PROPOSED FLAG LEVEL II AND III VISIBILITY ASSESSMENT

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ABSTRACT

The Federal Land Managers' Air Quality Related Values Work Group (FLAG) was developed to provide consistent policies and processes for identifying air quality related values (AQRVs) and evaluating the impact of new or modified sources on visibility, ozone, and atmospheric deposition. The FLAG visibility analysis calls for a two-level approach. Level I is strictly a ***screening*** process that employs many simplified assumptions to simulate and assess the impact of a source's emissions on visual air quality in class I areas (CIAs). This prescription includes positive and negative biases in the modeling system to arrive at a somewhat conservative estimate of a source's potential contribution to visibility impairment in CIAs. Because, in the level I analysis, predicted particulate concentrations arising from source emissions are averaged to 24 hours, the analysis should not be viewed as representative of the instantaneous visibility impact that source emissions will have. A source that passes level I of FLAG will most likely not have a significant impact on visibility and no further action is required. If a source fails this screening process, and further analysis is considered necessary, then a level II analysis could be conducted, employing a more detailed modeling, and possibly data collection, effort. A FLAG level II assessment has not been clearly defined, which has encouraged selective modifications of the level I protocol to minimize a source's impact. In this paper, more detailed, and possibly less conservative, analyses for assessing a source's impact on visual air quality is presented that could potentially be used in a FLAG level II or even a level III analysis. The analysis is based on more advanced visibility modeling to simulate the instantaneous degradation of visual air quality indexes along idealized sight paths under various ambient lighting conditions. This requires chemical transport modeling capable of simulating the spatial variability of pollutant concentrations due to the source throughout the CIAs on at most a 1-hour time period. The

concentration fields would then be used in a radiative transfer model that can simulate the change in visual air quality indexes for the idealized sight paths.

INTRODUCTION

The Federal Land Managers' Air Quality Related Values Work Group (FLAG) was developed to provide consistent policies and processes for identifying air quality related values (AQRVs) and evaluating the impact of new or modified sources on visibility, ozone, and deposition AQRVs primarily in class I areas (CIAs). The FLAG visibility analysis calls for a two-level approach. Level I is a screening process that has detailed guidelines for modeling air quality and its effects from proposed sources. The prescription specifies that many simplifying assumptions be used to simulate and assess the impact of a source's emissions on visual air quality in CIAs. The level I prescription includes positive and negative biases in the modeling system to arrive at a somewhat conservative estimate of a source's potential contribution to visibility impairment in CIAs. Therefore, a source that passes FLAG level I will most likely not have a significant impact on any CIAs and no further action is required. The FLAG level I analysis is a screening technique, and no ad-hoc modifications of the procedure are acceptable. If a source fails this screening process, then a level II analysis can be conducted, employing a more detailed modeling, and possibly data collection, effort. Level II of FLAG has not been clearly defined, which has encouraged selective modifications of the level I protocol to minimize a source's impact.

In this work we first review the processes that lead to visible haze from a source and summarize the FLAG level I prescription and its major information gaps. A refined approach is then proposed, based on more detailed, and possibly less conservative, modeling analyses for assessing a source's impact on visual air quality. The refined approach could potentially be used in FLAG level II and even level III analyses. The refined analyses are illustrated by assessing the impact of a proposed source in the Four Corners region on visibility in Grand Canyon National Park (NP).

PROCESSES LEADING TO VISIBLE HAZE

The primary physical/chemical/optical processes leading to visible haze from a source are presented in Figure 1. Air pollutants emitted from a source are transported and diffused while undergoing chemical transformations. The chemical transformation of sulfur dioxide and nitrogen oxides from primary gases to secondary particles is particularly important to visibility degradation. These transformation processes are dependent on the chemical environment in which the plume resides and whether or not the pollutants encounter clouds and fog. The wet phase transformation of sulfur dioxide to particulate sulfate in clouds and fog is considerably enhanced compared to the dry phase. The wet phase chemistry is particularly important since it can produce haze-forming particulate sulfate over short time periods, causing a source to impact visibility in nearby CIAs.

These atmospheric processes result in a three-dimensional concentration field of gases and particles that scatter and absorb light, i.e., light extinction (b_{ext}). If an observer is looking at a distant scene through these pollutants, then image-forming light is lost by the scattering and absorption along the sight path. In addition, ambient light from direct, diffuse, and reflected light is scattered into the sight path. If the pollutants are at high enough concentrations, then these processes can adversely affect the quality of an observer's view of a distant scene.

Landscape features in a scene are visible due to differences in the spectral radiance of light between adjacent features. That is, the color and brightness of the landscape features are different, for example, a white cloud against a blue sky. The relative difference between the radiance of two features is known as the contrast. Aerosols added to the atmosphere can result in visibility impairment in two ways: first, where the haze changes the color, contrast, form and brightness of landscape features, and, second, where the haze becomes visible itself. The first type of visibility impairment occurs under uniform haze conditions where the scene is enveloped in a haze, which reduces the contrast between landscape features (Figure 2).

The second type of impairment occurs under layered haze conditions, where there is a boundary between the haze and background landscape features or sky, and there is a perceptible difference in the contrast or color of the haze and the background (Figure 3). In addition, under high haze levels, a uniform haze can also become visible as a semitransparent curtain that can be seen as a separate haze entity, disassociated from the landscape features.[1] The human visual system is more sensitive to seeing sharp boundaries, so layered hazes are easier to perceive than changes in landscape features contrasts. Therefore, perceptible layered hazes occur at lower haze levels than perceptible uniform hazes. Haze is often confined to the mixing layer, the lowest 1–3 km of the atmosphere. If an observer is located within the mixing layer, the haze will be uniform; however, if the observer is above the mixing layer, e.g., on a mountain ridge, the haze will appear as a layered haze. Therefore, the distinction between a uniform and layered haze is often dependent on the observer's vantage point.

The appearance of haze is also dependent on its illumination or sun angle relative to the observer. This is illustrated in Figure 3, where in the forward scattering case, with the sun in front of the observer, the haze appears as a bright layer. However, in the backscattering case, with the sun behind the observer, the haze appears as a dark layer.

In general, simulating the atmospheric processes leading to visible haze is a challenging exercise, especially for CIAs located in complex terrain. Terrain can channel flow, limiting the plumes horizontal dilution, and it can block the flow, allowing emissions to accumulate in basins, increasing their ambient concentrations, and inhibiting their transport to nearby CIAs. Complex terrain also provides mountain backdrops, deep canyons, and observer vantage points that allow layered hazes to be generated and viewed. The complex terrain also allows for long sight paths not limited by the earth's curvature. The modeling of sources' impact on visibility for FLAG is made more complex by the fact that FLAG is concerned with the highest haze episodes. These episodes often coincide with cloud processing of the pollutants. Simulating meteorology and air quality in complex terrain with cloud interaction is one of the most challenging modeling situations.

In summary, the human perception of a scene (visibility) is a near-instantaneous event, dependent on the distribution of particulates and gases between the observer and landscape features, the observer's vantage point, i.e., uniform or layered haze, the illumination of the haze, i.e., forward and backward light scattering, and landscape features' colors, contrast, form and brightness. The visibility will change from one moment to another as the pollutant loadings, sun angle, and clouds vary.

FLAG LEVEL I VISIBILITY ANALYSIS FOR DISTANT SOURCES

FLAG level I provides different procedures and recommendations for assessing sources proposing to locate relatively near (within 50 km), and at farther distances (greater than 50 km), from CIAs. It also recommends impairment thresholds and identifies the conditions for which cumulative analyses could be warranted. The FLAG level I analysis recommends that CALPUFF be used for estimating the concentrations of visibility impairing pollutants. An hourly light extinction coefficient is calculated from these concentrations and averaged over 24 hours, which is in turn compared to an estimate of natural conditions. If the source increases light extinction by 5% relative to natural conditions, it is considered an impact of concern. A 10% increase in light extinction is defined as the threshold at which the FLM is "likely to object" to the permit. Although a 10% increase above natural conditions is defined as the threshold at which an FLM is "likely to object", FLAG was not intended to provide a bright-line test that would allow one to determine whether or not a source of air pollution does, or would, cause or contribute to an adverse impact. The adverse impact determination remains a project-specific management decision, the responsibility for which remains with the FLM. The proposed refinements to the FLAG modeling are to address shortcomings in the modeling of the more distant sources (greater than 50 km), but could also be applied to the sources relatively near CIAs.

INFORMATION GAPS IN FLAG LEVEL I VISIBILITY ANALYSIS

The simulation of the impact of a source on visibility is dependent on the input emissions and meteorology, and the modeling of the plume transport, atmospheric chemistry, deposition and visibility effects. Figure 4, provides a subjective estimate of the uncertainty in these inputs and processes and whether or not the best available information is being used in the FLAG level I analysis. As shown, the emissions are the only input/model category where the best available information is currently being used.

Meteorology

FLAG level I requires three years of prognostic meteorological data and recommends that the MM5 meteorological model be used to generate data on at most 36-km grid. MM5 is a current and, in many ways, state-of-the-art meteorological model, but there are two serious issues with the data used for FLAG. First, MM5 does not assimilate measured cloud and precipitation data into the simulations, and there can be large uncertainties in these fields. For example, in one evaluation of the MM5 precipitation in the Sierra Nevada Mountains by Grubisic et al.,[2] they found that "irrespective of the choice of the microphysical scheme we find that the skill of the MM5 model in placing the given amount of precipitation in the right location is rather low for a wide range of precipitation intervals (from 12.7 to 101.6 mm). Additionally, this skill appears to be no better than what would be achieved by a random forecast." Although this is an extreme example of the high uncertainty in modeled precipitation fields, poor simulation of clouds and precipitation is a problem with all readily available meteorological models.

The second issue is that the 36-km grid scale is relatively coarse and smoothes out complex terrain, minimizing the influence of the terrain on the meteorology, including winds, clouds, and precipitation. The impact of a coarse grid wind field on dispersion in complex terrain is illustrated in Figure 5, which presents snapshots of the emissions from a source located in the Four Corners region in the western United States from two different simulations. One simulation used a 4-km MM5 wind field and the other used EDAS wind fields generated on a 48-km grid, but saved out to an 80-km grid. As shown, using the 4-km winds, the plume is transported up the San Juan River valley to Lake Powell then channeled down the Grand Canyon. This transport occurred under a high pressure system. Previous tracer studies have shown similar transport patterns from Lake Powell into the Grand Canyon under similar weather patterns.[3] When the coarse grid EDAS winds are used, the plume is transported through a pass in the Chuska Mountains south of Lake Powel and the Grand Canyon. In this situation the coarse grid is wholly inadequate to simulate the impacts of this source on the Grand Canyon and CIAs in Utah. The differences in dispersion using 36-km MM5 wind fields compared to the 4-km winds would most likely be smaller than presented in Figure 5; however, the 36-km winds would still not capture all of the effects of the terrain forcing.

Dispersion

CALPUFF is a Gaussian puff model simulating dispersion through the transport of individual "puffs" of emissions that diffuse or grow in size based upon the Pasquill-Gifford Gaussian diffusion mechanism. Although there are more modern and superior dispersion mechanisms, the Gaussian puff model has been shown to adequately reproduce plume dispersion. However, in a FLAG level I analysis, CALPUFF is not generally operated with the puff splitting option. Over multi-day transport periods, the puffs will often grow in size so that they encompass more than one grid cell, both horizontally and vertically. Therefore, large gradients in the wind vectors across the puffs can exist. CALPUFF advects these large puffs by using wind vectors at the centroid of the puff, which can result in large transport errors. This can underestimate the diffusion of the puff, thus overestimating pollutant concentrations in the puffs. In addition, portions of the puff would be displaced, yielding concentrations in the wrong locations.

Deposition

CALPUFF uses an old, but standard, mechanism for the simulation of dry and wet deposition. While more modern and accurate mechanisms are available, the simulation of dry deposition is not likely a source of large errors in the modeling. However, the wet deposition is highly dependent on the ability of the meteorological models to adequately reproduce the precipitation fields and could be a source of large errors.

Chemistry

FLAG level I recommends that the MESOPUFF-II mechanism be used to simulate the transformation of SO_2 and NO_x to particulate sulfate and nitrate, respectively. This mechanism uses pseudo-first-order chemical rate equations where the rate coefficients are empirical equations based upon several atmospheric variables, e.g., ozone and relative humidity. The empirical equations were generated by statistically analyzing hourly transformation rates produced by a photochemical box model developed in 1982[4] using atmospheric conditions not representative of those found in rural CIAs; for example, temperatures used in its development were never below 50^{o} F and volatile organic carbon (VOC) concentrations never below 50 ppb.[5] In addition, the MESOPUFF-II mechanism does not properly account for wet phase chemistry in clouds.

The MESOPUFF-II chemical mechanism has recently been evaluated in several studies.[5,6] Morris et al.[6] found that when clouds were present CALPUFF underestimated the sulfate, but when clouds were not present the sulfate was generally overestimated. Morris et al.[5] evaluated the MESOPUFF-II mechanism at urban and rural sites for all meteorological conditions during January and July 2002. They found that the model systematically underestimated peak sulfate concentration in July by 11.5 $\mu g/m^3$ with a fraction bias ~ 54% but overestimated the peak sulfate concentrations in January by 6.5 $\mu g/m^3$ with a fraction bias ~ 55%. The nitrate concentrations were systematically overestimated in both months.

Visibility Assessment

The FLAG level I visibility assessment is based on the maximum 24-hour average b_{ext} values in a CIA and has two increasing levels of concern: first, if the source increases the b_{ext} above background level by 5% (0.5 deciview) or more, and, second, if the source increases b_{ext} by 10% (1 deciview) or more above background levels. The maximum daily b_{ext} in a CIA is meant to represent the maximum instantaneous sight path average b_{ext} during daylight. However, in general, a source's impact on a CIA will be a three-dimensional b_{ext} field with steep gradients. Therefore, the maximum b_{ext} could overestimate the sight path average b_{ext} within the CIA. Using 24-hour average, b_{ext} reduces any overestimation but may not eliminate the bias.

The deciview index has been shown to be related to human visibility in uniform haze, where a 1 deciview increment perceptibly changes scenic elements at the distance of the visual range.[7] However, short sight paths may not have many scenic elements at the edge of the visual range, and under these conditions a 1 deciview change may not be noticeable. Taken together, the assumptions used in the FLAG level I visibility assessment generally lead to a conservative estimate of a source's impact on visibility for a uniform haze case, which is appropriate for a level I screening tool. However, absent from the level I visibility assessment are the impact of layered hazes, the effect of changes in illumination, varying landscape features, and the distribution of pollutants along a sight path.

PROPOSED REFINEMENTS FOR FLAG LEVEL II AND III VISIBILITY ASSESSMENT

A refined modeling and visibility assessment should simulate the instantaneous degradation of visual air quality indexes along sight paths, accounting for the observer vantage point, changes in pollutant concentrations along the sight path, illumination of the scene, and landscape features. This requires chemical transport modeling capable of simulating the spatial variability of pollutant concentrations due to the source throughout the CIAs on, at most, a 1-hour time period. The concentration fields can then be used in a radiative transfer model that can simulate the change in visual air quality indexes for the sight paths. Following are refinements that could be used in a FLAG level II assessment and a more complex level III visibility assessment that account for all of the relevant processing mechanisms leading to visible haze.

Refined Level II Visibility Assessment

Four Dimensional Aerosol Concentration Fields

A level II analysis requires four-dimensional concentration fields. This could be generated using the CALPUFF model. However, the input meteorological data would need to be at a sufficiently fine spatial and temporal resolution to resolve the important terrain forcing on the wind fields. Many of the terrain features in the western United States are on the order of a few kilometers, and simulating transport in these areas would require wind fields with a similar resolution. In addition, the CALPUFF dispersion should use the puff splitting option. Without puff splitting, the model is missing one of the key atmospheric processes for regional scale dispersion.

As discussed, the CALPUFF chemistry mechanism is inadequate for simulating cloud-processed pollutants and is potentially biased during the highest concentrations. Also, the cloud and precipitation fields in the meteorological data are highly uncertain. Therefore, it is suggested that simulations be conducted to define an upper bound in the concentrations to capture the potential effects of cloud processing of the sources emissions. This could be done by using a constant but high sulfur dioxide to sulfate transformation rate. Alternatively, it could be assumed that there is 100% conversion of SO_2 to sulfate. That is, at each receptor the ammonium sulfate concentration is equal to the simulated ammonium sulfate plus the simulated sulfur dioxide concentration scaled to ammonium sulfate. This is based on the assumption that the source's emissions were cloud processed and all sulfur dioxide was converted to sulfate. Measured cloud fields from satellites, meteorological data, and photographs could be used to identify those time periods where the source's plume would likely encounter a cloud. For those periods where no cloud processing would occur, the standard CALPUFF sulfate concentrations would be used. It is clear that CALPUFF also overestimates the nitrate concentrations. The input ammonia concentrations could be decreased to decrease the particulate nitrate to more reasonable levels.

Visibility Assessment

A refined visibility analysis that includes most of the important atmospheric processes and mechanisms leading to visibly haze could be accomplished by first defining an idealized sight path important to the visitor experience in each class I area. At the end of each sight path a light and dark target would be placed to represent bright landscape features such as snow capped mountains or clouds and the dark features such as forests or landscape features in shadow. These targets represent the extremes in the radiances from the landscape features.

To account for different observer vantage points, the impact of the source's haze on the scene would be estimated, assuming the haze appears uniform or layered. In the uniform haze case the change in the contrast (delta contrast) between natural conditions with and without aerosol contributions from the source would be calculated. This process is illustrated in Figure 6. This would be done by using a radiative transfer model to first estimate the apparent contrast between the light and dark targets and between the targets and the sky that the observer would see under natural conditions. It is assumed that the natural aerosols extend well above the mixed layer enveloping the targets and sky. This is based on the fact that the natural aerosols are likely due to sources from a broad geographical region and transported over multiple days. The best estimate of the actual relative humidity along the sight path would be used in the radiative transfer model. Then, for a given moment in time, the three-dimensional simulated aerosol concentrations from the source would be added to the sight path and a new set of contrasts would be calculated. The delta contrasts would then be the differences between the contrasts with and without the contributions from the source. To account for different illuminations of the scene, the delta contrasts would be calculated under forward and backward scattering conditions, resulting in a total of six delta contrasts. These delta contrasts could then be compared to threshold values to determine if the haze is visible or not.

In the case of the layered haze, we are concerned most with whether the haze can be seen against the background or not. Therefore, as shown in Figure 7, the apparent contrast to the observer of the layered haze from the source against a light target, a dark target, and the sky would be calculated. To do this, the simulated three-dimensional aerosol concentrations and relative humidity fields for a given moment in time would again be used in a radiative transfer model. These three contrasts would be calculated for both forward and backward scattering conditions, resulting in six contrasts that can be compared to threshold values to determine if the layered haze is visible or not.

The haze from a source will likely have a different impact depending on the wave length of the visible light. For example, small particles will preferentially scatter blue light over red light. Therefore, the contrast should be calculated for different wavelengths within the visual spectrum and averaged together, weighted by the wavelengths' intensities in the visual spectrum.

Refined Level III Visibility Assessment

A level III assessment would attempt to do the most credible modeling and assessment possible. To aid this analysis, previous modeling and measurement studies involving CIAs potentially impacted by the proposed source, as well as the FLAG level II analysis, should be critically examined to understand the relevant atmospheric processes and time periods that the highest impacts are likely to occur. This information could then be used to devise credible and focused modeling efforts to assess the proposed source's impact on haze. Due to the large uncertainties in source apportionment models, multiple state-of-the-art air quality models that have detailed chemical mechanisms capable of simulating wet phase and nonlinear chemistry should be applied. These models could include Eulerian grid models such as CMAQ[8] and CAMx[9] and Lagrangian and puff models such as CALPUFF and SCICHEM.[10] All models would need to be evaluated against measured data to insure they do not have any systematic biases. The multiple modeling results assessing impacts of the proposed source on the CIAs would need to be compared and differences reconciled. The model evaluation and reconciliation process may require that additional meteorological and air quality data are measured. Results from the past modeling and measurements studies could also aid in the model evaluation and reconciliation.

The assessment of the simulated concentrations on the visibility in the CIAs would be evaluated using a similar method as describe in the level II analysis. However, instead of using an idealized sight path viewing a black and white target, an actual scene and sight path specific to the class I area would be used. Then the change in contrast between the various elements in the scene due to the addition of haze from the source could be estimated and compared to contrast thresholds. Image processing could also be used to modify a photograph of the scene to visualize the impact of the haze on the scene.

ILLUSTRATION OF A FLAG LEVEL II AND LEVEL III ANALYSIS

Plume Simulation and Application of FLAG Level I Visibility Criteria

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 (Figure 8). Four Corners is located on the Colorado Plateau, home to Grand Canyon NP 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 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 Grand Canyon NP and CIAs 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, the CAPITA Monte Carlo[11] particle dispersion model and the CAMx Eulerian grid model[9] were used to simulate the contributions of ammonium sulfate from the proposed and existing power plants during January 2001. The modeling and assessment efforts are fully described elsewhere.[12-15] In this section the simulated ammonium sulfate concentrations from the CAPITA Monte Carlo model are used to illustrate FLAG level II and III type analysis.

The Colorado Plateau is a region of complex terrain, so 4-km MM5 wind fields were used to capture effects of terrain forcing on the plume's dispersion. It was found that, during January 2001, four multi-day stagnation and recirculation events occurred in the Four Corner's region associated with high pressure systems over the region. During these stagnation events, emissions from the 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 of Grand Canyon NP showed that the plumes arrived in the canyon embedded in clouds, which rapidly convert SO_2 to sulfate (Figure 9). 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. Figure 10 presents the simulated sulfate and its contribution to b_{ext} for the Grand Canyon. In this figure, the data were aggregated following the FLAG level I visibility criteria. As shown, when using the 5% transformation rates, there were 4 days with the maximum 24-hour b_{ext} values in the Grand Canyon more than 10% greater than the natural background b_{ext}, with the January 27 value ~50% greater than background levels. When the 1% transformation rate was used, the sulfate and b_{ext} values decreased by about a factor of 3, resulting in three 24-hour maximum b_{ext} values more than 10% greater than the natural background b_{ext}.

Application of the proposed FLAG Level II Visibility Criteria

To illustrate the proposed FLAG level II assessment, a 93-km sight path from Desert View in Grand Canyon NP to the Vermillion Cliffs was defined. The impact of the simulated plume on this sight path was calculated for January 27, 8:00 am. Figure 11 show the sight path and the surface level concentrations using the CAPITA Monte Carlo results and a 5% transformation rate. It was assumed that the surface level concentrations were uniformly mixed up to 1 km in height. The average simulated ammonium sulfate concentration along this sight path was 0.56 $\mu g/m^3$, which was among the highest simulated hourly concentrations on this day. This is about half the maximum 24-hour January 27 concentration simulated in the Grand Canyon (Figure 10). During this time period, measured and model relative humidities were generally greater than 90%.

The effects of this concentration field on a white and black target positioned at the end of the sight path at the Vermillion Cliffs was modeled using the backward Monte Carlo radiation transfer model (BackMC).[16-18] BackMC is a general radiative transfer model capable of simulating the attenuation of image-forming light and addition of path radiance along a sight path, accounting for its specific geometry, varying illumination depending on sun angle, cloud cover, and reflections by ground, vegetation, and the targets. This model has been evaluated in several studies and the sky radiances generated with BackMC compared favorably with analytical solutions for Rayleigh atmospheres, published results from other existing radiation transfer models, and physical simulations where the scattering physics can be exactly defined and measured.[19]

BackMC is a backward photon trajectory, multiple-scattering, Monte Carlo, radiation-transfer model used to calculate sky radiances. The wavelength-dependent, scattered radiation, intensity, and polarization parameters are computed as functions of the observer elevation and azimuthal viewing angles. The model domain is determined by a set of three-dimensional boxes extending beyond the horizon in all directions and to the top of the modeled atmosphere. Each box can be defined as a horizontal surface, a vertical surface, or a free atmosphere. The free-atmosphere boxes can be further defined to have any molecular or aerosol optical properties desired, including specific wavelength-dependent extinction, scattering, and absorption coefficients and phase functions for every gas or aerosol species in each individual box. A spherical geometry is approximated by the appropriate deformation of the rectilinear boxes along any photon path. Lambertian reflection by the ground and elevated terrain are also included. Any general distribution of terrain, solar position, cloud distribution, or extinction can be modeled, providing the specific optical properties can be associated with each feature of every box. This includes complex terrain, uniform haze, layered haze, elevated plumes, clouds, or any combination thereof. The solution is obtained by averaging the radiance from many individual photon path results. Each photon can participate in as many interactions as possible in which each scattering or absorption event behaves randomly according to the appropriate probability distribution. These probabilities are directly determined from physical principles. The model contains no more limiting assumptions or approximations than those inherent in the descriptions of the each probability distribution.

Using BackMC and the geometry of the Desert View to Vermillion Cliffs sight path, the three-dimensional concentration field, and a constant relative humidity of 95%, a vertical profile of the apparent radiances to the observer from the black and white targets and the sky above was calculated for natural conditions and for natural conditions plus the contributions from the source. This was done assuming a uniform and layered haze for both a forward and backward scattering case. Figure 12 presents the vertical radiance profiles for the uniform and layered haze against a white target for the backscattering case. The contrasts and delta contrasts are calculated from these radiance profiles. For example, in the layered haze example in Figure 12, the radiance of the plume plus the natural background over the white target is ~8.5, while the radiance of the white target in natural background, i.e., above the plume, is ~9.85, resulting in a contrast of (9.85–8.5) / 8.5 ~ 0.16. The delta contrasts for the uniform haze and contrast for the layered haze conditions are presented Figure 13. As shown, the delta contrasts are about 0.1 or greater except for the delta contrast of the black and white target under forward-scattering conditions, which is less than 0.05. Under backward scattering conditions for the layered haze, the contrast between the plume and the sky under natural conditions was about -0.09, and between the plume and a white target the contrast was about 0.16. Laboratory studies have shown that for layered hazes contrasts between ±0.01 and ±0.05 are visible,[1] while for the uniform haze a delta contrast ~0.025 would be just noticeable.[1] Therefore, in this example, the contrast and delta contrasts due to haze from the source are significant and noticeable to most people. Note, had the results from the 1% transformation rate been used instead of 5%, the delta contrast would have been reduced by about a factor of 2. Most of these delta contrasts would still be visible to most observers.

Application of the proposed FLAG Level III Visibility Criteria

The primary difference in the proposed FLAG level III visibility assessment compared to the level II visibility assessment is that, instead of assessing the contrasts of a dark and light target for an idealized sight path and illumination, the change in an actual scene would be assessed. This can be done by using the BackMC radiative transfer model to estimate the change in contrast in the elements of a scene, where a scene element is one of the three-dimensional boxes used to define the geometry of the scene. The change in contrast between the various elements in the scene due to the addition of haze can be fed into an image processor to modify photographs to determine if the haze makes a visible difference to the scene.

A level III type of analysis is illustrated in Figure 13, a picture in Grand Canyon NP of Desert View looking from Hopi Point at 9:00 am in the morning. The first picture is of the scene under pristine conditions. In the other images the scene is modified due to a simulated layered haze. A layered haze, which is the typical wintertime haze in the Grand Canyon, is modeled. The layered haze is due to 1 $\mu g/m^3$ of ammonium sulfate, the maximum hourly sulfate concentration averaged over the site path simulated in the Grand Canyon using the CAPITA Monte Carlo during January 2001.[12,13] As shown, at a relative humidity of 90% the light extinction is 32 Mm^{-1} or 80% greater than natural background. At these levels, the layered haze in the Grand Canyon is clearly visible against the background. As expected, the layered haze is accentuated as the relative humidity increases.

SUMMARY

The Federal Land Managers' Air Quality Related Values Work Group (FLAG) was developed to provide consistent policies and processes for identifying air quality related values (AQRVs) and evaluating the impact of new or modified sources on visibility, ozone, and atmospheric deposition. The FLAG visibility analysis calls for a two-level approach. Level I is a screening process that employs many simplified assumptions to simulate and assess the impact of a source's emissions on visual air quality in CIAs. This prescription includes positive and negative biases in the modeling system to arrive at a somewhat conservative estimate of a source's potential contribution to visibility impairment in CIAs. A FLAG level II assessment has not been clearly defined. In this paper a more detailed and possibly less conservative analysis for assessing a source's impact on visual air quality was presented that could potentially be used in a FLAG level II and even a level III analysis.

The human perception of a scene is a near-instantaneous event, dependent on the distribution of light scattering and absorbing particulates and gases between the observer and landscape features, the observer's vantage point, i.e., whether the observer sees a uniform or layered haze, the illumination of the haze, i.e., forward and backward light scattering, and landscape features' such as colors, contrast, form and brightness. The visibility will change from one moment to another as the pollutant loadings, sun angle, and clouds vary.

To account for these variables in a level II visibility assessment, it is proposed that synthetic scenes be created for the CIAs and the impact of the sources on the synthetic scenes be assessed. This can be done by first defining an idealized sight path for a CIA. At the end of the sight path, a dark and light target would be placed to represent the range of possible light intensities from landscape features in an actual scene. The impact of the source on the synthetic scene would be assessed for a uniform and layered haze case. For the uniform haze case, the contrast of the targets between each other and the sky under natural conditions would be calculated using a radiative transfer model. The simulated three-dimensional distribution of aerosols from the source would then be added to the sight path and the contrasts recalculated. The differences between the contrasts with and without the contribution from the source, i.e., delta contrasts, can then be compared to threshold values to determine if the source visibly diminishes the synthetic scene. This would be done for forward and backward light-scattering conditions to account for varied illumination of the scene. In the layered haze case, the contrast between the haze from the source and the dark target, light target, and sky would be calculated for both forward and backward scattering conditions. These contrasts can then be compared to threshold values to determine if the layered haze is visible or not.

A FLAG level III assessment is similar to the level II assessment. However, the impact of the source on an actual scene for a CIA would be assessed. This can be done by using the radiative transfer model to estimate the change in contrast in the elements of a scene due to the addition of haze from the source. These contrast changes can be compared to threshold values and fed into an image processor to modify photographs to determine if the haze makes a visible difference to the scene or not.

The level II and III visibility assessment will likely reduce some of the conservative assumptions in the FLAG level I assessment. Therefore, it is critical that simulated concentration fields with sufficiently low errors are used. If the errors in the modeling system are too large, then bounding calculations should be conducted to simulate the highest aerosol concentration fields likely to occur from the source.

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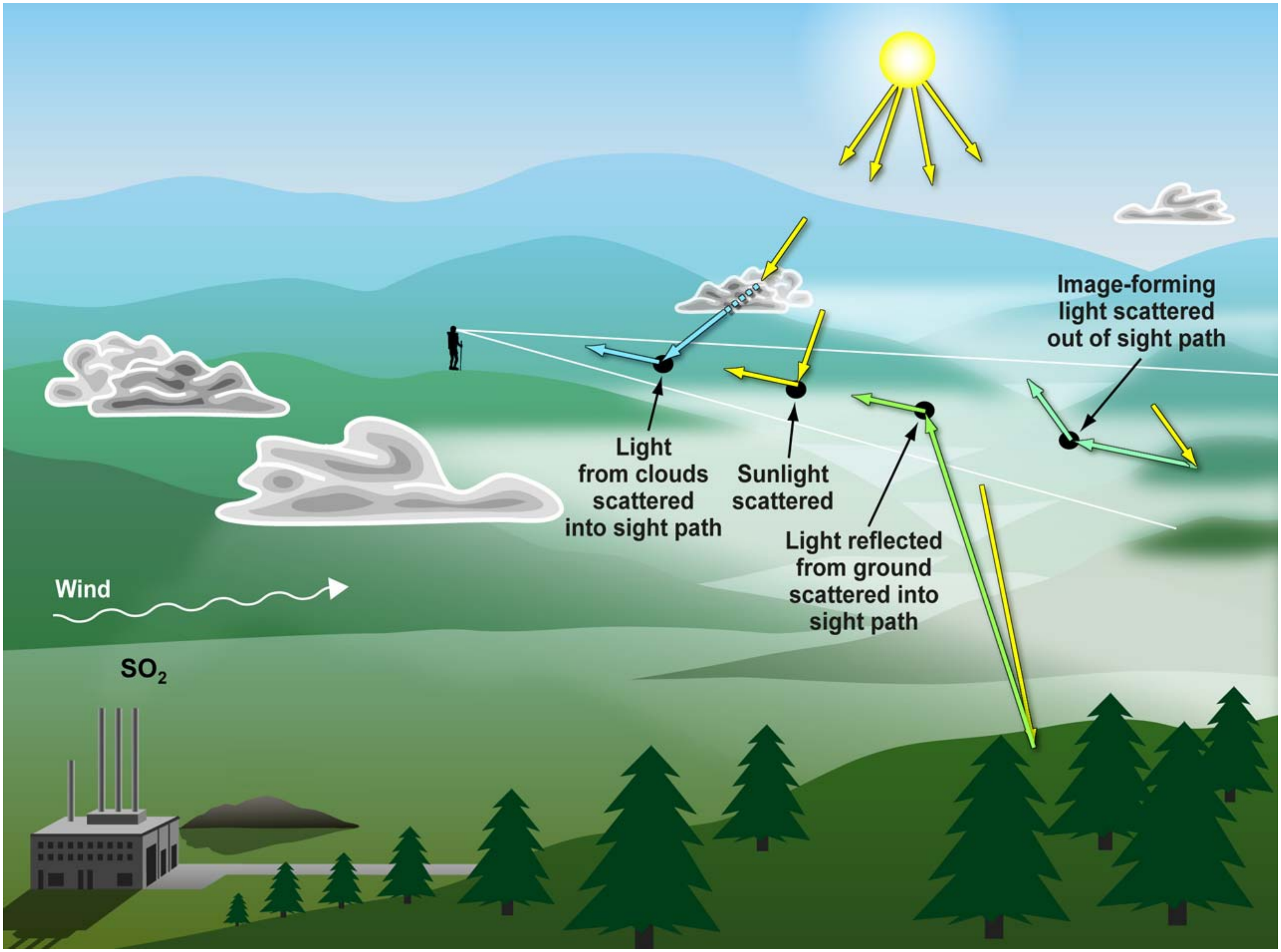


Figure 1. Schematic of the primary processes leading to visible haze.

Figure 2. Big Bend NP, Texas, under pristine conditions (top) and a uniform haze on a 20% best haze day (bottom), i.e., 80% of the days have higher haze levels.

Figure 3. A layered haze against the La Sal Mountains. The top figure is the haze under forward scatting conditions, i.e., the sun is in front of the observer. The bottom figure is the layered haze under backward scattering conditions.

Modeling System		Uncertainty	Best Available Information
Emissions	New Source	Low	Yes
	Other	Low (SO_2) - High (NH_3)	Yes
Meteorology		Medium (winds, temp) - High (Clouds, Precipitation)	Yes-No
Model	Dispersion	Medium (No puff splitting)	Yes-No
	Chemistry	**High**	**No**
	Deposition	Medium to High	Yes-No
Visibility Impact		**Very High**	**No**

Figure 4. Information gaps in the FLAG level I visibility assessment.

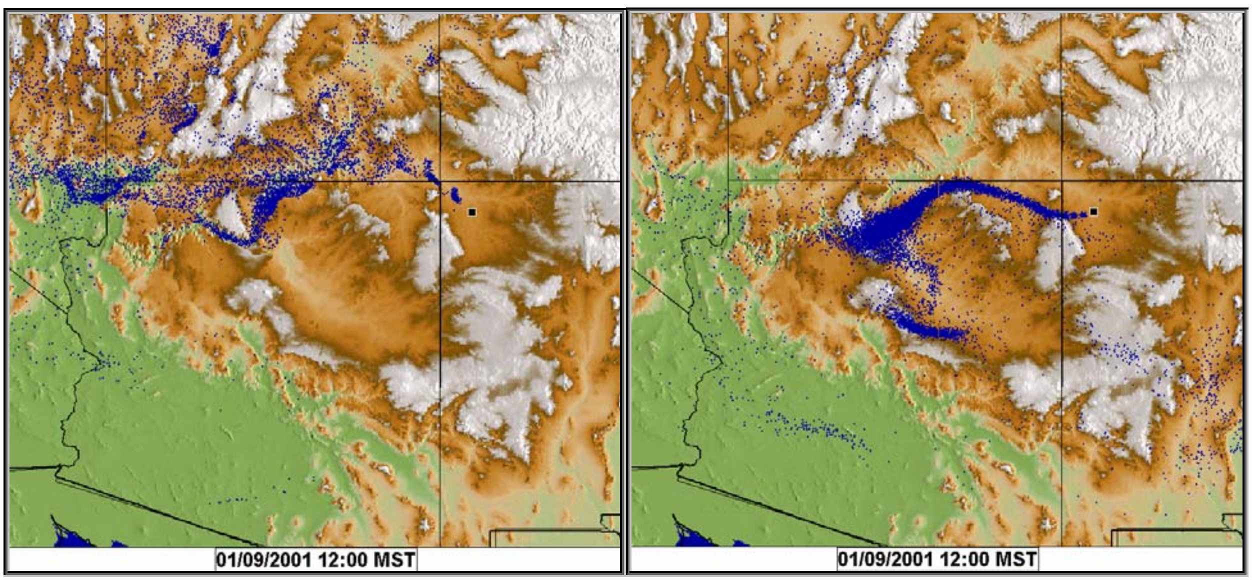
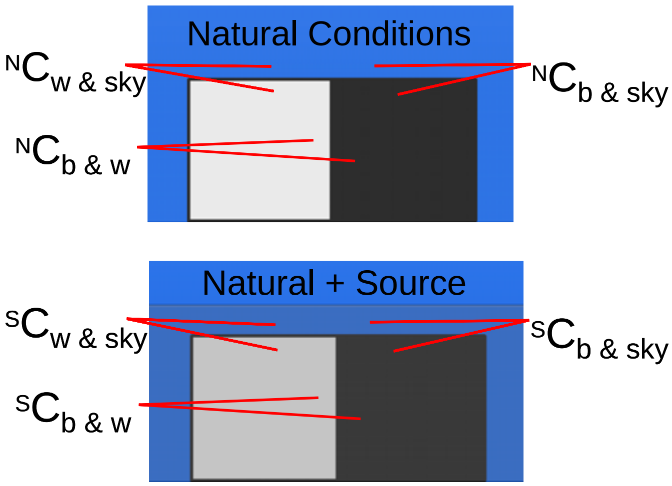


Figure 5. Simulation of a plume released in the Four Corners basin using 4 km MM5 wind fields (left) and 80 km EDAS wind fields (right).



Black and white target delta contrast $\Delta C_{b\&w} = {}^{S}C_{b\ \&\ sky} - {}^{N}C_{b\ \&\ sky}$
Black target and sky delta contrast $\Delta C_{b\&\ sky} = {}^{S}C_{b\ \&\ sky} - {}^{N}C_{b\ \&\ sky}$
White target and sky delta contrast $\Delta C_{w\&\ sky} = {}^{S}C_{b\ \&\ sky} - {}^{N}C_{b\ \&\ sky}$

Figure 6. The contrasts between a light and dark targets and the targets against the sky under natural conditions and natural plus contributions from the source, and the resulting delta contrasts needed for a FLAG level II visibility analysis under uniform haze conditions. The delta contrasts would be calculated for both forward and backward light scattering conditions results in a total of six delta contrasts.

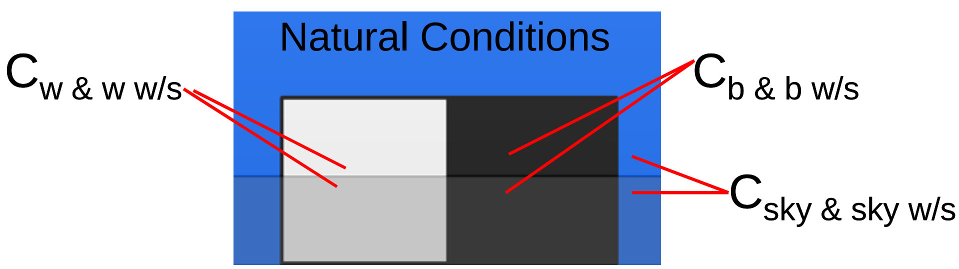


Figure 7. Under layered haze conditions, the impact of the source on visibility would be estimated by calculating the contrast between the source's haze and a dark target under natural conditions ($C_{b\ \&\ b\ w/s}$), the source's haze and a light target under natural conditions ($C_{w\ \&\ w\ w/s}$), and the source's haze and the sky under natural conditions ($C_{sky\ \&\ sky\ w/s}$). These contrasts would be calculated for both forward and backward light scattering resulting in six different contrasts.

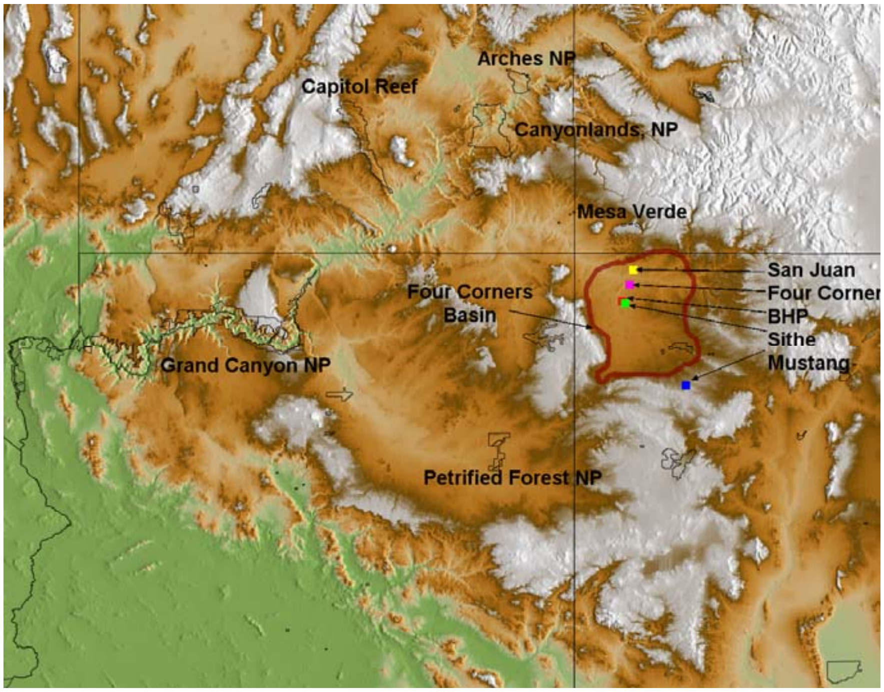


Figure 8. The terrain in the Four Corners states. The squares are the locations of existing and proposed power plants with yellow – Four Corners, purple – San Juan, green – Sithe, red – BHP, and blue – Mustang.

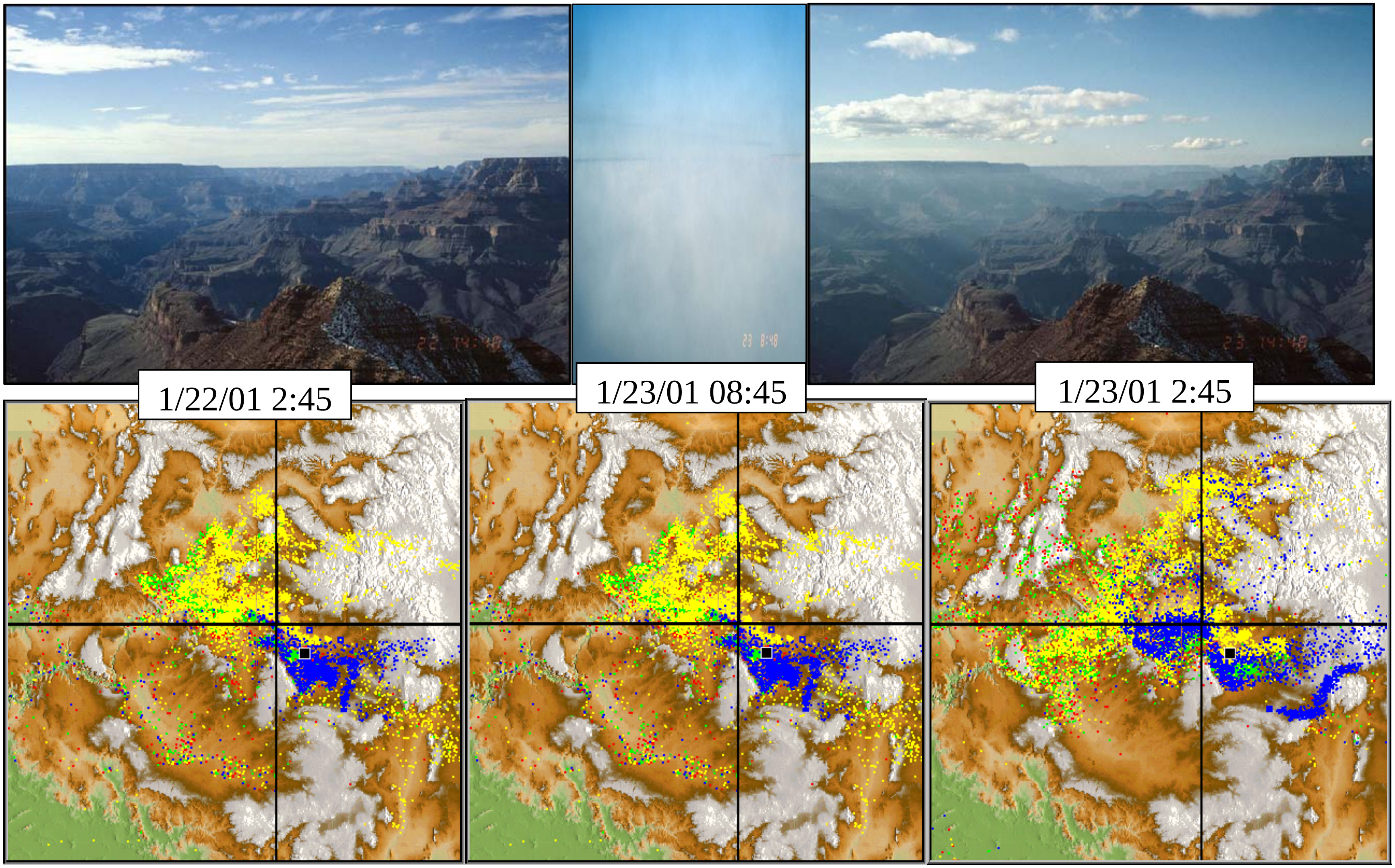


Figure 9. Pictures of the Grand Canyon from Desert View on January 22 and 23, 2001, and associated images of simulated plumes from the Four Corners power plants.

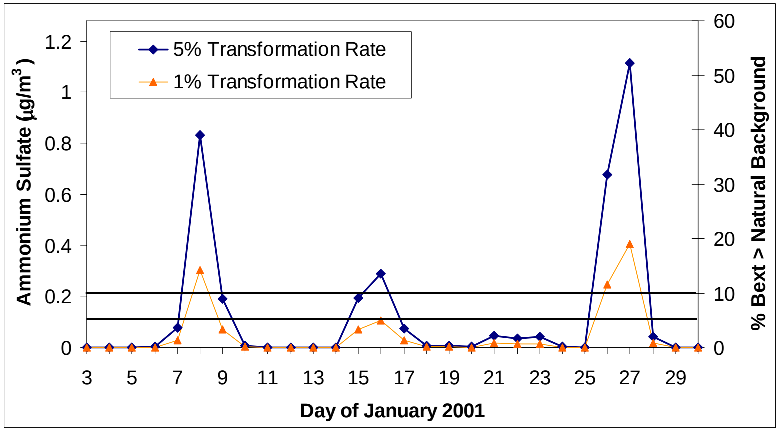


Figure 10. The maximum 24-hour ammonium sulfate concentration and % b_{ext} above the natural background levels in the Grand Canyon NP. The b_{ext} was calculated from the sulfate concentrations using the climatological relative humidity growth factors.

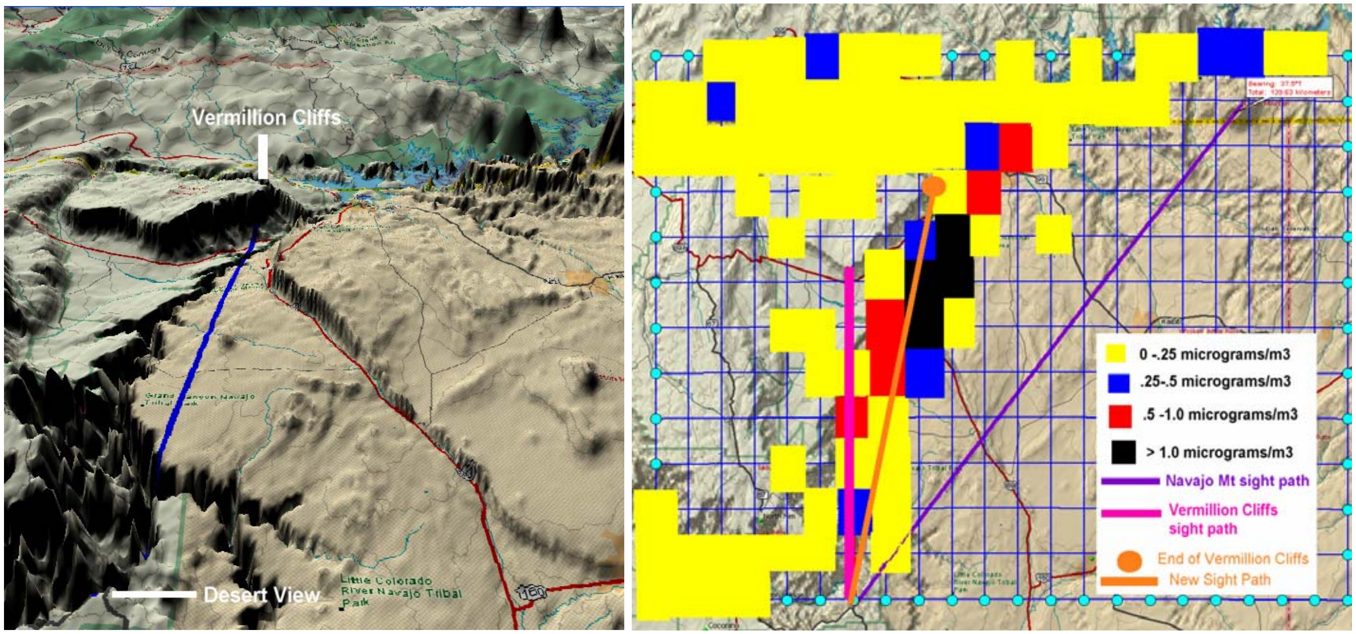
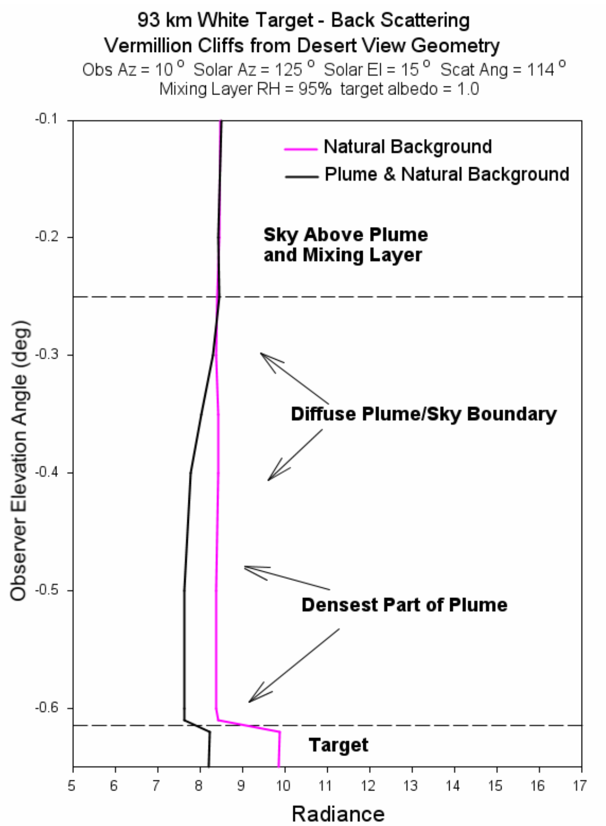


Figure 11. A sight path from Desert View in the Grand Canyon NP to the Vermillion Cliffs (left). The simulated surface ammonium sulfate concentrations along the sight path on January 27 8:00 am (right).



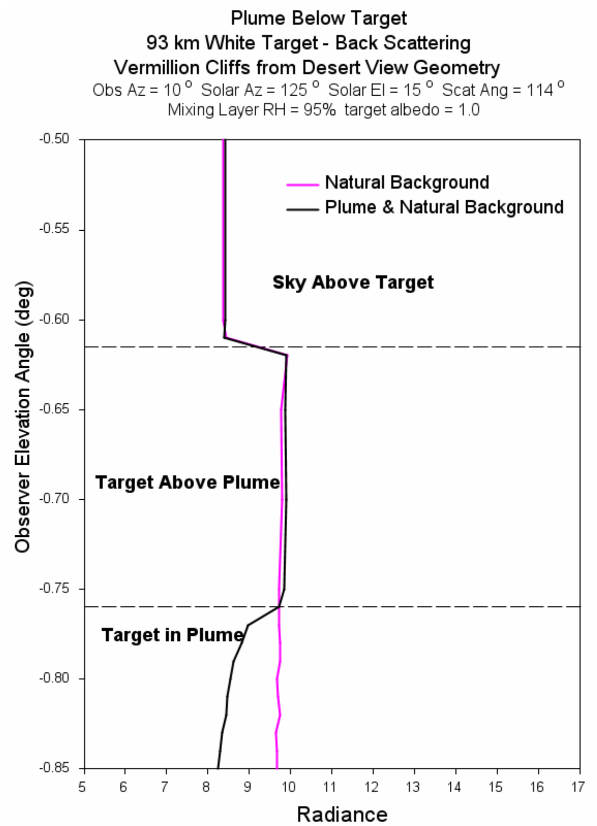


Figure 12. Vertical radiance profiles of the white target and sky above positioned at the Vermillion Cliffs as seen by an observer at Grandview under natural conditions and natural conditions plus the contribution from the source on January 27 8:00 am. The radiance profiles are for the backward scattering conditions for a uniform haze (left) and a layered haze (right).

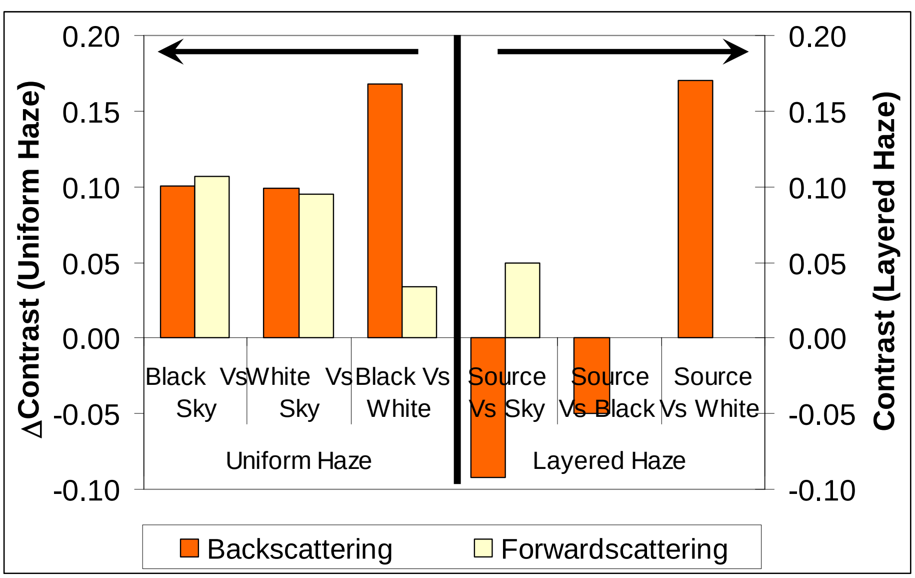


Figure 13. The delta contrast for the uniform haze and contrast of the haze against the background for layered haze case for the January 27 8:00 am episode. Note the contrasts for the layered haze against the white and black target under forward scattering were not calculated.

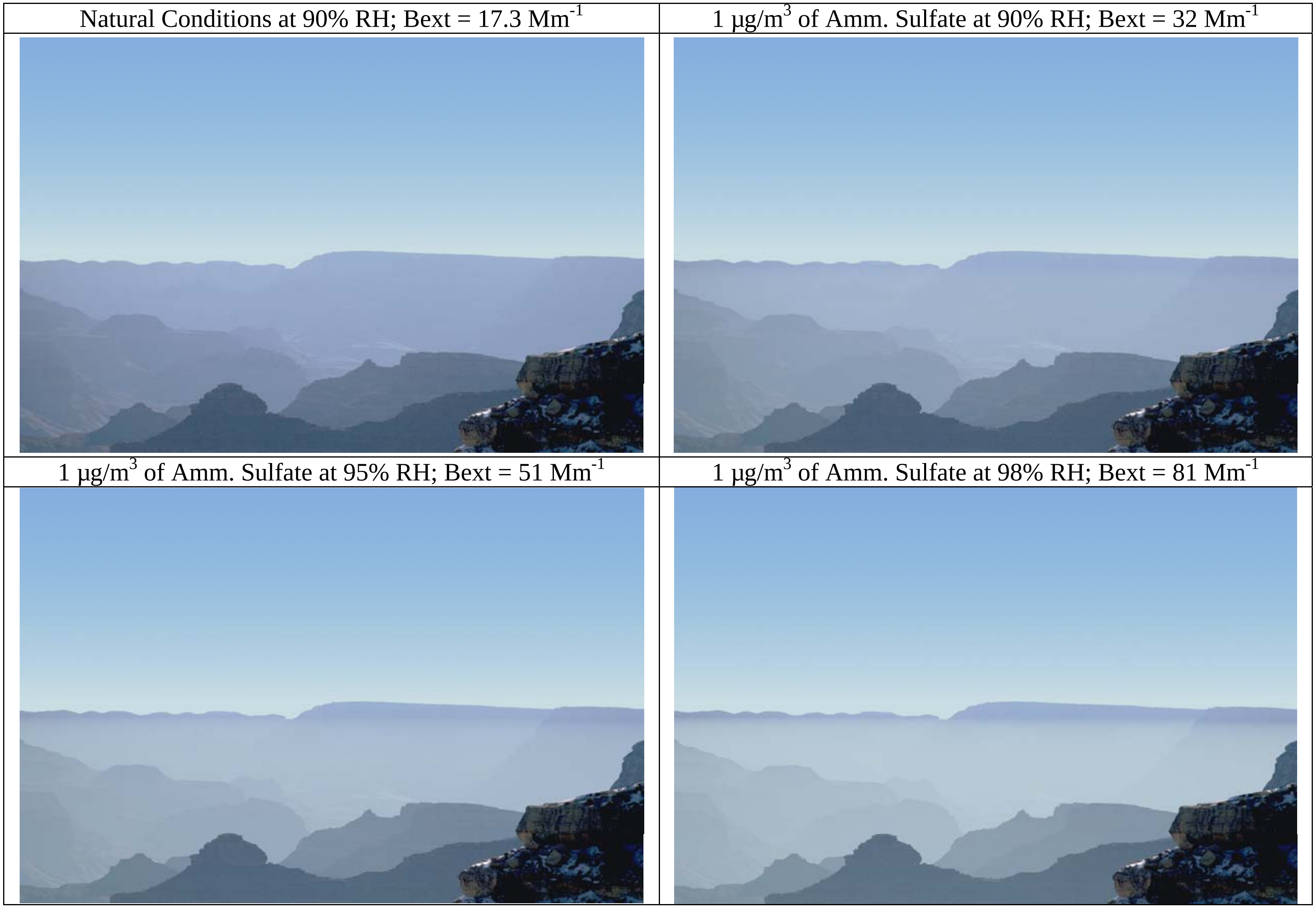


Figure 14. Looking at Desert View from Hopi Point at 9:00 am in Grand Canyon NP under natural conditions and different levels of a layered haze in the Grand Canyon resulting from the contribution of 1 $\mu g/m^3$ of ammonium sulfate.