Geospatial Analysis for the Causes of Haze Assessment

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ABSTRACT

A research study to assess the causes of haze at federal Class I areas in the west and central United States is being done to support federal, state, local and tribal regulatory decision makers. One goal of this study is to identify the emissions sources causing excessive haze levels at each Class I area based on analysis of historical air quality, meteorological, and emissions data. A comprehensive collection of spatial data is being used to assist in the descriptive data analysis phase of this research. This paper provides examples of how ArcGIS and ArcInfo can be utilized to systematically characterize the physical attributes of air monitoring networks, describe air pollutant emission sources and air flow patterns in various topographic environments, and analyze air mass trajectory model output.

1. INTRODUCTION

The Western Regional Air Partnership (WRAP) and Central Regional Air Planning Association (CENRAP) are two of five Regional Planning Organizations (RPOs) that have been created to evaluate, determine methods to improve, and track improvements in regional haze at sensitive locations within their jurisdictions. RPOs are newly-defined entities that intend to respond to the transport of visibility-reducing pollutants within and across state and international boundaries. RPOs need to assess current haze conditions, establish baseline levels, specify and coordinate emissions reduction strategies, and evaluate the effectiveness of those strategies for the coming six decades. The goal is to achieve "natural" visibility conditions by 2065. Quantifying "natural" visibility levels beyond the defaults offered by U.S. EPA (2001a) will be one of the major challenges faced by WRAP and CENRAP during their lifetimes. Identifying the emissions sources causing excessive haze levels and determining where and when emissions reductions are needed to make reasonable progress is another major challenge (Watson, 2002a, 2002b).

The WRAP region (including the states of Alaska, Arizona, California, Colorado, Idaho, Montana, New Mexico, North Dakota Oregon, South Dakota, Utah, Washington, and Wyoming, with Nevada as a non-member) includes more than 100 mandatory Class I areas for which the poorest visibility must be improved and the best visibility must be maintained under the U.S. Regional Haze Rule (U.S. EPA, 1999). Large cities are interspersed among these Class I areas along with many smaller cities and towns and large tracts of desert, mountains, valleys, farmland, open prairie, and forests. Industrial emitters, especially coal-fired power stations and copper smelters, are major sources of sulfur dioxide (SO_2) and oxides of nitrogen (NO_x) in the region. Natural, accidental, and prescribed fires occur often and with great intensity, especially during the dry summer months. Windblown dust storms from disturbed land within and outside the region are common. The WRAP region shares long international borders with Canada and Mexico, as well as with the neighboring CENRAP RPO, and visibility-reducing pollutants enter and leave the WRAP region across these borders.

Manmade emissions that cause haze have decreased in the western states since the 1980s despite substantial growth in population and economic activity. However, light extinction is several times that of natural levels in Western Class I areas for the 20% of days with poorest visibility. Depending on time and place, western light extinction includes important contributions from sulfates, nitrates, organic carbon, elemental carbon, and geological material. This contrasts with extinction in eastern states for which sulfate contributions far exceed contributions from other chemical components. This varied composition implies that all types of manmade emitters, not just SO_2 sources, must participate in emissions reduction strategies.

2. PROJECT GOALS AND OBJECTIVES

The goal of the Causes of Haze (COHA) project is to answer questions about the chemical components that cause regional haze, relationships of haze to meteorology, the emissions that cause haze, and the effects of previous and future emissions reductions on the poorest and best visibility levels. Specific objectives are to:

- Provide answers to specific questions using a variety of independent data analysis approaches and available data sets.
- Evaluate the uncertainty and generality of these answers by quantitative error analysis, comparison of results from different approaches, and informed judgment.
- Integrate and present results in concise and understandable language that can be used to support RPO evaluation of and justification for actions that improve visibility.

These objectives are satisfied using a variety of data analysis methods. The basis for visibility at each Class I area is from the IMPROVE monitoring network. Statistical analysis of the aerosol data and calculated extinction serves as a guide to indicate what chemical species are important, what emission sources to look at, and what times of the year do the best and worst visibility days occur. A large part of this project involves using spatial data to interpret the causes of haze for the many study sites.

The first part of this project involved assessing and gathering spatial data relevant to describing the environment and pathways of pollutants transport into each Class I area. Once the databases are archived in a common storage server, a descriptive data analysis of each Class I area is possible. A source descriptive analysis follows, identifying the locations of sources are with respect to the Class I areas. Airmass backtrajectories are being used to determine potential transport areas impacting each site. Episode analysis or case studies play an important role in the understanding of how sources, meteorology, chemical transformation and deposition interact to influence what is measured in the particulate sampler. For the first phase of the project preliminary conceptual models are prepared using these techniques. The second phase depends on more advanced statistical techniques that may involve time series and trend analysis, multivariate Receptor Source Apportionment Analysis and mesoscale meteorological analysis.

3. SOURCES OF DATA

Multiple spatial and non-spatial databases have been archived for use in the descriptive data analysis. These databases have been used to identify emission sources as well as the precursors of haze aerosols, to characterize the physical setting for use in meteorological data analysis and to identify existing environmental monitoring networks to help in the data analysis.

The Interagency Monitoring of PROtected Visual Environments (IMPROVE) aerosol data consists of 24-hour integrated $PM_{2.5}$ (particles with aerodynamic diameters less than 2.5µm) mass, elements, ions (sulfate and nitrate), and eight carbon fractions, as well as coarse mass, from many sites across the United States. Figure 1 shows the sites investigated for this project. Some IMPROVE protocol sites represent urban areas (e.g., Queen Valley, AZ, Puget Sound, WA, South Lake Tahoe & Bliss State Park, CA) and some are far removed from continental U.S. sources (e.g., Mauna Loa, HI and Denali AK). Data from these sites can be used to provide bounds for urban and background values. IMPROVE data are available from site initiation (some as far as 1988) through 2002 were used in the analyses described here. IMPROVE data and metadata were obtained through VIEWS (2004) and IMPROVE (2004), which also provide statistical summaries, conversions of chemical data to major $PM_{2.5}$ components, chemical light extinction, spatial and temporal plots, and trend maps. Watson (2002a) illustrates several examples of these displays and demonstrates how they can be interpreted. Much of the analyses described here will focus on the most recent measurements (2000-2002) because this period includes the largest number of sites, corresponds to the first three years of the 2000-2004 regional haze baseline period, and has not been subjected to as much analyses as previously collected data. Correlations between ambient levels and special emissions events (e.g., dust storms, fires) will use all of the data for which a correspondence can be made.

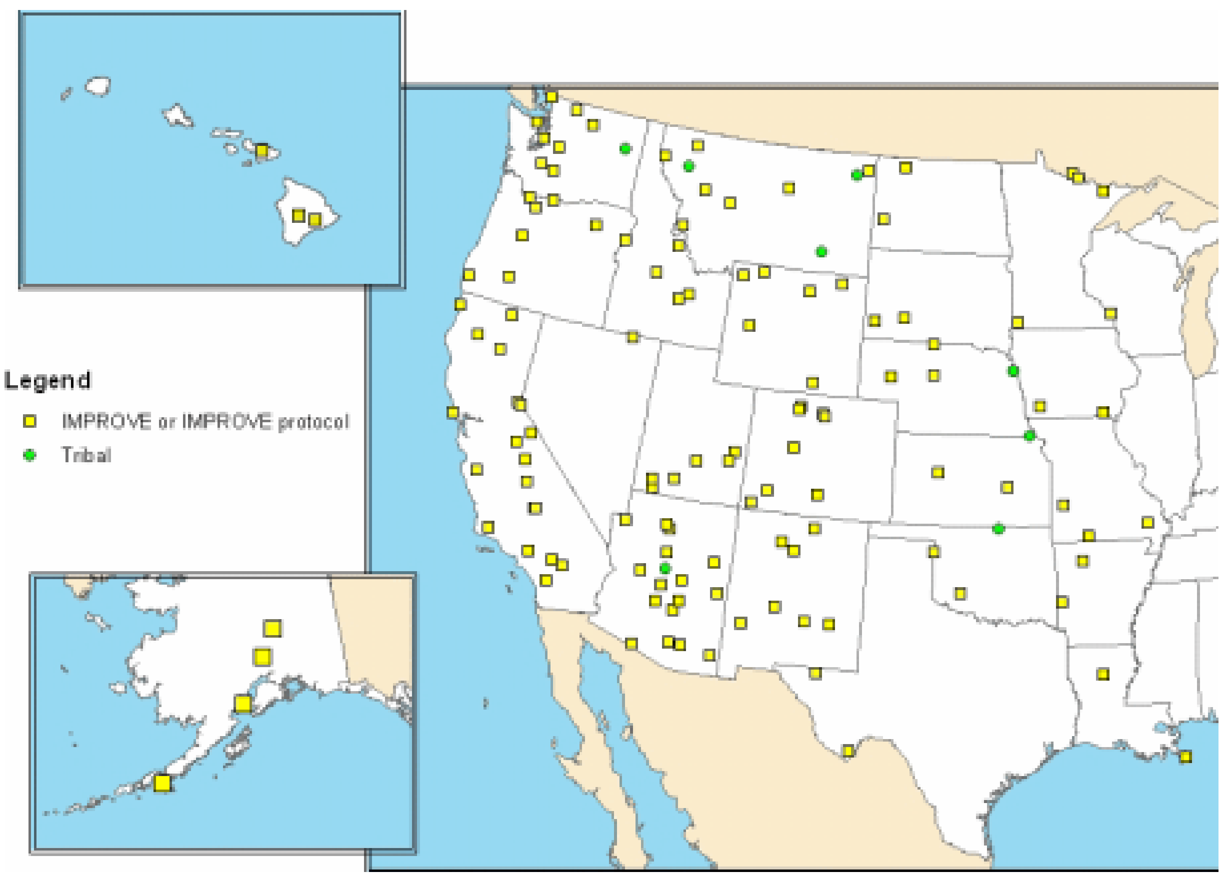

Figure 1. IMPROVE and IMPROVE protocol monitoring sites used in this study.

The Regional Climate Centers (2004) and the National Climatic Data Center (2004) provide meteorological measurements from hundreds of surface and upper air sites scattered throughout the U.S. Selections from this database have been used to identify periods of high winds, occurrences of fogs and clouds that might enhance sulfate formation, and to examine surface stagnation and vertical mixing for IMPROVE monitors located at different elevations.

National fire occurrence geographic information systems have being compiled at several federal land manager agencies. The DRI Program for Climate, Ecosystem and Fire Applications (CEFA), has quality assured several of these databases that identifies fire locations, durations, areas burned, and cause of the fire (Brown et al., 2002).

The well-documented April 1998 Asian dust storm (Husar et al, 2001) has shown that an aerosol study focused only on sources found in the continental US would be incomplete. Such global storms are common and can be identified by ground based aerosol and optical measurements, as well satellites. Dust storms can be inferred from high wind speeds at monitors near susceptible soils, and they might be identifiable from IMPROVE data by changes in elemental ratios and elevated coarse mass. Potential sources of dust include playas, sand dunes, barren land, agricultural land, disturbed rangeland and construction areas. Some of these can be inferred through the use of land use/land cover databases, aerial photos and multispectral satellite imagery.

Other sources of data are summarized in Table 1. All of the data in this study were obtained from public sources and most of them are readily available on websites.

Table 1. Major data themes used in this study

Theme	Database
Air Quality Networks	IMPROVE and IMPROVE protocol sites (archived from VIEWS)
	EPA Speciation Trends sites
	PM_{10}, $PM_{2.5}$, SO_2, O_3, CO, NOx at state/local agency managed stations
	Special studies (CRPAQS, CCOS, Mohave, Bravo, etc.)
Meteorological Networks	State/local agency sites
	National Weather Service (NWS)
	Remote Automated Weather Stations (RAWS)
	NWS Cooperative observers
	Department of Defense
	Climate data indicating max/min temperatures, precipitation (data archived)
	Gridded monthly precipitation for US

Table 1. Major data themes used in this study

Theme	Database
Air Emissions	WRAP 1996 point, mobile, area sources
	National Fire data 1970-2002 wildfire point locations
	USDA fire locations from MODIS satellite 2001-2003
	BLM fire locations for Alaska
	Carnegie Mellon ammonia inventory
	2000 street, airport and railroad centerlines from Census TIGER Line data
	Sources inferred from landuse/landcover data
	Vegetation from various agencies
Physical	USGS digital elevation data at 10m, 30m, 90m and 1 km resolutions
	USGS STATSGO soils
	Census Bureau water bodies, rivers, streams
	Vegetation from various agencies
	Satellite imagery (Landsat 5 imagery circa 1990 for all of US and recent MODIS for some areas)
Political	Census Bureau 2000 state, county, urban area, and zip codes boundaries
	Census Bureau 2000 census blocks and tract boundaries and demographic data converted to population density grids
	Land ownership of various state and federal agencies

4. DESCRIPTIVE DATA ANALYSIS

The purpose of the descriptive data analysis is to assist us in the general and detailed description of the meteorological setting of each site leading to the conceptual models of reduced visibility at all Class I areas in the WRAP and CENRAP regions. The analysis will also help us to understand the emission source-receptor relationships through spatial data analysis and data visualization. Sources are characterized by their locations, emitted pollutants, emission rates, and chemical compositions. Maps of major source areas (cities, highways, industrial point sources) in relation to IMPROVE measurements were produced to establish relationships between ambient concentrations and emissions. It is especially important to identify emissions that are likely to be channeled by surrounding terrain as well as those that can travel unimpeded by terrain obstacles. Maps of landuse and landcover were created to characterize the spatial nature of area sources that could potentially come from mines, rangeland, agriculture, forestry and barren land. Figure 2 shows an example of one such map for the Saguaro National Park in southern Arizona. For this study we obtained the National Land Cover Database from the USGS Seamless Data Distribution System, http://seamless.usgs.gov.

Multispectral satellite imagery serves as an import tool to identify natural dust sources such as playas that are common in some areas in the western U.S. Landsat mosaic imagery from NASA's

Earth Science Applications Directorate, https://zulu.ssc.nasa.gov/mrsid/, were obtained for the U.S. west of the Mississippi River. Because they include an infrared band, these images were also useful in clearly identifying cropland agricultural areas. Aerial photography also played an important role when identifying unpaved roads in the immediate area around the monitoring site. Images from the USGS National Aerial Photography Program (NAPP) were used in several instances to easily identify unpaved roads. However, much of the NAPP imagery has been collected several years ago and the roads may have been paved since the photos were acquired by the USGS. Since this project did not intend to build a detailed emission inventory of unpaved roads, but use existing databases, recent images were not collected.

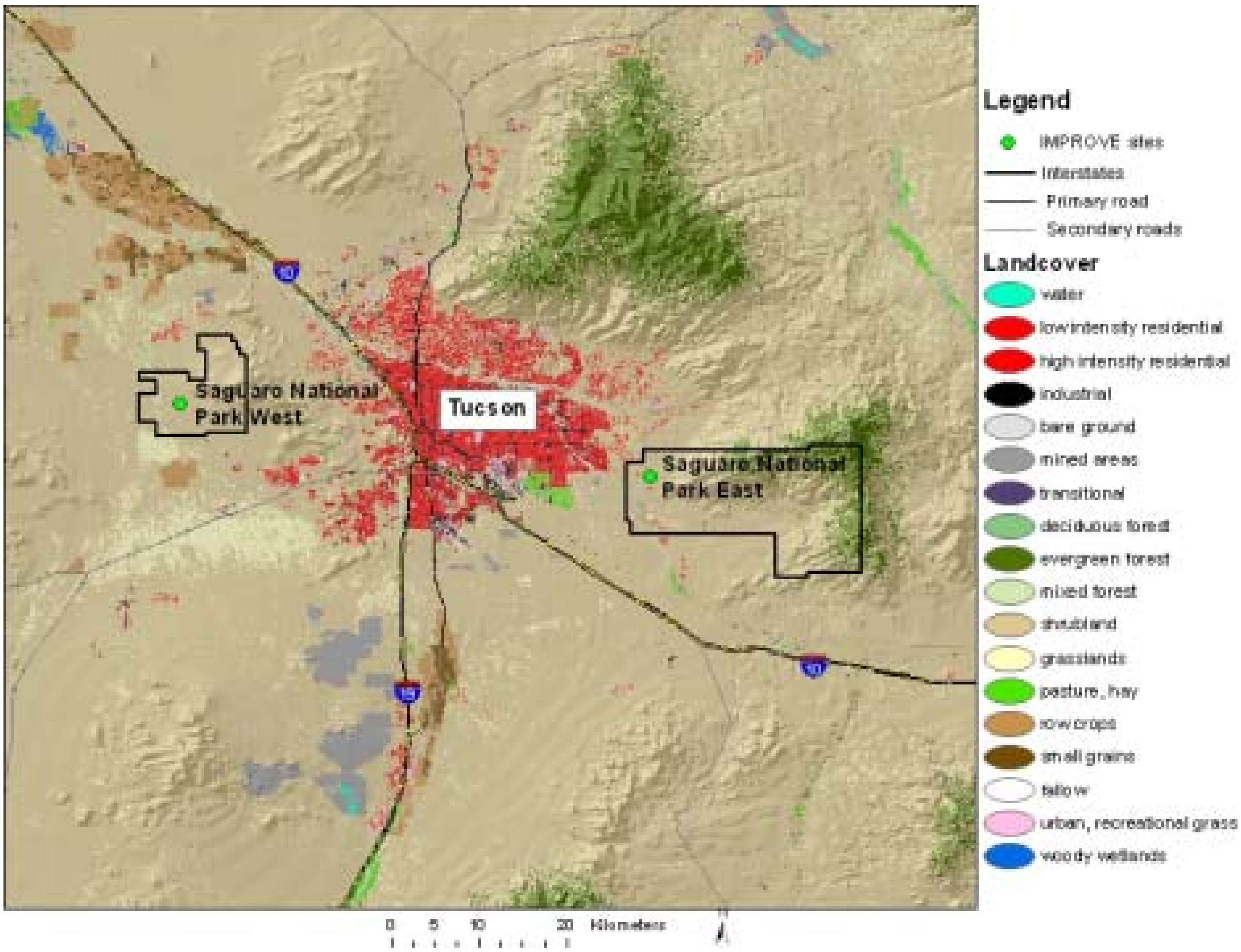

Figure 2 Example landuse map for Saguaro National Park based on the USGS National Land Cover Database and 30 meter National Elevation Database.

Depending upon the elevation of an IMPROVE site in relation to terrain features, the site may represent local to regional conditions. Terrain maps of each Class I area indicating the location of the IMPROVE sampler have been completed. These maps have been produced at two scales; one showing the terrain in the immediate area around the sampler and one to show the terrain of the entire Class I area. Low-elevation sites are susceptible to influence by local or drainage flows, which may be in an opposite direction from synoptic scale flow. This is most likely to be an important issue in winter, when mixing depths are low. Other sites may be elevated above low-level haze layers during stable atmospheric conditions. In summer, mixing generally smoothes out the vertical gradients, although vertical gradients may still be important, particularly at near-coastal areas where vertical mixing is inhibited by the presence of cool marine air below warmer, drier, air.

5. THE HAZAGON ANALYSIS

This project needed a method to study the temporal and spatial variations of light extinction from the nationwide network of IMPROVE aerosol monitors. While time series plots and static summary maps are useful for this analysis, they do not fully utilize the interpretation strengths that the human brain is capable of. While limiting ourselves by using ArcGIS, we created a simple method to animate maps over time while providing an easy to understand symbolization scheme. We wanted to visualize how several important chemical compounds affect the total light extinction. A symbol called “hazagon” was created to fill that purpose. Hazagon maps were created as a way to visualize each measurement in the network by determining how the extinction on that day ranks in comparison to all of the measurements over that year. For those measurements that fall within the 20 percent worst category (i.e. 80th and greater percentiles), a site is represented by a hexagon divided into six triangles. Each triangle represents the contribution of sulfate, nitrate, organic mass by carbon, light absorbing carbon, fine soil, and coarse mass to the total extinction as shown in Figure 3. If a particular component contributes more than 40 percent of the total extinction on that day, that triangle is filled in with black as shown in Figure 4. For components that contribute between 10 to 40 percent to the total extinction that triangle is filled in with grey.

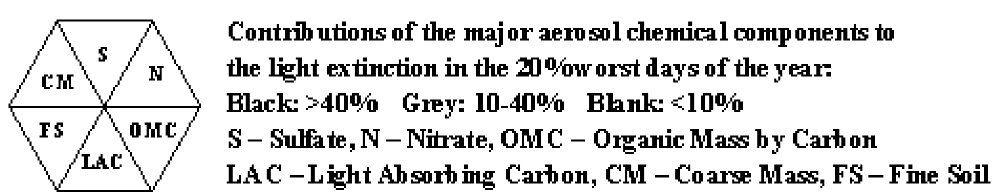

Figure 3. Hazagon legend showing how the hexagon symbol is partitioned to six individual sections corresponding to the major chemical components contributing to aerosol extinction.

For daily extinction categorized in the 0 to 80th percentile, the symbols are shown below in Figure 4. Missing data is represented by a white circle.

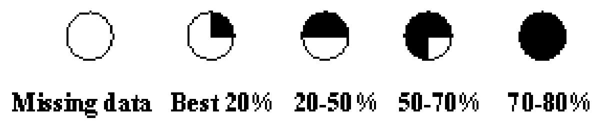

Figure 4. Symbols to show measurement ranks between the 0th to 80th percentile.

Animations of hazagon maps provide a convenient way to see both clean and haze episodes that vary over time and space. Each image of the animation were created using ArcGIS and converted to the GIF format. The AVI animations were created using JASC Animation Shop from these GIF images. Animations were also created for use on the website utilizing a simple Java script code. One advantage of the Java script version is that it allows a user to save individual images for their own use.

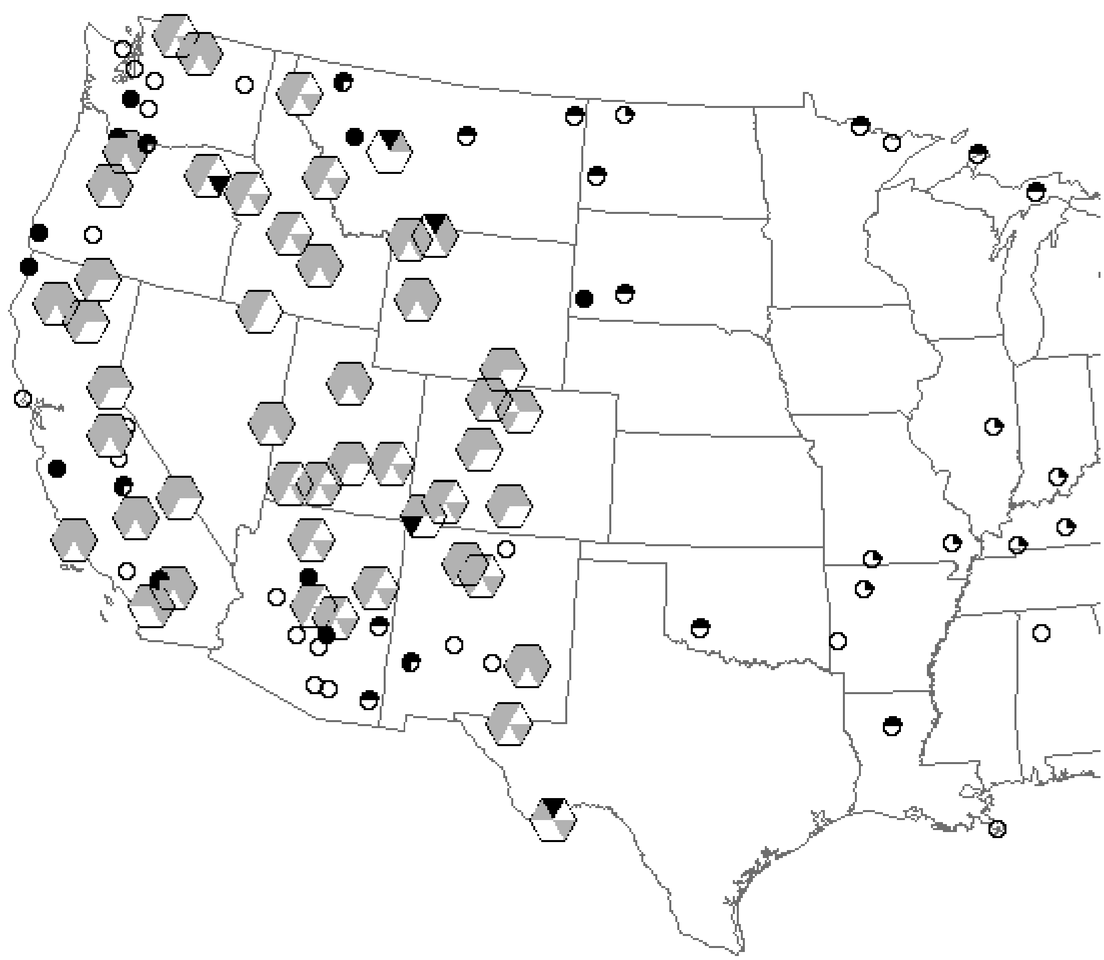

Figure 5. Example of a hazagon map for April 16, 2001

Figure 5 shows a portion of a hazagon map from an Asian dust episode in 2001. This map shows many sites in the west were characterized as having 20 percent worst day from that year. As this figure indicates, Asian dust may cause haze in a large area and last several days depending on the regional and local weather conditions in the United States. Usually soil particles with elemental composition (Al, Si, Ca, Fe) dominate the aerosol light extinction in the whole western United States during the Asian dust episode. In this case most of the extinction was not due to one single component but several to include sulfate, nitrate and organic carbon. The dust cloud may also move to the Eastern U.S. and influence some of the eastern sites, although the influence is usually much smaller in both spatial scale and loading. Most of the Asian dust episodes happen in the spring during the Month of March to May. Based on our preliminary analysis of IMPROVE measurements over the year 1997 to 2002, the predominant Asian dust episode occurs about 1-3 times per year, and its influence may last several days to about a week depending largely on the local and regional climate conditions.

6. TRAJECTORY MODELING

Trajectory or backtrajectory analyses use interpolated measured or modeled meteorological fields to estimate the most likely central path over geographical areas that provided air to a receptor at a given time. The method essentially reverses the wind field and moves a parcel of air backward in time. Backtrajectories are an oversimplification of the atmosphere in that dispersion is not accounted for and the potential source areas contributing to a receptor are underestimated for any given trajectory. Two of the most commonly used atmospheric Lagrangian trajectory models include HYSPLIT (Draxler and Hess, 1997) and FLEXPART (Stohl and Siebert, 2001). The commonly applied HYSPLIT model uses archived 3-dimensional meteorological fields generated from observations and short-term forecasts. HYSPLIT has five options for vertical transport; the default uses the average interpolated vertical velocity. The trajectory analysis in this project used the HYSPLIT model maintained by NOAA Air Resources Laboratory. Investigators often run HYSPLIT backtrajectories from multiple heights to capture the effects of vertical variation of horizontal winds within the mixed layer depth. The models produce a series of "endpoints" representing longitude, latitude, and elevation of the parcel at one-hour intervals.

For individual days, plots of the individual trajectories are informative. For periods of many days or years, or for certain conditions, such as best 20% visibility days, a graphical method of summarizing the data is best. Calculated trajectories can be used for several purposes. For a single event, the trajectory provides an approximate direction over which the air passed to arrive at a location. This is useful for examining episodes that correspond to a fire or dust storm. For many days grouped together, e.g. by good or poor visibility, trajectory origins and the areas they pass over are summarized in graphical isopleths.

Trajectories can also be used to classify receptor concentrations into transport sectors and difference in concentration can be examined as a function of sector. Year-to-year trends can be tracked for sector-averaged subsets, thereby decreasing the effects of inter-annual meteorological variability on the detection of trends. There are uncertainties in the windfields that drive trajectory models. Green et al. (2000) found large deviations between measured and Nested Grid Model (NGM)-modeled wind fields near the Pacific coast.

6.1. Trajectory Model Parameters

For the continental US, the National Oceanic and Atmospheric Administration's (NOAA) Air Resources Laboratory (ARL) Eta Data Assimilation System, NOAA (2004), meteorological data was used in the model. For Alaska and Hawaii, the hemispheric FNL data set was used. EDAS assimilates observed data into short-term Eta model calculations to obtain meteorological fields. The EDAS fields are archived at 80 km horizontal resolution. ARL archives the FNL meteorological field at 190 km resolution. In general, higher resolution fields are desirable in that flow features on smaller scale may be captured. However, all the meteorological fields mentioned above cannot capture local or mesoscale flows. Backtrajectories spanning the years 2000 through 2002 were computed for each IMPROVE monitoring site and Class I area. We have calculated backtrajectories for 186 sites in the US. Some of the model parameters are summarized in Table 2.

Table 2. HYSPLIT model parameters

Model Parameter	Value
Trajectory duration	8 days (192 hours) backward in time
Top of model domain	14,000 meters
Vertical motion option	Use model data
Receptor heights	10, 500 and 1500 meters above ground level

The HYSPLIT trajectory model version 4.6 was used to calculate backtrajectories from each site every 3 hours starting from 00:00 UTC. We generated backtrajectories at three starting heights: 10, 500 and 1500 meters above ground level. These starting heights were selected to characterize certain air mass pathways that might occur during all seasons. For example, in the summer, atmospheric pollutant are typically well mixed through a deep layer several kilometers due to heating of the surface. Input files to run the model were generated using a Visual Basic code written by Gebhart (2001a). The model was run in a batch mode using Windows Scripting Host with over a million separate trajectories. Processing for all sites took approximately 1 month of processing time with a Pentium 4, 2.4 GHz processor.

6.2. Trajectory Output Processing

To enable the backtrajectories to be used with other spatial data layers, a program referred to as Hysplit_ShapeMaker was developed in Visual Basic 6. The program converts raw data from the HYSPLIT model output files into point and polyline types of Shapefiles. The trajectory model outputs a longitude and latitude position as well as height above the ground for each hour backward in time from the release time. For each day, a maximum of 1536 trajectory points are generated by the model. The Hysplit_ShapeMaker code coverts each point into a shapefile record for use with post processing codes. The code also generates a polyline shapefile that appends each trajectory over the three year period to a single layer. This way individual trajectories can be queried in ArcGIS for use in episode analysis tasks.

6.3. Residence Time Maps

Residence time analysis computes the amount of time (e.g. hours) or percent of time the parcel is in a horizontal grid cell. In Figure 6, residence time is shown as percent of total hours in each grid cell. The domain of interest is divided into areas such as one-degree latitude by one-degree longitude cells. These data behind the maps were produced using AML codes in

Workstation ArcInfo 8.3. Map templates in ArcGIS were generated to mass produce these products. This data was contoured and plotted on a map using the Geostatistical Analyst extension. The map in Figure 6 is the raw grid before contouring. Geographic areas associated with bad and good visibility days can be determined by running trajectories and plotting residence times separately for these conditions. Figure 6 indicates that the worst extinction days associated with soil particles come from the southeast over the Gulf of Mexico. This reinforces the fact that Big Bend National Park can be influenced by dust coming from the Saharan Desert which traverses over the Gulf of Mexico before making landfall in Texas (Pitchford et al. 2004; Perry et al., 1997; Ashbaugh et al., 2001; Gebhart et al., 2001b).

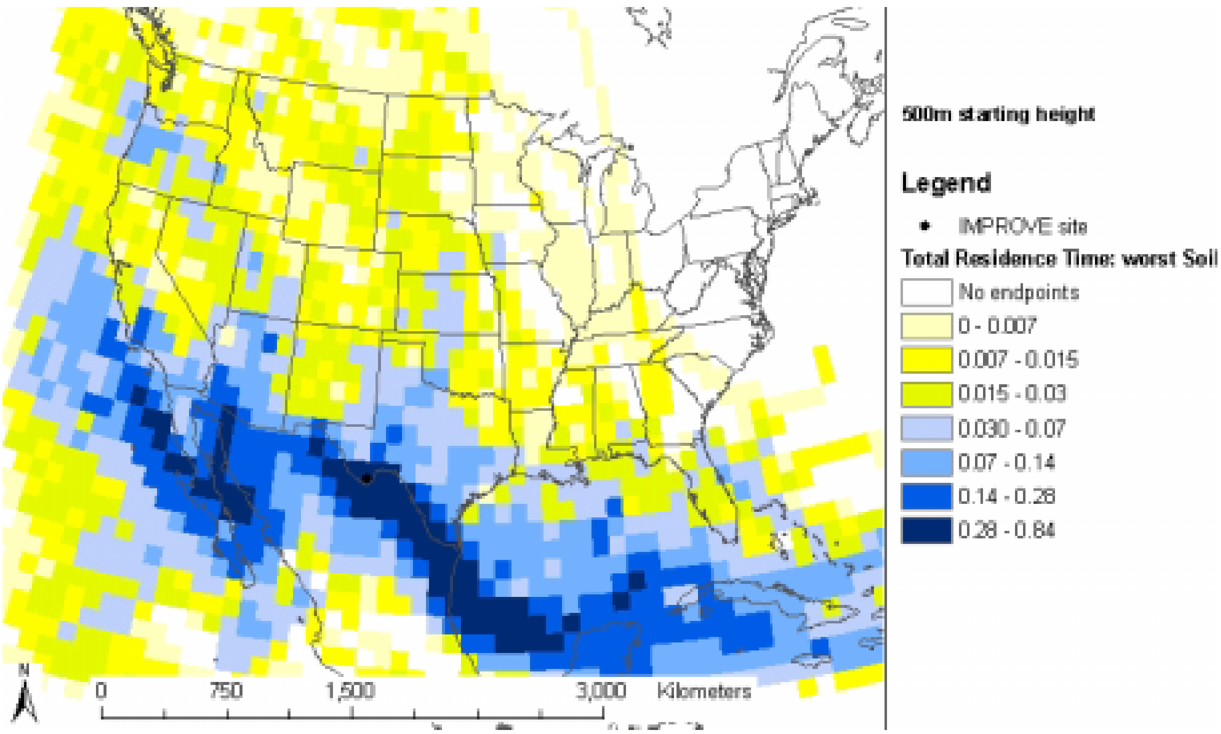

Figure 6. Residence time for fine soil at Big Bend National Park for 20% worst case.

6.4. Conditional Probability Maps

Conditional probability maps show the fraction of times a certain condition is met when a trajectory passes over a grid cell enroute to the receptor. A conditional probability map for 20% worst visibility days shows the likelihood of having 20% worst visibility occurring when air passed over each grid cell (The average would be 20%). Areas with high conditional probability indicate that when air passes over those grid cells, it is very likely to be associated with poor visibility at the receptor. It says nothing about the frequency of airflow from the grid cells - the residence time plots give that information. Figure 7 shows an example of a conditional probability map for the worst 20% days when sulfate was the major contributor at Big Bend National Park. This product alone indicates that trajectories from the eastern US are likely during the worst 20 percent days. In our opinion, making conclusions based on only one map is not sound particularly when there may not be a full three years of IMPROVE measurements to analyze.

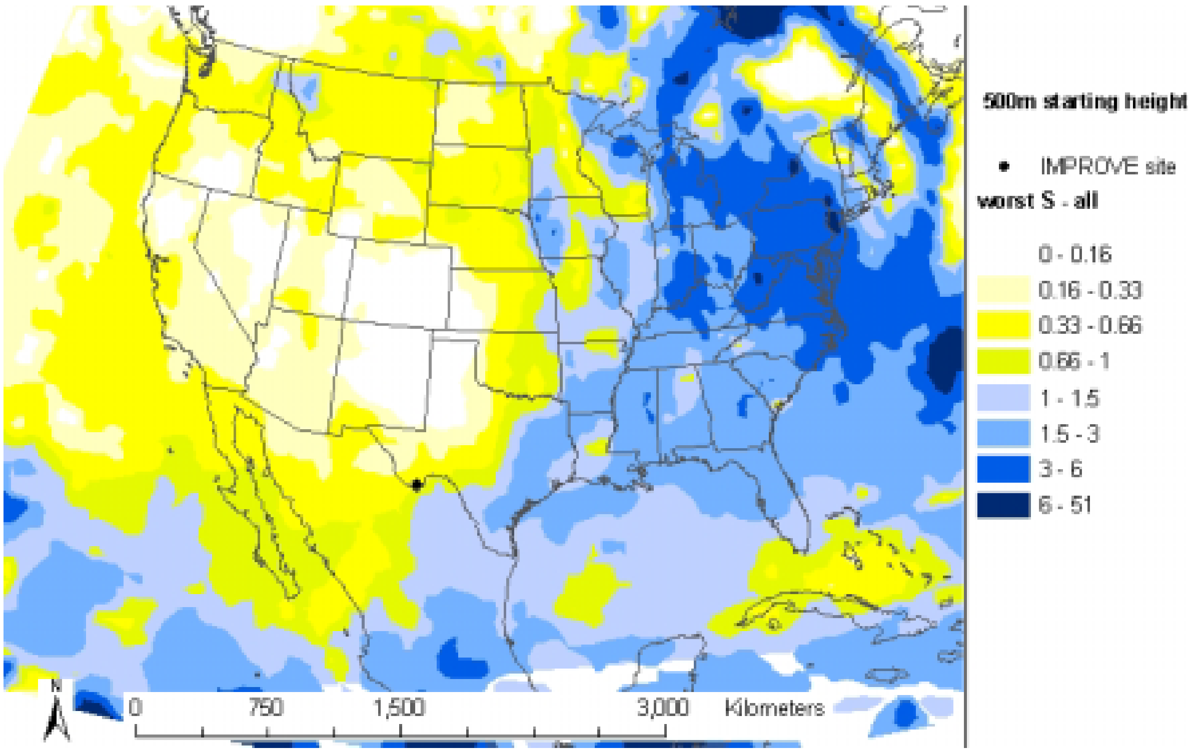

Figure 7. Sulfate conditional probability map for Big Bend National Park.

7. CONCEPTUAL MODEL DEVELOPMENT

A conceptual model describes the emissions and meteorological phenomena that cause excessive haze. It examines the weight of evidence from several assessment projects, including those undertaken as part of this study and those previously published. The conceptual model must support the IMPROVE measurement summaries such as shown in Figure 8 where it shows the average contributions of chemical components during the worst 20 percent days of total extinction. Several conceptual models have been found for different sub-regions within the WRAP and CENRAP jurisdiction. These may include transport from urban or industrial source areas, aging and transformation of primary emissions in foggy valleys with subsequent mixing of secondary aerosol aloft for transport, major dust storms and fires, superposition of local emissions on a regional background, carry back of previously emitted pollutants by upslope and downslope flows, and a large number of other possibilities. Several of the episode studies examined in the initial part of the project have created conceptual models for various sub-regions and these have served as a starting point for integrating and reconciling the results of this assessment.

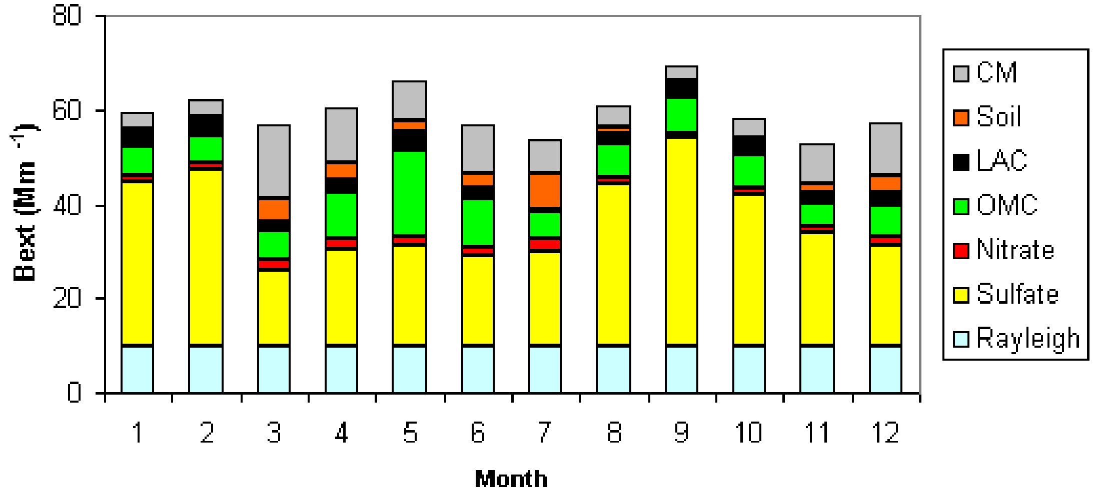

Figure 8. Average contributions of major aerosol chemical components to light extinction during 20 percent worst days in each month at Big Bend National Park (Based on data available in 1997-2002). CM is coarse mass, Soil is fine soil, LAC is light absorbing carbon, OMC is organic mass by carbon, and Rayleigh is the contribution from the clean gaseous atmosphere.

8. VIRTUAL REPORT

Results of this project are assembled in a virtual report on the Causes of Haze website, http://coha.dri.edu. Figure 9 shows the front page of the draft web site. Reports for each site can be accessed through several thematic hyperlinks. The COHA website serves as a platform to integrate and present results in concise and understandable language that can be used to support regional evaluations of and justification for actions that improve western visibility. The website allows access to the virtual reports using multiple pathways. Users can simply select a site of interest using a map or from a list of sites. Other methods of accessing the reports are thematically based on regions, similarities in aerosol composition or meteorology. From various hyperlinks, a user can view descriptive analysis discussions on aerosol composition, the emissions surrounding each site, the physical terrain, and meteorological conditions. Other specific products of this project are have been used to help determine what is causing haze are air mass trajectory maps, maps of emission sources that include point, area, mobile and biogenics, terrain and landuse maps, satellite images, and maps showing locations of urban areas.

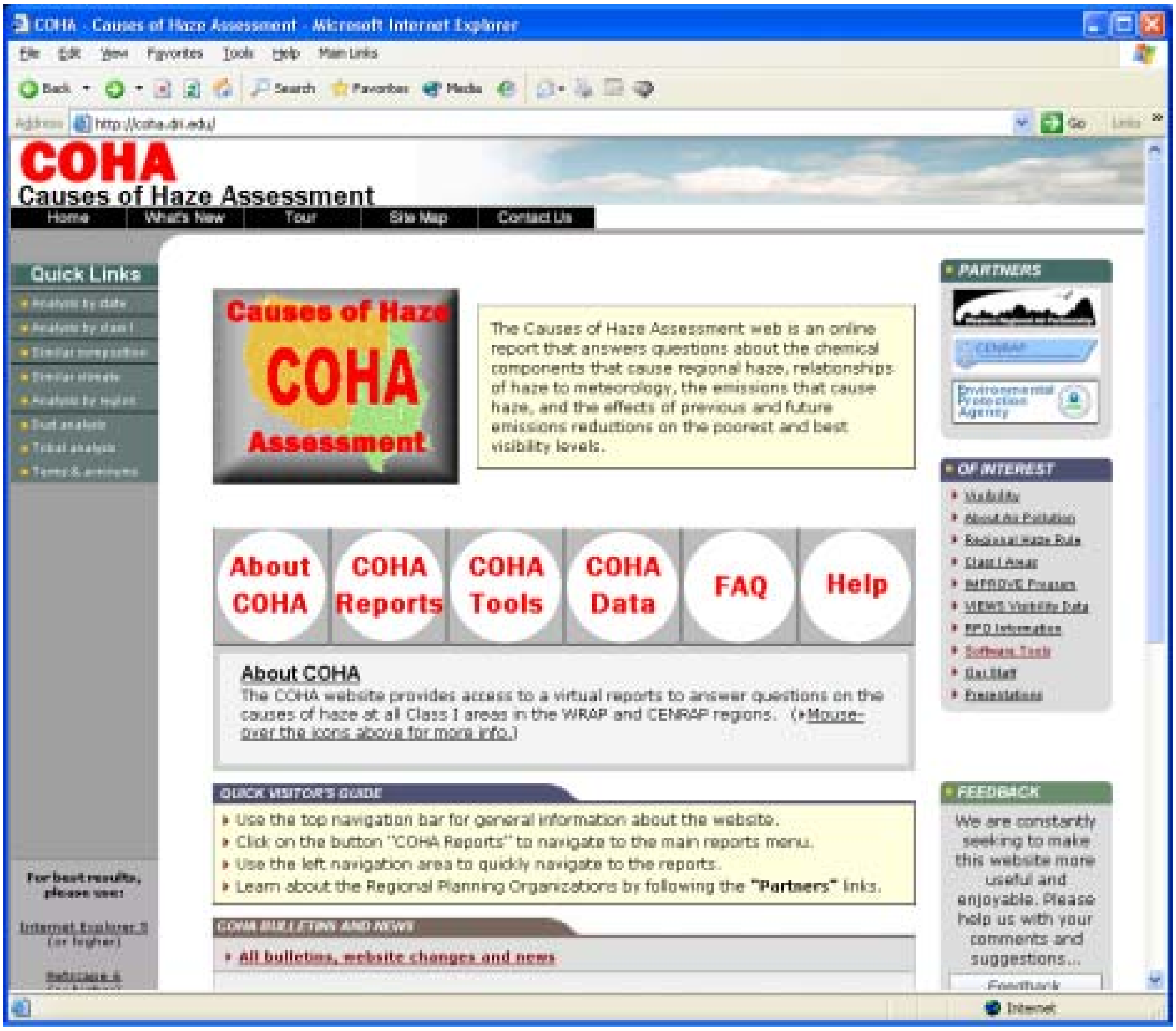

Figure 9. Opening page on the Causes of Haze website

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