Simulation of the Impact of the SO_2 Emissions from the Proposed Sithe Power Plant on the Grand Canyon and other Class I Areas

Bret A. Schichtel, William C. Malm, Michael G. Barna, and Marco A. Rodriguez

Abstract

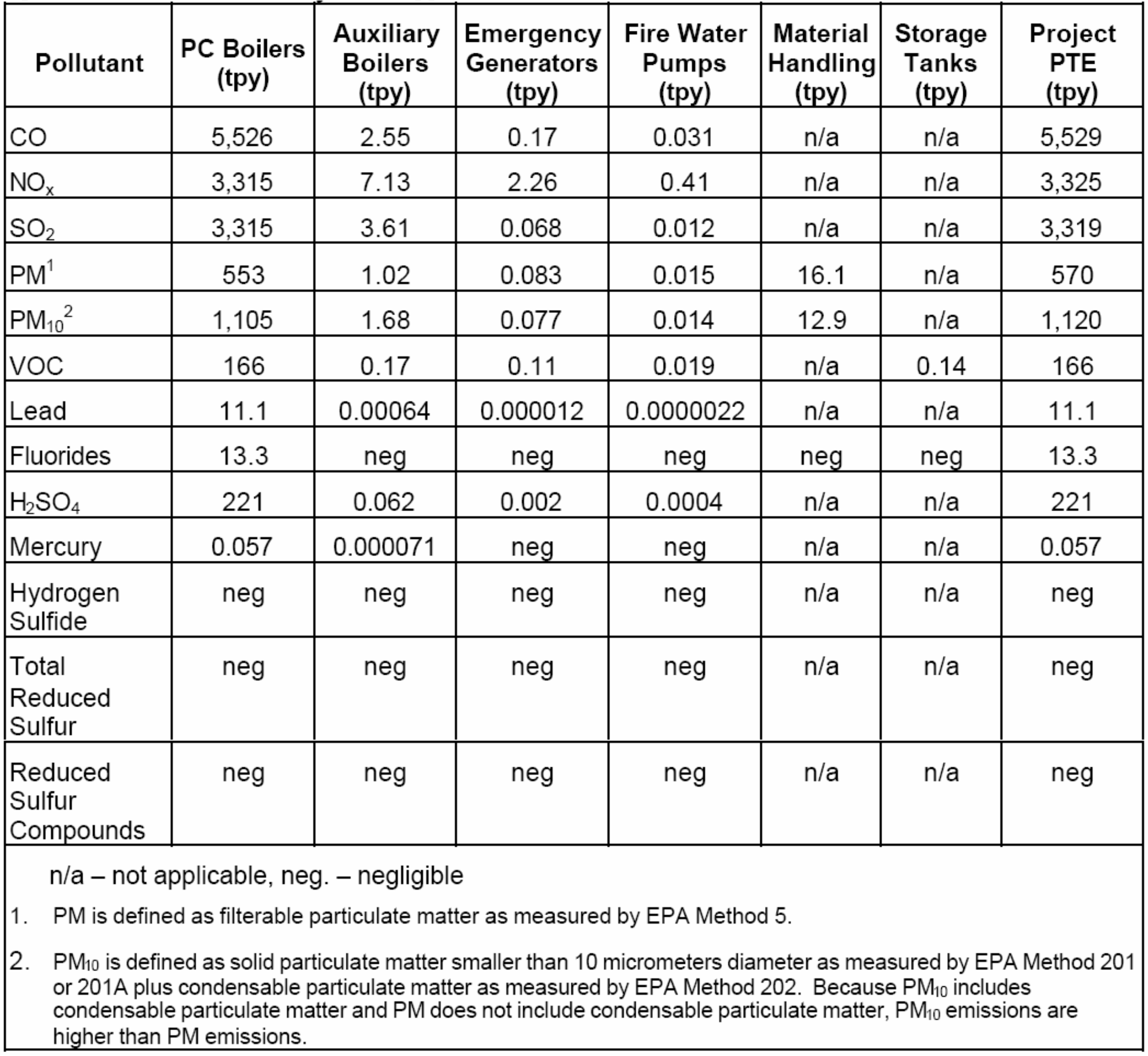
A 1500 MW coal-fired power plant is proposed to be built by Sithe Energies Inc. in the Four Corners basin near the existing Four Corners and San Juan power plants. Four Corners is located on the Colorado Plateau, home to the Grand Canyon National Park and other class I areas, where visibility is an integral 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 of the Grand Canyon can significantly contribute to haze in the Grand Canyon NP 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. To investigate the potential impact of the proposed power plant on these class I areas, a particle dispersion model was used to simulate the proposed and existing power plant plumes during January 2001. Four-km MM5 wind fields were generated for input into the model. The plume simulation was combined with photographs taken from the Desert View watch tower on the rim of the Grand Canyon. During the month, four multi-day stagnation and recirculation events in the Four Corners region occurred associated with polar high pressure systems over the region. During these stagnation events, emissions from the three simulated power plants mixed together and accumulated in the basin. The combined plumes were then transported to Lake Powell and into the Grand Canyon as well as other class I areas. Photographs showed the plumes embedded in clouds, which rapidly convert SO_2 to sulfate. Prior to the plumes being ventilated from the canyon, the clouds evaporated and a layered or uniform haze remained, presumably due to emissions from Four Corners, San Juan, and other sources. Linear first-order kinetics was added to the dispersion model to simulate the transformation of sulfur dioxide to ammonium sulfate and their removal. Constant transformation rates of 1% and 5% per hour were used to simulate the efficient in-cloud conversion processes. Peak simulated ammonium sulfate concentrations varied between 0.4 and 2 $\mu g/m^3$, depending on the class I area and modeling assumptions. Simulation of these concentration on the scenes at the class I areas showed that the haze levels would be visible to most visitors.

Introduction

The Colorado Plateau is a geologically and topographically unique region, home to many national parks, tribal parks, and wilderness areas. The Colorado Plateau has some of the clearest air in the United States and visibility is an integral component of a visitor's experience to the parks and wilderness areas. However, the Colorado Plateau is also an area of rich coal deposits and oil and gas reserves, and development of these resources could diminish the visibility and air quality. On the Colorado Plateau's southeast corner is the Four Corners region where coal is currently mined and burned in the San Juan and Four Corners power plants. In addition, there are three proposed power plants, BHP, Sithe, and Mustang, with the proposed Sithe power plant currently in the permitting phase of planning (Figure 1).

The Sithe power plant would be built by Sithe Energies Inc. under contract from the Diné Power Authority (DPA) and would be called the Desert Rock Energy Facility. 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. 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 1120 tpy of particulate matter less than 10 microns in diameter (PM_{10}) (Table 1). 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).

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.

There is concern that this facility would exacerbate existing haze on the Colorado Plateau. An air quality impact analysis following the guidelines in Federal Land Managers' Air Quality Related Values Workgroup (FLAG) showed that the Sithe power plant could significantly impact the 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 the proposed power plant increased the haze 27% above the natural background estimate.

The proposed Sithe plant is located within highly complex terrain, and micrometeorological processes, such as orographic clouds, fogs, and pollutant transport blocked and channeled by the terrain, could be important in plume dispersion and chemistry, particularly over multi-day transport periods. Modeling these processes is challenging and beyond the capabilities of most readily available models and the modeling approaches employed in FLAG. Therefore, in this work past studies are examined to identify the important atmospheric processes that lead to haze on the Colorado Plateau from emissions in the Four Corners region and to develop a conceptual model based upon these processes. Particular attention is given to the Grand Canyon National Park since this is a large park with long scenic vistas, and layered hazes can set up on the deep canyon that are clearly visible to visitors, even at low haze levels. Based upon the conceptual model, a simple diagnostic model is used to assess the impact of particulate sulfate from Sithe's SO_2 emissions on class I areas. Detailed air quality and radiative transfer modeling is then conducted to assess a range of potential impacts of the Sithe facility on the air quality at Grand Canyon and other class I areas.

Terrain Features and Wintertime Meteorology Controlling Plume Dispersion in the Southwestern United States

The Colorado Plateau is a region of complex terrain with large, deep canyons and high mountains. The Four Corners region is a basin surrounded by mountains, many extending more than a kilometer above the floor (Figure 1). These mountains can act as effective barriers to airmass transport, allowing emissions from power plants located in the basin to accumulate. Three passes exist in which trapped air in the Four Corners region can escape. One exit is to the northwest along the San Juan River valley between the San Juan and Chuska mountains leading to Lake Powell. A second exit is to the southwest through a pass between the Chuska and Zuni mountains leading to the Painted Desert and Petrified Forest. The pollutants could then follow the Little Colorado River to the Grand Canyon. The third exit is between the San Mateo and Jemez mountains leading to Albuquerque, New Mexico.

The influence of the terrain blocking and channeling flows is most pronounced under stable atmospheric conditions and low inversion heights blocking vertical mixing of air and pollutants. 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 frequency of occurrence and duration of these polar highs were examined in the southwestern United States for 1980–84 (Pielke *et al.*, 1987 and Malm *et al.*, 1989). They showed that during the winter months the polar highs occurred over 60% of the time over the Colorado Plateau and about 65% over northern Arizona and New Mexico. The period of stagnation varied from 3 to over 14 days with a mean duration of 6 days. A polar high over the Four Corners region would allow for the accumulation of emissions from the proposed Sithe plant. 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, due to the anticyclonic transport around the center of the high pressure system.

This complex terrain under shallow mixing layers presents some of the most difficult conditions for which to properly simulate the meteorology, including winds, clouds, and precipitation, and associated plume dispersion and pollutant removal and transformation processes. A simulation must be able to reproduce the stagnation and confinement leading to the accumulation of emission in this region, the transport through the passes, and then the transport along features such as the Little Colorado and San Juan River valleys.

Previous Studies of the Causes of Haze in the Grand Canyon and on the Colorado Plateau

The contribution of emissions from power plants located on the Colorado Plateau on the Grand Canyon National Park (GCNP) and other national parks has been extensively studied over the past 15 years. Two important studies were the Winter Haze Intensive Tracer Experiment (WHITEX) and Measurement of Haze and Visual Effects (MOHAVE). WHITEX was a six-week study in January and February 1987 designed to evaluate the feasibility of attributing single point source emissions to visibility impairment in Grand Canyon National Park (Malm *et al.*, 1989); and project MOHAVE was an extensive monitoring, modeling, and data assessment project designed to estimate the contributions of the Mohave Power Plant (MPP) and other large pollution sources to haze at the Grand Canyon and other national parks. The field study component of project MOHAVE was conducted in 1992 and included two intensive monitoring periods (~30 days in the winter and ~50 days in the summer) (Pitchford *et al.,* 1999).

Principal findings from these two studies include that large emitting power plants, such as the Mohave power plant, located west of GCNP on the Colorado River, and the Navajo Generating Station, located east of GCNP on the Colorado River, could significantly contribute to haze in GCNP; power plants located east of GCNP are most likely to have significant impacts in the winter months, and due to the complex terrain and important micrometeorological processes, modeling the impact of power plants on the Grand Canyon was particularly challenging and no model was able to properly reproduce all of the relevant processes of a haze episode. These studies also identified the atmospheric processes leading to a GCNP wintertime layered haze episode.

Development of Layered Haze Episode in the Grand Canyon

As part of the WHITEX study a camera was set up at the Desert View Watch Tower to visually document haze levels in the GCNP (Malm *et al.*, 1989). Figure 2 presents a series of these photographs illustrating the relevant processes necessary for creating a visible layered haze in the GCNP. Figure 2a is at the early stages of the episode and illustrates drainage flow filling the Grand Canyon with clouds, sulfur dioxide, and other pollutants entrained in the clouds. In Figure 2b, the drainage flow has stopped and now the Grand Canyon is filled with clouds. In effect, the Grand Canyon has become a confined reaction chamber with the sulfur dioxide undergoing highly efficient wet phase oxidation producing particulate sulfate. The clouds begin to evaporate (Figure 2c) leaving behind a thick sulfate haze layer giving the Grand Canyon a milky appearance with clear blue sky and cumulus clouds above (Figure 2d). In similar episodes the measured ammonium sulfate concentrations were about 8 $\mu g/m^3$. The next day, the haze is blown out revealing the many features and colors of the Grand Canyon (Figure 3).

These pictures show drainage flow from the rim of the canyon bringing in clouds and pollutants. In project MOHAVE it was illustrated that pollutants around Lake Powell could be transported to the Grand Canyon and drain into the canyon. As part of this study, unique, nondepositing, nonreactive perfluorocarbon tracer (PFT) was continuously released from Dangling

Rope, on the shore of Lake Powell, during the winter intensive period (Figure 4) (Pitchford *et al.*, 1999; Pitchford *et al.*, 2000). The tracer allowed for the direct tracking of airmass transport and diffusion from the Lake Powell region, which could include emissions from sources east of the GCNP, since prevailing winter mesoscale and nocturnal drainage winds often transport emissions from these sources toward GCNP.

The tracer released from Dangling Rope was often transported down the Grand Canyon following the Colorado River. Under these conditions, the dispersion was impeded by confinement within the canyon resulting in large concentrations even as far away as the Mohave power plant at the other end of the Grand Canyon. The channeling of the flow down the Grand Canyon is illustrated in Figure 5, where on February 2, 1992, high tracer concentrations were measured at Marble Canyon (47 fl/l) and down the canyon at Indian Gardens (29 fl/l) near the Colorado River. The concentrations at all other sites are near zero including Hopi Point, which is on the rim of the canyon above Indian Gardens. Therefore, the tracer was confined within the Grand Canyon below its rim. On January 17 (Figure 5B) elevated tracer concentrations were measured at sites along the Colorado River canyon at the west exit of the Grand Canyon, but not at monitoring sites away from the Colorado River. Therefore, the tracer was transport through the Grand Canyon from Lake Powell to the MPP.

As shown in Figure 6, the in-canyon transport of tracer from Dangling Rope frequently occurred. Monitoring sites near the Colorado River throughout the length of the Grand Canyon had concentrations above the background in more than 40% of the samples. Greater than 20% of the samples as far down river as the Mohave Power Plant had concentrations above background levels. Transport west of Dangling Rope was not exclusively down-slope and in-canyon, as shown by the small, but non-zero, frequency for tracer concentrations above the background to the north of the Grand Canyon NP.

Grand Canyon Layer Haze - Conceptual Model

The results from the WHITEX and MOHAVE studies illustrate the relevant processes creating a winter time layered haze in the Grand Canyon. First pollutants from Lake Powell are transported southwest and drainage flows bring these pollutants from the rim into the Grand Canyon. These pollutants can then be transported throughout the length of the Grand Canyon following the Colorado River. Second, over the course of a day or two, the sulfur dioxide gas is converted to particulate sulfate. Wintertime gas phase oxidation of SO_2 in the southwest is slow. Therefore clouds need to be present to obtain the higher oxidation rates needed to create a sulfate haze. Last, the clouds evaporate leaving behind the in-canyon sulfate haze with clear sky above the canyon. 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.

Simulation of Plume Transport from the Four Corners Region to the Grand Canyon

The set of processes resulting in the Grand Canyon wintertime layered haze is challenging to model. In order to fully capture the drainage flows, fine scale meteorology, with a grid scale of less 0.5 km and time resolution of 1 – 5 minutes would be required. This resolution is beyond most meteorological models and the input data to drive the models at this resolution is generally unavailable. In addition, meteorological models have difficulty reproducing precipitation and clouds which are fundamental to reproducing these events. Therefore, the potential impact of the proposed power plants in the Four Corners region is examined by analyzing the individual processes and illustrating potential impacts from existing sources.

A central question for the evaluation of proposed power plants in the Four Corners region, which has not been addressed in past work, is: Can the power plant emissions at sufficient concentrations be transported to Lake Powell? It is known that these emissions, once at Lake Powell, can be transported to the rim of the Grand Canyon, and drainage flows can bring these pollutants into the canyon, down to the Colorado River.

To address this question, the CAPITA Monte Carlo model (CMC) driven by a 4-km MM5 wind field nested in a 12-km MM5 wind field was used to simulate plume dispersion from the existing and proposed power plants in the Four Corners region during January 2001. The 4-km wind field domain encompassed the Grand Canyon and Four Corners region while the 12-km wind field encompassed Utah, Colorado, Arizona, and New Mexico. The average width of the Grand Canyon is approximately 16 km and the main geographic features of the Little Colorado River and San Juan River valleys are ~16 and 4+ km, respectively. Therefore 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 be able to capture the drainage flows into the canyon and its confinement and dispersion throughout the canyon.

The CMC model is a Lagrangian dispersion model that directly simulates a plume’s transport and diffusion by tagging power plant emissions with thousands of inert tracer particles with no mass. The particles are independently transported via advection due to the meteorological wind fields, and horizontal and vertical diffusion, simulated using a random process based upon turbulent mixing processes. Thus, the model captures the spreading of the plume due to wind shear and veer, the principal processes responsible for regional scale dispersion. In addition, the model will simulate air flow channeling due to the complex terrain that is captured by the meteorological model winds. Appendix A, attached to the report, provides a complete description of the model and a recent evaluation against perfluorocarbon tracers in the Big Bend region, a region of complex terrain.

The CMC model was used to simulate the plume dispersion from the existing Four Corners and San Juan power plants and the proposed Sithe, BHP, and Mustang power plants. In this simulation, 150 particles were released every hour from each power plant and tracked for 9 days or until they left the 12-km grid. The emissions were released at an effective stack height defined by the power plants’ stack heights and plume rise.

Plume dispersion can be sensitive to the initial height of the plume. A plume emitted into an unstable boundary layer will be mixed down to the surface and be transported in the surface layer. A plume that is emitted above the boundary layer will be transported by geostrophic winds which can follow different paths from surface winds. For example, an elevated plume could travel over a mountain barrier, while a surface level plume would be blocked. In addition, the plume would not contribute to surface level haze until the mixing layer grows to the height of the plume mixing it down or it is entrained in a subsiding airmass.

In order to assess the impact of the plume release height on the plume dispersion, a sensitivity analysis was conducted by releasing the plume at several different fixed heights and a variable height using a set of effective stack height equations. These equations estimate the plume release height as the Sithe stack height plus a plume rise due to buoyant and momentum forces acting on the plume. The plume rise is based on a standard set of semi-empirical equations that are used in many air quality models such as CALPUFF. However, the empirical coefficients in these equations can have large errors, leading to large errors in the effective stack height (Arya 1998).

The results from this analysis are presented in Appendix B. In summary, the sensitivity analysis showed that if the plume was released anywhere within the afternoon mixing layer, all plumes followed similar transport pathways. However, if the plume was consistently released above the afternoon mixing layer, then the plume transport could differ considerably from the surface level transport. Effective stack heights of 400 meters or less were usually within the afternoon mixed layer and produced similar multi-day transport results.

Visualization of Plume Dispersion

The simulation of the power plant plumes was animated to visualize their transport and dispersion for January 2001. From these animations, it was seen that multi-day stagnation and recirculation events over the Four Corners region occurred, allowing the accumulation of the power plant emissions. For example, Figure 7 presents the plume positions at noon over the course of four days from January 4-7, 2001. During this time period a high pressure system was over the Four Corners region with meandering winds and low mixing heights, < 500 meters. The plumes mostly remained in the Four Corners region and the particles tracking the power plant plumes accumulated in the basin.

On January 8, the accumulated particles in the Four Corners region were transported along the San Juan River valley to Lake Powell (Figure 8). These particles were then channeled down the Grand Canyon past the Kaibab Plateau. The particles remained in the Canyon until the end of January 10 when they were blown away. Not all of the tagged power plant emission traveled into the Grand Canyon. A large fraction of particles traveled north of Lake Powell following the low lying terrain and impacting other class I areas in Utah, including Bryce Canyon NP, Canyonlands NP, and Arches NP (Figure 8).

The simulation shows the plume entered the Grand Canyon at Lake Powell, and exited near Mt. Emma on the west side of the Kaibab Plateau. As was shown using the MOHAVE tracer data, once the plume entered the Grand Canyon, it most likely would have been transported to its west exit. This illustrates that the modeling system was able to reproduce many but not all of the important transport features.

This event shows the ability of power plant emissions in the Four Corners region to accumulate over multiple days. Subsequently, the pollutants can be transported along the San Juan River valley to Lake Powell and impact the Grand Canyon and other class I areas in Utah. The multi-day stagnation period allows for significant sulfur dioxide concentrations to accumulate from even a low emitting power plant. This was not a unique event. Over the course of January 2001, four such events occurred (Table 2).

Table 2. 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 12:00	2
Event 2	1/15 16:00 – 1/18 06:00	1.6
Event 3	1/22 12:00 – 1/24 12:00	2
Event 4	1/26 20:00 – 1/28 00:00	1.16

Photographic Evidence of Haze in the Grand Canyon Associated with Transport from the Four Corners Region

A camera is installed at the Desert View Watch Tower with a field of view to the west–northwest down the Grand Canyon. This camera takes pictures every six hours, capturing weather and haze events. Using these pictures, the visual air quality for every day during the four events was examined. Figure 9 presents the pictures and simulated plume snapshots for the 1/22 – 24 event. At 3 PM on January 22 there is a clear view from the watch tower and the simulated power plant plumes are in the Lake Powell region. Over the next day, the plumes are transported into the Canyon embedded in clouds. These clouds enhance the sulfur dioxide to particulate sulfate oxidation rates. On January 23, (Figure 10) the plumes remained in the Grand Canyon, but the clouds had evaporated leaving a haze layer that extends from in the Canyon to the cloud base.

The Four Corners and San Juan power plants located in the Four Corners basin have a combined emission rate of 70,000 tons of sulfur dioxide a year. Presumably, the haze that is left behind is due to the sulfur dioxide emissions from these sources, as well as emission from any other source entrained in the airmass, such as from the Navajo Generating Station (NGS). Any new emissions in the Four Corners region would also contribute to and exacerbate this haze.

All four simulated events in which power plant emissions from the Four Corners region impacted the Grand Canyon were found to be embedded in clouds as the plumes first passed the Desert View camera. These clouds eventually evaporated, leaving a visible layered haze in the Grand Canyon. This is shown in the attached Appendix C which provides pictures and simulated power plant plumes for each event.

Simulated Impact of the Proposed Sithe Power Plant on the Grand Canyon and other Class I Areas

The CMC model can simulate the sulfur dioxide and sulfate concentrations by weighting each particle by the power plant SO_2 emissions and using simple quasi first order rate processes to simulate the transformation of SO_2 to ammonium sulfate particles and the removal of SO_2 and ammonium sulfate (Schichtel and Husar 1997; Schichtel and Husar 1997; Schichtel *et al.*, 2004). In this application, constant rate coefficients were used with a transformation rate of 5%/hr and SO_2 and ammonium sulfate removal rates of 1.5%/hr and 0.7%/hr respectively. These are typical removal rates for SO_2 and ammonium sulfate (Seinfeld, 1986). The SO_2 to sulfate transformation rate for gas phase chemistry in the rural southwest during the winter will be less than 1 %/hr. However, in cloud SO_2 to sulfate transformation can be 100%/hr (Seinfeld, 1986). In all simulated events in which the Four Corners power plants impacted the Grand Canyon, the plumes were embedded in clouds, thus the 5% transformation rate was used in the simulations. Reducing the transformation rate to 1% would reduce the simulate sulfate concentration by about a factor of 2.5 to 3. Appendix B provides a sensitivity analysis of the simulated concentrations due to different transformation rates.

In the Monte Carlo approach to air quality simulation the concentrations are determined by simply defining a box over a receptor site, summing the ammonium sulfate weight for each particle that falls into the box, then dividing the sum by the volume of the box. In this application, the surface area of the receptor box was defined by an 8 km grid cell and a height of 1 km. Due to the low mixing heights, most particles were below 0.5 km. However, the 4 km meteorological grid does not capture the true depth of the Grand Canyon. Therefore, a 1 km height was used since these layered hazes in the Grand Canyon extend from the Tonto Plateau to the rim of the canyon, about 1 km in elevation.

There are large uncertainties in both the plume rise equations and the MM5 mixing heights used in the CMC model. The simulated plume rise can place the plume above the mixed layer, when in actuality the plume should be within the mixed layer. In order to obtain a range of plausible results, two different effective stack heights were used. One simulation used a constant stack height of 430 m, the estimated effective stack height of the Sithe plume under stable conditions, and the second used the variable stack height which was usually above 430 m. At 430 m, the plume was always released below or near the afternoon mixed layer, so the plume is generally transported within the surface layer.

Ammonium Sulfate Simulation Results

The simulated hourly ammonium sulfate concentrations for the Grand Canyon NP are presented in Figure 11. The proposed Sithe power plant impacted during all four episodes in Table 2. If the plume is released within the afternoon mixed layer (Figure 11 a), then the concentrations averaged across in-canyon grid cells from Indian Gardens through the Marble Canyon, the Sithe plant could contribute up to 1.7 µg/m^3 during January 9 and 27. The episodes during January 16th and 23rd had smaller concentrations with peak values of 1 and 0.6 µg/m^3, respectively. The peak concentrations within the canyon are higher at over 3 µg/m^3 during January 9 and over 5 µg/m^3 on January 27. The fact that peak concentrations are two to three times larger than the average in-canyon concentration illustrates the heterogeneity in the in-canyon concentrations. Similar variations of in-canyon tracer concentrations were also seen in the MOHAVE tracer study (Pitchford *et al.*, 2000)

When the variable effective stack height is used, the maximum in-canyon and average in-canyon concentrations generally decreased. The average in-canyon concentrations peaked between 0.8 and 1 µg/m^3 for the three episodes on January 9, 17, and 27 with peak hourly concentration between 2 and 4 µg/m^3. The Sithe power plant had little impact during the January 22–23 period.

The impact of the proposed Sithe power plant on Canyonlands, Arches, and Capitol Reef National Parks in Utah are presented in Figures 12–14. As shown, the Sithe plume impacted these three parks during the same four time periods as it impacted the Grand Canyon NP. The maximum hourly ammonium sulfate concentrations exceeded 3 µg/m^3 at all three sites and exceeded 5 µg/m^3 in Canyonlands NP. When the Sithe plume was released within the afternoon mixing height, the average concentrations over the parks could exceed 2 µg/m^3 in Canyonlands, but were generally less than 0.75 µg/m^3 in Arches and Capitol Reef. The Sithe plume simulation using the variable effective stack height did not appreciably change the simulated impacts at Canyonlands, Arches, and Capitol Reef. The average ammonium sulfate concentrations over the parks increased and decreased depending on the episode.

The January 22–23 episode is one of the more interesting. When the plume was released within the afternoon mixing layer, it contributed to ammonium sulfate concentration at all four national parks, and at the Grand Canyon the average in-canyon concentrations could exceeded 0.5 µg/m^3. However, when the variable effective stack heights were used, the plume had little impact on the Grand Canyon, and the contributions of ammonium sulfate to Canyonlands and Arches NP increased with concentrations average through the parks above 1 µg/m^3. This is an illustration of the surface layer transport traveling to the Grand Canyon, while the higher elevation transport traveled more north impacting Canyonlands and Arches NP. It is not known which pathway of the Sithe plume is correct. Unfortunately, in either transport direction the plume is impacting unique national parks where the visual scene is integral to a visitor's experience, and the plume is potentially contributing to haze obscuring visitors' views.

Impact of Sithe on Haze Levels

The maximum impact of the proposed Sithe power plant on the ammonium sulfate concentration at the four national parks is summarized in Table 3. Average values over the parks are used since visibility is dependent on the concentrations throughout the visual path length. As shown, Sithe has its largest impacts on Grand Canyon NP and Canyonlands NP where the maximum ammonium sulfate concentrations are predicted to be between 0.34 and 1.7 µg/m^3 in the Grand Canyon and between 0.8 and 2.5 µg/m^3 in Canyonlands.

Table 3. The maximum simulated ammonium sulfate concentrations averaged, over the respective national park, due to impacts from the proposed Sithe power plant. All concentration values are in µg/m^3.

Particle Release Height	**In the Mixed Layer**		**Variable Effective Stack Hgt**	
Oxidation Rate	**1%/hr**	**5%/hr**	**1%/hr**	**5%/hr**
Grand Canyon NP	0.56	1.7	0.34	1.0
Canyonlands NP	0.81	2.2	0.91	2.5
Arches NP	0.53	1.8	0.43	1.1
Capitol Reef NP	0.28	0.86	0.27	0.93

The impact of these concentrations on haze at the four national parks is presented in Table 4 as both the light extinction in Mm^{-1} and as the fraction above the natural background. The size of the sulfate particles grow as relative humidity (RH) increases causing them to scatter more light and increasing the haze. Therefore, the haze levels are given at three different RH levels, 90%, 95% and 98%. As shown, the simulated Sithe power plant plume can increase the haze over the natural background in the Grand Canyon and Canyonlands from a minimum of 30% to over 500%. The impact at Arches and Capitol Reef is lower, varying from 20% to over 350%. Note, that these are hourly extinction values averaged over the respective park. FLAG modeling guidance uses the maximum 24-hour average concentration in the park. These 24 hour average values would likely be lower; however, the park average hourly values are more representative of what a visitor would experience.

Table 4. The maximum simulated hourly light extinction (haze), averaged over the respective national park, due to ammonium sulfate concentrations from the proposed Sithe power plant. The light extinction values are in Mm^{-1} and the values in parenthesis are the fraction above the natural background.

				In the Mixed Layer		**Variable Effective Stack Hgt**	
	RH (%)	**f(RH)**	**Natural Background**	**1%/hr Ox. Rate**	**5%/hr Ox. Rate**	**1%/hr Ox. Rate**	**5%/hr Ox. Rate**
Grand Canyon	90	4.7	17.3	8 (0.5)	24 (1.4)	5 (0.3)	14 (0.8)
	95	9.8	20.4	17 (0.8)	49 (2.4)	10 (0.5)	30 (1.5)
	98	18.1	25.4	31 (1.2)	91 (3.6)	18 (0.7)	56 (2.2)
Canyonlands	90	4.7	17.3	11 (0.6)	30 (1.8)	13 (0.7)	35 (2.)
	95	9.8	20.4	22 (1.1)	64 (3.1)	27 (1.3)	73 (3.6)
	98	18.1	25.4	40 (1.6)	117 (4.6)	49 (1.9)	134 (5.3)

Arches	90	4.7	17.3	9 (0.5)	25 (1.5)	6 (0.4)	16 (0.9)
	95	9.8	20.4	18 (0.9)	53 (2.6)	13 (0.6)	33 (1.6)
	98	18.1	25.4	34 (1.3)	97 (3.8)	23 (0.9)	61 (2.4)
Capitol Reef	90	4.7	17.3	4 (0.2)	12 (0.7)	4 (0.2)	13 (0.8)
	95	9.8	20.4	9 (0.4)	25 (1.2)	8 (0.4)	27 (1.3)
	98	18.1	25.4	16 (0.6)	47 (1.8)	15 (0.6)	51 (2.)

These haze levels are clearly visible to visitors at any one of the national parks. As an example, the impact of the haze on a scene in the Grand Canyon resulting from 1 and 1.7 µg/m^3 of ammonium sulfate from the Sithe power plant at 90, 95, and 98% relative humidity was modeled and presented in Figures 15 and 16. The scene is of Desert View looking from Hopi Point at 9 am in the morning. A layered haze is modeled which is the typical wintertime haze in the Grand Canyon.

The haze model directly accounts for the impact of haze on a scene, generating a picture of what a scene would look like under different haze levels (Malm *et al.*, 1983; Molenar *et al.*, 1994). Haze is the result of image forming light being removed from the sight path between an object and the observer due to light scattering and absorption from gases and particles, such as sulfate. Also, haze is due to the addition of “air light”, ambient light scattered into the sight path. To model these processes a radiative transfer model was used to account for the removal of image-forming light and addition of the air light. The change in the amount and form of the light reaching the observer from all objects in a scene, due to the haze, is fed into an image processor to adjust a photograph to reflect the changes in color and removal of textures and elements from the scene of a clear day (Malm *et al.*, 1983; Molenar *et al.*, 1994).

As shown, in Figure 15, at 1 µg/m^3 of sulfate and a relative humidity of 90% the light extinction is 32 Mm^{-1} or 80% greater than natural background. The layered haze in the Grand Canyon is clearly visible, turning the rock formations a dull white. The haze is accentuated as the relative humidity and ammonium sulfate concentration increase (Figure 15 and 16).

The impact of a uniform haze in the Grand Canyon, Canyonlands and Capitol Reef due to the Sithe plume on top of a natural background is presented in Figures 17–19. This modeling was done using the Win Haze software which performs a similar set of calculations as in the layered haze model to adjust a photograph of a clear day (Malm *et al.*, 1983; Molenar *et al.*, 1994). The haze levels are estimated from the maximum ammonium sulfate concentrations averaged over the respective park during the January 2001 simulations and are presented in Table 4. The simulation where the Sithe plume was released below the afternoon mixing layer and a 5% sulfur oxidation rate was used.

As shown in Figure 17, under natural conditions Mount Trumbull is visible from Yavapai point in the Grand Canyon as are an array of red, green and tan colors. Mount Trumbull is 65 miles (105 km) from Yavapai Point (Figure 17b). If 1.7 µg/m^3 of sulfate from the Sithe power plant are added to the scene at 90% RH, then Mount Trumbull is no longer visible and the colors are now obscured. At 98% relative humidity, the haze is so thick that only the Alligator, three miles (5 km) from the camera (Figure 17b), is clearly visible. The scene at Canyonlands is similarly diminished by the haze from the modeled Sithe plume. Of the four parks examined, Capitol Reef had the lowest concentrations of sulfate. However, even at only 0.86 µg/m^3 of sulfate at 90% RH, there is noticeable discoloration of the sky and Henry Mountains which is only 35 km from the camera.

Simulated Impact of Sithe SO_2 emissions on Views from Mesa Verde National Park, CO

Mesa Verde NP is located in southwestern CO just north of New Mexico. From Mesa Verde one can look into New Mexico, across the San Juan river valley at Ship Rock and the Chuska Mountains about 70 and 100km away respectively (Figure 20). During the winter months the polar highs over this region trap emission from towns, including Farmington and Shiprock and the existing San Juan and Four Corners power plants, creating a layered haze that is visible from Mesa Verde. For example, Figure 21 is a picture of a December layered haze extending from the surface to the top of Ship Rock, about 600 meters above the surface.

The potential impact of Sithe's SO_2 emissions on the view from Mesa Verde into New Mexico was examined using a similar CMC modeling set up as that used to investigate the potential impact of Sithe's SO_2 emissions on the Grand Canyon and national parks in Utah. However, instead of aggregating the concentration over the respective national park, the concentrations were average over the view shed from Mesa Verde to the Chuska Mountains (Figure 22). Vertically, the simulation was averaged from the surface to 500 meters, the approximate top of the layered hazes in this region, e.g. see Figure 21. A transformation rate of 5% was used in all simulations since during the winter clouds often cover this region enhancing the transformation rate.

Figure 23 presents the simulated hourly ammonium sulfate concentrations averaged over the Mesa Verde view shed when the plume was released in the afternoon mixing layer (IAML) and when a variable effective stack height (VESH) was used. As shown, when the plume is released within the afternoon mixed layer, three episodes had hourly concentrations above 1 $\mu g/m^3$ and as high as 1.6 $\mu g/m^3$¸ and another six periods had ammonium sulfate concentrations 0.4 $\mu g/m^3$ and above. When the plume was released using a variable effective stack height the concentrations substantially decrease and were generally less than 0.1 $\mu g/m^3$. The maximum VESH hourly concentration was 0.6 $\mu g/m^3$.

The difference is due to the fact that the variable effective stack height was usually above the 430 meters used in the "in afternoon mixed layer" simulation, and the average effective stack height was about 600 meters. Therefore, the two plumes were subjected to different wind speeds and directions and the elevated plume may not be mixed down to the surface and contribute to surface level concentrations. For example, the maximum IAML concentration occurred on 1/14/2001 while concentrations from the VESH simulation were near zero. The cause of this was that the elevated plume in the VESH simulation was transport to the southeast while the surface layer was transport to the northwest, into the Mesa Verde view shed. However on January 22nd, the VESH plume traversed the Mesa Verde view shed but was not mixed down and contributed little to the surface level concentrations. While an elevated plume will not contribute to a surface haze, it will also not be diluted due to surface level mixing. Therefore, it can remain as a coherent plume with high concentrations of SO_2, NO_x and particulate matter. These types of plumes are often visible from long distances causing plume blight. A simulation of the potential for plume blight was conducted using PlumeView (Seigneur et al., 1984). Unfortunately, under typical wintertime meteorological conditions an elevated Sithe plume transport to the northwest would be clearly visible from Mesa Verde.

Conclusions

These results showed that during January 2001 the confluence of events that are needed for emissions in the Four Corners region to significantly impact visibly at the Grand Canyon and other class I areas on the Colorado Plateau occurred four times. Using the simple dispersion modeling, it was shown that it is possible for the SO_2 emissions from the proposed Sithe facility to visibly contribute to the haze in the Grand Canyon and other national parks on the Colorado Plateau. This analysis only examined the contributions due to the SO_2 emissions. The Sithe facility also would have high emissions of nitrogen dioxide and particulate matter. The NO_2 plume could adversely impact nearby class I areas, such as Mesa Verde NP, CO; San Pedro Parks WA and Petrified Forest NP, through plume blight via absorption of visible light. At more distant parks, such as the Grand Canyon, some of the NO_2 would be converted to particulate nitrate and contribute to haze. The primary emissions of particulate matter will also contribute some to the haze at both near and distant parks.

The modeling conducted in this analysis used semi-quantitative chemical transformation and removal mechanisms, so the results are not definitive. More sophisticated modeling that better captures these physical/chemical processes is needed. However, prior to their application it needs to be demonstrated that the input clouds and precipitation are properly simulated and the model is capable of simulating wet phase chemistry.

References

Arya, S.P. Air Pollution Meteorology and Dispersion. Oxford University Press, New York, 320 pp., 1998.

Husar, R.B., D.E. Patterson, J.D. Husar, N.V. Gillani. 1978. Sulfur budget of a power plant plume. *Atmos. Environ.* **12**, 549-568.

Malm W., K. Gebhart, D. Latimer, T. Cahill, R. Pielke, and J. Watson. 1989. National Park Service Report on the Winter Haze Intensive Tracer Experiment (WHITEX).

Malm, W.C., Molenar, J.V., and Chan, L.L. "Photographic Simulation Techniques for Visualizing the Effect of Uniform Haze on a Scenic Resource," *Journal of the Air Pollution Control Association,* **33**(2):126-129, 1983.

Molenar, J.V., Malm, W.C., and Johnson, C.E., "Visual Air Quality Simulation Techniques," *Atmospheric Environment,* **28**(5):1055-1063, 1994.

Pitchford M., Green M., Tombach I., Malm W.C., Farber R.J. 1999. Project MOHAVE Final Report.

Pitchford M., Green M., Kuhns H., Farber R.J. 2000. Characterization of regional transport and dispersion using Project MOHAVE tracer data. *J. Air Waste Manage. Assoc.* **50, 7**33 – 745.

Pielke R.A., Garstang M., Lindsey C., Gusdorf J. 1987. Use of a Synoptic Classification Scheme to Define Seasons. *Theoretical and Applied Climatology.* **38 (2)**: 57- 68.

Seinfeld, John H. 1986. Atmospheric Chemistry and Physics of Air Pollution. John Wiley and Sons. New York.

Seigneur, C., C.D. Johnson, D.A. Latimer, R.W. Bergstrom and, H. Hogo, 1984. User's Manual for the Plume Visibility Model (PLUVUE II). EPA Publication No. EPA-600/8-84-005. U.S. Environmental Protection Agency, Research Triangle Park, NC. (NTIS No. PB84- 158302).

Schichtel, B.A. and Husar, R.B. (1997) Regional simulation of atmospheric pollutants with the CAPITA Monte Carlo model. *J. Air Waste Manage. Assoc.* **47,** 331 – 343.

Schichtel, B.A. and Husar, R.B. (1997) Derivation of SO_2 – SO_4^{2-} transformation and deposition rate coefficients over the Eastern US using a semi-empirical approach. Presented at the *A&WMA/AGU International Specialty Conference,* Bartlett, New Hampshire. Paper 120-S9.123.

Schichtel B.A., Barna M., Gebhart K., Malm W.C., 2004. Evaluation Eulerian and Lagrangian Air Quality Models using Inert Tracers in the BRAVO Study. Submitted to *Atm. Environ.*

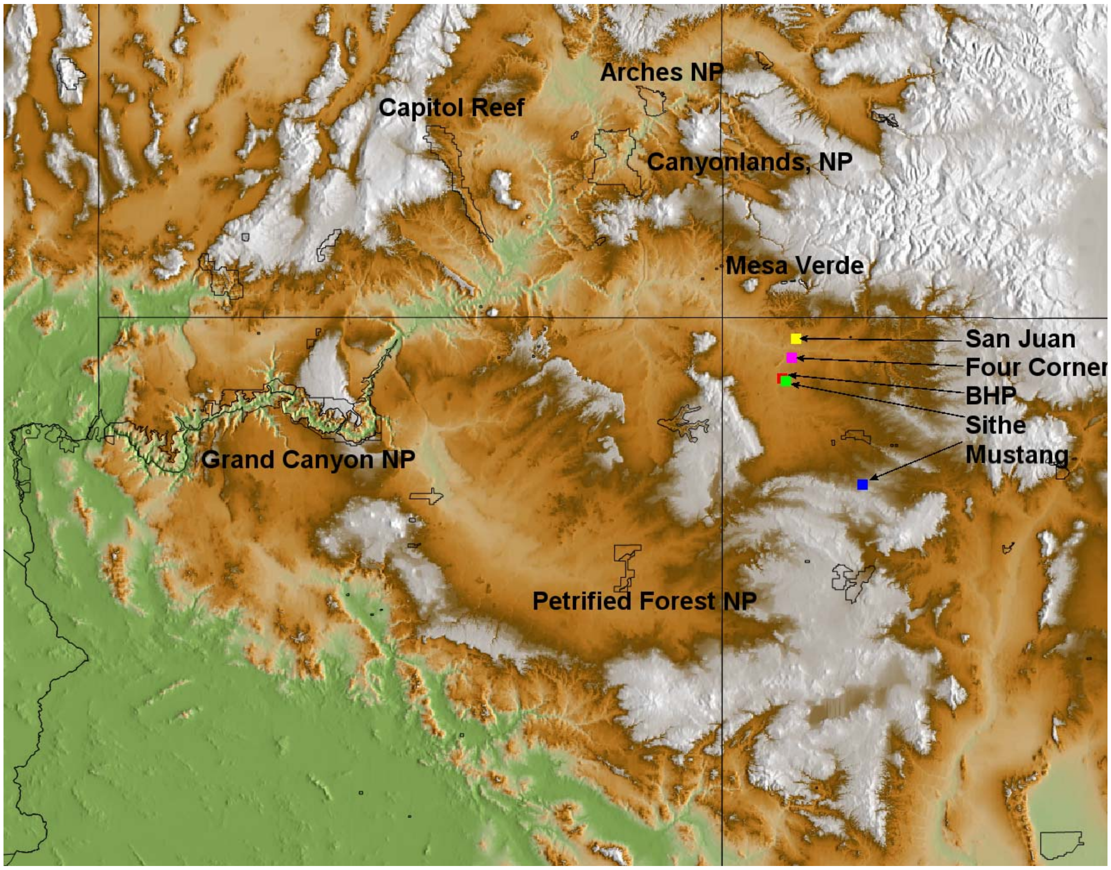


Figure 1. The terrain in the Four Corners states. The squares are the location of existing and proposed power plants with yellow – Four Corners, purple – San Juan, green – Sithe, red – BHP, and blue – Mustang.

Figure 2. Easterly and westerly views of the Grand Canyon from Desert View Watch Tower in February 1987. The series of photographs illustrates the filling of the Grand Canyon with clouds and SO_2, followed by in-cloud transformation of SO_2 to sulfate particulates. When the clouds evaporated a layered haze of sulfate particles is left behind in the Grand Canyon.

Figure 3. View of the Grand Canyon the next day after the haze was blown out.

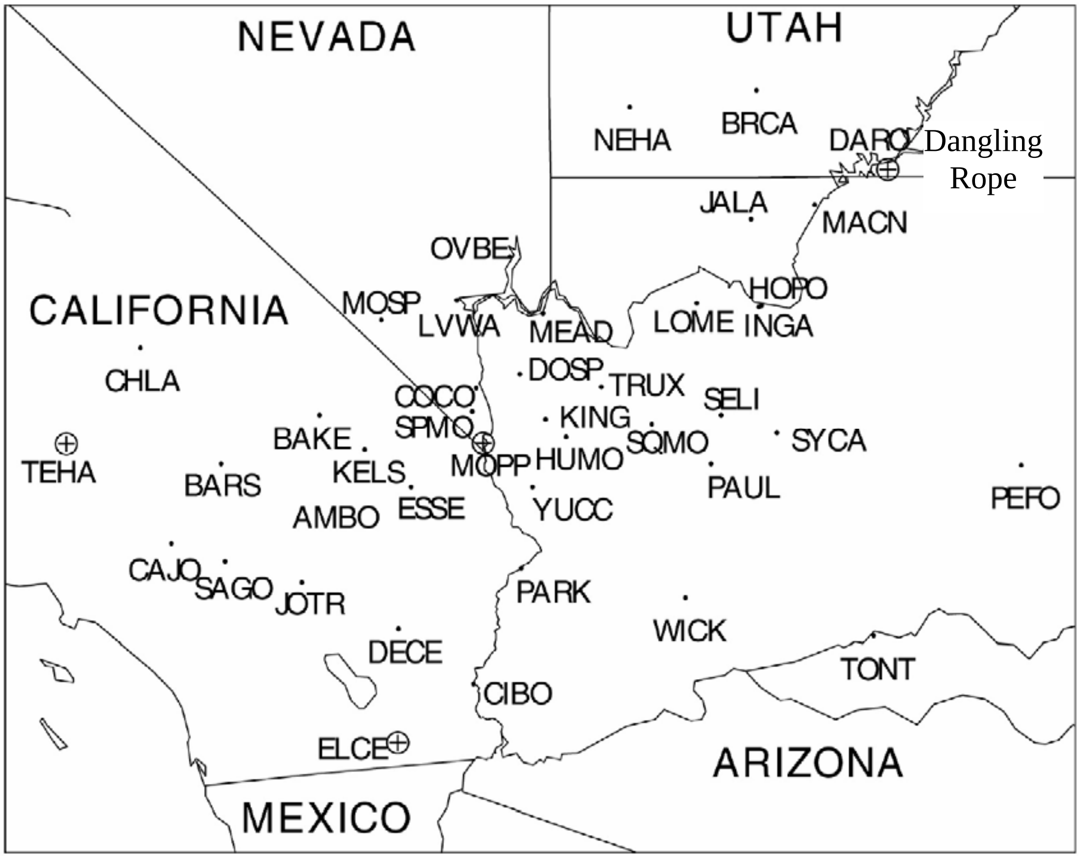


Figure 4. Site map of tracer release and monitoring locations for project MOHAVE. Locations labeled with ⊕ are tracer release sites.

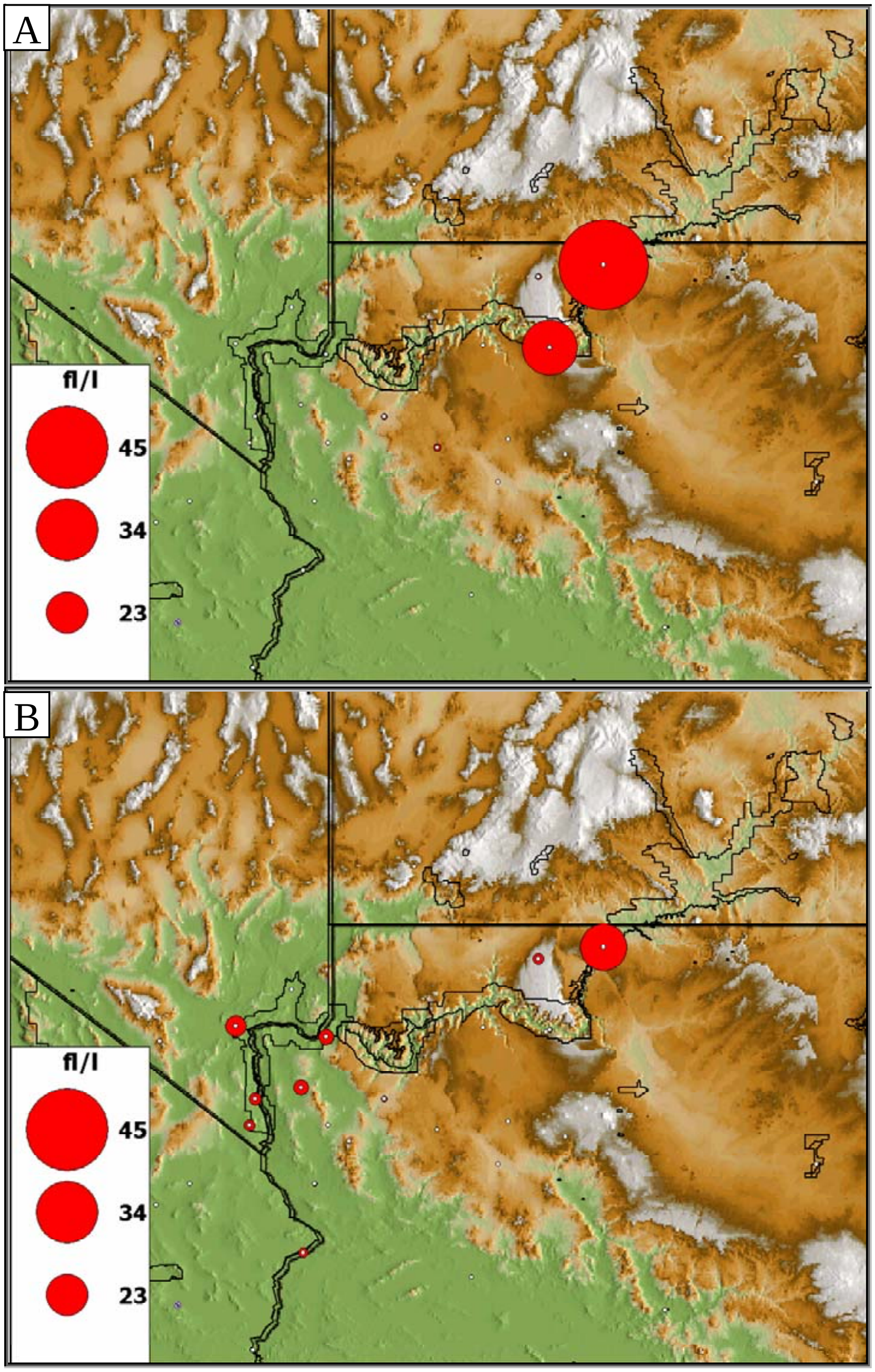


Figure 5. Concentrations of tracer released from Dangling Rope at the monitoring sites on A) February 2, 1992 and B) January 17, 1992.

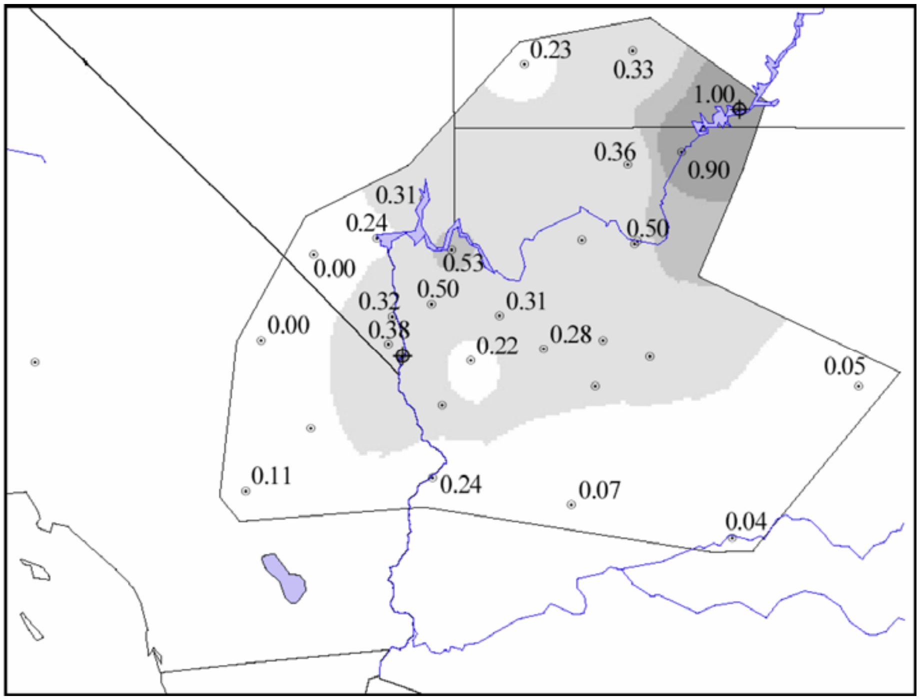
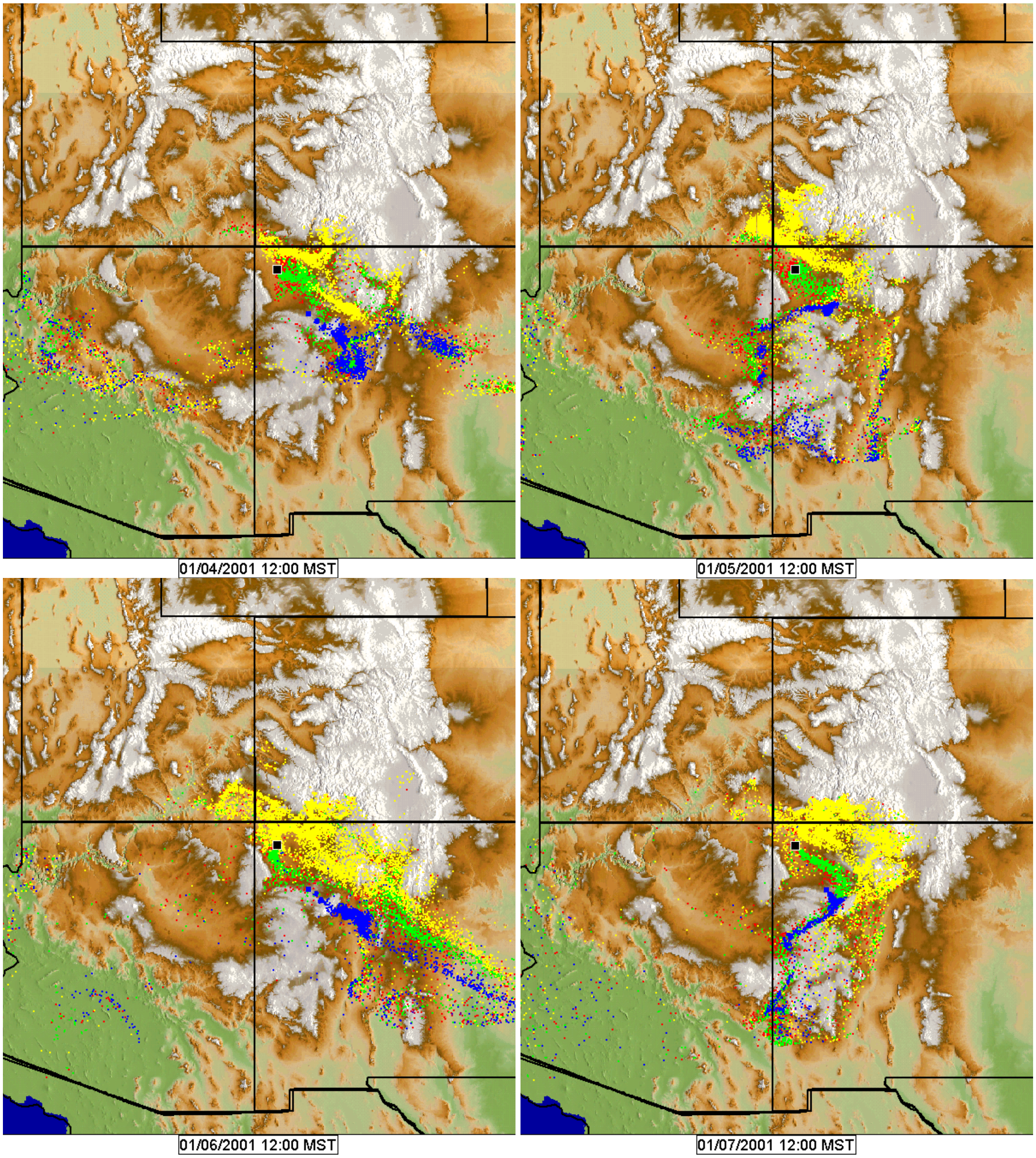


Figure 6. Frequency that tracer released from Dangling Rope was detected above background at each monitoring site (Pitchford et al., 2000).



01/04/2001 12:00 MST

01/05/2001 12:00 MST

01/06/2001 12:00 MST

01/07/2001 12:00 MST

Figure 7. Snap shots of the simulated plumes from the existing and proposed power plants in the Four Corners region at noon from 1/4- 1/7/2001. The plumes were released at a constant effective stack height of 430 m. The yellow plumes are from the existing Four Corners and San Juan power plants, and the green, red and blue plumes are the proposed Sithe, BHP and Mustang power plants respectively. These images illustrate the accumulation of emissions from the power plant due to meandering winds over the four day period 1/3 – 1/7/2001.

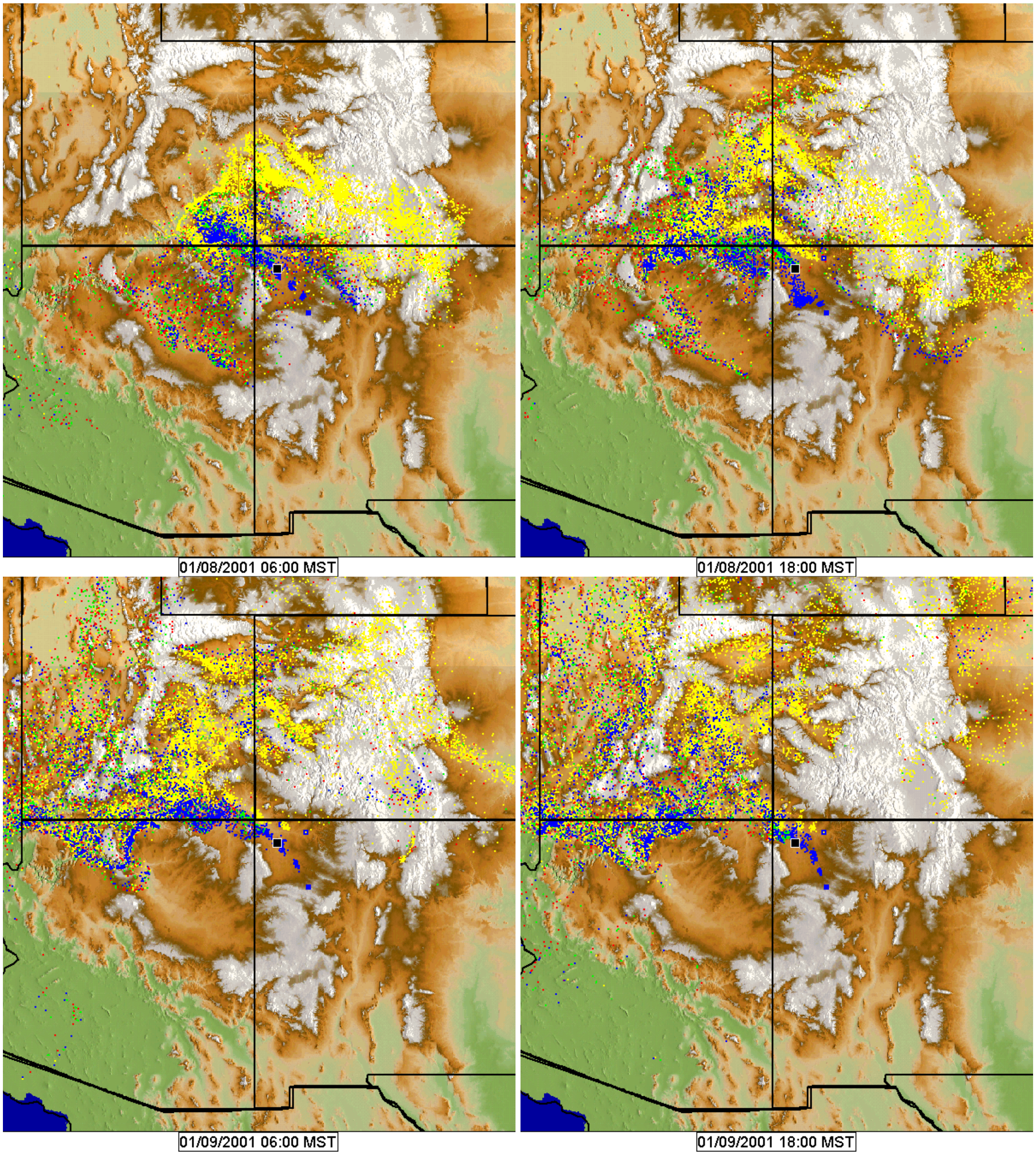


Figure 8. Similar to Figure 7, but snap shots are every 12 hours from 1/8 6:00 to 1/9/2001 18:00. These images illustrate the transport of the accumulation of emissions from the power plant in the Four Corners region to Lake Powell which are then channeled down the Grand Canyon.

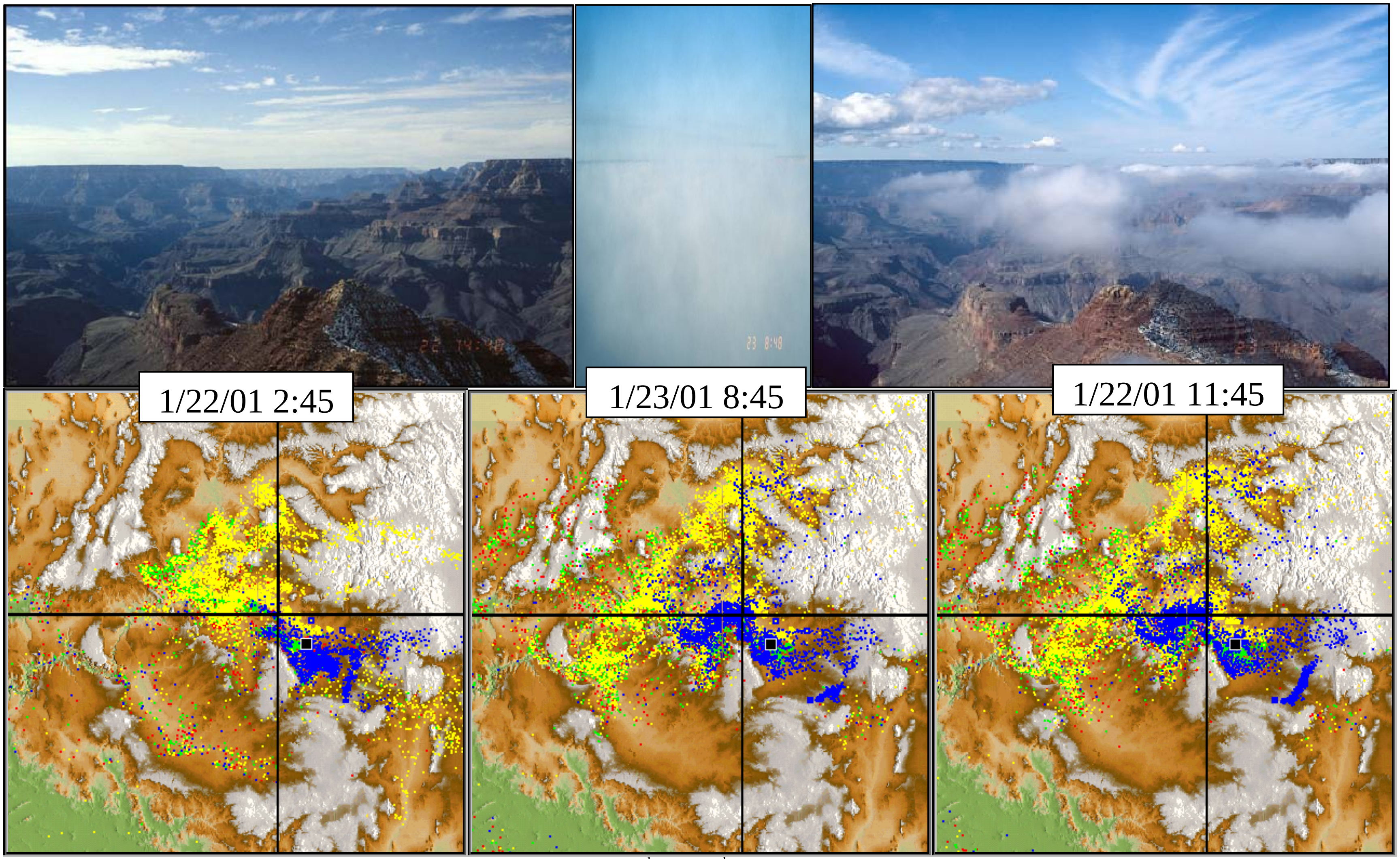


Figure 9. Pictures of the Grand Canyon from Desert View on January 22nd and 23rd, 2001 and associated images of simulated plumes from the Four Corners power plants.

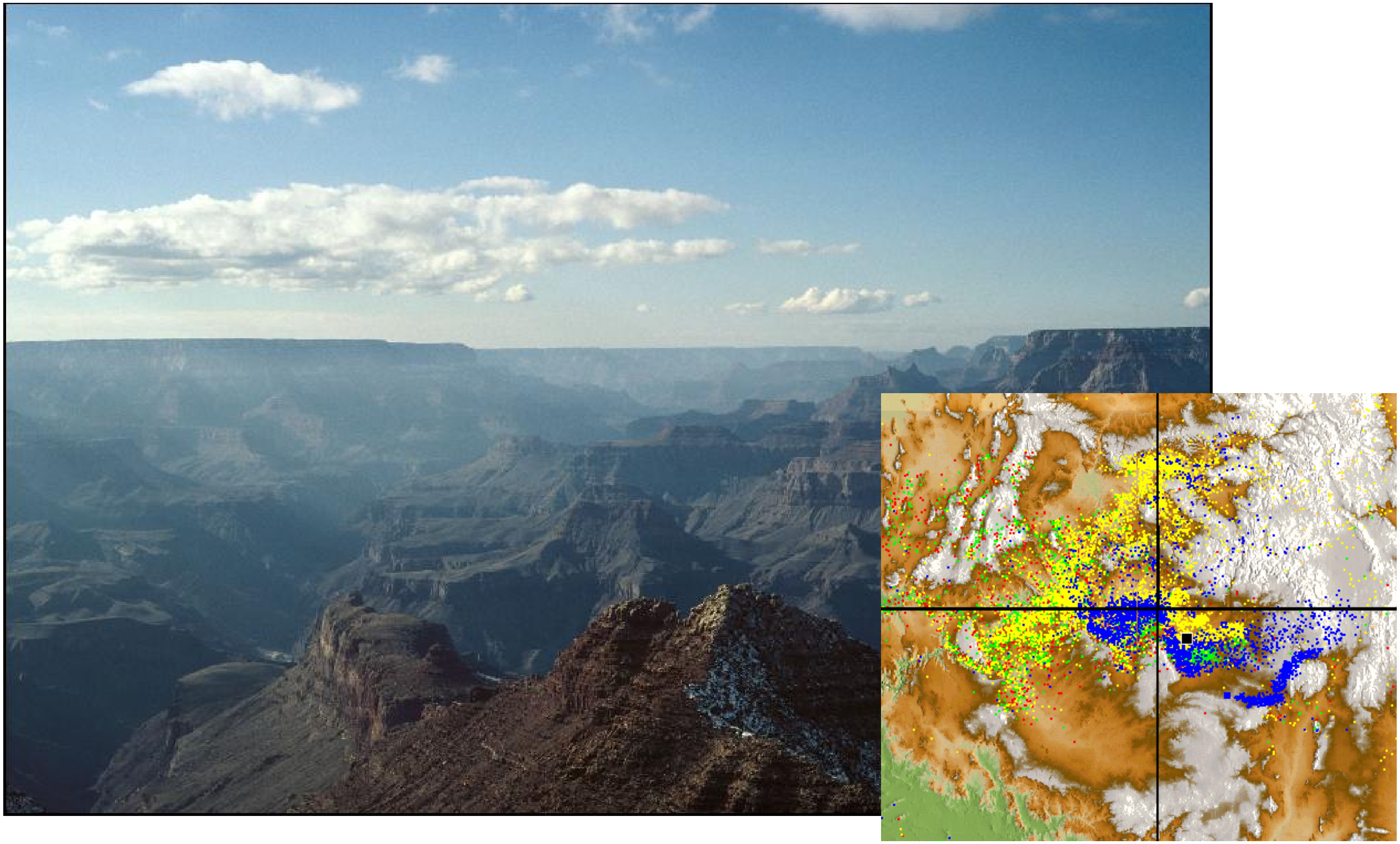


Figure 10. Picture of the Grand Canyon from Desert View on January 23rd, 3:00 PM 2001 and associated image of simulated plumes from the Four Corners power plants.

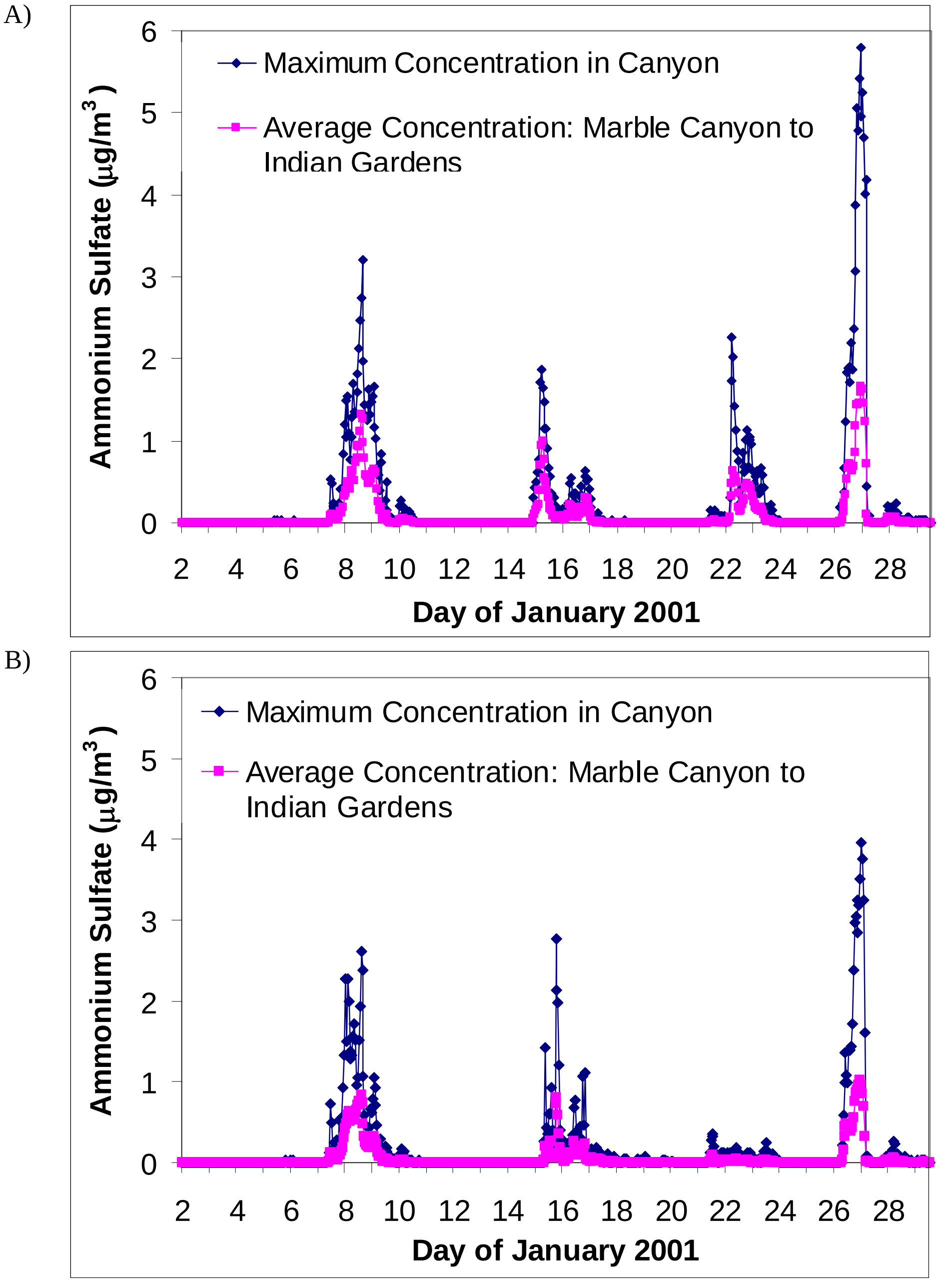


Figure 11. Simulated hourly ammonium sulfate concentrations in the Grand Canyon from the proposed Sithe power plant. A) Plume released within the daytime mixed layer B) plume release height based on a variable effective stack height. The ◆ is the maximum concentration for any in-canyon grid cell and ■ is the average of all in-canyon grid cells from Lake Powell to Indian Gardens

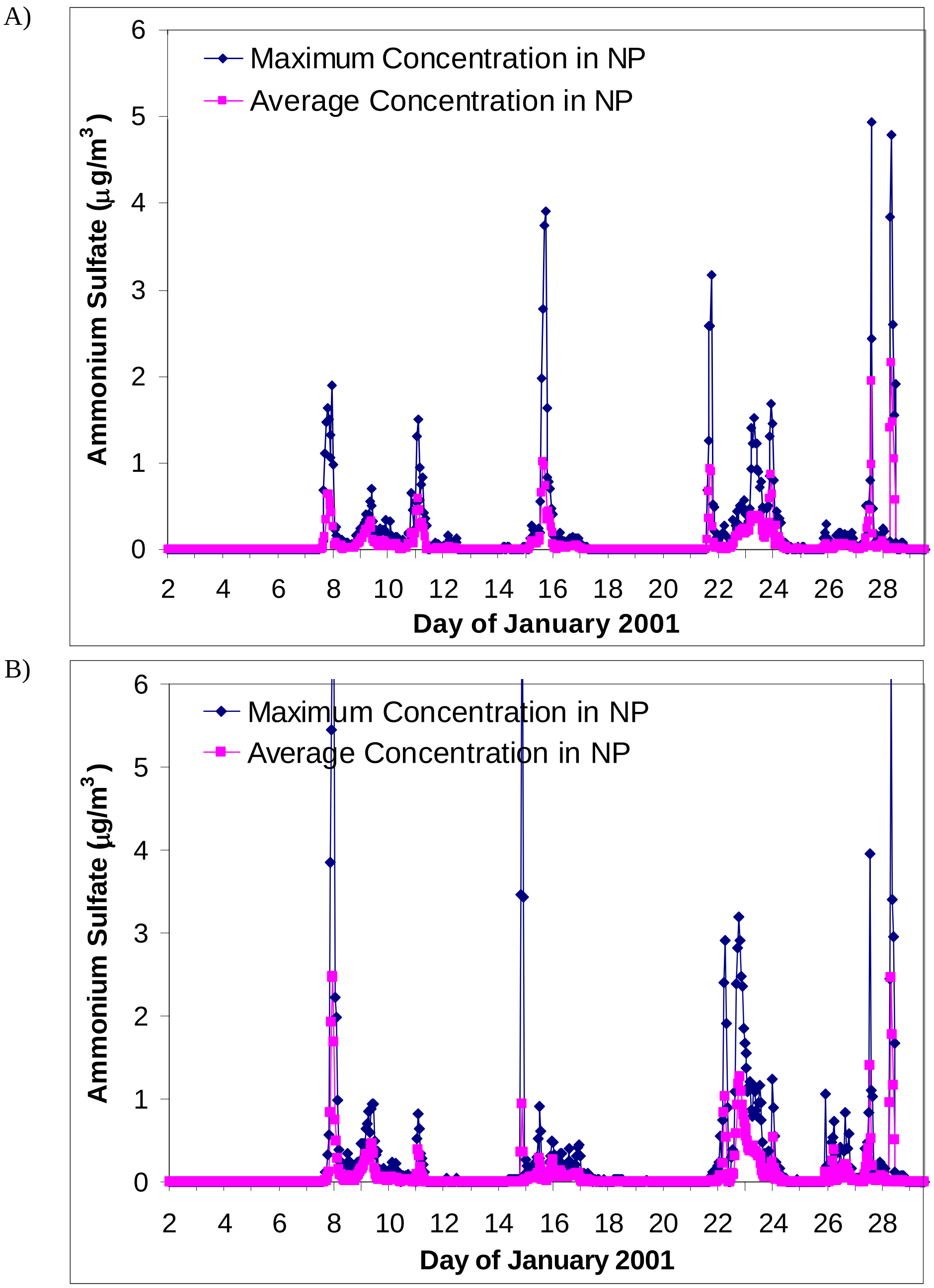


Figure 12. Simulated hourly ammonium sulfate concentrations in Canyonlands, NP in Utah due to the proposed Sithe power plant. A) Plume released within the daytime mixed layer B) plume release height based on a variable effective stack height. The ◆ is the maximum concentration for any grid cell in the park and ■ is the average of all grid cells in the park.

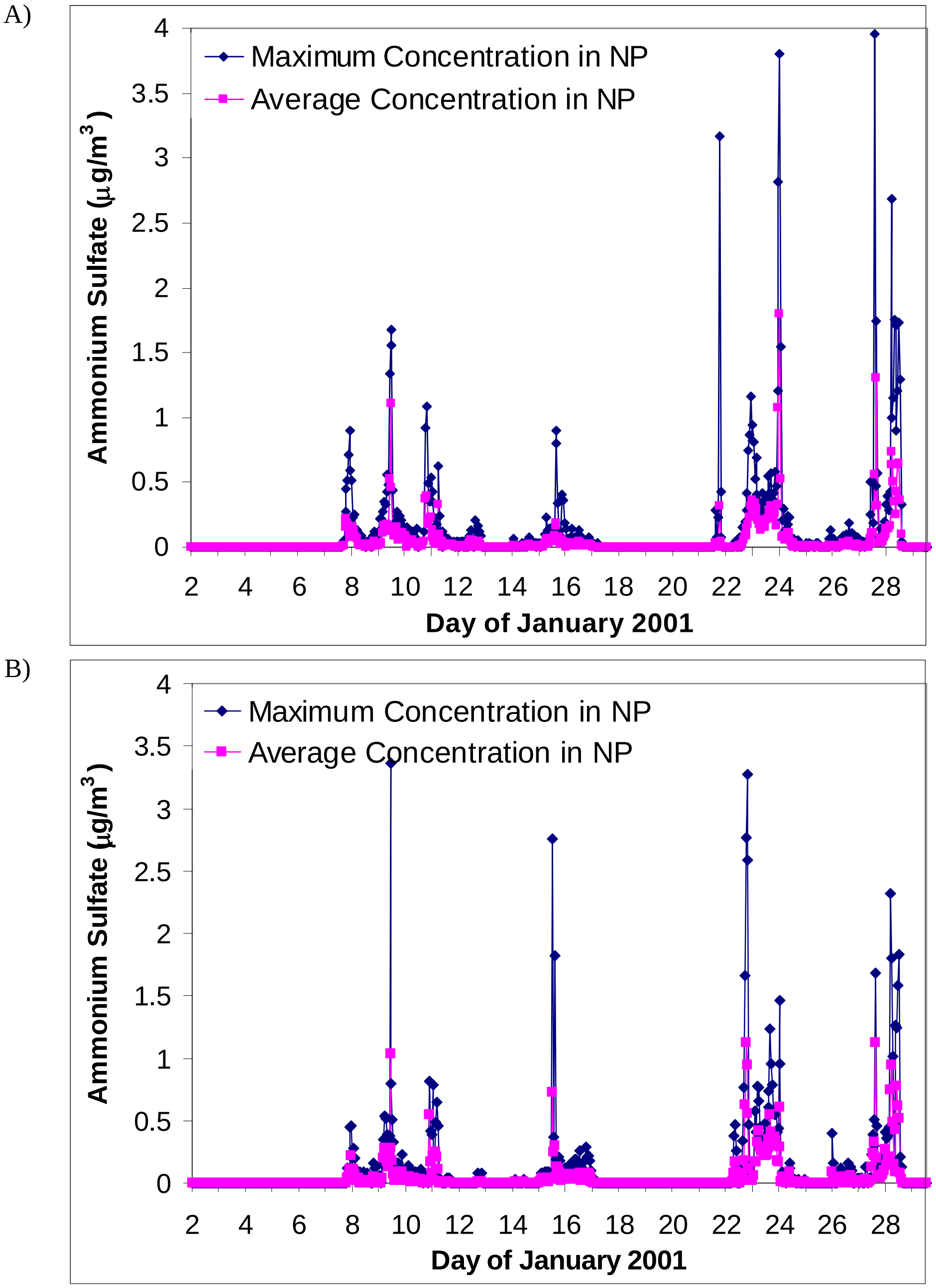


Figure 13. Simulated hourly ammonium sulfate concentrations in Arches NP in Utah due to the proposed Sithe power plant. A) Plume released within the daytime mixed layer B) plume release height based on a variable effective stack height. The ◆ is the maximum concentration for any grid cell in the park and ■ is the average of all grid cells in the park.

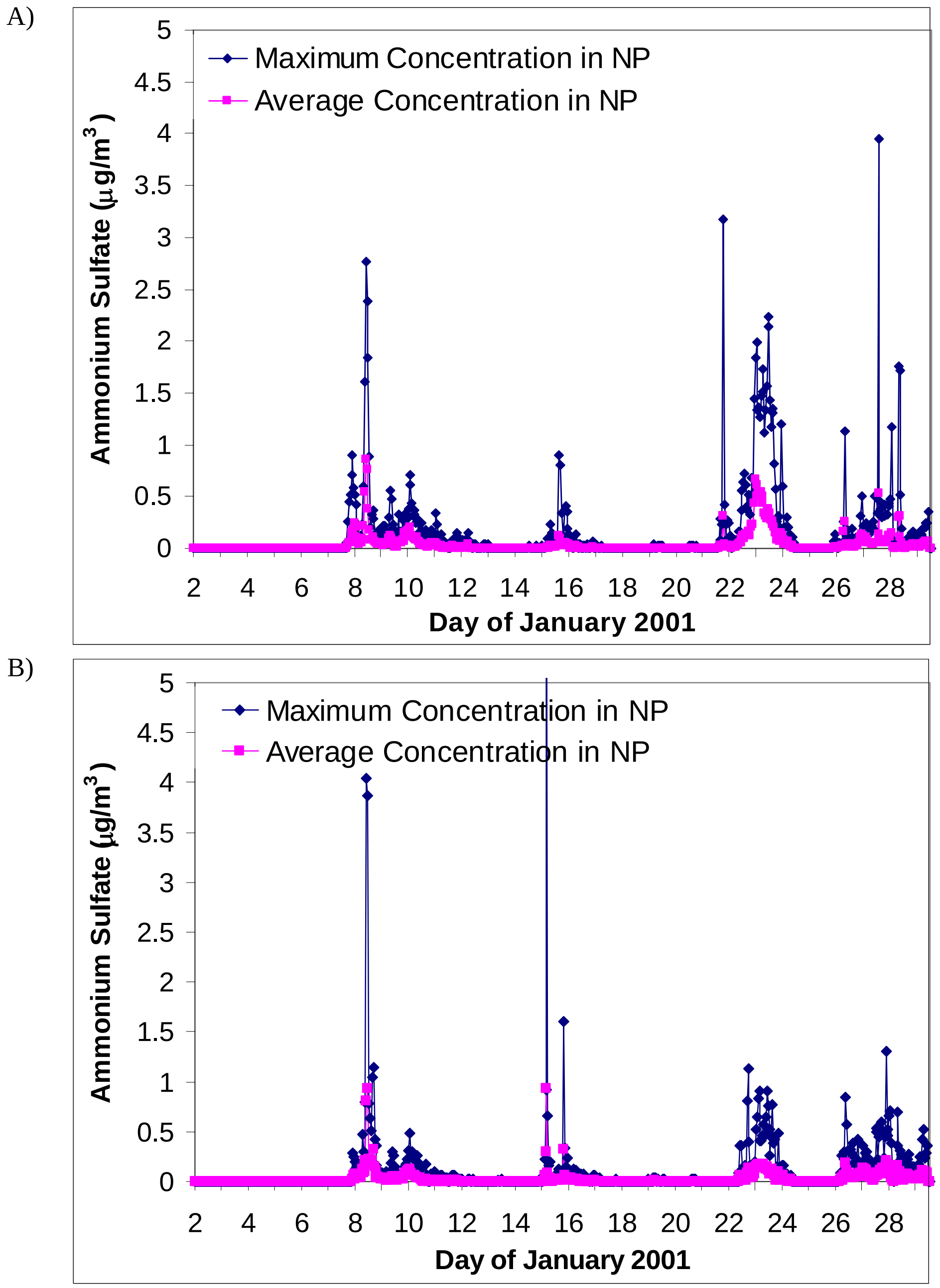
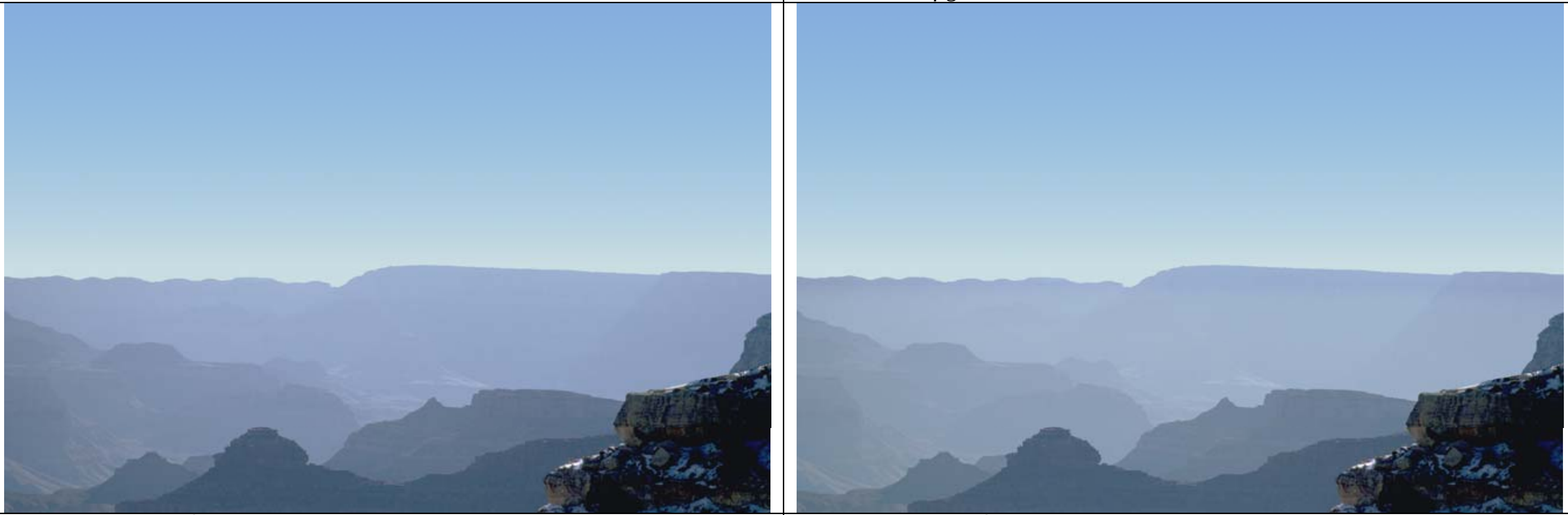
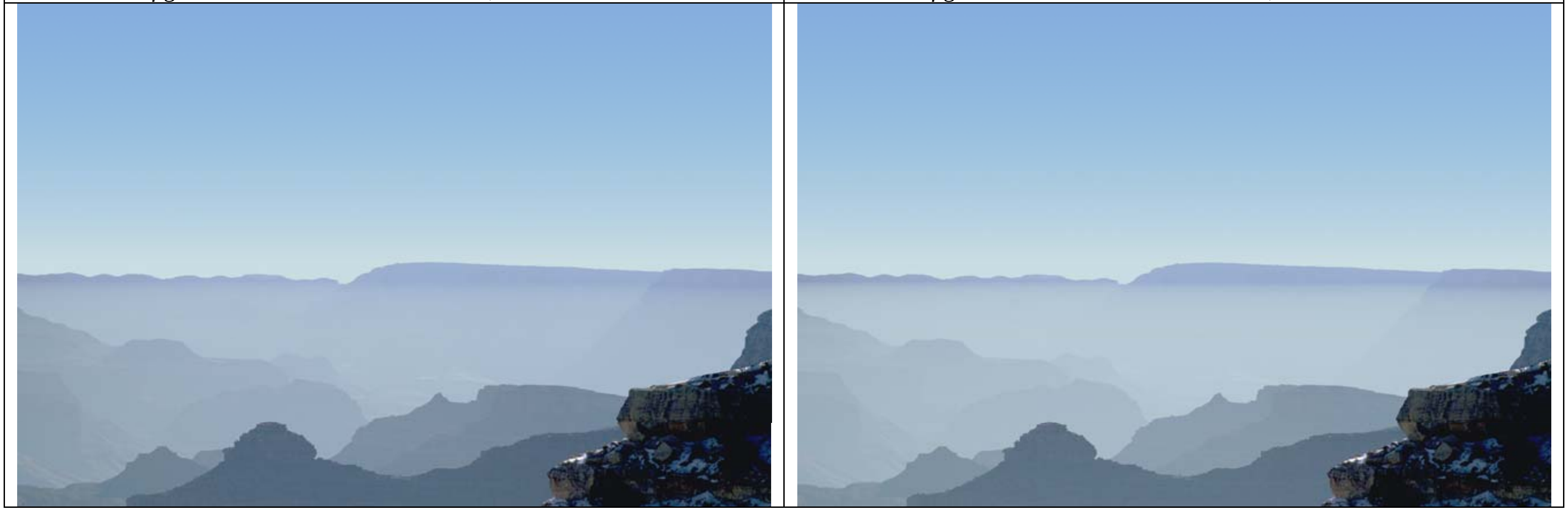


Figure 14. Simulated hourly ammonium sulfate concentrations in Capitol Reef NP in Utah due to the proposed Sithe power plant. A) Plume released within the daytime mixed layer B) plume release height based on a variable effective stack height. The ◆ is the maximum concentration for any grid cell in the park and ■ is the average of all grid cells in the park.



Natural Conditions at 90% RH; Bext = 17.3 Mm^{-1}

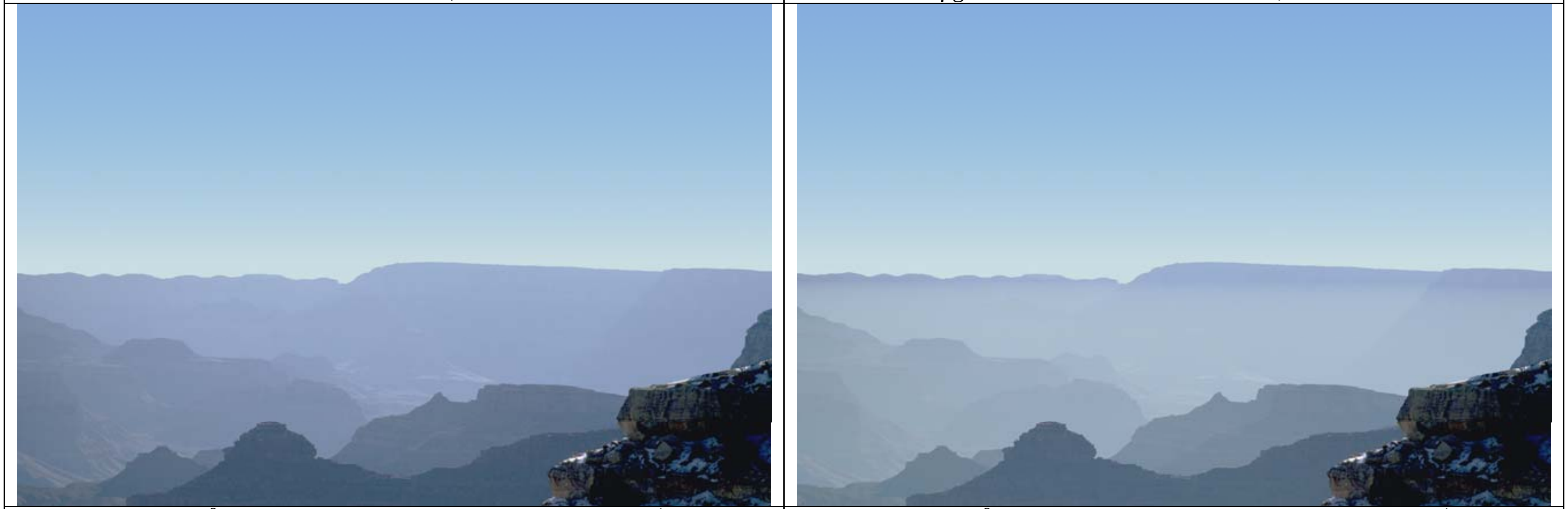
1 $\mu g/m^3$ of Amm. Sulfate at 90% RH; Bext = 32 Mm^{-1}



1 $\mu g/m^3$ of Amm. Sulfate at 95% RH; Bext = 51 Mm^{-1}

1 $\mu g/m^3$ of Amm. Sulfate at 98% RH; Bext = 81 Mm^{-1}

Figure 15. Looking at Desert View from Hopi Point at 9 AM in the Grand Canyon NP under natural conditions and different levels of a layered haze in the Grand Canyon resulting from the contribution of 1 $\mu g/m^3$ of ammonium sulfate from the proposed Sithe power plant.



Natural Conditions at 90% RH; Bext = 17.3 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 90% RH; Bext = 41 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 95% RH; Bext = 70 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 98% RH; Bext = 118 Mm^{-1}

Figure 16. Looking at Desert View from Hopi Point at 9 AM in the Grand Canyon NP under natural conditions and different levels of a layered haze in the Grand Canyon resulting from the contribution of 1.7 µg/m^3 of ammonium sulfate from the proposed Sithe power plant.

Natural Conditions at 90% RH; Bext = 17.3 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 90% RH; Bext = 41 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 95% RH; Bext = 70 Mm^{-1}

1.7 µg/m^3 of Amm. Sulfate at 98% RH; Bext = 118 Mm^{-1}

Figure 17a. Mount Trumbull in the Grand Canyon NP viewed from Yavapai Pt under natural conditions and different levels of uniform haze resulting from the potential contribution from the proposed Sithe power plant. The distance of the major features in the scene from Yavapai point are in Figure 15b.

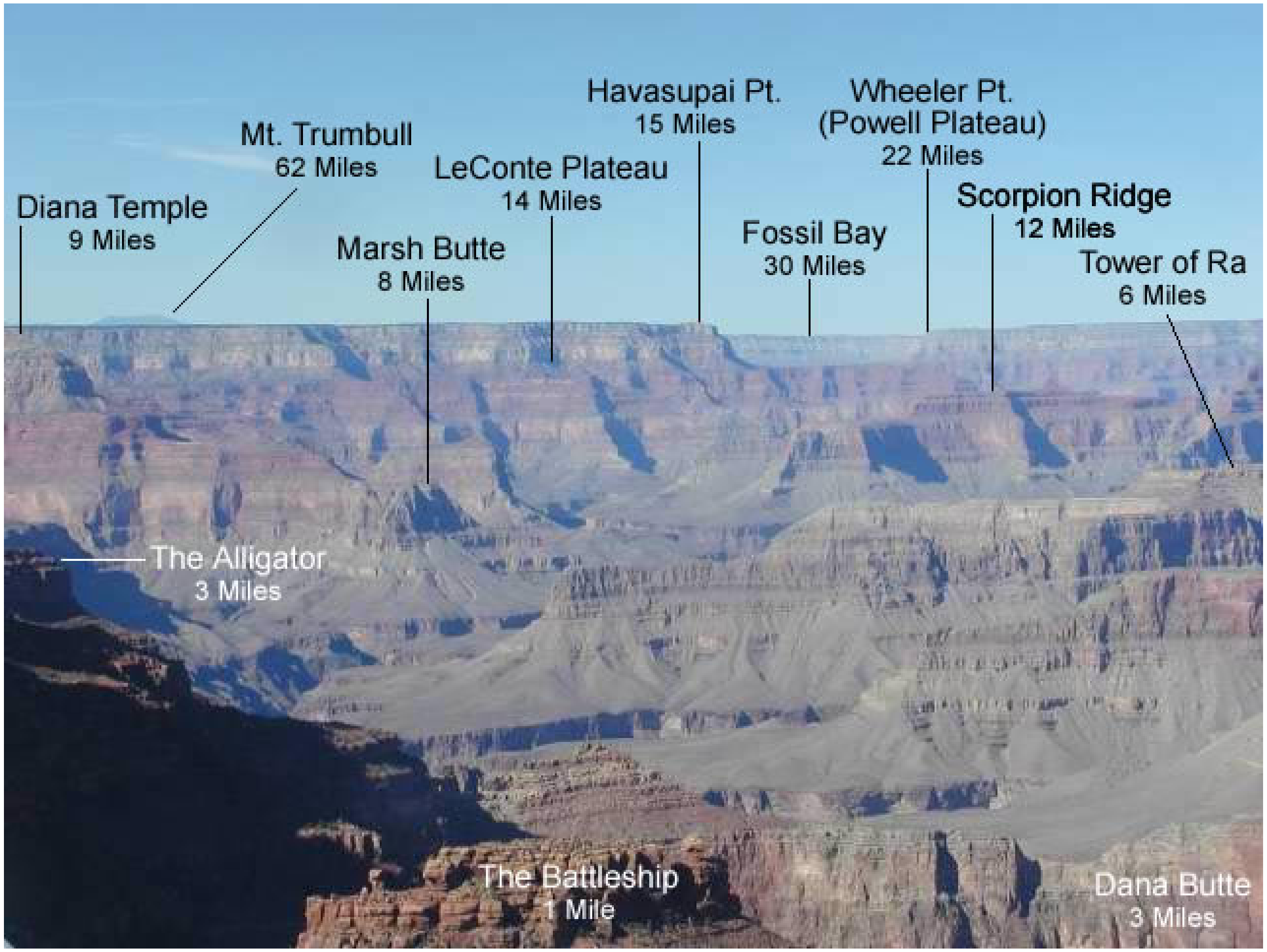


Figure 17b. The distances of a number of elements in the Grand Canyon scene from Yavapai Point. This is image is from the Grand Canyon webcam at: http://www2.nature.nps.gov/air/webcams/parks/grcacam/grcacam.htm

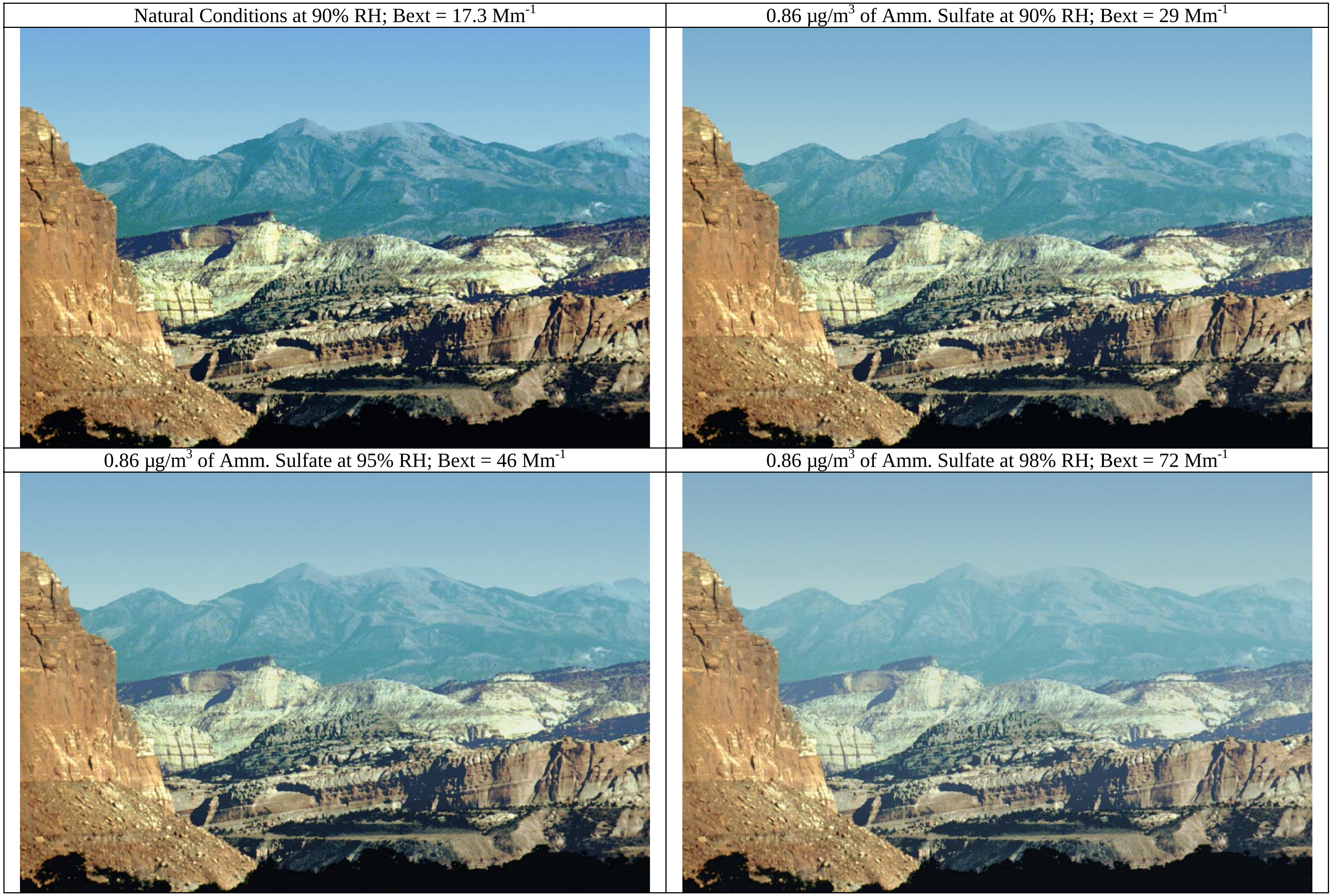
Natural Conditions at 90% RH; Bext = 17.3 Mm^{-1}

2.2 μg/m^3 of Amm. Sulfate at 90% RH; Bext = 48 Mm^{-1}

2.2 μg/m^3 of Amm. Sulfate at 95% RH; Bext = 84 Mm^{-1}

2.2 μg/m^3 of Amm. Sulfate at 98% RH; Bext = 143 Mm^{-1}

Figure 18. A view in Canyonlands NP under natural conditions and different levels of uniform haze resulting from the potential contribution from the proposed Sithe power plant. The La Sal mountains are in the background about 50 km from the camera and the distant ridge is 18 km away.



Natural Conditions at 90% RH; Bext = 17.3 Mm^{-1}

0.86 $\mu g/m^3$ of Amm. Sulfate at 90% RH; Bext = 29 Mm^{-1}

0.86 $\mu g/m^3$ of Amm. Sulfate at 95% RH; Bext = 46 Mm^{-1}

0.86 $\mu g/m^3$ of Amm. Sulfate at 98% RH; Bext = 72 Mm^{-1}

Figure 19. A view in Capitol Reef NP under natural conditions and different levels of uniform haze resulting from the potential contribution from the proposed Sithe power plant. The Henry Mountains are in the background about 35 km away.

Figure 20. View of Ship Rock, New Mexico from Mesa Verde, Colorado on a pollution free day during 6/25/1993.

Figure 21. View of Ship Rock, New Mexico from Mesa Verde, Colorado on during 12/16/1994. A layered haze exists from the surface to the top of Ship Rock. The top of the Chuska Mountains stick out of the layered haze.

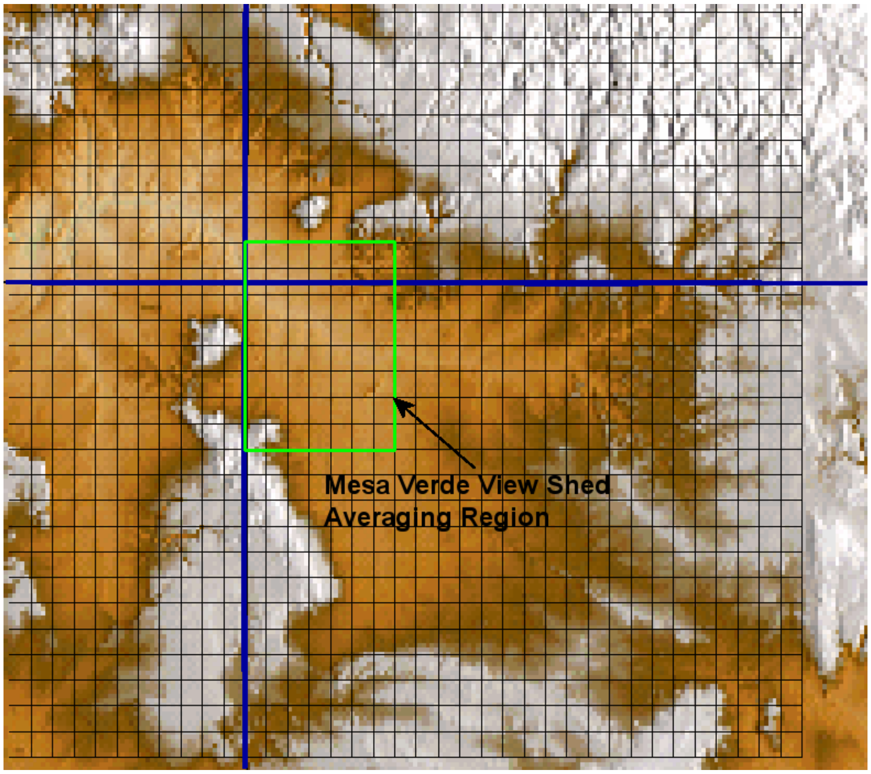


Figure 22. The region that the CMC simulation was averaged over representing the view shed from Mesa Verde to the Chuska Mountains. The fine grid is the grid used in the CMC model to estimate the concentration fields from the distributions of the particles.

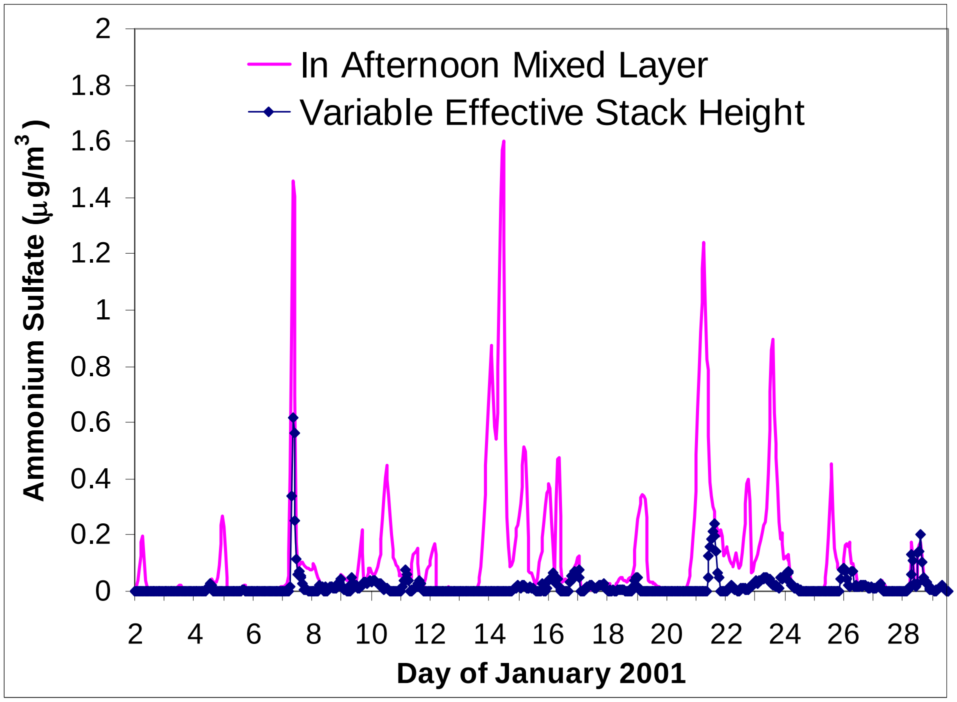


Figure 23. Hourly simulated ammonium sulfate concentrations averaged over the Mesa Verde view shed.