Simulation of the potential impacts of the proposed Sithe power plant in the Four Corners basin using CAMx

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Abstract

The Diné Power Authority (DPA) has contracted with Sithe Energies, Inc., (Sithe) to develop a 1500 MW green field power plant located on Navajo Nation trust land southeast of Shiprock, NM in the Four Corners basin. This would be a large point source emitting 3,319 tons per year (tpy) of sulfur dioxide (SO_2), 3,325 tpy of nitrogen oxides (NO_x), 1,120 tpy of particulate matter (PM_{10}), and other pollutants. The Four Corners basin is located on the Colorado Plateau, home to Grand Canyon National Park (GRCA) and other class I areas, where visibility is an integral component of a visitor's experience. There is concern that the proposed power plant will cause or exacerbate existing haze on the Colorado Plateau. Past monitoring and modeling studies have shown that power plants located to the east and west of the Grand Canyon can significantly contribute to haze in the Grand Canyon NP. Power plants to the east of the Grand Canyon had their largest contribution to haze during the winter months, when pollutants that reached Lake Powell drained down the Grand Canyon following the Colorado River to Lake Mead. The Four Corners basin is to the southeast of the Grand Canyon NP and other class I areas in Utah including Canyonlands NP, Capitol Reef NP, and Arches NP.

This study investigates the potential impacts of the Sithe power plant on class I areas located around the Four Corners basin during January 2001 with the "Comprehensive Air Quality Model with Extensions" (CAMx) photochemical dispersion model (Environ, 2005). The MM5 mesoscale model (Grell et al., 1994) was used to generate 4 km horizontal resolution meteorological fields used as input for CAMx. The simulation of plume transport in this region is difficult due to the complex terrain within the model domain. Additional challenges stem from the nature of the weather conditions characterized by polar high pressure systems with weak synoptic forcing and stagnant winds followed by anticyclonic transport around the center of the high pressure system that favors pollutant drainage into the Grand Canyon.

The impact of the proposed power plant was evaluated using two different emission scenarios: 1) an inert tracer, and 2) all area and source emissions in the region plus the emissions from the proposed power plant. The values from the first simulation represent the upper limits for ammonium sulfate that CAMx could predict under the most favorable conditions of SO_2 chemical transformation, whereas the other two scenarios provide a more realistic estimate of sulfate concentrations in the region.

Modeling results indicate that ammonium sulfate attributable to the Sithe EGU reaches up to 0.6 $\mu g\ m^{-3}$ inside Grand Canyon NP during four major episodes. Concentrations as large as 1.5 $\mu g\ m^{-3}$ are observed in the Lake Powell area. Other regions affected include Mesa Verde, Arches and Canyonlands NP with ammonium sulfate concentrations ranging from 0.4 to 1 $\mu g\ m^{-3}$.

1. Introduction

The Diné Power Authority (DPA) has contracted with Sithe Energies, Inc. (Sithe) to develop an electric power generation facility, called the Desert Rock Energy Facility (hereafter referred to as Sithe, or EGU). The proposed facility is a 1500 MW green field power plant located on Navajo Nation trust land southeast of Shiprock, NM in the Four Corners basin. Most of the electricity generated is slated to satisfy the growing needs of Las Vegas, NV. The plant will use Navajo Nation coal reserves from a nearby mine operated by BHP Billiton. Since the proposed facility has the potential to be a major source of air pollutants, Sithe applied for a Prevention of Significant Deterioration (PSD) permit and ENSR Corporation performed an air quality impact analysis consistent with the guidelines in Federal Land Managers' Air Quality Related Values Workgroup (FLAG) (ENSR, 2006).

Initial air quality simulations developed with CALPUFF (Scire et al., 2000) showed that the Sithe facility could significantly contribute to haze at a number of class I areas. For example, 14 days had haze impacts greater than 10% over natural conditions and on one day at the San Pedro Parks Wilderness Area, NM the proposed power plant increased haze by 27% above the natural background estimate.

The proposed Sithe power plant is located within highly complex terrain, and micrometeorological processes, such as orographic clouds and pollutant transport blocked and channeled by the terrain, could be important in plume dispersion, particularly over multi-day transport periods. During winter months, fogs and clouds often occur over this region. The interaction of Sithe's plume with these clouds and fog can be the primary route for the formation of haze particles in the plume. The simulation of plume transport in this region is difficult due to the complex terrain within the model domain. Additional challenges stem from the nature of the weather conditions which favor plume transport into the Grand Canyon, characterized by strong temperature inversions, and low-level clouds. During the winter months, November through March, the southwestern United States is often influenced by polar highs. These are characterized by stagnant airmasses and subsiding air creating near-surface and elevated inversions. The period of stagnation varies from 3 to over 14 days with a mean duration of 6 days. If the high pressure system then moved to the north or east of Four Corners, these emissions would be transported through the northwest passage toward Lake Powell and the Grand Canyon National Park (GRCA), due to the anticyclonic transport around the center of the high pressure system.

In the PSD application, CALPUFF modeling was performed using a coarse grid of 40 km for 2001 and 2002, and 20 km for 2003. The "puff splitting" option, which can significantly influence puff transport in high-shear conditions, was not invoked. CALPUFF does not estimate the aqueous phase oxidation of sulfur dioxide to particulate sulfate, and hence could not account for enhanced sulfate particle formation from clouds and fogs. The coarse meteorological wind fields (20 km and 40 km) and selected options in the CALPUFF modeling are inadequate to simulate the relevant dispersion and chemistry processes governing the potential impact of Sithe's plume on haze in the Grand Canyon National Park and other class I areas on the Colorado Plateau (Pitchford *et al.*, 1999).

The formation and causes of haze on the Colorado Plateau have been extensively studied, and the relevant processes that create winter time layered hazes in the Grand Canyon have been determined. The companion document "Simulation of the Impact of the SO_2 Emissions from the Proposed Sithe

Power Plant on the Grand Canyon and other Class I Areas" (National Park Service, 2005) reviewed the results from some of these studies and formulated the following conceptual model of the processes that lead to wintertime layered haze in the Grand Canyon: First pollutants from Lake Powell are transported southwest and drainage flow bring these pollutants from the rim into the Grand Canyon. The pollutants usually arrive into the Grand Canyon embedded within clouds. The wet phase chemistry in clouds is very efficient at converting the sulfur dioxide to particulate sulfate. The clouds then evaporate leaving behind the in-canyon sulfate haze with clear sky above the canyon creating a layered haze. Human observers are particularly sensitive to layered hazes, since a sharp boundary exists between the haze in the canyon and the canyon walls and sky above. The human eye is sensitive to these sharp changes in contrast and a layered haze is visible at lower levels compared to a uniform haze. The pollutants can remain in the canyon for a day or more and be transported throughout the length of the Grand Canyon following the Colorado River.

The CAPITA Monte Carlo Lagrangian dispersion model was also applied (National Park Service, 2005) to directly simulate the transport of pollutants from the Sithe EGU to the Grand Canyon NP and other class I areas located around the Four Corners basin during a winter time episode. An alternative modeling analysis is conducted using two Eulerian dispersion models. This study presents the results obtained with CAMx for the same episode during January 2001 evaluated in National Park Service, (2005) while REMSAD results are discussed in detail on Appendix 2.

CAMx is an Eulerian photochemical dispersion model that allows for an integrated "one-atmosphere" assessment of gaseous and particulate air pollution over many spatial and temporal scales. CAMx simulates the emissions, dispersion, chemical reaction, and removal of pollutants in the troposphere by solving the pollutant continuity equation for each chemical species on a system of nested three-dimensional grids. The MM5 mesoscale modeling system generates 12 km and 4 km horizontal resolution meteorological fields used as input for CAMx.

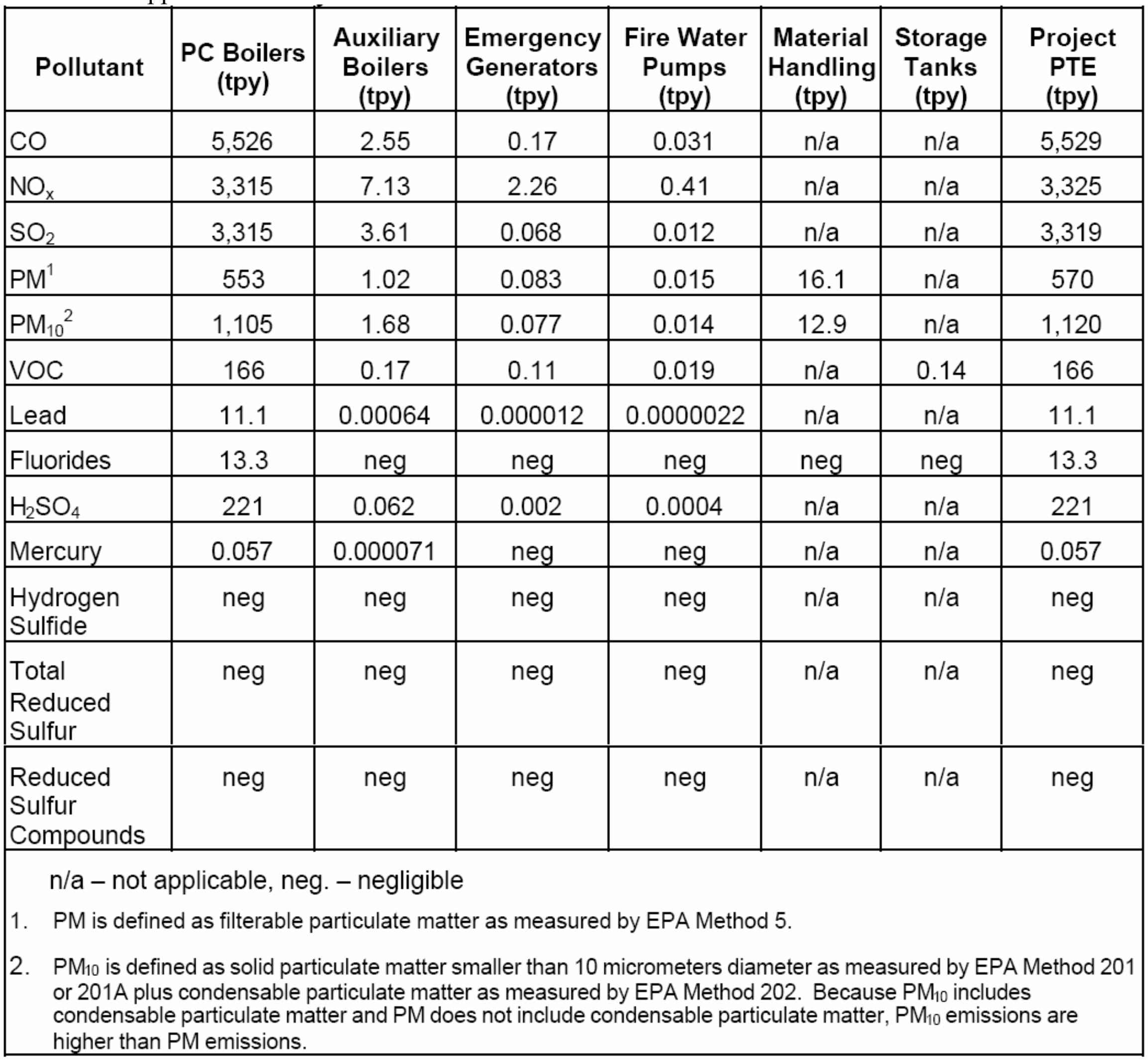
The impacts of the proposed power plant are evaluated using two different emission scenarios. First, transport into the canyon is evaluated using an inert tracer run; then the influence of the emissions of the proposed power plant is also investigated along with all available area and source emissions in the region. Concentrations estimated in the first scenario represent the upper limits that CAMx predicts for ammonium sulfate formation under the most favorable conditions of SO_2 chemical transformation, whereas the other scenario provides a more realistic estimate of sulfate concentrations in the region. Primary particulate matter, nitrates, and organics from the Sithe EGU are not considered in this analysis, but would also have a contribution to PM loadings and haze.

2. Emissions

The proposed power plant would be a large stationary source emitting 3,319 tons per year (tpy) of sulfur dioxide (SO_2), 3,325 tpy of nitrogen oxides (NO_x) and 1,120 tpy of particulate matter less than 10 microns in diameter (PM_{10}). The Sithe facility is classified as a "major stationary source" of air emissions exceeding the major source thresholds for SO_2, NO_x, PM_{10}, carbon monoxide (CO), volatile organic compounds (VOC), and hazardous air pollutants (HAP). All the potential emissions from the proposed EGU are summarized in Table 1. The stack characteristics (the stack height, the stack diameter, the stack exit temperature, the stack exit velocity, the stack flow rate and the species point emission rate) of the Sithe EGU are shown in Table 2. These values are used by CAMx to estimate the plume rise.

The emissions inventory used in this study corresponds to the preliminary version of the 2002 base emissions inventory (“Pre02d”) developed by the Western Regional Air Partnership Regional Modeling Center (WRAP RMC) (WRAP, 2005). The WRAP RMC used improved 2002 emissions data for the United States, Mexico, and Canada to create a base 2002 annual emissions database for use in the CMAQ and CAMx models. Sources for emissions inventory and ancillary modeling data included WRAP emissions inventory contractors, other RPOs, and EPA. This inventory includes 22 different emissions categories with a spatial resolution of 36 km. Since the master computational domain used in this study has a resolution of 12 km, the 36 km area emissions inventory was re-sampled to match the finer domain. Although the inventory corresponds to 2002, it can be assumed that the differences in emissions between 2002 and 2001 are negligible. Figure 1 shows area and point source sulfur dioxide emissions including those of the Sithe EGU.

Table 1. Summary of the maximum potential emissions of pollutants from the Sithe facility. This table is a reproduction of Table 5-1 in the PSD application.



Pollutant	PC Boilers (tpy)	Auxiliary Boilers (tpy)	Emergency Generators (tpy)	Fire Water Pumps (tpy)	Material Handling (tpy)	Storage Tanks (tpy)	Project PTE (tpy)
CO	5,526	2.55	0.17	0.031	n/a	n/a	5,529
NO_x	3,315	7.13	2.26	0.41	n/a	n/a	3,325
SO_2	3,315	3.61	0.068	0.012	n/a	n/a	3,319
PM[1]	553	1.02	0.083	0.015	16.1	n/a	570
PM_{10}[2]	1,105	1.68	0.077	0.014	12.9	n/a	1,120
VOC	166	0.17	0.11	0.019	n/a	0.14	166
Lead	11.1	0.00064	0.000012	0.0000022	n/a	n/a	11.1
Fluorides	13.3	neg	neg	neg	neg	neg	13.3
H_2SO_4	221	0.062	0.002	0.0004	n/a	n/a	221
Mercury	0.057	0.000071	neg	neg	n/a	n/a	0.057
Hydrogen Sulfide	neg	neg	neg	neg	n/a	n/a	neg
Total Reduced Sulfur	neg	neg	neg	neg	n/a	n/a	neg
Reduced Sulfur Compounds	neg	neg	neg	neg	n/a	n/a	neg

n/a – not applicable, neg. – negligible

1. PM is defined as filterable particulate matter as measured by EPA Method 5.
2. PM_{10} is defined as solid particulate matter smaller than 10 micrometers diameter as measured by EPA Method 201 or 201A plus condensable particulate matter as measured by EPA Method 202. Because PM_{10} includes condensable particulate matter and PM does not include condensable particulate matter, PM_{10} emissions are higher than PM emissions.

Table 2. Location and stack characteristics of Sithe EGU.

latitude	36^{o} 29' 46"
longitude	108^{o} 32' 50"
stack height (m)	280
stack diameter (m)	11
exit velocity (m/s)	25
exit temp (deg K)	323

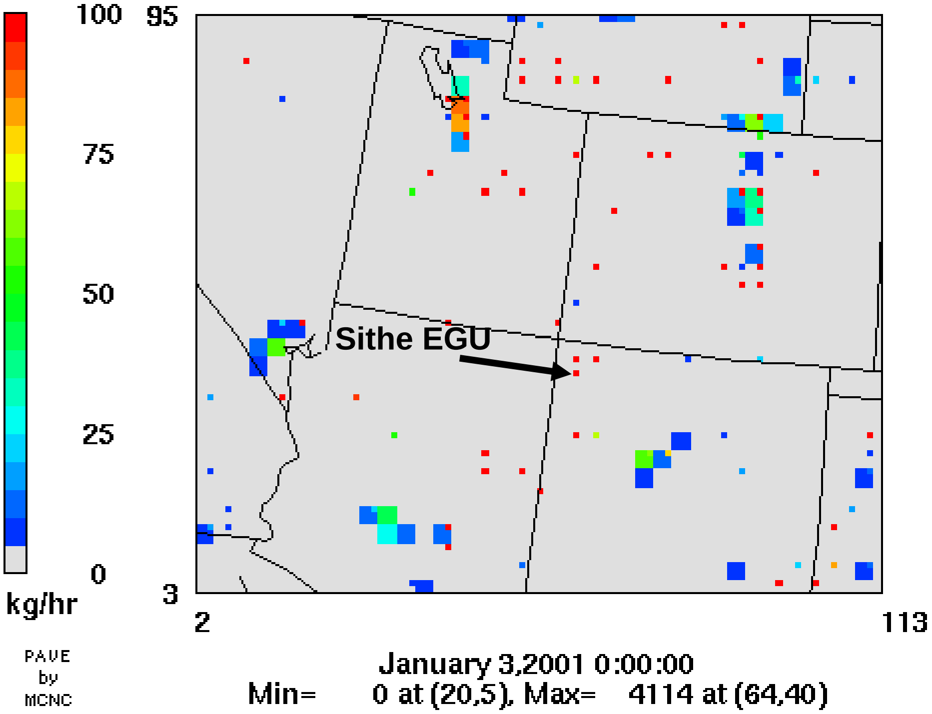


Figure 1. Area and point source sulfur dioxide emissions (kg/hr) within the CAMx 12 km model domain used in the "full chemistry" CAMx simulations.

3. Inert tracer transport simulation

The potential transport of pollutants from the Sithe EGU into the Grand Canyon and other class I areas was first investigated with an inert tracer simulation. A non-reactive, non-depositing tracer was released from the Sithe EGU at the same rate as the sulfur dioxide emissions. In this simulation, CAMx was used to advect and disperse the inert tracer from January 3 to 29, 2001 driven by 4-km MM5 meteorological fields nested in 12-km MM5 fields. The 4-km field domain includes the Grand Canyon and Four Corners region while the 12-km wind field covers Utah, Colorado, Arizona, and New Mexico (Figure 2). It is expected that the 4-km wind fields are able to resolve the influence of the Grand Canyon and river valleys on general airmass transport. However, these winds are too coarse to capture the drainage flows into and dispersion throughout the canyon.

The Eulerian model was run using a two-way nested grid structure. The master domain has a horizontal grid resolution of 12 km with 113 (East-West) by 95 (North-South) cells and a vertical resolution that spans from the surface up to 15 km using 19 sigma layers (Table 3). The nested domain has a resolution of 4 km and includes Grand Canyon National Park.

Since visibility is greatly affected by ammonium sulfate particles, this analysis assumes that SO_2 emitted from the Sithe EGU is completely oxidized to fine particulate sulfate and that full neutralization of the fine particulate sulfate occurs to form ammonium sulfate. This approach establishes an upper bound in terms of the maximum ammonium sulfate impacts from Sithe, concentrations of the magnitude presented here would be anticipated if clouds were present, given the rapid conversion of sulfur dioxide to sulfate that occurs in cloud droplets.

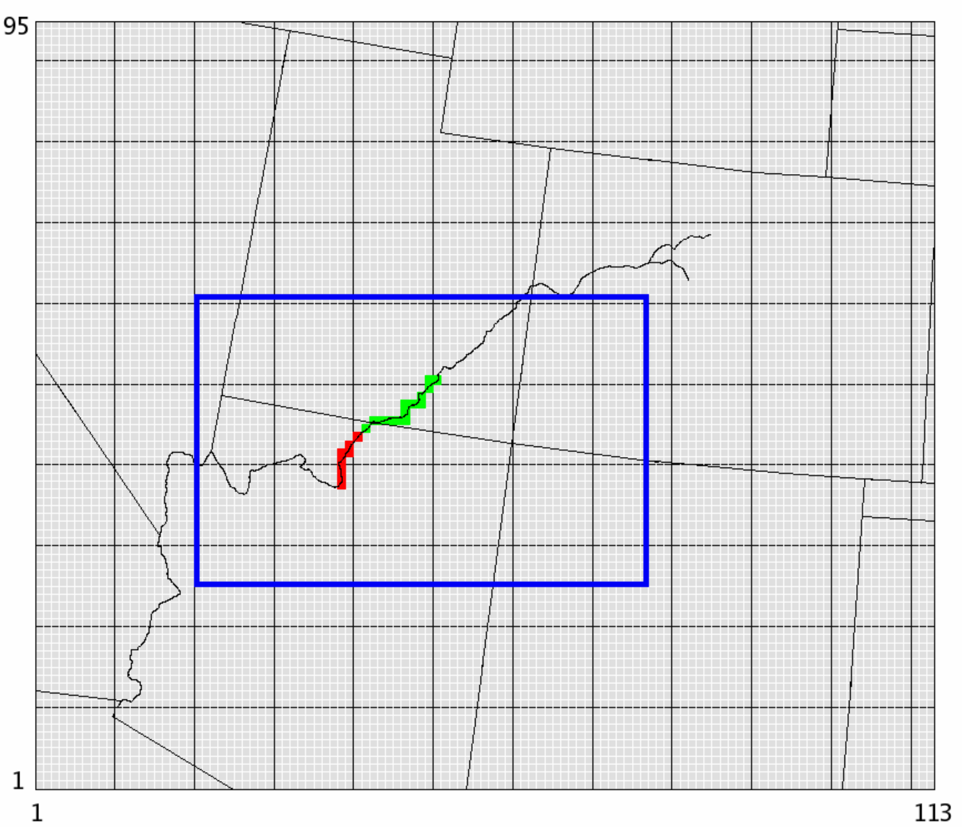


Figure 2. Computational master (12 km) and nested 4 km (in blue) domains used by the Eulerian dispersion model. The figure also shows the selected cells used to compute averaged time series in the Grand Canyon NP (red) and Lake Powell (green) regions.

Table 3. The 19 MM5 sigma layers used in this study, equivalent pressure and approximate height from surface.

MM5-sigma	P (mbar)	Height (km)
0.060	154.8	15.03
0.340	410.4	7.23
0.500	556.5	4.79
0.620	666.1	3.35
0.695	734.5	2.57
0.755	789.3	2.00
0.815	844.1	1.46
0.870	894.3	1.00
0.890	912.6	0.84
0.905	926.3	0.72
0.925	944.5	0.56
0.945	962.8	0.41
0.955	971.9	0.33
0.965	981.0	0.26
0.975	990.2	0.18
0.9825	997.0	0.13
0.9875	1001.6	0.09
0.9925	1006.2	0.05
0.9975	1010.7	0.02

3.1 Results

Different instances in which the simulated plume reaches the Lake Powell and Grand Canyon regions are illustrated in Figure 3. The MOHAVE project tracer results showed that when the tracer was released at Lake Powell during the winter, it was often transported into and throughout the Grand Canyon. It was demonstrated (National Park Service, 2005) that the Monte Carlo modeling system was able to reproduce many of the important transport features in this complex terrain. The Eulerian model, however, does not seem to fully capture the influence of the Grand Canyon and river valleys on the drainage flow. The CAMx model seems too diffusive and the in-canyon concentrations are fairly diluted. Nonetheless CAMx correctly reproduces the transport of pollutants from the Sithe facility to Lake Powell. Consequently, the influence of the EGU in both the Lake Powell and Grand Canyon NP are examined separately in this study.

The impacts of the Sithe EGU on the Grand Canyon and Lake Powell are presented as hourly ammonium sulfate concentrations (Figures 4 and 5) estimated with a spatial average of specific cells in the CAMx domain that fall along the Colorado River as shown in Figure 2. Figure 4a shows there are four distinct episodes during January 2001 (Table 3) in which the Grand Canyon is affected by Sithe's emissions. In general, the modeled impacts last for two days or more.

Table 3. Time periods where the simulated Four Corners power plant plumes impacted the Grand Canyon.

	Time Period	Duration (Days)
Event 1	1/8 12:00 – 1/10 23:00	2.5
Event 2	1/15 14:00 – 1/18 08:00	2.8
Event 3	1/22 12:00 – 1/25 14:00	3
Event 4	1/26 22:00 – 1/28 16:00	1.8

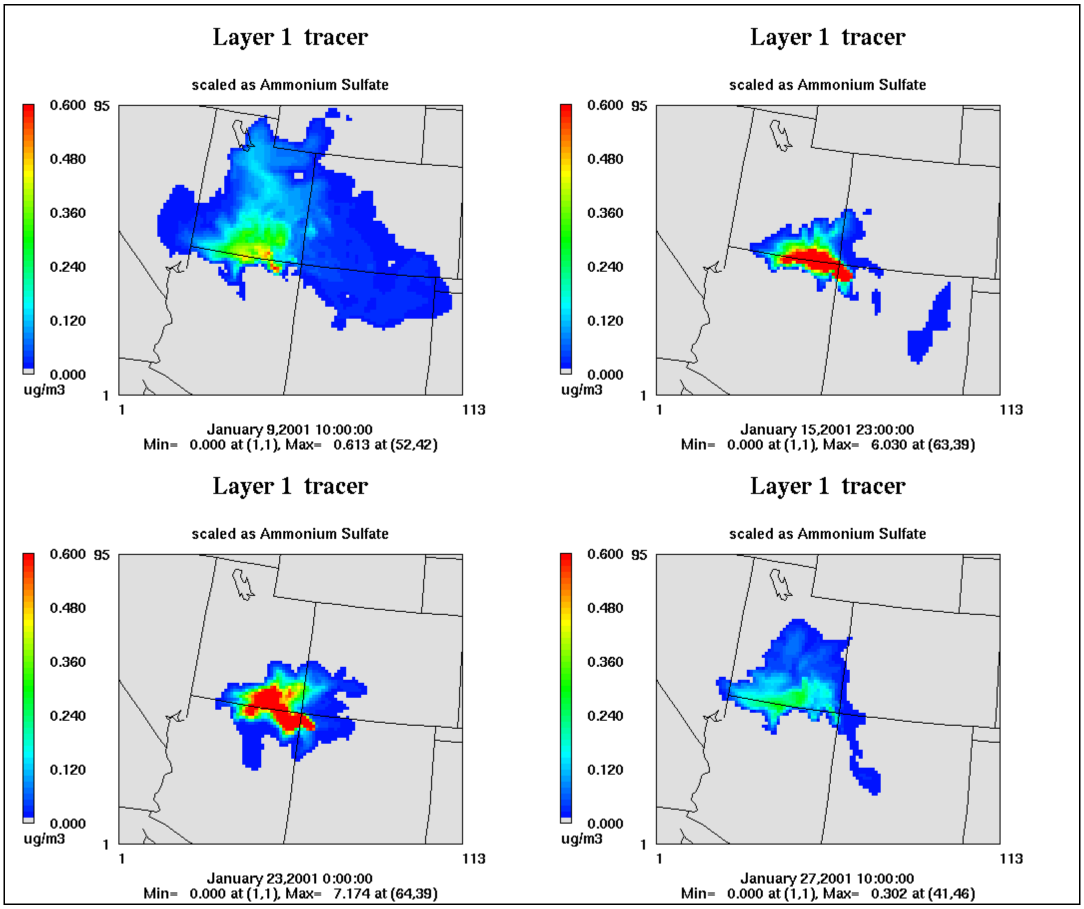


Figure 3. Four instances in which concentrations originated from the Sithe EGU reach the Lake Powell and Grand Canyon regions.

Average ammonium sulfate concentrations in the Lake Powell area reach values as high as 0.8 μg m^{-3}, while peak concentrations reach 1.5 μg m^{-3} during January 22. The event during January 15 is the second most severe with average concentrations of 0.6 μg m^{-3} and peak concentrations exceeding 1 μg m^{-3}. The two remaining events during January 9 and 27 are comparatively minor, with average concentrations of 0.3 μg m^{-3} and peak concentrations that do not exceed 0.5 μg m^{-3}. These values represent the upper limits that CAMx can predict for ammonium sulfate under the most favorable conditions of SO_2 chemical transformation and with no loss through deposition. Impacts in the Grand Canyon are generally less pronounced. For instance, ammonium sulfate concentrations averaged across in-canyon cells reach values of 0.4 μg m^{-3}, while peak concentrations do not exceed 0.6 μg m^{-3} during January 16.

Hourly ammonium sulfate concentrations for other class I areas and the Monument Valley Tribal Park are presented in Appendix 1. Table 4 summarizes the number of events for which modeled concentrations are larger than 0.1 μg m^{-3} were observed

Table 4. Number of events in which ammonium sulfate concentrations exceeded 0.1 μg m^{-3} in each of the regions investigated.

Region	Number of Events	Peak Concentration (μg m^{-3})	Average Duration (Days)
Monument Valley	10	2.3	1.2
Mesa Verde NP	7	1.3	1.4
Canyonlands NP	5	1.4	2.5
Arches NP	5	0.5	2.0
Zion NP	4	0.3	2.4
Petrified Forest NP	3	0.8	1.9
Capitol Reef NP	2	0.4	2.5

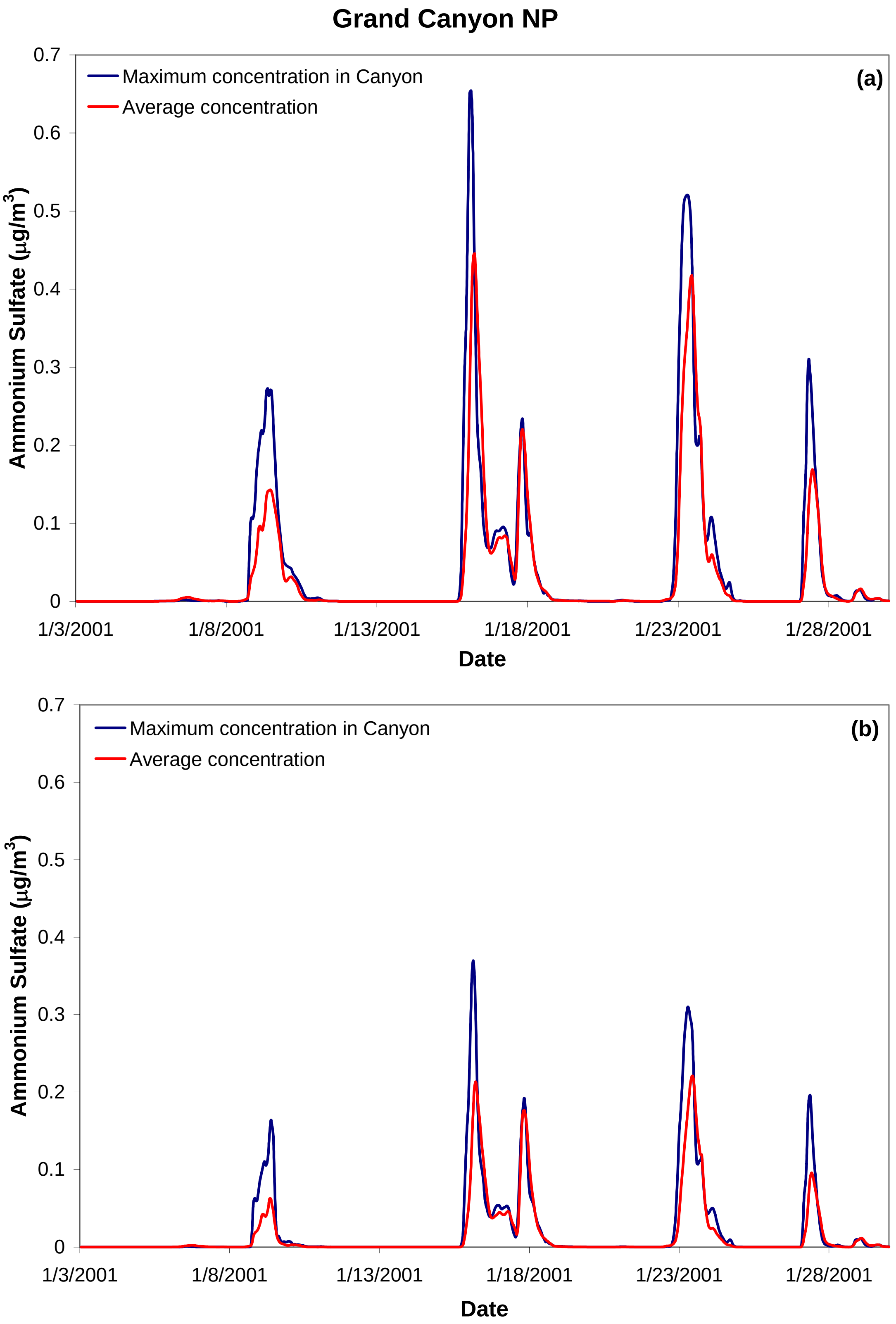


Figure 4. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum in-Canyon impact while the red line represents the average impact over all the cells shown in Figure 2.

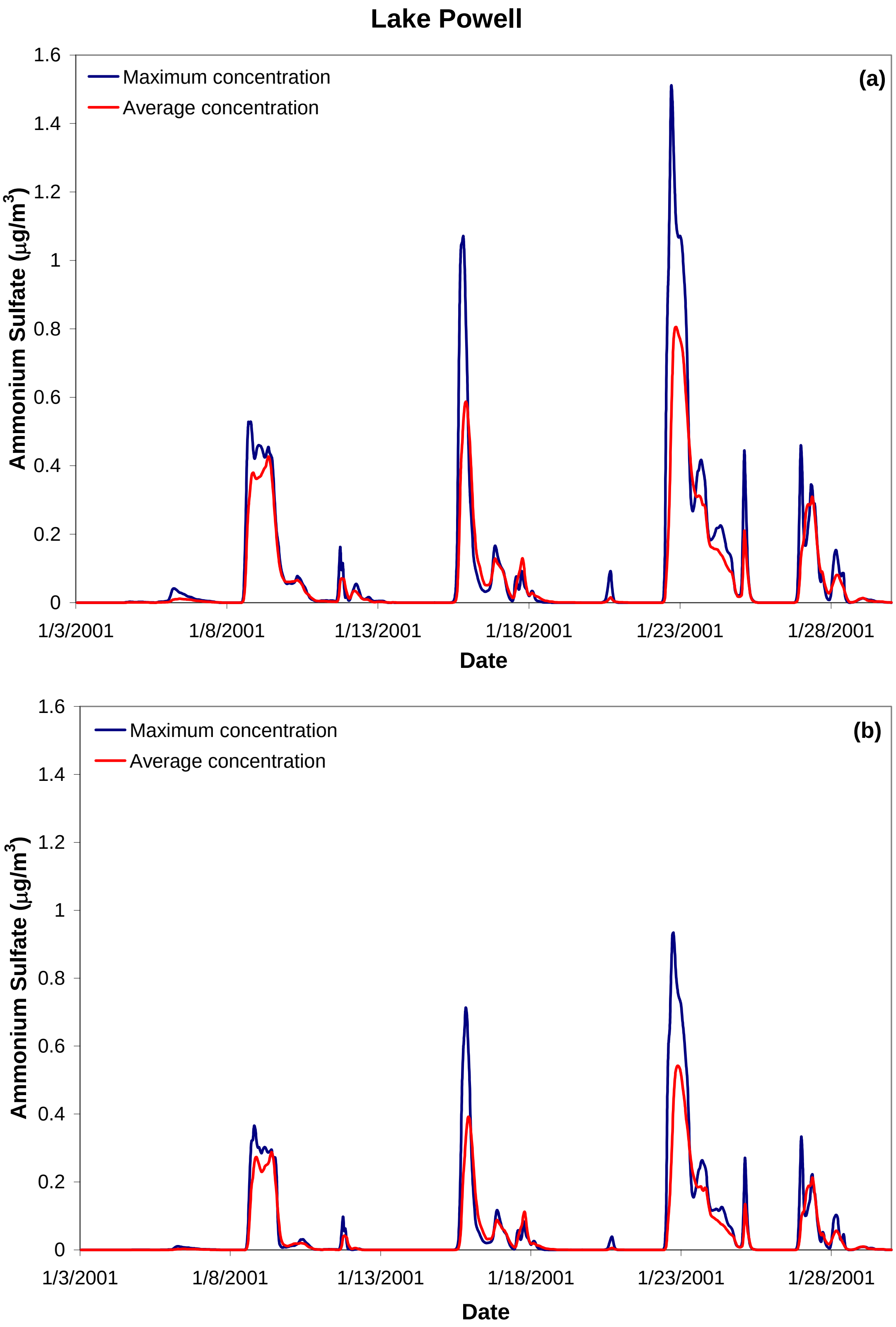


Figure 5. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over the Lake Powell region.

4. Full chemistry simulation

In addition to the tracer run, two other CAMx simulations are considered in this analysis. First, a "base case" simulation is created that explicitly calculates the transport, chemistry and deposition of several species, including sulfate, SO_2 and NO_x, using all available emission sources in the computational domain. Once the base case is established, the effects of the proposed power plant are determined through an identical simulation with the only difference being the addition of the Sithe's emissions to the current inventory.

4.1 Results

The full chemistry simulations are defined using the same conditions and grid resolution as the tracer simulation. Although the model can estimate the contribution of SO_2 and sulfate separately, the results are reported as total sulfur that fully neutralizes to form ammonium sulfate. This assumption is made in part due to shortcomings in the MM5 meteorology that does not fully capture the actual cloud fields during the simulated period. The WHITEX study showed that the drainage flow fills the Grand Canyon with clouds, sulfur dioxide, and other pollutants entrained in the clouds. It is the presence of those clouds that allow the rapid conversion of sulfur dioxide to sulfate. Once the flow stops, the Grand Canyon becomes in effect a confined reaction chamber with the sulfur dioxide undergoing highly efficient wet phase oxidation producing particulate sulfate.

The hourly impacts of the Sithe EGU on the Grand Canyon and Lake Powell regions are presented in Figures 4 and 5. These impacts combine the results from both full chemistry simulations, since they are defined as the base case results subtracted from the simulation that includes the Sithe power plant:

Sithe's impact = EGU simulation – base case

Figure 4b shows in red the average in-canyon concentrations of total sulfur (SO_2 + $(NH_4)_2SO_4$) impacts of the Sithe EGU scaled as ammonium sulfate. The blue line shows the maximum total sulfur impacts expected in GRCA. Figure 4b shows that results from the full chemistry runs do not equal the sulfur concentrations of the tracer run, despite their similar temporal trends. This difference, all things being equal, is due to both dry and wet deposition. Appendix 1 shows the results of the tracer and full chemistry simulation for other class I areas considered in this work, while Appendix 2 provides the simulations of Sithe impacts in the Four Corners Region with the Eulerian photochemistry model REMSAD.

5. Ammonia in the Four Corners

Ammonia plays an important role in the formation of particulate matter. Competition between sulfate and nitrate for available ammonia results in a complex non-linear system. Sithe's PSD air quality impact analysis (ENSR, 2006) reported an alternative set of regional haze results using a lower background ammonia concentration (0.1ppb instead of 0.2 ppb) for cold-weather months (November – March). The ammonia concentrations from the CAMx model run using the WRAP emissions inventory were examined to help quantify the ammonia concentration in the Four Corners regions. Figure 6 presents the resulting monthly average ammonia concentrations for the month of January. As shown, the ammonia concentrations in the Four Corners region always exceed 0.1 ppb and typically varied between 0.2 ppb and 0.4 ppb.

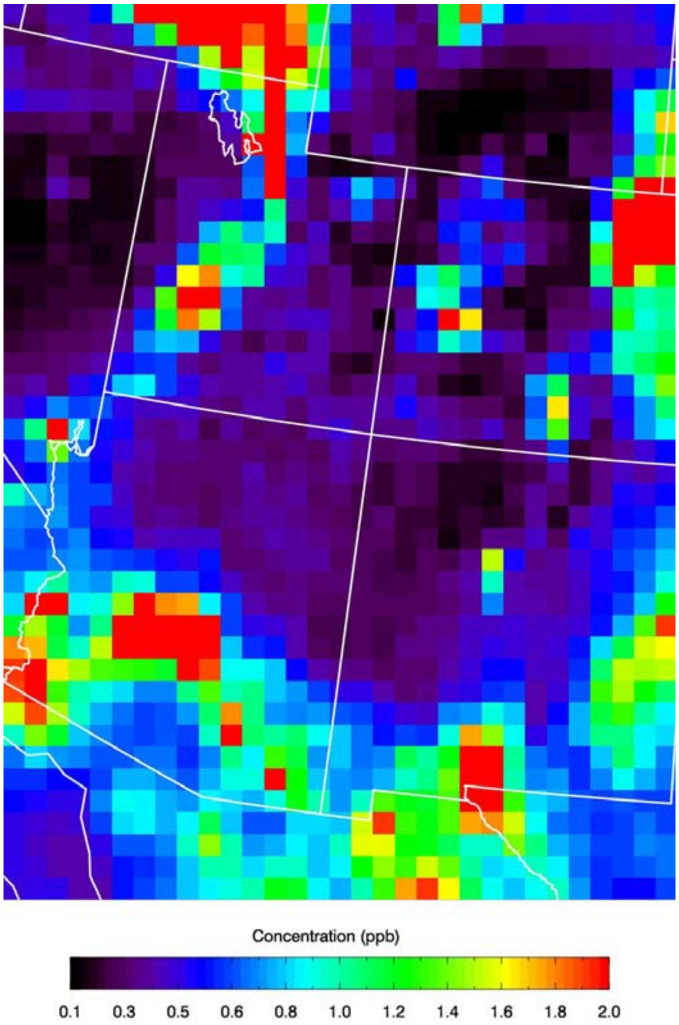


Figure 6. Monthly average ammonia concentrations in the Four Corners region estimated with CAMx for the month of January.

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APPENDIX 1

CAMx Simulations of the Sithe Impacts in the Four Corners Region

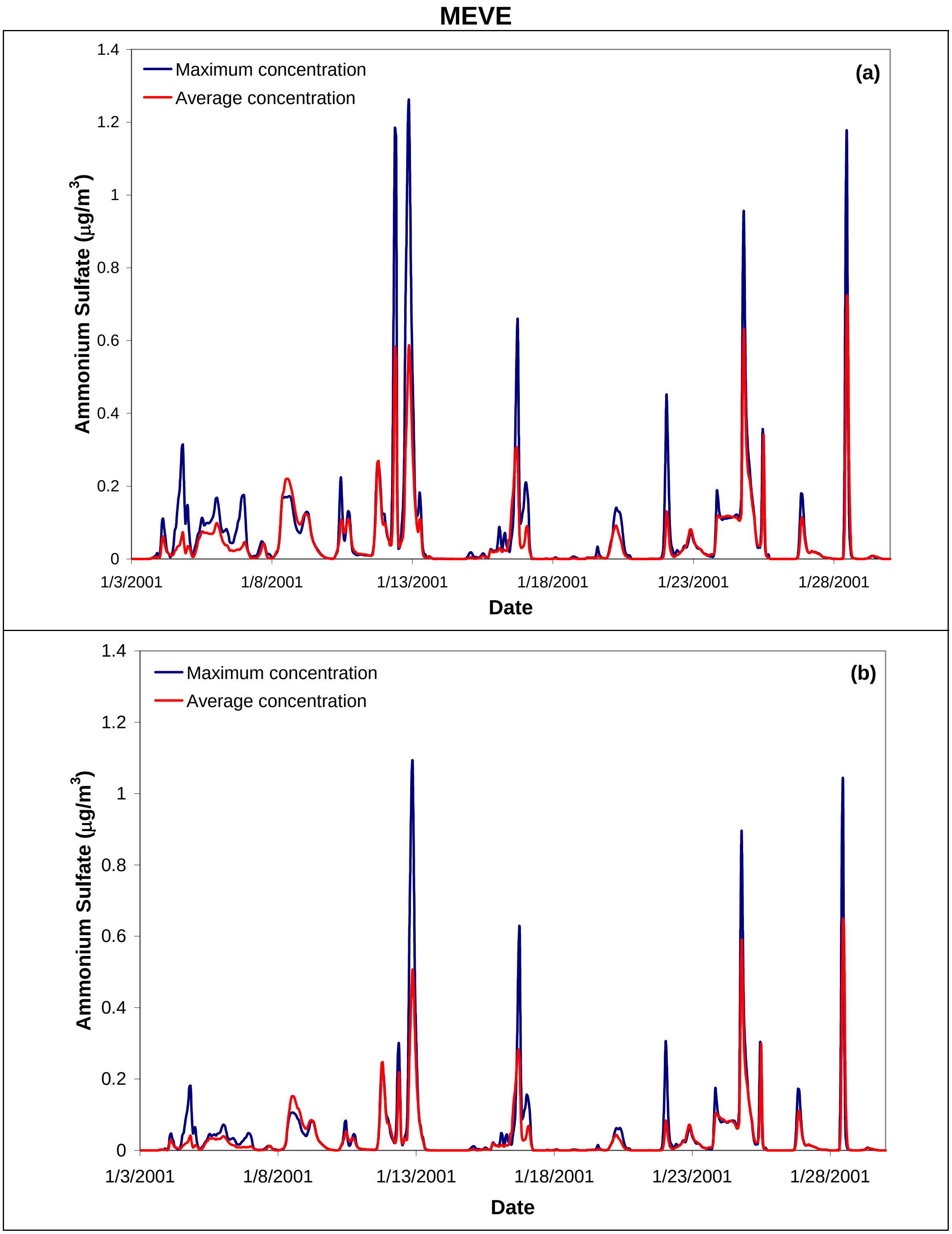

Figure A1-1. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Mesa Verde NP.

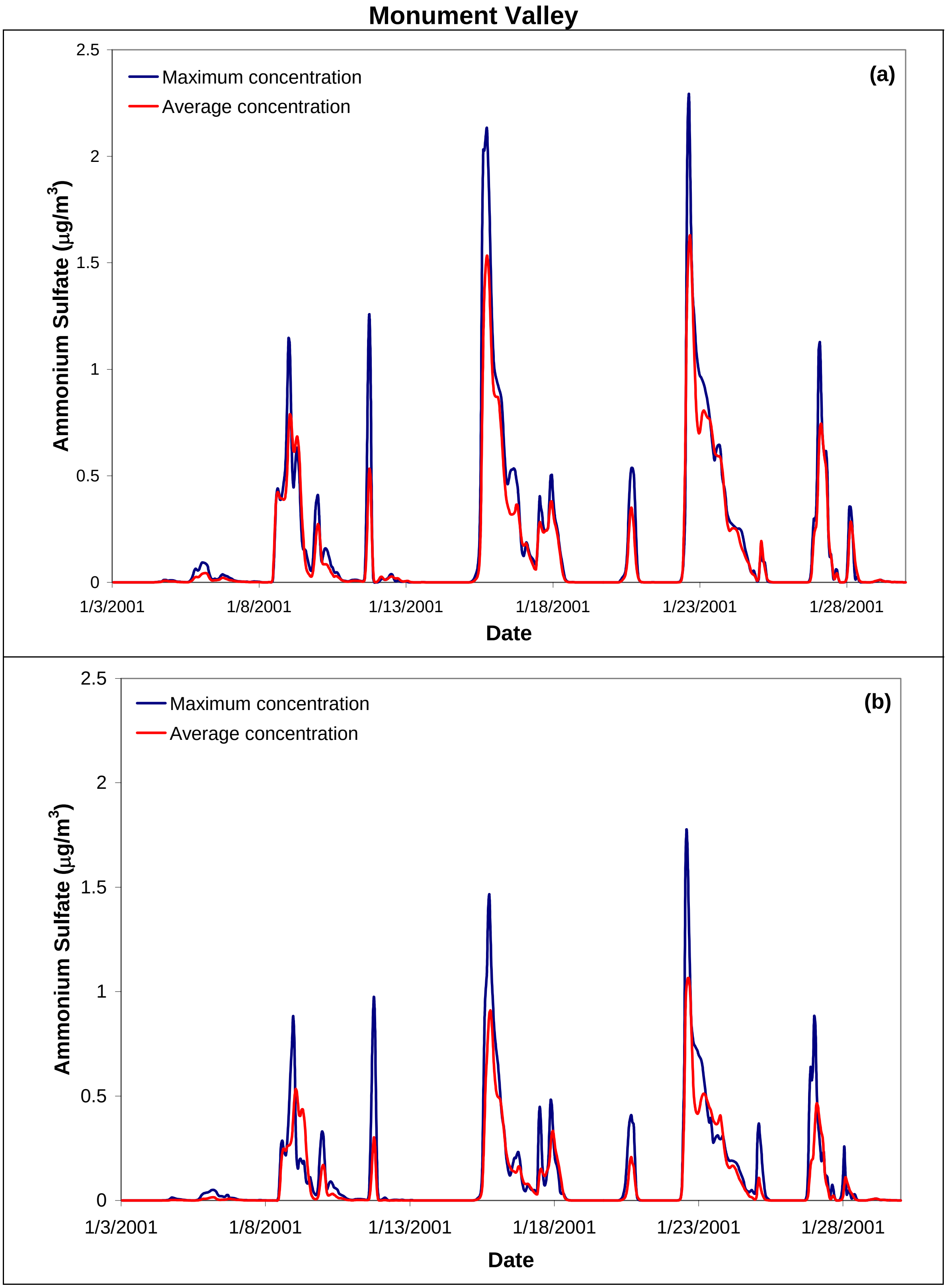

Figure A1-2. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Monument Valley.

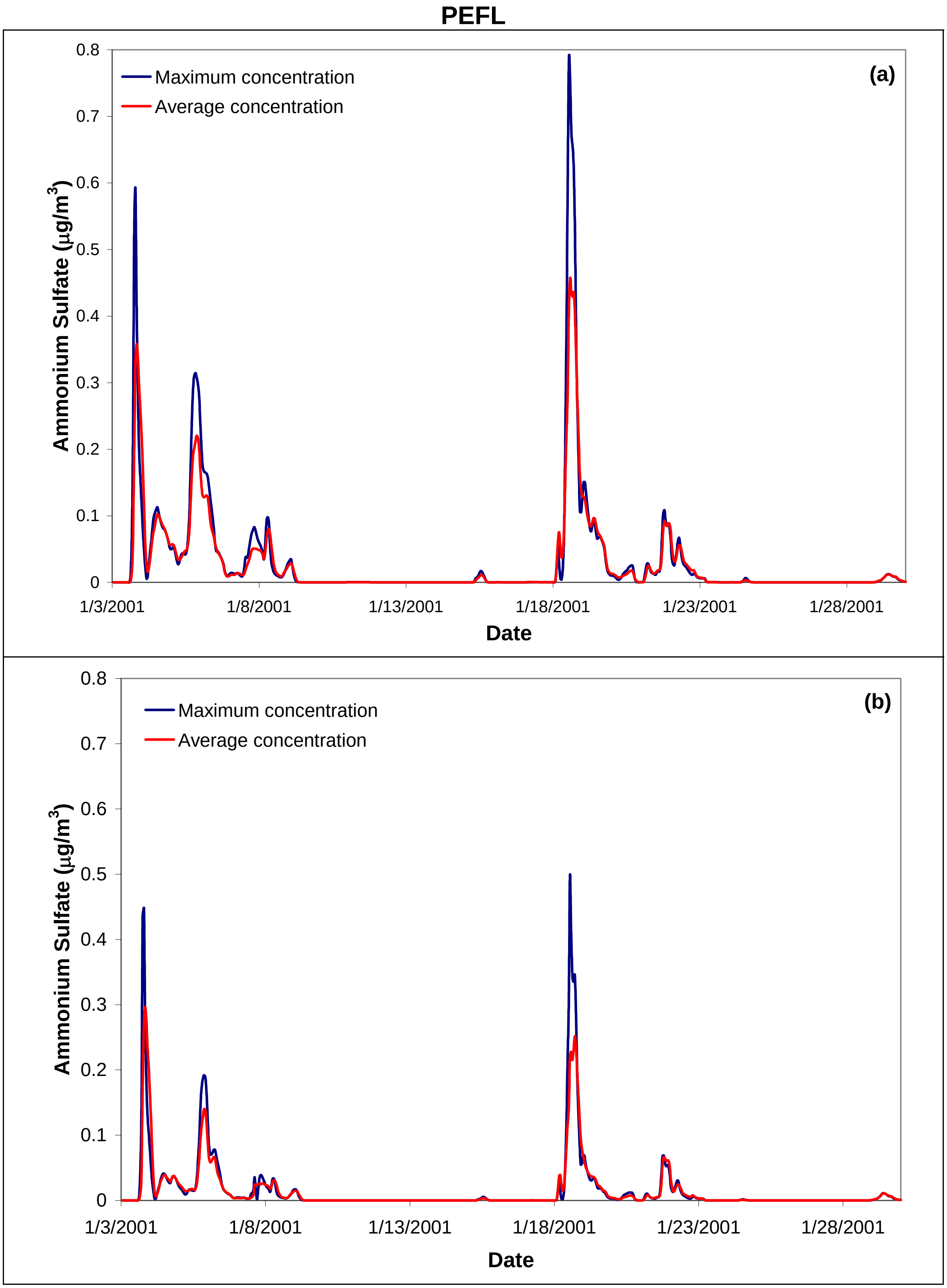

Figure A1-3. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Petrified Forest NP.

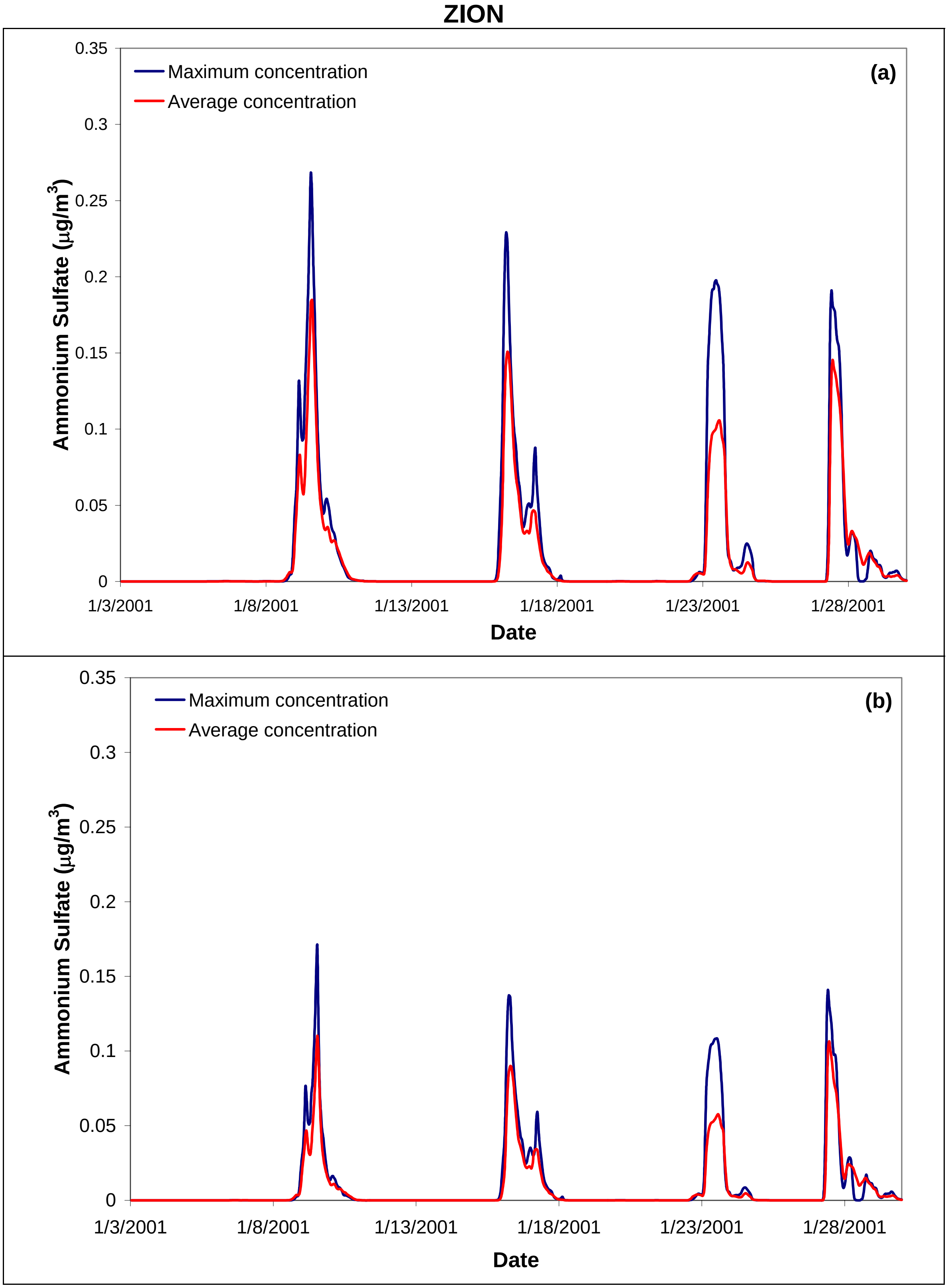

Figure A1-4. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Zion NP.

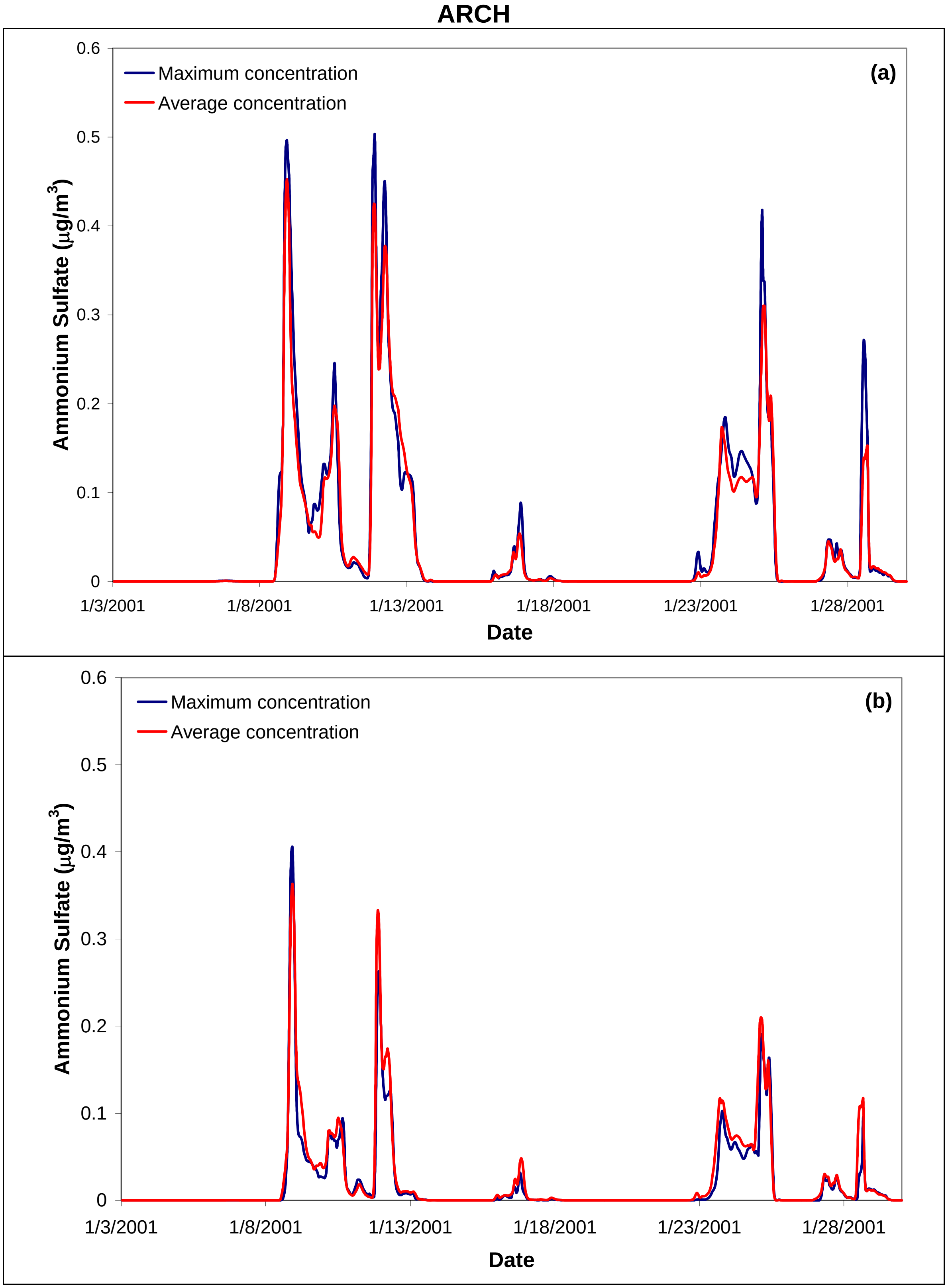

Figure A1-5. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Arches NP.

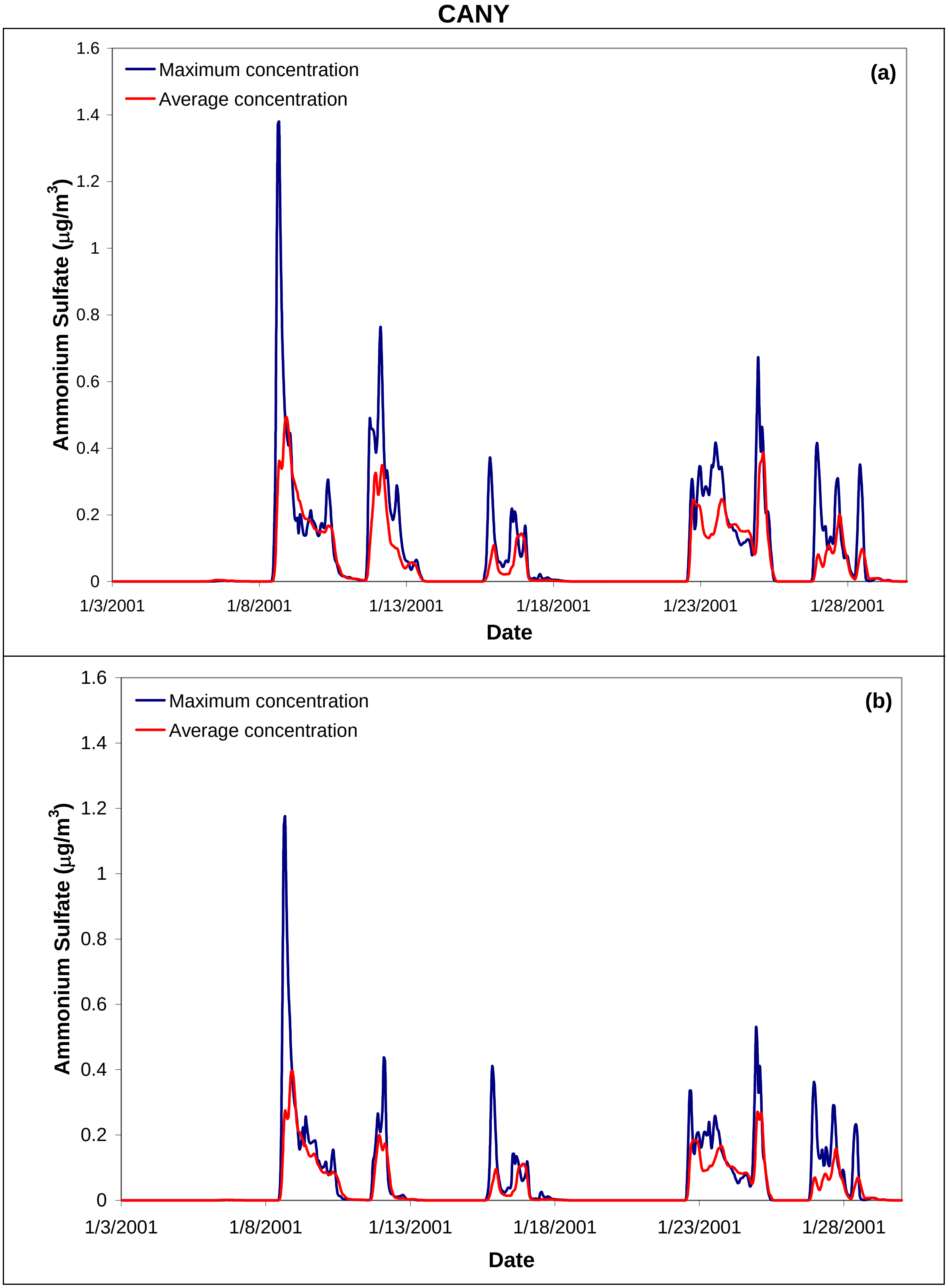

Figure A1-6. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Canyonlands NP.

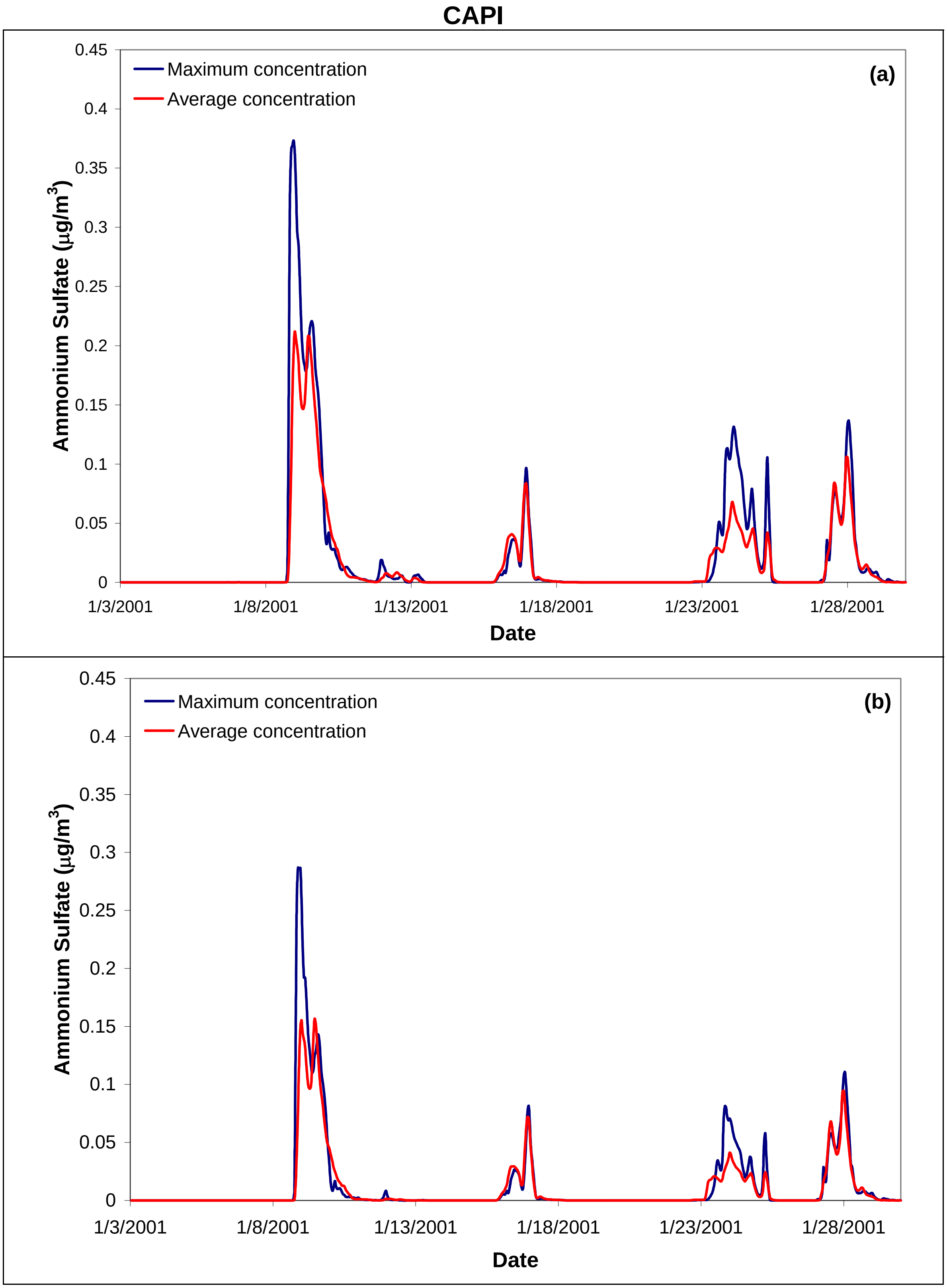

Figure A1-7. Time series concentrations scaled as ammonium sulfate for a) the tracer and b) the full chemistry simulations. The blue line represents the maximum impact while the red line represents the average impact over Capitol Reef NP.

APPENDIX 2

REMSAD Simulations of Sithe Impacts in the Four Corners Region

INTRODUCTION

The Regional Modeling System for Aerosols and Deposition (REMSAD) was used to predict sulfur pollution from the proposed Sithe coal-fired power plant in the Four Corners region of the southwestern U.S. This modeling system was originally used to predict regional sulfate contributions to Big Bend National Park (TX) as part of the Big Bend Regional Aerosol and Visibility Observational Study (BRAVO), and details of the BRAVO REMSAD simulations can be found in Barna et al. (2006 a,b). This study is an extension of the original BRAVO REMSAD simulations, and considers the impacts arising from sulfur emissions from Sithe at fourteen Class I areas in the Four Corners region (Figure 1 and Table 1). The simulation period was July 1 – October 31, 1999, corresponding to the BRAVO field measurement campaign.

MODELING SYSTEM

REMSAD is an Eulerian air quality model designed to predict the formation and transport of aerosols and their precursors and simulates the physical and chemical processes that affect atmospheric pollutants and their precursors, including advection, diffusion, wet and dry deposition, and chemical transformation. The domain covers most of the contiguous U.S. and northern Mexico. A geodetic (latitude/longitude) horizontal coordinate system is used, with a model grid resolution of approximately 36 km. The domain extends from 74° W to 120° W at the eastern and western boundaries, respectively, and from 49° N to 16° N for the northern and southern boundaries, respectively. The vertical dimension is defined in terrain-following sigma-pressure coordinates. Thirteen vertical layers are used, with thinner layers near the surface and thicker layers aloft. The top of the model domain is set to 50 mb.

The chemistry mechanism in REMSAD treats gas-phase, aqueous-phase, and aerosol equilibrium processes. Gas phase chemistry is calculated with the "Micro" Carbon Bond IV mechanism (μCB-IV), which is based on a reduced formulation of the Carbon Bond IV mechanism (ICF Consulting, 2002). Sulfur dioxide oxidation via ozone, molecular oxygen (catalyzed by iron and manganese), and hydrogen peroxide in the aqueous-phase is simulated. The MARS-A thermodynamics module is used to predict the equilibrium between nitrate, sulfate and ammonia.

Input meteorological fields for REMSAD were simulated by MM5 (Grell et al., 1994). The application of MM5 in BRAVO is described in Seaman and Stauffer (2003). Four dimensional data assimilation (FDDA), using both analysis nudging and observational nudging, was employed.

An emission inventory for the U.S. and northern Mexico was developed for BRAVO and consisted of hourly, gridded emission rates of sulfur dioxide, primary particulate sulfate, nitrogen oxides, ammonia, various anthropogenic and biogenic volatile organic compounds, coarse particles (aerodynamic diameter < 10 μm), and carbon monoxide (Kuhns et al., 2005). Primary particulate sulfate constitutes a small portion of the overall sulfur emissions at less than 2%. For this study, only sulfur emissions from the proposed Sithe power plant (3,319 tons per year of SO_2) were considered. Hence, all sulfur concentrations within the model domain can be attributed to emissions from Sithe. To maintain realistic oxidant concentrations, only sulfur emissions were modified, while all other emissions (e.g., nitrogen oxides, volatile organic compounds, etc.) were left at their base emission rates. Stack parameters for Sithe are shown in Table 2.

RESULTS

To determine the maximum potential impact from Sithe, the results are presented as hourly ammonium sulfate concentrations estimated at the fourteen class I sites assuming 1) complete oxidation of sulfur dioxide to fine particulate sulfate, and 2) full neutralization of fine particulate sulfate to ammonium sulfate (Figures 2 – 15). Wet and dry deposition of sulfur dioxide and sulfate are simulated. Although this approach represents an upper bound in terms of maximum ammonium sulfate impacts from Sithe, concentrations of the magnitude presented here would be anticipated if clouds were present, given the rapid conversion of sulfur dioxide to sulfate that occurs in cloud droplets. It should also be noted that the relatively coarse scale of the REMSAD model grid (36 km) results in an immediate diffusion of emissions from Sithe within a model grid cell, lessening its impact. It is presumed that a finer model grid (e.g., 12 km or 4 km) or the explicit treatment of plumes at a sub-grid scale would lessen the dilution effect and result in higher concentrations. This is especially true at sites near Sithe.

The largest impacts from Sithe occur at Mesa Verde National Park, which lies approximately 80 km north of proposed power plant in southwestern Colorado (Figure 9). Estimated ammonium sulfate concentrations exceeding 0.10 μg m^{-3} occur frequently (64 times during the four-month simulation), with peak concentrations of approximately 0.5 μg m^{-3} occurring in early September and late October. Other class I areas lying northwest, north, or east of Sithe are also frequently impacted: Arches National Park (Figure 2), Bandelier National Monument (Figure 3), Canyonlands National Park (Figure 5), Capital Reef National Park (Figure 6), Great Sand Dunes National Monument (Figure 8), San Pedro Parks Wilderness (Figure 11), Weminuche Wilderness (Figure 12), Wheeler Peak Wilderness (Figure 13), and White River National Forest (Figure 14). Class I areas lying west or southwest of Sithe were less frequently impacted: Bryce Canyon National Park (Figure 4), Grand Canyon National Park (Figure 7), Petrified Forest National Park (Figure 10) and Zion National Park (Figure 15). These results reflect synoptic transport patterns that generally favored westerly winds during this period, particularly during July and August. Table 3 shows the frequency of Sithe's impacts on the fourteen class I areas, defined as the number of days in which ammonium sulfate concentrations exceed 0.1 μg m^{-3} (hourly average). Maximum hourly ammonium sulfate concentrations estimated at the fourteen class I areas are shown in Table 4. Concentrations range from 0.16 μg m^{-3} at Great Sand Dunes National Monument to 0.51 μg m^{-3} at Mesa Verde and Petrified Forest National Parks, with higher concentrations estimated at sites closest to Sithe.

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Table 1. The fourteen class I areas in the Four Corners region considered for this study.

Symbol	State	Name	Latitude (dec. deg.)	Longitude (dec. deg.)
ARCH	UT	Arches National Park	38.783	-109.583
BAND	NM	Bandelier National Monument	35.780	-106.266
BRCA	UT	Bryce Canyon National Park	37.618	-112.174
CANY	UT	Canyonlands National Park	38.459	-109.821
CAPI	UT	Capitol Reef National Park	38.302	-111.293
GRCA	AZ	Grand Canyon National Park	36.066	-112.154
GRSA	CO	Great Sand Dunes National Monument	37.725	-105.519
MEVE	CO	Mesa Verde National Park	37.198	-108.491
PEFO	AZ	Petrified Forest National Park	35.078	-109.768
SAPE	NM	San Pedro Parks Wilderness	36.014	-106.845
WEMI	CO	Weminuche Wilderness	37.659	-107.800
WHPE	NM	Wheeler Peak Wilderness	36.586	-105.451
WHRI	CO	White River National Forest	39.152	-106.819
ZION	UT	Zion National Park	37.459	-113.224

Table 2. Stack characteristics of the proposed Sithe coal-fired power plant.

latitude	36^{o} 29' 46"
longitude	108^{o} 32' 50"
stack height (m)	280
stack diameter (m)	11
exit velocity (m/s)	25
exit temp (deg K)	323

Table 3. Number of days when hourly ammonium sulfate concentrations estimated at each of the fourteen class I sites exceeded 0.1 μg m^{-3} during the four month (July – October 1999) simulation.

Site	No. of Days
ARCH	34
BAND	45
BRCA	12
CANY	38
CAPI	19
GRCA	8
GRSA	6
MEVE	64
PEFO	15
SAPE	39
WEMI	24
WHPE	15
WHRI	6
ZION	6

Table 4. Peak hourly ammonium sulfate concentrations (μg m^{-3}) estimated at each of the fourteen class I sites and the date of occurrence.

Site	Date	$(NH_4)_2SO_4$ (μg m^{-3})
ARCH	14-Sep-99	0.36
BAND	20-Sep-99	0.41
BRCA	19-Aug-99	0.26
CANY	28-Oct-99	0.44
CAPI	24-Jul-99	0.28
GRCA	27-Oct-99	0.34
GRSA	16-Oct-99	0.16
MEVE	25-Oct-99	0.51
PEFO	14-Oct-99	0.51
SAPE	7-Aug-99	0.45
WEMI	3-Sep-99	0.29
WHPE	29-Oct-99	0.30
WHRI	15-Aug-99	0.17
ZION	19-Aug-99	0.23

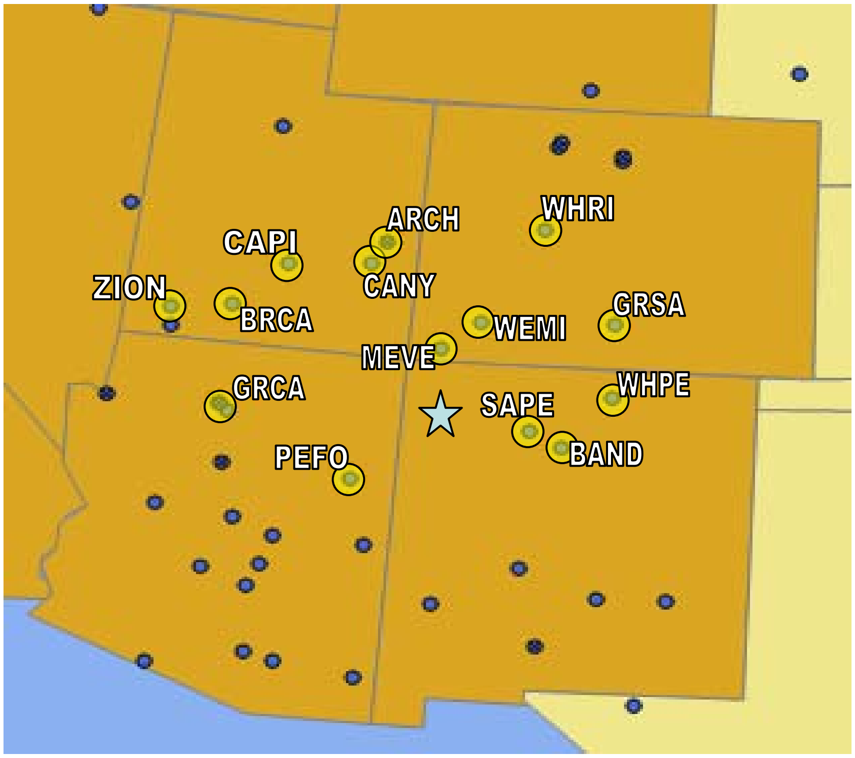

Figure 1. Site of proposed Sithe power plant (“9”) and class I areas evaluated in this study (“, ”).

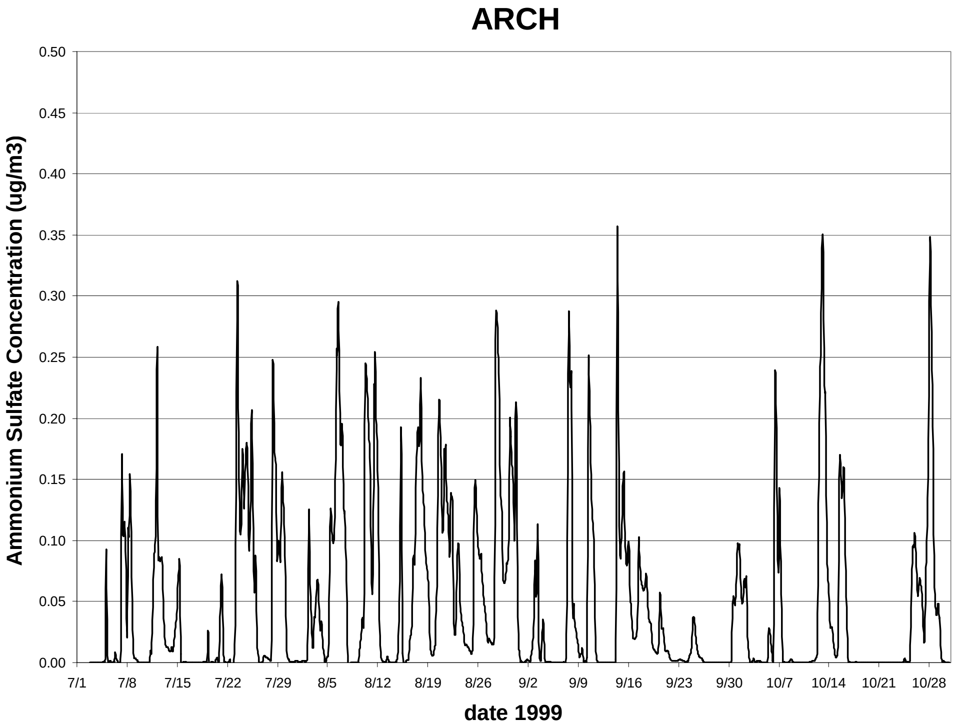

Figure 2. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Arches National Park (UT), assuming complete oxidation of SO_2.

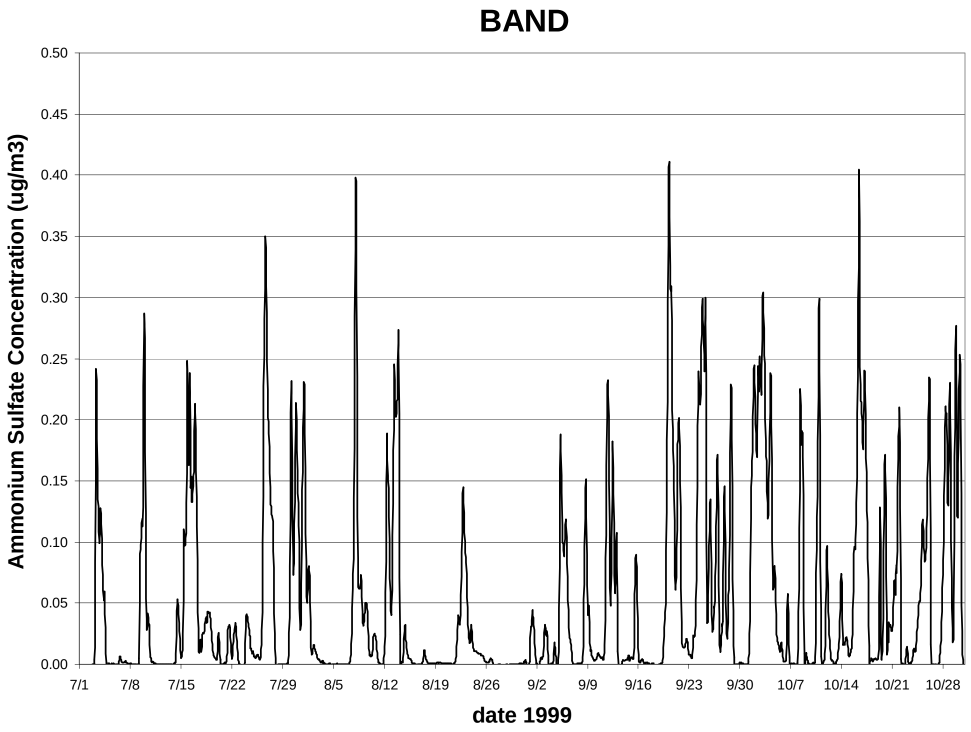

Figure 3. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Bandelier National Monument (NM), assuming complete oxidation of SO_2.

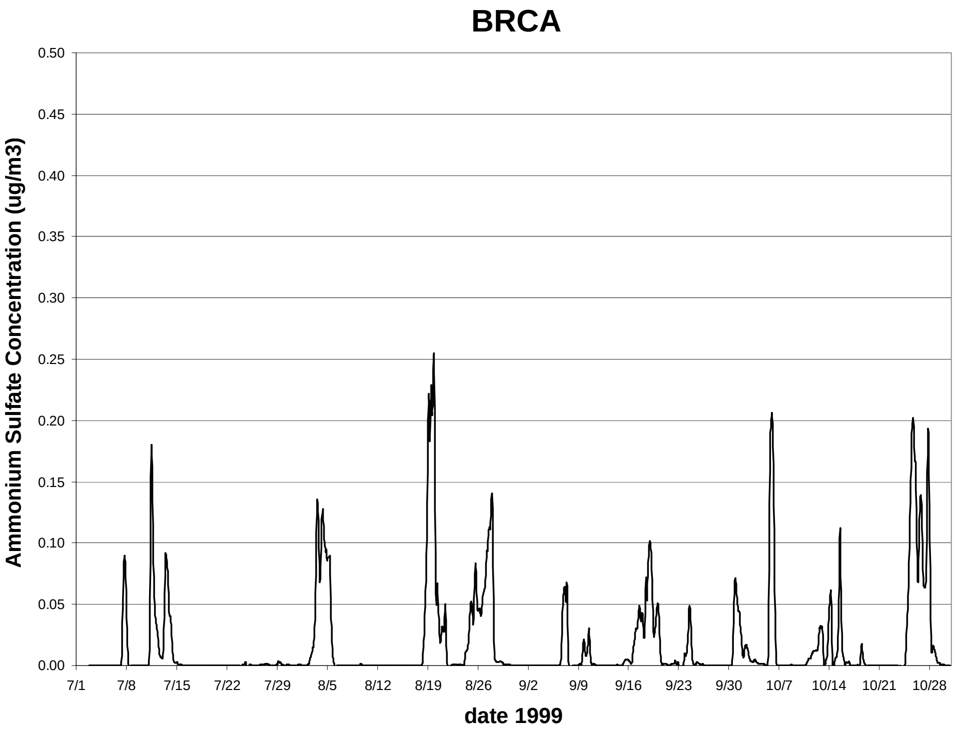

Figure 4. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Bryce Canyon National Park (UT), assuming complete oxidation of SO_2.

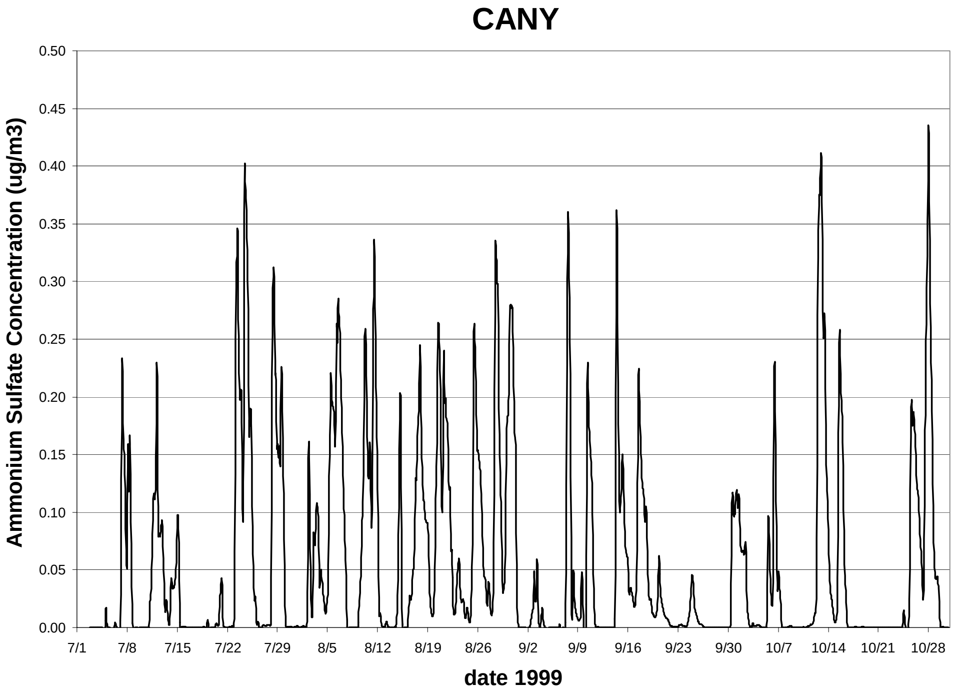

Figure 5. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Canyonlands National Park (UT), assuming complete oxidation of SO_2.

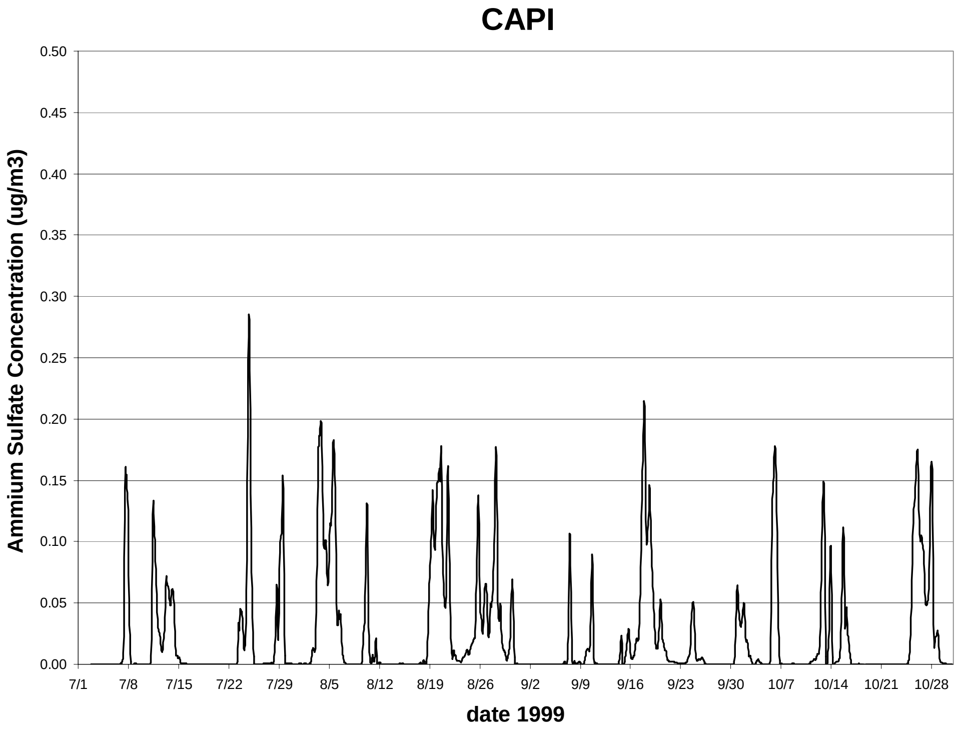

Figure 6. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Capital Reef National Park (UT), assuming complete oxidation of SO_2.

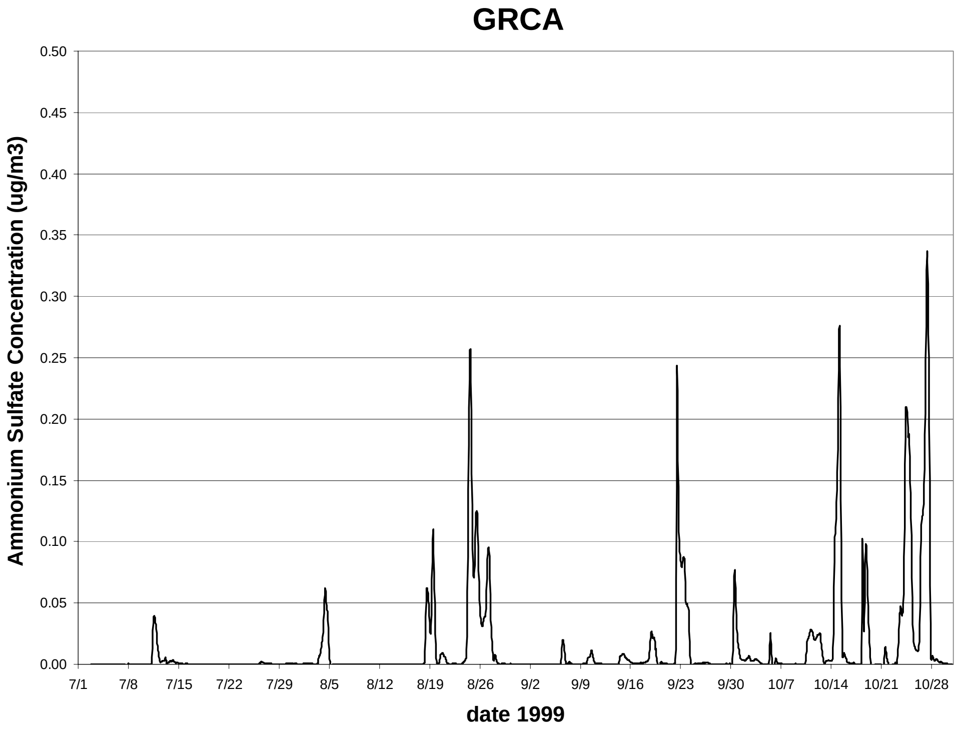

Figure 7. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Grand Canyon National Park (AZ), assuming complete oxidation of SO_2.

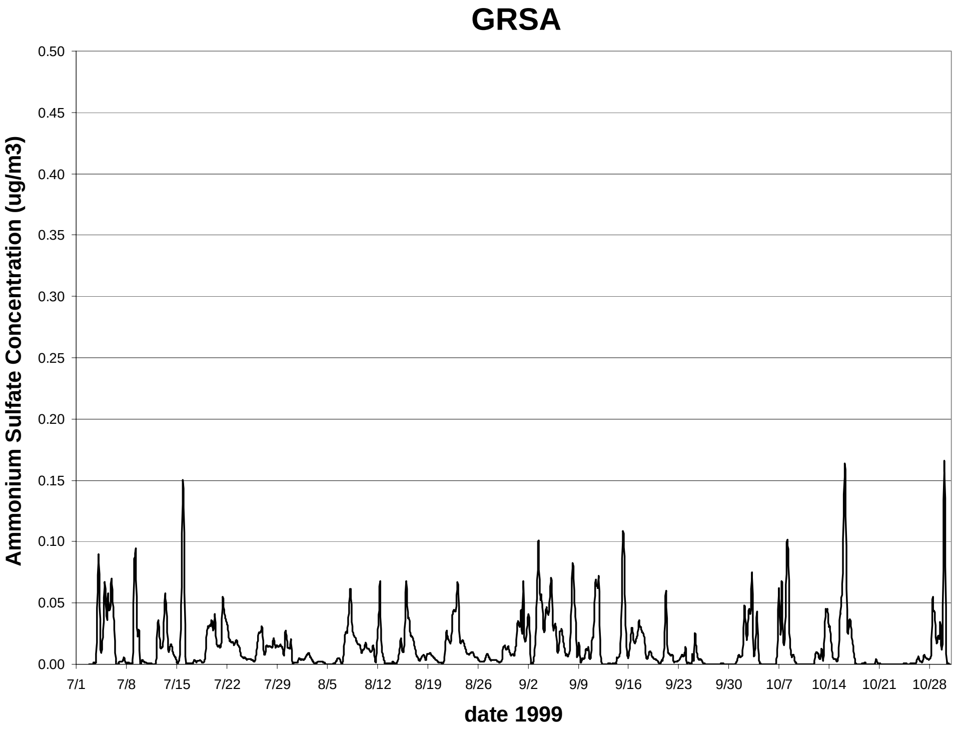

Figure 8. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts (μg m^{-3}) from the proposed Sithe power plant at Great Sand Dunes National Monument (CO), assuming complete oxidation of SO_2.

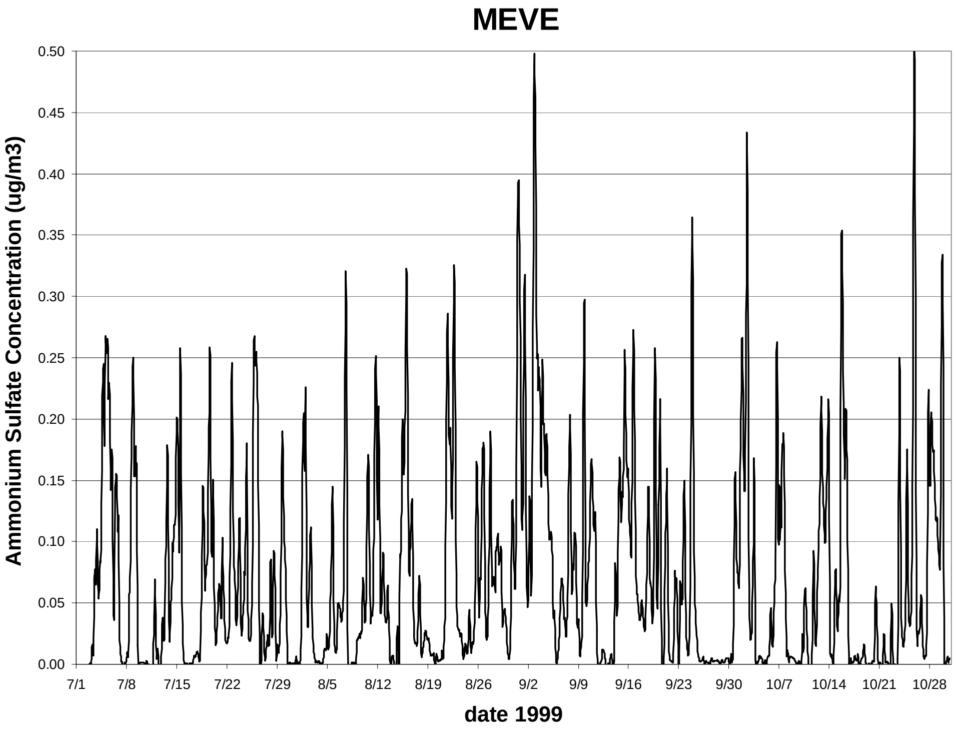

Figure 9. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Mesa Verde National Park (CO), assuming complete oxidation of SO_2.

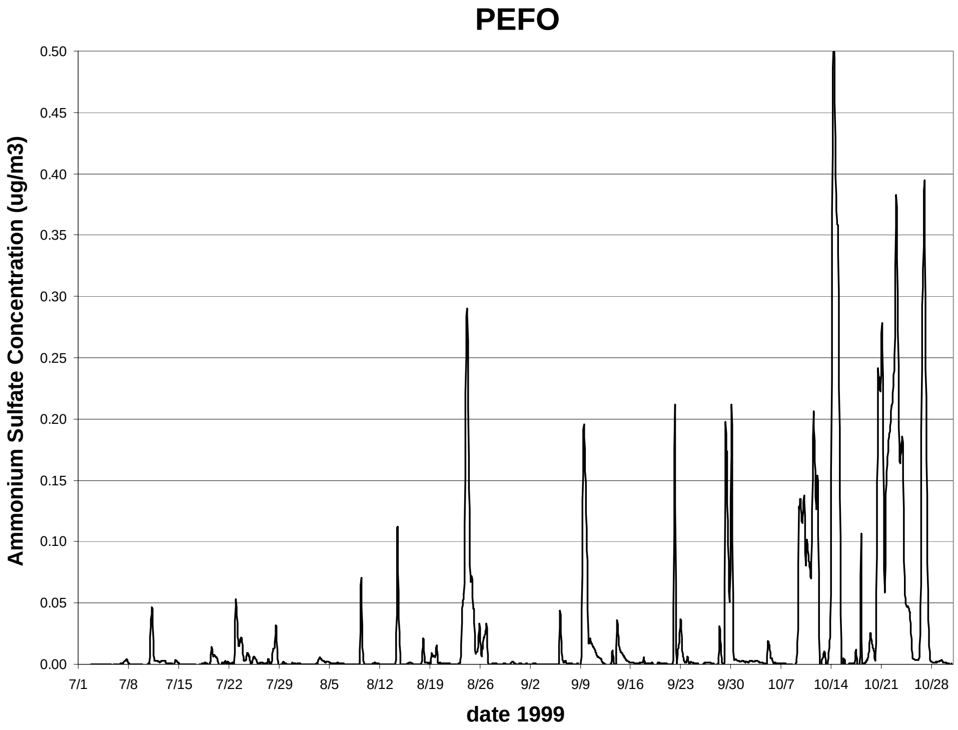

Figure 10. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts (µg m^{-3}) from the proposed Sithe power plant at Petrified Forest (AZ), assuming complete oxidation of SO_2.

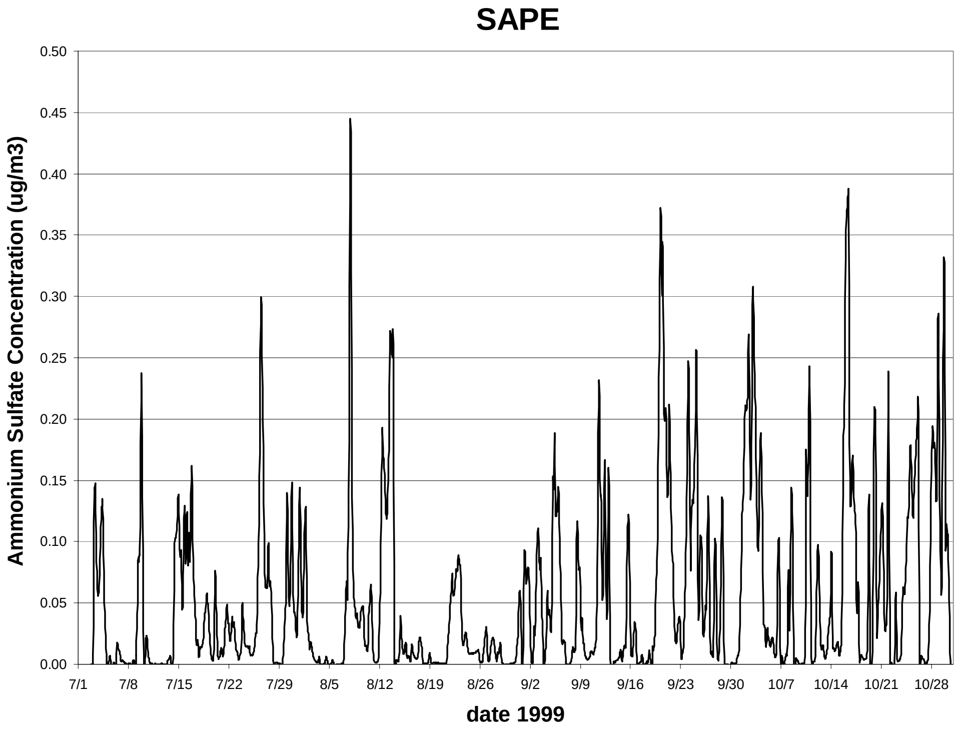

Figure 11. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at San Pedro Parks Wilderness (NM), assuming complete oxidation of SO_2.

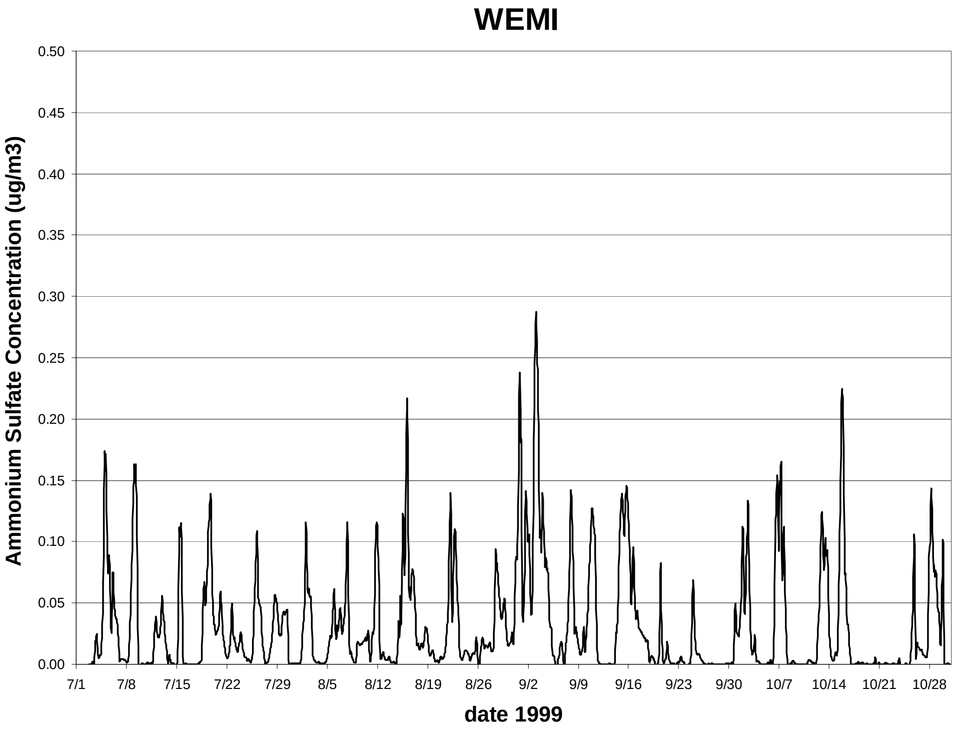

Figure 12. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts (μg m^{-3}) from the proposed Sithe power plant at Weminuche Wilderness (CO), assuming complete oxidation of SO_2.

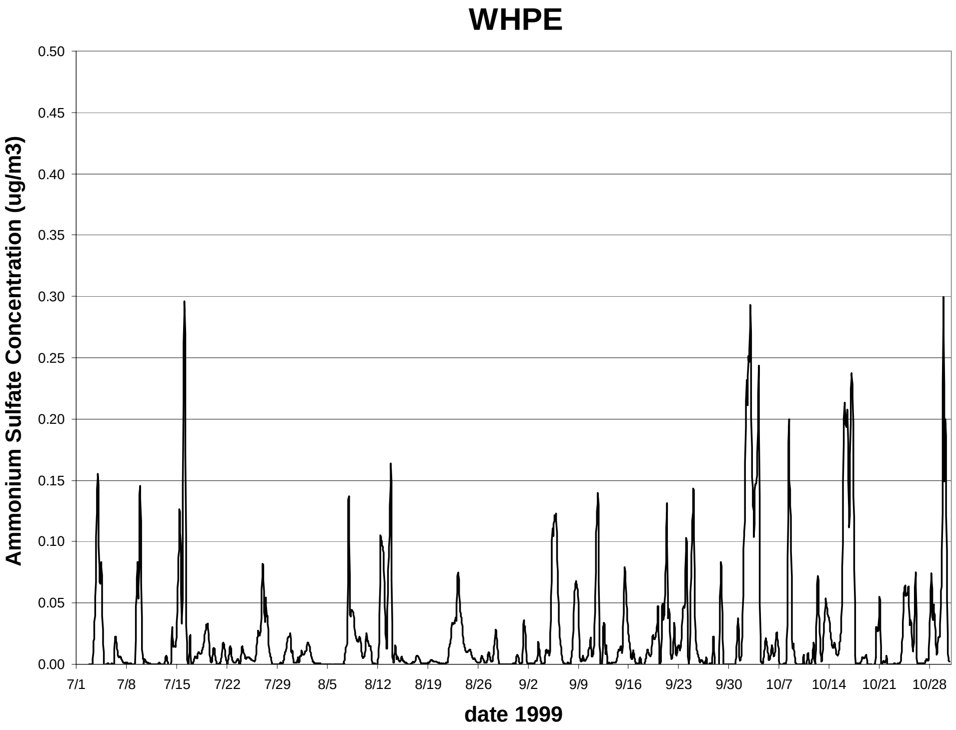

Figure 13. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at Wheeler Peak Wilderness (NM), assuming complete oxidation of SO_2.

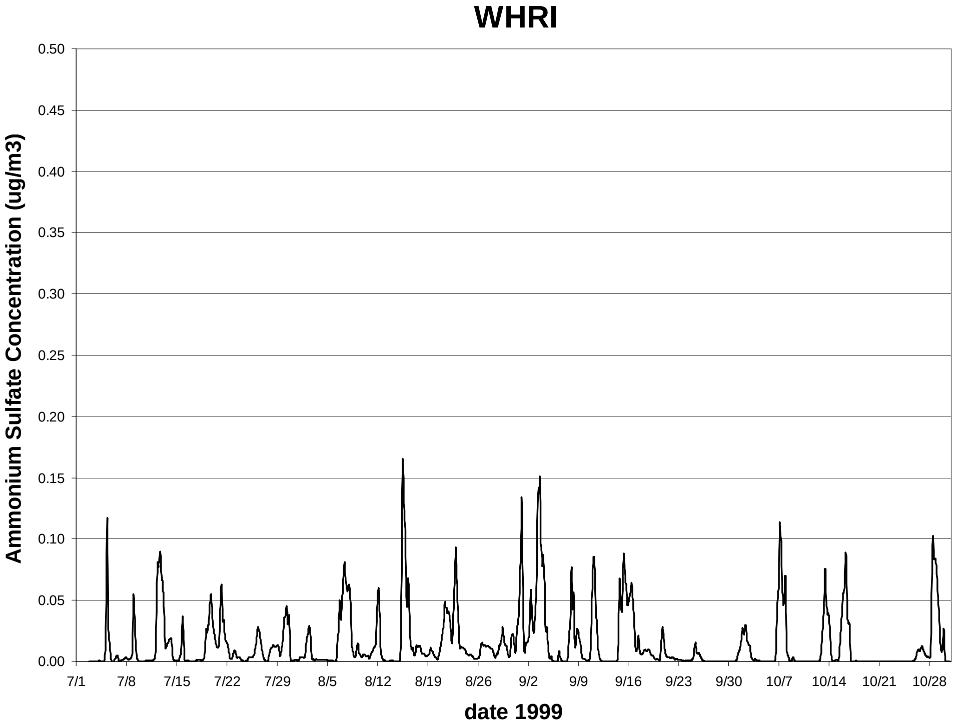

Figure 14. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts ($\mu g\ m^{-3}$) from the proposed Sithe power plant at White River National Forest (CO), assuming complete oxidation of SO_2.

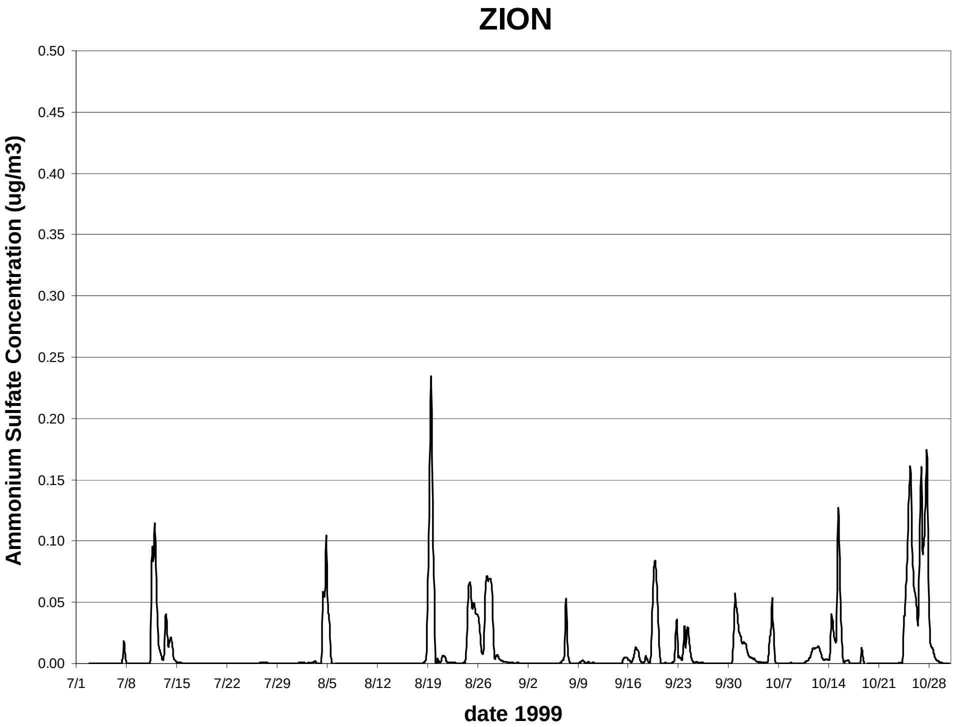

Figure 15. REMSAD predictions of hourly $(NH_4)_2SO_4$ impacts (μg m^{-3}) from the proposed Sithe power plant at Zion National Park (UT), assuming complete oxidation of SO_2.