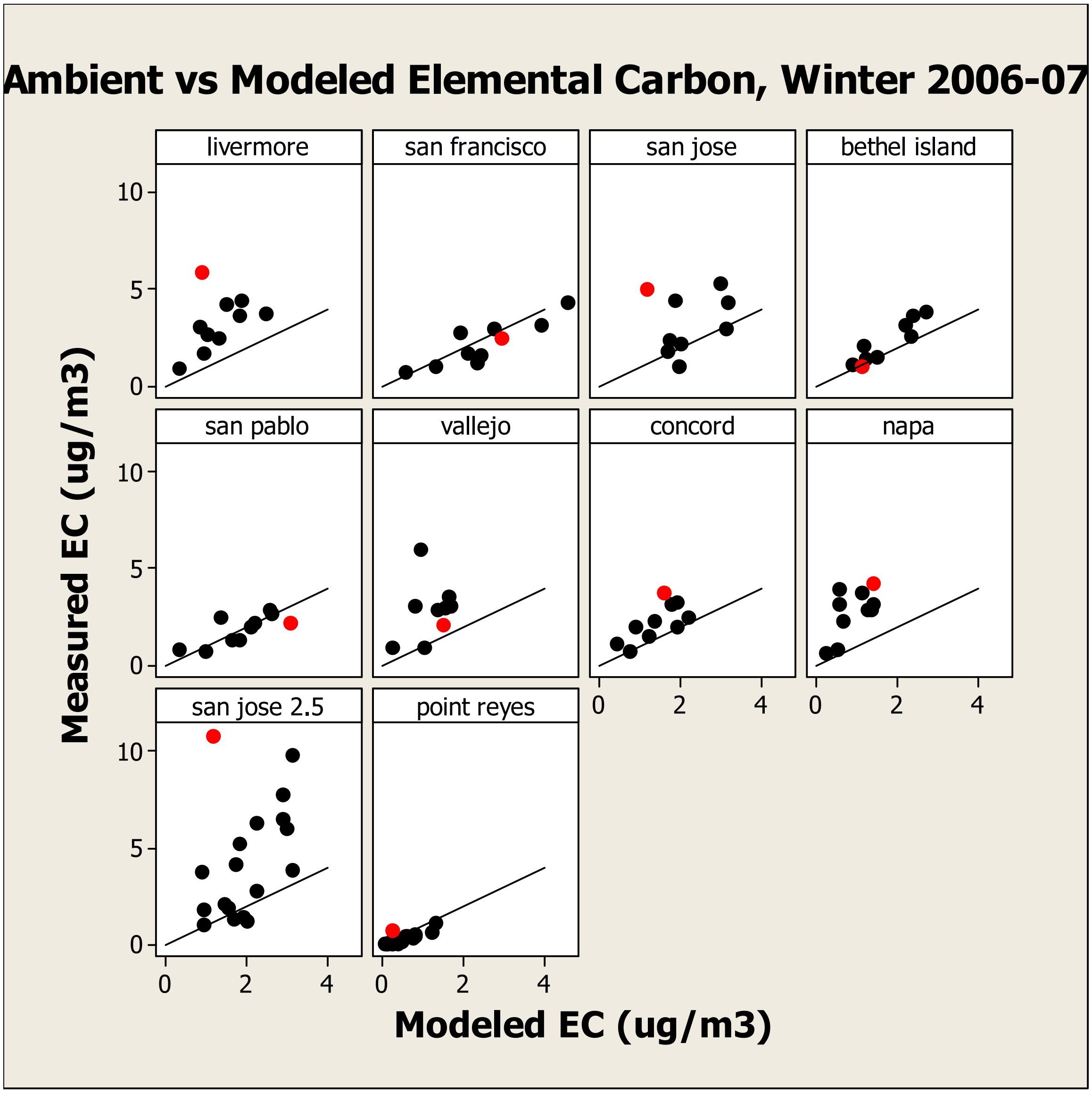


Figure C-3. Scatter plots for measured versus simulated $PM_{2.5}$ EC component levels.

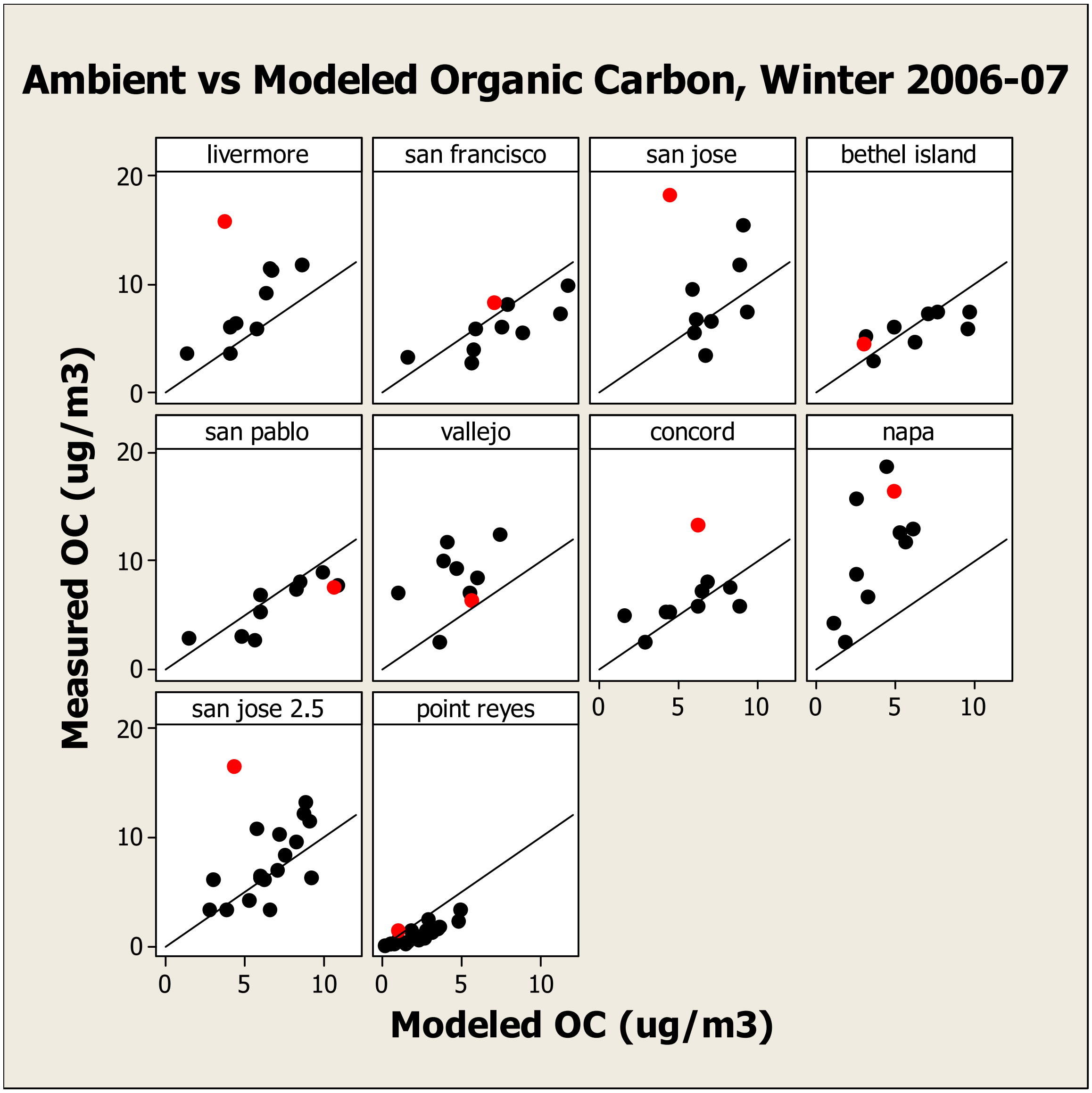


Figure C-4. Scatter plots for measured versus simulated $PM_{2.5}$ OC component levels.

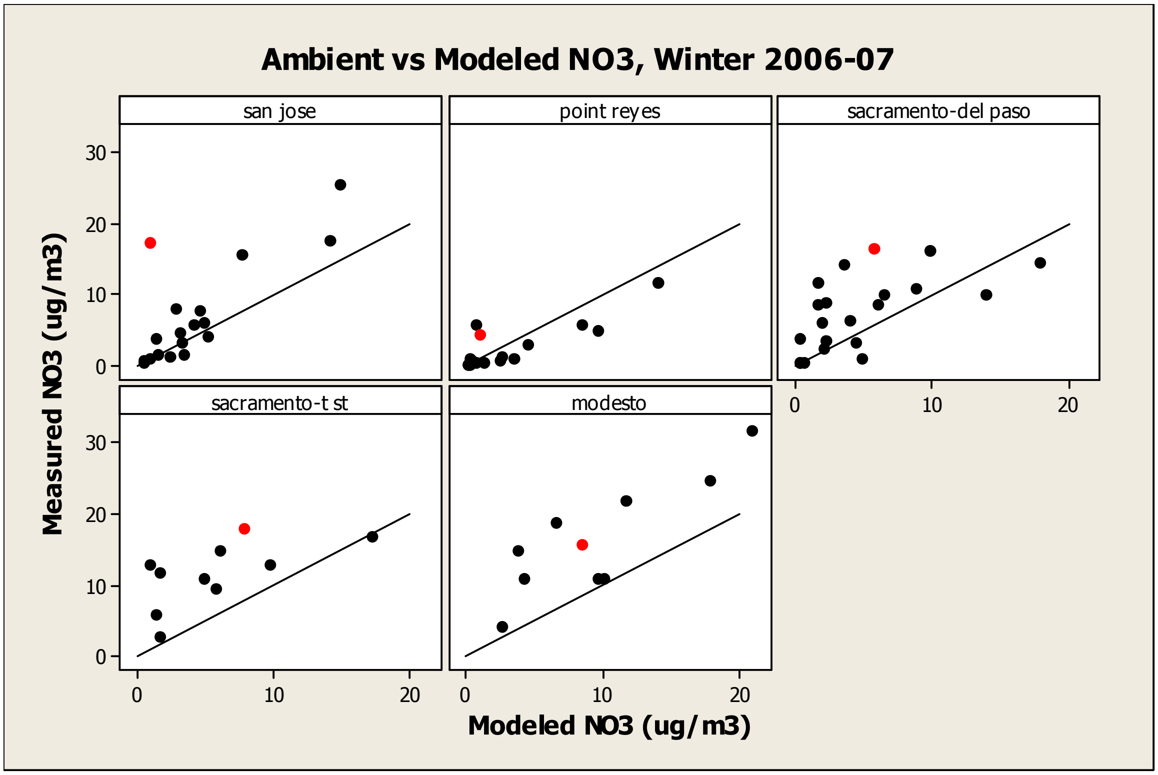


Figure C-5. Scatter plots for measured versus simulated $PM_{2.5}$ nitrate component levels.

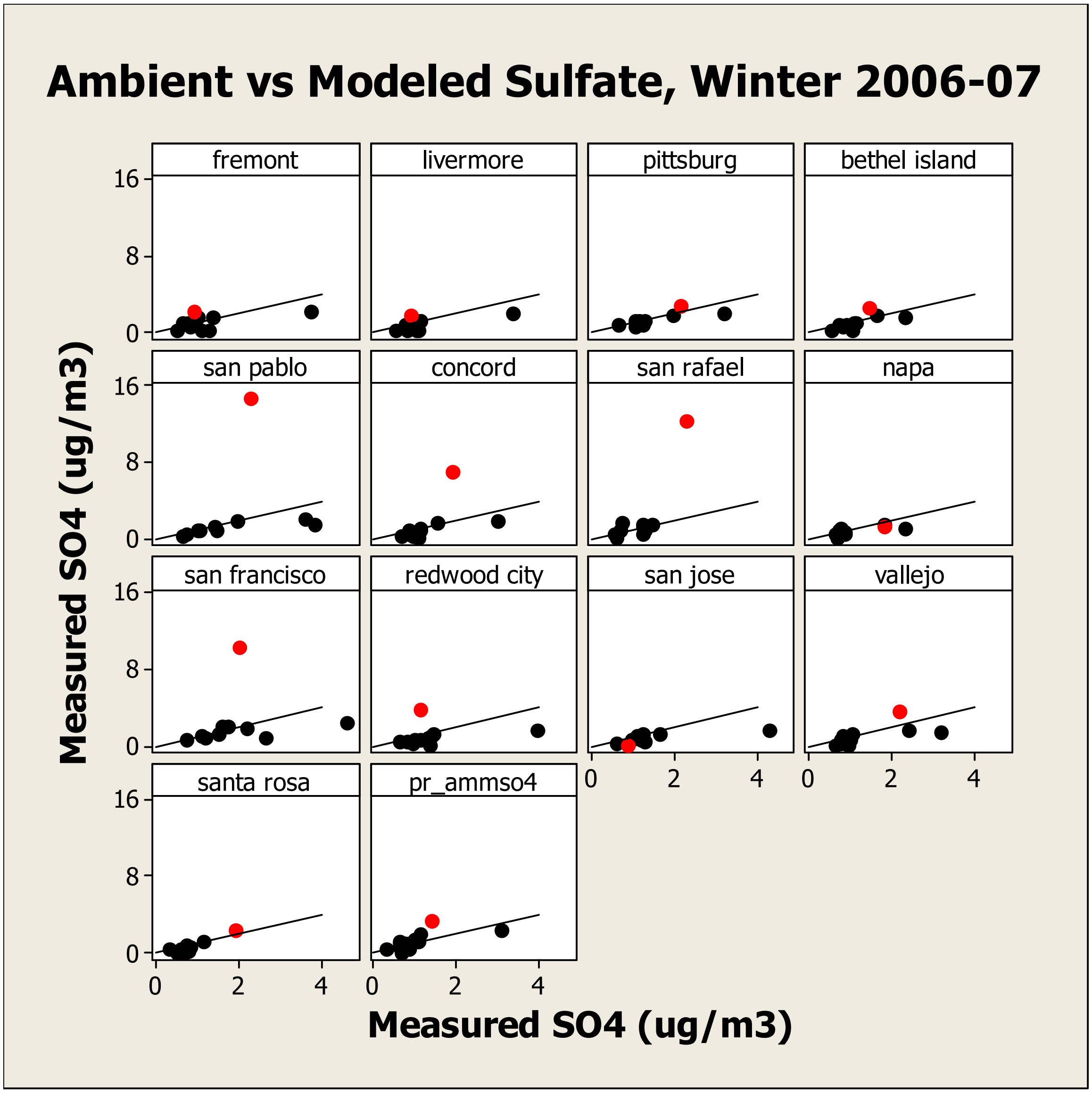


Figure C-6. Scatter plots for measured versus simulated $PM_{2.5}$ sulfate component levels.