Columbia River Gorge Air Quality Study

Science Summary Report

Columbia River Gorge National Scenic Area

FINAL REPORT

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Contributing Authors

Marc L. Pitchford	National Oceanic and Atmospheric Administration, Las Vegas, NV
Mark C. Green	Desert Research Institute, Reno, NV
Ralph Morris	ENVIRON International, Novato, CA
Chris Emery	ENVIRON International, Novato, CA
Rachel Sakata	Oregon Department of Environmental Quality, Portland, OR
Christopher Swab	Oregon Department of Environmental Quality, Portland, OR
Paul T. Mairose	Southwest Clean Air Agency, Vancouver, WA

FOREWORD

This report summarizes the results of six years of planning, ambient monitoring and visibility assessment activities to understand and characterize visibility conditions and the causes of visibility impairment in the Columbia River Gorge National Scenic Area. This study was prompted by an amendment to the Gorge National Scenic Area Management Plan in 2000, which stated:

> *Air quality shall be protected and enhanced, consistent with the purposes of the Scenic Area Act. The States of Oregon and Washington shall: (1) continue to monitor air pollution and visibility levels in the Gorge; (2) conduct an analysis of monitoring and emissions data to identify all sources, both inside and outside the Scenic Area that significantly contribute to air pollution. Based on this analysis, the States shall develop and implement a regional air quality strategy to carry out the purposes of the Scenic Area Act, with the U.S. Forest Service, the Southwest Air Pollution Control Authority [now the Southwest Clean Air Agency] and in consultation with affected stakeholders. ...*

The U.S. Forest Service has been primarily responsible for monitoring "*air pollution and visibility levels in the Gorge*" by providing and supporting the IMPROVE monitors, meteorology stations and nephelometers at Wishram and Mt. Zion. The states of Oregon and Washington have provided several additional monitoring locations for the purpose of this study program.

The studies summarized in this report were undertaken to accomplish the second part of the above charge – "*conduct an analysis of monitoring and emissions data to identify all sources, both inside and outside the Scenic Area that significantly contribute to air pollution.*" Funding for these studies was provided by the States of Washington and Oregon and by the Environmental Protection Agency through Congressional funding. Much of this work would not have been possible without the Congressional funding. Staff from several agencies, universities, consultants, industrial facilities, and environmental groups participated in making this project successful.

This project is not concluded with issuance of this report. Rather, this scientific report and the underlying detailed technical reports will serve for many years to form the basis on which future policy decisions can be made. While we now have a sound preliminary understanding of visibility within the Gorge, much remains to be understood about the extent of the impairment and how it relates to the entire Gorge ecosystem. Finally, this scientific information will be used to *develop and implement a regional air quality strategy to carry out the purposes of the Scenic Area Act.*

Table of Contents

Executive Summary

a) Introduction

In order to implement the May 2000 Gorge National Scenic Area Management Plan amendment, plans were made to conduct technical assessment activities designed to answer a series of questions concerning the nature and causes of haze in the Gorge. These activities included collection and analysis of additional monitoring data, development of an emissions inventory for the region, and application of regional meteorological and air quality modeling of two typical multi-day Gorge haze episodes during 2004 (see Table ES-1). Separate reports were prepared for these activities. The purpose of this Science Summary Report is to combine the information from these reports with other available information to address the questions concerning haze in the Gorge. The body of the report summarizes the technical information from the various studies organized by activity. This Executive Summary was written for non-scientists so it includes a brief overview of haze science. The purpose of the Executive Summary is to provide an overview of our current understanding of haze in the Gorge.

Table ES-1. Columbia River Gorge Study Activity Summary Table.

Activity	Description	Organization (Completed)
Haze Gradient Study	a) Haze monitoring (nephelometers and meteorology) at 9 sites in the Gorge from July, 2003 to Feb, 2005 b) Data analysis and reporting	a) Southwest Clean Air Agency & Oregon Department of Environmental Quality b) Desert Research Institute (January 2006)
Causes of Haze in the Gorge (CoHaGo)	a) Gaseous pollutants and particulate matter monitoring at 3 sites in the Gorge from November 2003 to February 2005 b) Data analysis and reporting	a) Southwest Clean Air Agency & Oregon Department of Environmental Quality / UC Davis b) Desert Research Institute (July 2006)
Emission Inventory	a) Development of point and area source emissions and input parameters for mobile, non-road and biogenic emissions for 2004 b) Compilation of mobile, non-road and biogenic emissions for 2004 for model input c) Outyear emission inventory development for 2018 Point and Area Sources d) Outyear emission inventory development for 2018 Mobile Soures e) Data analysis and reporting	a) Southwest Clean Air Agency & Oregon Department of Environmental Quality b) ENVIRON & Alpine Geophysics c) Eastern Research Group under contract to Western Regional Air Partnership (January 2006) d) ENVIRON under contract to Western Regional Air Partnership (May 2006) e) Oregon Department of Environmental Quality (September 2007)
Meteorological & Air Quality Modeling	a) Meteorological modeling (MM5) b) Emissions modeling and processing (SMOKE) c) Photochemical and dispersion modeling (CAMx) d) Modeling report	ENVIRON & Alpine Geophysics (August 2007)

To put haze in the Gorge into perspective, Gorge haze levels are not as great as in the Eastern U.S., but are among the highest in the West. Wishram (east Gorge) and Mt. Zion (west

Gorge) have the highest and third highest measured haze at remote area monitoring sites in the Western U.S. This is caused largely by winter stagnations that trap pollutants and fog that make the Columbia River Basin particularly productive in the generation of secondary PM from gaseous precursors. Haze in many urban settings can be much worse than the remote locations shown in Figure ES-1. Monitoring locations are represented by dots in Figure ES-1 below and generally do not include the urban locations.
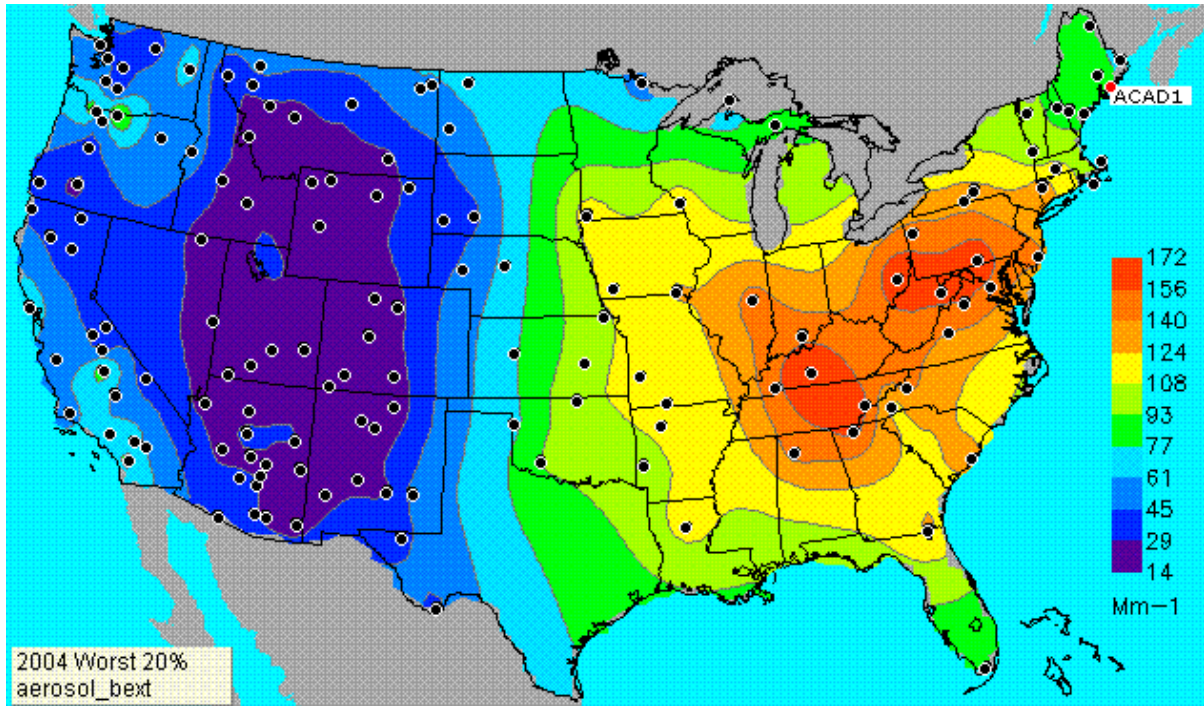
Figure ES-1. Spatial and Seasonal Pattern Map from the VIEWS Website. This data represents the 20% Worst Days for 2004 as represented by aerosol_bext. The underlying data is gathered from IMPROVE monitors and reported through the VIEWS website at the following web address:
http://vista.cira.colostate.edu/views/Web/AnnualSummary/ContourMaps.aspx

b) Haze Science Fundamentals

Haze is the obscuration of a scene caused by air pollution. There are a number of metrics used to quantify haze including visual range, light extinction, and the deciview perceptual haze metric. Each is related to the other by simple equations; however for the purposes of this document light extinction will be used. Light extinction is the fraction of light that is scattered and absorbed by the atmosphere per unit of distance, and is measured in units of inverse megameters (i.e. 1/1million meters, written Mm^{-1}). Haze increases as light extinction increases. Gases in a clean atmosphere (e.g. nitrogen and oxygen) contribute to light extinction ($8 \ Mm^{-1}$ to $12 \ Mm^{-1}$ depending on elevation), which is the reason that your vision is limited even when there is no air pollution. Except as otherwise noted, this report will exclude this clean air contribution to haze, so we can focus on pollution contributions to haze.

The air pollutants responsible for haze are particulate matter (PM). Gaseous pollutant (e.g. ozone or carbon monoxide) do not contribute significantly to visible haze, though some gaseous precursor pollutants (e.g. sulfur dioxide, nitrogen oxides, ammonia, and some organic compounds) can be converted to PM in the atmosphere by chemical and physical processes. PM released directly into the atmosphere is referred to as "primary", while PM chemically formed in the atmosphere from precursor gases is referred to as "secondary". The fraction of the emitted precursor gases that form secondary particles and the rate at which the gases are transformed vary considerably depending on conditions in the atmosphere (e.g. sunlight, temperature, humidity and the presence of other gases, etc.). The rate of transformation is generally much greater if the gases are dissolved in fog or cloud drops. While an unpolluted fog evaporates completely and leaves a clear atmosphere when relative humidity drops below 100%, a haze composed of secondary PM in small water solution droplets can persist at relative humidity levels well below 100%.

This report includes a summary of emissions rates and ambient concentrations by their various compositional components. Knowledge of the emission rates for the primary PM and precursor gases can not be used in any simple way to gain insight into the ambient concentrations of the PM components. Emissions are transported, diluted, chemically transformed in varying degrees, and removed from the atmosphere depending on meteorological conditions. Air quality models are employed to simulate all of these complex interactions so we can make the connection between emissions and air quality.

Particle size and composition are important characteristics of PM with respect to how much haze a given PM mixture produces at any concentration level. Small particles (also referred to as fine particles or $PM_{2.5}$, which refers to particles with diameters less than 2.5 microns[1]) have a greater contribution to haze than the same mass concentration of larger particles (also referred to as coarse particles or $PM_{10-2.5}$). Some particles, such as those containing sulfate, nitrate and other inorganic salts can absorb water and swell in size as relative humidity increases; this increases their efficiency at scattering light, causing more haze than they would at lower humidity. The amount of haze caused by particles, referred to as particle light extinction, is estimated by multiplying the concentration of each particle species by a light extinction efficiency value for that species. The light extinction efficiency values range from 0.6 m^2/g to 10 m^2/g depending on the chemical species. For those species that swell in size as humidity increases an additional multiplying term is applied that ranges from 1 for low humidity conditions to values greater than 10 near 100% relative humidity. This approach to estimating light extinction permits both the total and the individual species components of haze to be estimated from measured or modeled particulate species concentrations.

The major particle species found in the atmosphere include ammonium sulfate, ammonium nitrate, organic compounds, elemental carbon (soot), fine soil and coarse PM mass. The sulfate and nitrate particles are both secondary PM species formed from sulfur dioxide and nitrogen oxides that are emitted by a wide variety of sources like industrial processes (e.g.

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[1] A micron is a millionth of a meter in length. Typical human hair is about 90 microns in diameter.

fossil fuel power plant, manufacturing and processing facilities), by transportation sources (e.g. automobiles, trucks, trains, ships and aircraft), by urban/commercial/residential sources, and by natural sources including wildfires and volcanoes. While some of the ammonia required for these particle species originates from natural sources, much of it comes from animal agricultural and fertilizer use. Primary organic and elemental carbon species result from incomplete combustion of carbon based fuels, including gasoline and diesel engines, residential heating by wood burning and biomass burning, with wildfire being an especially large source during the dry summer and fall seasons. Secondary organic PM is chemically produced in the atmosphere from specific types of organic precursor gases. Most of the gases are emitted from natural vegetation (especially pine and oak forests) and much less from man-made sources (industrial, commercial, residential, transportation). Dust in the form of both coarse and fine PM is generated by wind erosion of dry exposed low vegetation soil surfaces and by mechanical suspension of crustal components (e.g. construction, driving on unpaved roads, agriculture).

c) Summation

Figure ES-2 below shows the regional air quality model 4-km grid domain and sub regions that are referred to in the discussions that follow. Influence from sources outside this domain are also accounted for by the modeling and sometimes referred to as distant source impacts, or when flow is from the west, as beyond the U.S.
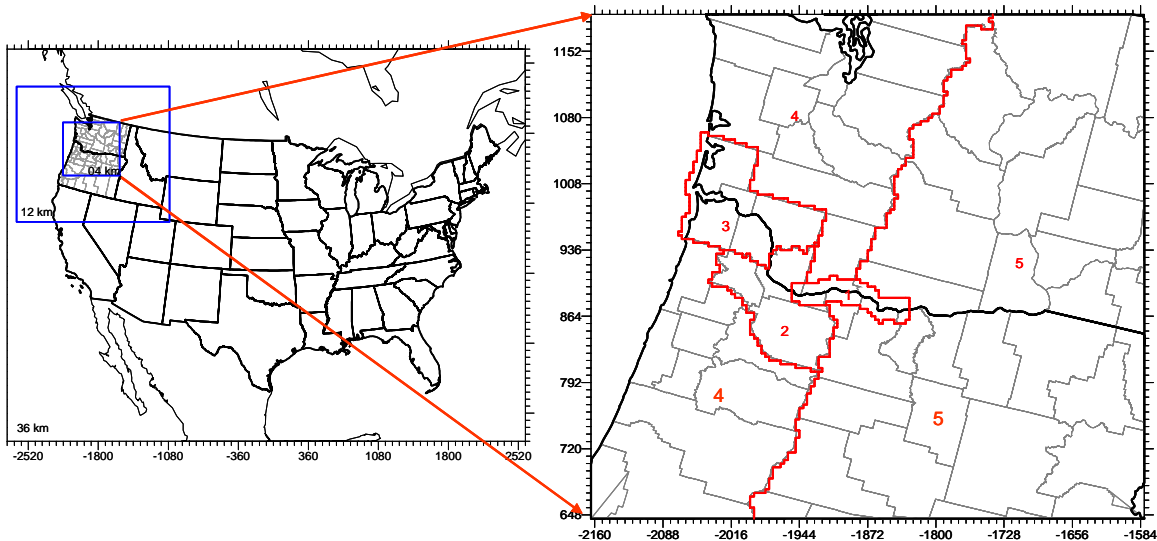
Figure ES-2. Breakdown of the 4-km modeling grid into 5 source regions for use in the CAMx PSAT application. A sixth region was defined for all areas outside the 4-km grid. Regions are referred to as (1) in-Gorge, (2) Portland/Vancouver metropolitan area, (3) northwest of Gorge, (4) west of Gorge, and (5) east of Gorge.

The causes of haze episodes in the Columbia River Gorge are quite different in the summer compared to the winter. In the summer winds flow predominately from the west, transporting emissions from the Portland metropolitan area into the Gorge, as well as those from beyond the U.S. (i.e. outside of the modeling domain) and in the domain to the Northwest of the Gorge. These three major contributing source regions are jointly

responsible for just over half of the haze at the western end of the Gorge during the August 2004 modeled haze episode. Another significant contributor, responsible for about 33% of the haze in Gorge during the August episode, is secondary organic PM formed principally from biogenic emissions (principally trees) from all source regions. At the eastern end of the Gorge in summer, emissions from beyond the U.S. continue to be significant, but the contribution to haze by emissions from Portland and Northwest of the Gorge are considerably reduced by dilution during transport. During the specific August 2004 episode modeled in this study, wildfires east of the Gorge contributed substantially at the eastern end of the Gorge (~20%) and to a lesser extent at the western end of the Gorge (~4%). More generally during the summer and fall, wildfires throughout the region have the ability to significantly contribute and even to dominate Gorge haze when their smoke is transported into the Gorge. Emissions from within the Gorge contribute modestly to haze at both ends of the Gorge during the summer (~6% and ~9% at the east and west ends of the Gorge respectively during the August 2004 episode).

The situation is considerably different in the winter (i.e. November through February), when atmospheric and vegetation moisture levels are higher so that hazes caused by wildfires are not an issue. Colder temperatures reduce the emissions and transformation of biogenic volatile organic precursor gases responsible for much of the secondary organic PM making them somewhat less important. Winter stagnation and the fog common in the Columbia River Basin (from eastern Washington and Oregon to the Pacific Ocean) are responsible for the rapid conversion of precursor gases (sulfur dioxide, nitrogen oxide and ammonia) emitted by numerous sources throughout the region. When the fog droplets evaporate they leave high concentrations of nitrate and sulfate PM, which are principally responsible for making the intense winter hazes in the Gorge. At the western end of the Gorge during the modeled November episode, emissions from Portland are the largest contributor to haze (~28%), followed by those from outside of the modeling domain (~19%). Emissions from within the Gorge and east of the Gorge each contribute about 13% to the haze at the western end of the Gorge. The haze contributions at the western end of the Gorge are primarily in the form of sulfate and nitrate PM (~75%), but include a significant fraction of primary organic and elemental carbon PM (~9%) from sources such as residential wood smoke, and vehicular sources in the Portland and in-Gorge regions. Precursor gaseous emissions from the region east of the Gorge are responsible for the majority of the haze (~57%) during the winter at the east end of the Gorge. About half of this is from the electric utilities east of the Gorge, with the remainder coming from vehicular emissions. Emissions from outside of the modeling domain (~23%) and within the Gorge (~10%) are responsible for most of the remaining haze during the November modeled episode.

The contributions to haze in the Gorge from man-made emissions are likely to decrease modestly by 2018 in spite of population growth, but the decreases in haze levels may not be noticeable, especially during the summer. The large contributions to summer haze episodes by fire and secondary organic PM from biogenic sources, plus the contributions by distant sources places a significant restriction on the maximum amount of haze reduction possible during summer episodes. The greatest opportunity for improvement in haze levels in the Gorge is during winter haze episodes, when man-made emissions from sources within the region are responsible for well over half of the impairment. However, the emissions

responsible for the winter haze in the Gorge are from numerous emissions sources throughout the region so there is no single action that will make a dramatic difference to the haze levels.

d) Questions and Responses

The first four questions below were included in Haze Study planning documents in 2001, while the last two were written during the preparation of the Science Summary Report. Sub-questions were included in the planning documents in each section to ensure that the main question was fully answered. The sub-questions in each section are not individually answered in this Science Summary document but are answered as part of the complete answer for each section.

Table ES-2. Columbia River Gorge Haze Study Questions.

1) What aerosol components are responsible for haze?
a. What are the major components for best, worst, and average days and how do they compare? b. How variable are they episodically, seasonally, inter-annually, spatially? c. How do the relative concentrations of the major components compare with the relative emission rates nearby and regionally?
2) What is meteorology's role in the causes of haze?
a. How do meteorological conditions differ for best, worst and typical haze conditions? b. What empirical relationships are there between meteorological conditions and haziness? c. How does the spatial difference in meteorology and climate between west and east Scenic Area account for the haze differences observed between west and east Scenic Area? d. How well can haze conditions be predicted solely using meteorological factors? e. How well can inter-annual variations in haze be accounted for by variations in meteorological conditions?
3) What are the emission sources responsible for haze?
a. What geographic areas are associated with transported air that arrives at sites on best, typical and worst haze days? b. Are the emission characteristics of the transport areas consistent with the aerosol components responsible for haze? c. What do the aerosol characteristics on best, typical and worst days indicate about the sources? d. What does the spatial and temporal pattern analysis indicate about the locations and time periods associated with sources responsible for haze? e. What evidence is there for urban impacts on haze and what is the magnitude and frequency when evident? f. What connections can be made between sample periods with unusual species concentrations and activity of highly sporadic sources (e.g., major fires and dust storms, point source activity changes such as aluminum plant shut-downs, etc.)? g. What can be inferred about impacts from sources in other regions?
4) Are there detectable and/or statistically significant multi-year trends in the causes of haze?
a. Are the aerosol components responsible for haze changing? b. Where changes are seen, are they the result of meteorological or emissions changes? c. Where emissions are known to have changed, are there corresponding changes in haze levels? (e.g., aluminum plant shutdowns or emission controls on the Centralia power plant)?
5) How much of the haze in the Gorge is beyond reasonable regional control?
a) How would visibility in the Gorge be different if we had only natural impacts? b) What contributions do sources outside of OR/WA play in the Gorge haze?

6) How will the haze change in the Gorge for 2018?
a) Will the source contributions be substantially different from 2004 in 2018?
b) Will the pollutant mix be substantially different or will other pollutants become the significant
    contributors in 2018 as compared to 2004?
c) What are the anticipated contributions to haze from sources outside of OR/WA in 2018?

1) What aerosol components are responsible for haze?

PM composition data from monitoring sites in the Gorge, in particular the two long-term
monitoring sites at Mt. Zion and Wishram, provide the data used to respond to this question
(see Table ES-1). To show the differences between the haze in the Gorge and the regional
haze measured at higher elevations, data from the Mt. Hood long-term monitoring site,
located about ~45 km south of the Columbia River, but at higher elevation (1531 m), is also
displayed in Table ES-1.

Table ES-1. Average light extinction (Mm^{-1}) data for all days, and for best and worst 20% days each year for
2002 through 2004 at Mt. Zion and Mt. Hood, and 2003 – 2004 at Wishram.

Light Extinction (Mm-1)	Nitrate	Sulfate	Elemental Carbon	Organic Mass	Fine Soil	Coarse Mass	Sea Salt	Total
Mt. Zion								
All Days	12.1	13.4	3.3	10.9	0.4	3.2	1.3	44.5
Best Days	2.6	4.1	1.5	3.3	0.1	0.9	1.1	13.7
Worst Days	33.6	25.2	5.9	25.3	0.6	4.1	0.9	95.6
Wishram								
All Days	15.5	11.5	3.4	10.3	0.7	3.8	0.9	46.1
Best Days	2.3	3.6	1.5	2.7	0.2	2.0	0.8	13.1
Worst Days	57.0	22.3	5.9	20.4	0.7	3.7	0.4	110.4
Mt. Hood								
All Days	2.4	5.3	1.2	5.1	0.2	0.9	0.4	15.5
Best Days	0.3	1.0	0.2	0.2	0.0	0.1	0.3	2.1
Worst Days	5.9	11.2	3.1	16.8	0.5	2.5	0.1	40.2

Haze levels at both in-Gorge sites are dominated by nitrate, sulfate and organic species on
average and for the worst days, with each contributing from ~20% to ~50% of the total
particulate light extinction. Of these, nitrate is the greatest contributor on worst haze days
with ~35% at Mt. Zion and ~50% at Wishram. Nitrate has a smaller relative contribution to
haze, ~15% at the higher elevation Mt. Hood site.

Some species have an east – west concentration gradient in the Gorge. Nitrate and the
components of dust (i.e. coarse mass and fine soil) concentrations are higher in the east
(Wishram), while sulfate and sea salt concentrations are higher in the west (Mt. Zion).
Average concentrations of the carbonaceous components (i.e. elemental carbon and organic

mass) are nearly the same at both in-Gorge sites. Average concentrations for Mt. Hood are consistently smaller than the corresponding in-Gorge average concentrations.

At both Wishram and Mt. Zion nitrate is the largest contributor to particulate light extinction in the colder months of the first and fourth calendar quarters, and sulfate is the largest contributor in the second and third quarters, each with a contribution of ~35-40%. Similar PM mixtures are found at Mt. Zion and Wishram except that there are more dusts (coarse mass and fine soil) at Wishram, especially during the second and third quarter of the year. During typical summertime episodes organic compounds and sulfate contribute most to haze. During typical winter episodes nitrate, sulfate, and organics all contribute significantly to haze.

For inter-annual comparisons, long-term PM data are only available for the Wishram monitoring site. Wishram has seen a statistically significant decrease in sulfate concentrations during 1994-2004. Total haze levels at Wishram have no significant trend. Thus, while the sulfate fraction of the haze has been reduced, nitrate has increased but that change is not statistically significant.

2) What is meteorology's role in the causes of haze?

Meteorology influences Gorge haze in a number of ways. Wind transports pollutants from emission sources; turbulence mixes pollutants from multiple sources promoting chemical transformations and dilutes the pollutants by mixing them with cleaner air. Temperature, humidity, amount of sunlight (related to cloud cover and time of day) and the presence of fog or low clouds affect the rate of transformation of gases to secondary PM. Finally, precipitation is an important mechanism to remove air pollutants and is often responsible for pollutant concentration gradients.

Five basic wind patterns were identified for the Gorge: strong westerly, moderate westerly, light westerly, light easterly and winter easterly. Winter easterly is termed as such because it occurred only in the months from October through April, never in summer. Winter easterly was the most common winter pattern and strong westerly was the most common summer pattern. Average haze levels for each pattern are shown in Figure ES-2. The following summarizes the relationship between haze and meteorological pattern:

a) For all sites except Steigerwald, winter easterly flow is associated with the highest average haze (b_{sp}) of the five patterns. For all sites, strong westerly flow is associated with the lowest average haze. Thus, the most typical summer pattern and most typical winter pattern have the lowest and highest haze, respectively for nearly all sites.

b) The eastern sites (from Memaloose east) have much larger variations in average haze levels between wind patterns than do the other more westerly sites (Steigerwald, Mt. Zion, Strunk, and Bonneville).

c) For the four eastern gorge sites, average haze is inversely proportional to the westerly flow component.
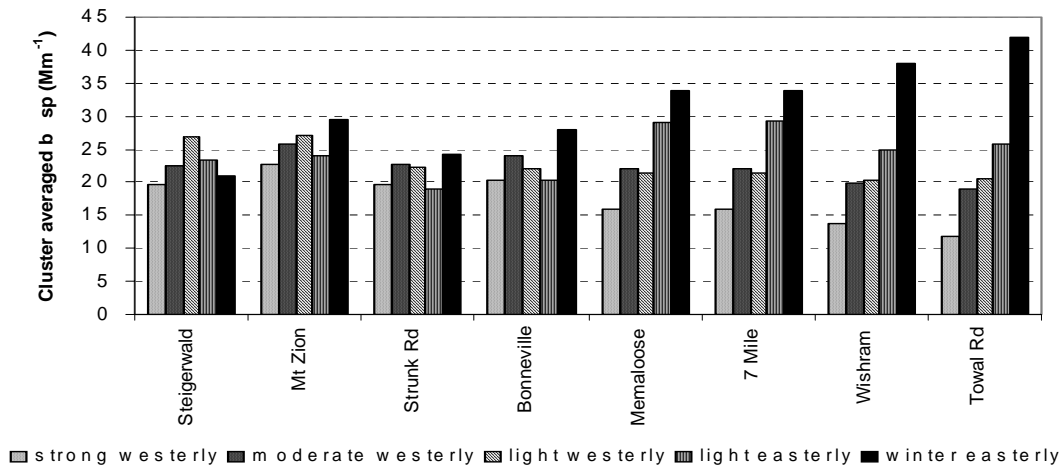
Figure ES-2. Average haze levels (particle light extinction) at the eight Gorge monitoring sites (arranged from west to east) for each wind pattern.

During summer the eastern Gorge has lower haze levels than the western Gorge due to higher rates of dispersion of haze causing particles. Because of the hotter, drier summer conditions in the eastern Gorge compared to the western Gorge, the atmosphere is mixed vertically deeper allowing for more dispersal of haze causing particles. The low humidity during the summer reduces light extinction efficiency for sulfate and nitrate. Also, the wind speeds tend to increase from the western to eastern Gorge in summer causing additional dispersion. The western Gorge sites also are more affected by haze causing pollutants emitted in the Portland/Vancouver urban area than the more easterly sites.

In winter conditions with easterly winds, haze levels are typically worse in the eastern Gorge than the western Gorge. During these conditions the eastern gorge typically has light winds whereas the western Gorge typically has stronger winds, which again allow for more dispersion of haze particles. The eastern Gorge and Columbia River Basin often experience extensive and persistent fog during winter, which may be responsible for much faster generation and greater concentrations of secondary PM, especially ammonium nitrate and ammonium sulfate. Sources thought to be responsible for the worst wintertime haze in the Gorge are closer to the eastern Gorge than the western Gorge and thus have more impact there.

The regional modeling results for the two episodes examined (August and November 2004) also support the conclusions presented above that the meteorological and climatological differences between the western and eastern ends of the Gorge contribute to the observed difference in visibility. The meteorological differences that were identified include major gradients in temperature, humidity, turbulent mixing rates and precipitation. The importance of fog in the chemistry for the November episode was demonstrated by the air quality modeling where nitrate levels were significantly underestimated in preliminary model results, but were subsequently improved by making adjustments that added fog to the modeled conditions for the eastern Columbia River Basin for periods when it was observed.

3) What are the emission sources responsible for haze?

This question can be best addressed individually for the two episodes that were modeled. The major haze components during the summer episode (August, 2004) included smoke from wildfires and secondary organic PM from biogenic (vegetative) sources. Primary inert PM from dust sources and motor vehicle combustion sources in the Gorge and from Portland (i.e., elemental and organic carbonaceous material) were also rather large contributors. Secondary PM such as sulfate and nitrate were relatively low. Ammonium sulfate typically existed at low to moderate concentrations. Ammonium nitrate was usually very low or zero in the summer due to the fact that it is it does not form in warm, dry conditions.

The majority of haze during the winter episode (November, 2004) was comprised of secondary PM salts, including both sulfate and nitrate, both of which preferentially form in the fog associated with cool humid climates. Carbonaceous PM also comprised a large fraction of wintertime haze, mostly from residential wood smoke. Very little secondary organics were attributed to anthropogenic sources, although biogenic source continued to contribute even in this late season given the abundance of evergreen forests. Primary PM from dust sources was mostly squelched due to wet surface from precipitation.

On the episodic scale, there can be dramatic hourly and day-to-day variations in haze levels and in the PM mass composition, according to variations in meteorology (discussed above) and the influences from very specific, localized, intermittent emission events (such as fire activity). On the seasonal scale, both meteorology and emissions influence the components of haze, as discussed below (see also Sections 3, 4, and 5 of this report).

In the summer, wildfires are obviously very episodic and spatially variable; thus they can play a major role, and can even dominate the PM and extinction budgets during certain summertime haze events. Wildfire impacts are entirely dependent upon the location of the fires relative to the location of interest in combination with the wind patterns that set up during the episode that carry the smoke over potentially great distances. Biogenic organics are also dominant (especially in the absence of fires), and are more diffuse and widespread; thus this component exhibits little spatial or temporal variation. Dust is greatly affected by wind speeds and is generally concentrated in areas of disturbed dry soil (agricultural, mining, and construction activities). A large fraction of the man-made carbonaceous PM is from vehicular sources (highways, barges, and railroads) near Portland and all along the Gorge. Sulfate stems from very regional sources well outside the Gorge, including surrounding states, Canada, and off-shore sources. There are also some impacts from local sulfur sources, such as coal-fired power plants and pulp mills, depending on atmospheric transport patterns and the specific location of focus in the Gorge. Ammonia is mostly attributed to local agricultural activities (feed lots and fertilizer applications in the eastern areas of Oregon and Washington).

In the winter, much of the secondary inorganic PM (sulfate and nitrate) is attributed to regional sources over Oregon, Washington, neighboring states, Canada, and even off-shore. These salts form from sulfur dioxide and nitrogen oxide emissions in cool humid climates – the episode examined in this modeling study was driven in large measure by persistent fogs

that set up in the basin of Oregon and Washington, which dramatically increased the chemical formation of sulfate and nitrate. Local sources include power plants, other industries, and vehicular sources. Ammonia is mostly attributed to local agricultural activities (feed lots/dairies and fertilizer applications in the eastern areas of Oregon and Washington). Carbonaceous PM has a very large contribution from residential wood smoke (with Portland being a very large source region) and non-road sources. Thus the carbon PM tends to exhibit stronger spatial and temporal variations than sulfate and nitrate.

According to these modeling results, there is a strong connection between urban emissions and haze in the Gorge, especially from the Portland/Vancouver metropolitan area. The magnitude and frequency of urban impacts is very dependent upon the specific area of the Gorge considered. For example, the simulated man-made PM concentrations at the Mt. Zion site were consistently dominated by urban emissions from area (residential wood smoke and dust) and vehicular sources. On the other hand, simulated PM at the Wishram site was occasionally impacted by Portland emissions, mainly during periods of strong winds from the west (e.g., the August episode), but the amount of the man-made PM was much smaller relative to other sources in the eastern Gorge area.

The modeling and associated observational data analysis conducted as part of the model performance evaluation shows a strong connection between sporadic sources and jumps in particular PM species. For example, occasionally large spikes from primary carbonaceous species was observed and simulated during periods when wildfire smoke was blown into the Wishram area. This is not surprising given the shear magnitude of mass emitted into the atmosphere from such sources (e.g. a single wildfire's daily emissions of primary $PM_{2.5}$ on August 18th was a factor of 30 greater than that of the entire Portland metropolitan area). However, there were also some specific industrial source fluctuations during the modeling episode in 2004 (e.g., the PGE Boardman power plant was shut down for a short period in the November episode), but an associated signal in sulfate and nitrate concentration was not obvious.

The modeling demonstrated that a rather large fraction of man-made emissions from sources outside the states of Oregon and Washington contribute to secondary sulfate and nitrate, as well as primary PM such as carbonaceous species, in both modeling episodes. This strengthens our conclusions that haze in the Columbia River Gorge is caused by a wide variety of source types and source regions, and that no single facility, category, or region can be singled out as the dominant cause of haze.

Additional insight was sought in the modeling effort to better understand the significance of five identified "what-if" scenarios (sensitivity analyses) to answer the question of what sources or source categories are contributing to haze. The five "what-if "scenarios are (1) Zero Boardman power plant emissions; (2) Zero ammonia emissions in the east of the Gorge region; (3) Zero on-road mobile source emissions in the Portland metropolitan region; (4) Zero major point source emission in the Portland metropolitan region; and (5) Zero major point source emissions in the Gorge region. Very little sensitivity to any of the "what-if" scenarios was seen at both Mt. Zion and Wishram. Since major sulfur dioxide and nitrogen oxide emission reductions at the Boardman Plant are already reflected in the 2018 inventory

(i.e., presumptive BART controls), practically zero sensitivity to scenario (1) is seen. As we have seen in both the 2018 projection (relative to the 2004 base case) and a few of the "what-if" scenarios, the sulfate and nitrate estimates response to changes in emissions is mixed reflecting the complex chemistry processes involved. Again, the August episode is dominated by "natural" emissions that were not removed in any of these scenarios. Somewhat more influence from each what-if scenario is seen on the worst PM days of the November episode, especially scenarios (2) and (3) at Mt. Zion, which remove Eastern Gorge ammonia and Portland on-road mobile sources, and scenarios (1) and (5) at Wishram, which remove major point sources from the in-Gorge area. The less obvious signals stemming from the "what-if" scenarios should be examined in further modeling efforts; but overall these effects are not significant to the overall conclusions of this study.

4) Are there detectable and/or statistically significant multi-year trends in the causes of haze?

The average contribution of each major chemical component of haze by year at Wishram is shown in Figure ES-3. It should be noted that nitrate data between 1996 and 1999 are suspect because they were found to be lower than prior and more recent year's data at sites across the country, so no nitrate trend should be inferred from these data. The trend analysis shows a statistically significant change with decreasing concentrations only for sulfate. No statistically significant trend in total light extinction (haze) was found.
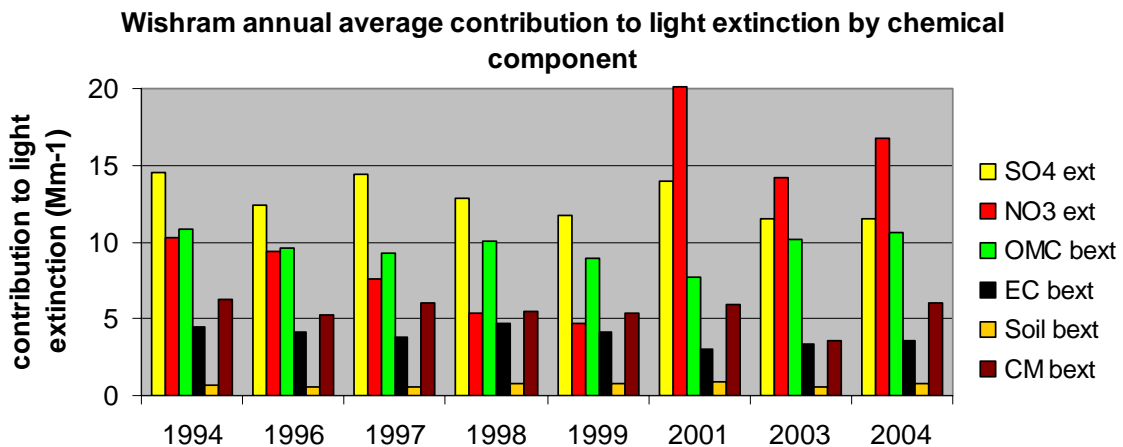
Figure ES-3 Contributions to light extinction by the major PM species for the eight years with complete data between 1994 and 2004 at Wishram.

5) How much of the haze in the Gorge is beyond reasonable regional control?

The answer to this question must rely on the modeling conducted for the August and November 2004 haze episodes. An advanced analysis tool integrated into the model was employed to track and apportion specific emission sources and geographic regions in Oregon and Washington to total PM and PM components at Mt. Zion and Wishram. For the purpose

of responding to this question, contributions from secondary biogenic, wildfire and dust sources of PM within the 4-km model domain (i.e. most of Washington and Oregon) were considered to be from natural sources, while contributions from sources outside of the 4-km model domain were considered beyond the regional controls. By this approach the natural source contributions are necessarily only those from within the domain and so it underestimates the amount of natural PM. On the other hand, the contributions form the distant sources (i.e. outside the domain) includes distant natural source contributions, so the natural plus distant components shown in Table ES-4 are less affected by the underestimation of natural PM for these two episodes.

Table ES-4 Comparison of model estimated haze levels (particle light extinction in Mm^{-1}) will all sources, natural sources only, and natural plus distant source contributions at Mt. Zion and Wishram for the two modeling episodes. The fraction of the total particle light extinction (i.e., All Sources) is shown parenthetically for Natural Only and Natural + Distant source categories.

Particle Light Extinction (Mm^{-1})	August 2004 Episode			November 2004 Episode		
	All Sources	**Natural Only**	**Natural + Distant**	**All Sources**	**Natural Only**	**Natural + Distant**
Mt. Zion	36	14 (39%)	22 (61%)	116	14 (12%)	36 (31%)
Wishram	28	16 (57%)	22 (79%)	190	10 (5%)	54 (28%)

During the summer episode, the western end of the Gorge (Mt. Zion) is more impacted by man-made sources (i.e. haze from all minus natural sources) than the eastern end. Most of the natural haze in the Gorge during this episode is from secondary organic PM. The somewhat greater natural haze levels in the eastern Gorge are due to wildfires in eastern Washington during this episode. Distant source contributions are somewhat greater at Mt. Zion than at Wishram (8 Mm^{-1} and 6 Mm^{-1}, respectively), but when combined with the natural source contributions produce the same level of Gorge haze beyond reasonable control during this August 2004 episode (22 Mm^{-1}).

In the winter, the vast majority of haze is attributed to man-made emissions. There are no wildfire impacts, dust emissions are squelched, and PM from vegetative sources contributes a much smaller fraction of total PM. The absolute magnitude of the natural source emissions are similar to those during the summer episode principally because of reduced atmospheric dilution for all pollutants associated with winter stagnation. This is undoubtedly also a factor in the much higher than summer haze contributions by distant sources (22 Mm^{-1} and 44 Mm^{-1}, respectively for Mt. Zion and Wishram).

By this assessment, a dramatic improvement in the winter episode haze levels would be achieved if all regional man-made emissions were removed (e.g. from 190 Mm^{-1} to 54 Mm^{-1}). By comparison, for the summer episode, the maximum available improvement that would be achieved if all man-made emissions within the model domain were removed would be noticeable, but not very dramatic (e.g. from 36 Mm^{-1} to 22 Mm^{-1}).

6) How will the haze change in the Gorge for 2018?

Projecting haze into future years is a difficult and complex task, and necessarily involves many assumptions about how a region's population, industrial, and economic environment will change, as well as how effective emission control programs, both planned and already in effect, will be in reducing pollutant emissions. The result of this effort is a projected 2018 emissions inventory (EI) that can then be modeled using the same approach that was successful in estimating the 2004 PM component concentrations. The 2004 meteorology was used to model 2018, so only the effects of emissions changes are estimated.

The Gorge Study 2004 EI is a refinement and updated version of the Western Regional Air Partnership (WRAP) 2002 EI. Because of resource limitations, the 2018 emissions inventory projections developed by WRAP from their 2002 EI was used instead of making projections starting from the 2004 Gorge Study EI. After the modeling was completed, a number of issues associated with this choice were identified and shown to be responsible for some noticeable inconsistencies. The most important of these inconsistencies involved several aluminum smelter sources in and around the Gorge that were listed in the WRAP 2018 EI though they had been temporarily shut down prior to 2004 and a power plant that was mislocated in 2004. Thus some of the emissions within the Gorge were incorrectly shown to be higher in 2018 than in 2004. Short of rerunning the modeling (prevented by schedule and budget restrictions), we can only note the inconsistencies and speculate about the magnitude of this error.

Tables ES-5 through ES-8 show the projected changes to haze levels and contributions from the five source regions of the modeling domain plus the secondary organic PM contributions for all regions. As indicated above, the EI projection for 2018 overestimated the emissions from some sources within the Gorge, so the haze shown from the Gorge is biased somewhat high in these tables. For all of the other source regions, the emissions and the resulting contribution to haze are about the same or lower in 2018 compared to 2004. It is reasonable to expect that sources in the Gorge will be similarly about the same or lower. That speculation is reflected in the tables where the same contributions for 2004 are entered parenthetically into the table for 2018. The reader is cautioned in the use of these values.

Table ES-5. Model-estimated current and projected haze contributions for each source region (aggregated over all species and source categories) and secondary organic PM for all source regions for August episode at Mt. Zion. No growth in haze from the Gorge is shown parenthetically as a reasonable alternative to the modeling of incorrectly inflated emission for 2018.

Mt. Zion – August	2004		2018		Change
Region	Mm^{-1}	Contribution	Mm^{-1}	Contribution	Mm^{-1}
BC/Outside 4 km domain	7.8	22%	5.8	17%	-2
Portland	7.1	20%	6.7	20%	-0.4
NW of Gorge	4.4	12%	4.0	12%	-0.4
Gorge	2.3	6%	1.9 (2.3)	6%	-0.4
East of Gorge	1.6	4%	1.6	5%	0
West of Gorge	1.2	3%	1.6	5%	+0.4
Secondary Organic PM	12	33%	12	35%	0
Total Light Extinction	36	100%	34 (34)	100%	-2

Table ES-6. Model-estimated current and projected haze contributions for each source region (aggregated over all species and source categories) and secondary organic PM for all source regions for August episode at Wishram. No growth in haze from the Gorge is shown parenthetically as a reasonable alternative to the modeling of incorrectly inflated emission for 2018.

Wishram – August	2004		2018		Change
Region	Mm^{-1}	Contribution	Mm^{-1}	Contribution	Mm^{-1}
East of Gorge	6.4	23%	5.9	20%	-0.5
BC/Outside 4 km Domain	6.3	22%	4.1	14%	-2.2
Gorge	2.6	9%	7.0 (2.6)	24%	+4.4
West of Gorge	1.6	6%	1.9	7%	+0.3
NW of Gorge	0.97	4%	0.50	2%	-0.47
Portland	0.81	3%	0.64	2%	-0.17
Secondary Organic PM	9	32%	9.4	32%	+0.4
Total Light Extinction	28	100%	29 (25)	100%	+1

Table ES-7. Model-estimated current and projected haze contributions for each source region (aggregated over all species and source categories) and secondary organic PM for all source regions for November episode at Mt. Zion. No growth in haze from the Gorge is shown parenthetically as a reasonable alternative to the modeling of incorrectly inflated emission for 2018.

Mt. Zion – November	2004		2018		Change
Region	Mm^{-1}	Contribution	Mm^{-1}	Contribution	Mm^{-1}
Portland	32	28%	28	26%	-4
BC/Outside 4 km domain	22	19%	22	21%	0
East of Gorge	15	13%	9.0	8%	-6
Gorge	15	13%	25 (15)	23%	+10
West of Gorge	10	9%	8.8	8%	-1.2
NW of Gorge	7.7	7%	2.1	2%	-6.5
Secondary Organic PM	13	11%	13	12%	0
Total Light Extinction	116	100%	107 (97)	100%	-9

Table ES-8. Model-estimated current and projected haze contributions for each source region (aggregated over all species and source categories) and secondary organic PM for all source regions for November episode at Wishram. No growth in haze from the Gorge is shown parenthetically as a reasonable alternative to the modeling of incorrectly inflated emission for 2018.

Wishram – November	2004		2018		Change
Source Region	Mm^{-1}	Contribution	Mm^{-1}	Contribution	Mm^{-1}
East of Gorge	109	57%	86	51%	-23
BC/Outside 4 km domain	44	23%	41	25%	-3
Gorge	18	10%	27 (18)	16%	+9
Portland	4.6	2%	3.0	2%	-1.6
NW of Gorge	3.2	2%	0.0	0%	-3.2
West of Gorge	2.2	1%	0.25	0%	-1.95
Secondary Organic PM	10	5%	10	6%	0
Total Light Extinction	190	100%	167 (158)	100%	-23

According to the 2018 modeling results, the August 2004 haze levels will not improve perceptibly from the 2004 conditions, even if the Gorge contribution to haze is assumed to be constant. However, the November 2004 haze levels will improve a small and perhaps noticeable amount, principally due to reductions in regional sulfur emissions. These results of small improvements in haze levels are consistent with independent 2018 annual projection results for the 20% worst haze days of 2002, as conducted by WRAP and reported for the Mt. Hood and Mt. Adams Wilderness Areas.

Modeling results show that the source contributions will not be substantially different from 2004 to 2018. There will be minor changes associated with contributions from local power plants and pulp mills as these sources are controlled or shut down, and also from continuing evolution of the vehicle fleet (in terms of number, fuels, emissions control technologies, etc). But these differences will result in only minor changes in the source mixtures responsible for haze in the Gorge.

By extension, the pollutant mix of the haze will also not be significantly different. With existing and planned controls on major industrial sources (power plants, pulp mills) and on the vehicle fleets (automobile technology, diesel engine technology and fuel sulfur limits) the fraction of sulfate will be reduced accordingly. This will have a larger impact on the wintertime episodes than the summertime episodes.

Regional sources outside of Oregon and Washington, according to the projected emission inventories used in this modeling, will continue to contribute about 20% to total PM in the Gorge during winter episodes, but will reduce a few percentage points in summer episodes. Given that we did not apportion regional emissions by source type, it is not possible to know which sector is responsible for the reduction without a detailed analysis of the regional emission inventory.

e) Working Conclusions and Observations

There are many conclusions and observations that can be made from a study as comprehensive as this. This section will generally not repeat detailed conclusions from the report about who is causing haze, how much haze exists, or from which region haze comes from. Rather, it will provide observations that could help focus the policy discussion surrounding further haze reduction efforts in the Gorge. Some are more obvious than others, but they bear highlighting here.

1) The purpose of this study was two-fold. The first was to monitor and assess conditions in the Gorge for calendar year 2004. This was done and the resulting findings are presented in sections 1 through 5 of this report. The second was to develop a tool that could be used to forecast conditions for the out-year of 2018 to determine if there was a visibility trend that could be identified based on current and planned emission control strategies. That tool has been developed and a projection for visibility conditions in 2018 has been provided in Section 7 of this report. This tool will also help the future testing of proposed reduction strategies. As a result, the objectives of the study have been achieved.

2) Visibility impairment is worst in the winter, and especially so at the east end of the Gorge. During winter, the manmade contribution to the haze is highest. Likely, any strategy developed for winter will have varying corresponding improvements in the summer as it is expected that any emission reductions would be made on an annual basis. Manmade emissions from throughout the region impact visibility at both the east and west ends of the Gorge in both winter and summer to varying degrees given the season and location.

3) The manmade pollutants most contributing to haze in both summer and winter episodes are sulfates and nitrates. These are secondary aerosol pollutants and their precursor gases (sulfur dioxide, nitrogen oxide and ammonia) come from a wide range of human activities and human-controlled sources.

4) Visibility improvement can only come as a result of emission reductions. The only emission reductions that can be made are those that are the result of manmade activities. Therefore, opportunities for improvement should be focused on those times and locations that have the worst impairment and have the most manmade emissions impact recognizing that some of these pollutants come from outside the region.

5) The 2018 results presented in Section 7 conclude that no single solution exists to remedy haze. Rather, a multifaceted approach may be necessary if further reductions are desired. Because there is not a dominant manmade source of emissions that is responsible for haze in the Gorge, numerous smaller emission reduction opportunities would be required to make any meaningful improvements.

6) The data presented in this report is as accurate as can be provided at the time of publication given the project's budget and schedule limitations. It is essential to continue to monitor Gorge haze levels to track trends and provide data that will be needed for future evaluation and refinement of modeling tools. Several improvements and updates could be

applied to the air quality model, emissions inventory, and model re-runs prior to any specific source attribution exercise or detailed cost benefit analyses. Whether, when and how to accomplish this additional work are policy questions beyond the scope of this scientific report.

1) Introduction

a) Geographic/Air Quality Setting

i) Results of previous monitoring and assessments

Numerous studies have been conducted in recent years of air quality and visibility in the Columbia River Gorge. A listing of known applicable studies is given below. Some of these were conducted prior to the Columbia River Gorge Haze Study or as a part of the planning process for the Gorge Haze Study (labeled Preliminary Studies), while others were a part of the Gorge Haze Study or conducted independent of it.

Preliminary Studies:
1. "On the Composition and Patterns of Aerosols and Haze Within the Columbia River Gorge September 1, 1996 – September 31, 1998", Core Environmental Consulting, January 12, 2001.
2. "Columbia River Gorge Visibility and Air Quality Study Working Draft: Existing Knowledge and Additional Recommended Scientific Assessment to Consider", Mark C. Green, DRI, June 7, 2001 (updated July 26, 2001).
3. CALPUFF Draft Footprint Report, Brian Lamb, WSU, March 26, 2003.
4. CMB Final Report. Hampden Kuhns, DRI, March 28, 2003.
5. PMF Analysis of Columbia River Gorge IMPROVE Data, Keith Rose, USEPA, March 26, 2003.
6. ISOPART Modeling Final Report, Sara Pryor, Univ. of Indiana, September 15, 2003.

Gorge Haze Studies:
1. Columbia River Gorge Haze Gradient Study, Final Report, Mark Green, et al., January 27, 2006.
2. Causes of Haze in the Gorge Final Report, Mark Green, et al., July 31, 2006.
3. Emission Inventory Report, Final, Rachel Sakata, et al, ODEQ, January 31, 2008.
4. Modeling Analyses Conducted for the Columbia River Gorge National Scenic Area, Chris Emery, et al, ENVIRON, August 28, 2007.

Independent Studies:
1. Updated Air Quality Trends for the Columbia River Gorge, Kent Norville, Air Sciences, Inc., August 9, 2006.
2. Who is Polluting the Columbia River Gorge?, Dan Jaffe, Northwest Air Quality Inc., December 31, 2006.
3. Winter Deposition of Nitrogen and Sulfur in the Eastern Columbia River Gorge National Scenic Area, Mark Fenn, USFS, February 3, 2005.
4. Atmospheric deposition inputs and effects on lichen chemistry and indicator species in the Columbia River Gorge, USA. Mark Fenn, et al. journal article in Environmental Pollution 146 (2007) 77-91. Accepted June 24, 2006.

Table 1-1 summarizes the objectives, approach, and the key findings of these previous studies.

Table 1-1. Summary of Columbia River Gorge Air Quality Studies

Reference	Objectives	Approach	Findings
Core, 2001	Characterize haze in the Gorge during 1996-1998.	Used IMPROVE aerosol, wind, and nephelometer data to analyze aerosol component contributions to haze, temporal patterns and wind direction effects	Nitrates and sulfates dominate haze. Worst haze at Mt. Zion with west winds, worst at Wishram with east winds
Green, 2001	Summarize existing air quality knowledge and develop a study plan for future detailed assessment.	Summarize existing emissions, meteorology, particulate composition, and visibility; develop hypotheses and design study to test hypotheses	For each $PM_{2.5}$ component (except soil) Mt. Zion has higher levels in summer, Wishram higher in winter. Both sites SO_4 peak in July, NO_3 in December-January, OC in autumn. Moderate correlation (r^2=0.5) for sulfate between sites; high correlation for OC and EC between sites in summer, low in winter. Wishram greater variation in b_{ext} winter to summer than Mt. Zion mainly due to large difference in RH summer to winter. SO_4, NO_3, OC all important contributors to $b_{ext.}$ Hypotheses stated and field program/modeling plan proposed to support or refute them.
Lamb, 2003	Determine source footprint of contributions on high aerosol days.	Run CALPUFF in reverse mode and multiply "backpuff" dispersion calculations by travel time weighted gridded emissions. Results summarized by 5 areas: Portland area, Puget Sound, CR Gorge, Yakima, Tri-cites and "rest of grid".	Portland, the Gorge, and "rest of grid" dominated the source contributions. Puget Sound, Yakima, and Tri-Cities contributions were minimal.
Kuhns, 2003	Apportion PM2.5 and haze to source types.	CMB analysis of $PM_{2.5}$ chemically speciated data at Wishram and Mt. Zion for 1996-1998. Used source profiles collected in other studies. Used only lime kiln profile for paper mills, but kraft recovery boilers are a	Primary motor vehicle exhaust, secondary ammonium sulfate, primary vegetative burning, and soil were the major contributors to $PM_{2.5}$ at both sites. On average, 50% of the $PM_{2.5}$ mass was attributed to carbonaceous aerosol (motor vehicle and vegetative burning) and ~24% to ammonium sulfate at both the Mt. Zion and Wishram sites. Wishram

		major source with mostly NaSO₄ particles.	contained 50% more soil than at Mt. Zion (9% and 6% of $PM_{2.5}$, respectively). Ammonium nitrate and aged marine aerosol (sodium nitrate) together accounted for ~12% of the aerosol mass at both locations. Aluminum smelters accounted for 7% of the fine aerosol mass at Wishram but only 2% at Mt. Zion. Contributions from paper mill and coal power plants were indistinguishable from primary soil and secondary sulfate sources.
Rose, 2003	Determine source factors at Wishram and Mt. Zion and their contributions to $PM_{2.5}$ mass.	Run PMF on IMPROVE data at Wishram and Mt. Zion from 1996-1998	At both sites vegetative burning and secondary sulfate each accounted for about ¼ of the mass. Aluminum reduction and secondary nitrate were about 15 and 10% respectively at Wishram. Secondary nitrate and pulp mills contributed about 10% each at Mt. Zion.
Pryor, 2003	Perform source-oriented modeling for $PM_{2.5}$ and compare with measurements at Wishram & Mt. Zion.	Used ISOPART, a Lagrangian trajectory model with diffusion and chemistry using MM5 meteorological fields and gridded emissions	ISOPART provided a reasonable estimate of $PM_{2.5}$ mass and the fraction for each major component. Nitrate at Mt. Zion appears to be ammonia limited.
Green, 2006a	Determine relationships among wind and light scattering patterns along the gorge.	Developed wind pattern classification scheme and computed average hourly wind and light scattering at each site by wind pattern type.	Five wind patterns were constructed: strong westerly flow; moderate westerly flow; light westerly flow; light easterly flow (diurnal reversal at eastern sites); winter easterly flow (light at east end, strong at west end) Strong westerly was the predominant pattern in mid-summer; Winter easterly was the most frequent winter pattern. Light westerly and light easterly were most frequent in fall and spring transition months; moderate westerly was most frequent in late summer to early fall. Winter easterly had the highest average b_{sp}. The transport and b_{sp} gradient pattern suggests that for winter easterly sources east of the Gorge cause much of the haze. Summertime showed diurnal patterns of increasing b_{sp} progressing easterly to the Bonneville site during the day

			suggesting the Portland/Vancouver urban area as a significant contributor to aerosol in the Gorge in summer. Light easterly and winter easterly showed an increase in b_{sp} from Wishram to Sevenmile Hill and Memaloose, suggesting impact from The Dalles area.
Green, 2006b	Determine main source types and source areas responsible for haze in the Gorge.	Build upon haze gradient study by using additional time resolved aerosol data, analysis of speciated aerosol data, case study analysis, and PMF analysis.	Winter often had winds from the east with very high levels of b_{sp}, especially at the eastern gorge sites with sources east of the Gorge responsible for much of the haze. The major chemical components responsible for haze were organic carbon, sulfate, and nitrate. Positive Matrix Factorization (PMF) indicated seven source factors in the western Gorge and five factors in the eastern Gorge. Organic mass is a large contributor to haze in the gorge all seasons, with a peak in fall. PMF suggests about half of organic mass is biomass smoke with mobile sources the second largest contributor. PMF showed nitrates mainly attributed to a generic secondary nitrate factor with the next largest contributor being oil combustion at Mt. Zion and mobile sources at Wishram. Sulfate a significant contributor in all seasons peaking in summer.
Fenn, 2005, 2007	Determine N and S deposition in fog, bulk deposition and throughfall and pH of fog and precipitation in the Gorge.	Monitoring at 11 sites. Bulk precipitation and fog water in open areas, throughfall beneath Ponderosa pines.	High N deposition measured at levels expected to have ecological impact from N enrichment. Ammonium deposition in throughfall highest at easterly sites. Bulk deposition of NO_3^-, $SO4$, NH_4^+ higher in western Gorge (higher precipitation). pH levels usually between 4.0 and 4.5.

Norville, 2006	Assess trends in urban and rural area air pollution in and near the gorge.	Used Oregon DEQ, AIRS, and IMPROVE data sets. Generated summary measures by year (e.g, average of 20% worst day extinction) and fit trend lines. No statistical significance tests reported for the analysis (e.g. for slope of trend line).	Levels either flat or improving for all measures. Nitrate and extinction trends at Wishram and Mt. Zion inconclusive because of nitrate measurement issues.
Jaffe, 2006	Determine transport directions on worst case days at Wishram and trends analysis of $PM_{2.5}$ mass at Wishram.	Used HYSPLIT back trajectory analysis for 50 highest $PM_{2.5}$ mass days at Wishram (using IMPROVE aerosol data). Trend analyses with statistical significance tests for annual and seasonal $PM_{2.5}$ mass.	Eastern end of gorge sources dominated worst 50 days; western gorge sources likely contributed during some of worst days. Nitrates significantly elevated with easterly flow. October and November accounted for about ½ of worst 50 days over 12 years. Some improvement in annual mean $PM_{2.5}$ (but not statistically significant at 95% confidence level. Spring only season with statistically significant decrease in mean $PM_{2.5}$ mass.

ii) Challenges associated with complex terrain

The Columbia River Gorge is an area with highly complex terrain, making it difficult to accurately describe through measurements or modeling exercises, the 3-dimensional characteristics of the meteorological fields of importance to air pollution such as the transport and dispersion of air pollutants. The glossary of meteorology defines complex terrain as "A region having irregular topography, such as mountains or coastlines. Complex terrain can also include variations in land use, such as urban, rural, irrigated, and unirrigated. Complex terrain often generates local circulations, or modifies ambient synoptic weather features, to create unique local weather characteristics. In regions of complex terrain, weather forecast models must have high resolution to reproduce numerically the terrain-induced weather features".

The Columbia River Gorge is a narrow gap in the Cascade Mountains of Washington and Oregon. Cut by the flow of the Columbia River, the Gorge is approximately 190 km in length, 5 km wide (at river level) and 1000 m deep, and is generally oriented east-west. The elevations at river level are less than 100 m above sea-level (MSL). The western portion of the gorge is characterized by a maritime air mass while the eastern Gorge is semi-arid. Annual average precipitation at Troutdale at the western end of the gorge is 1135 mm (44.7 in), while at The Dalles at the eastern end of the Gorge annual average precipitation averages 360 mm (14.2 in).

The Columbia River Gorge is affected by a type of local wind called a gap wind. Gap winds are the result of a pressure gradient located along a break or gap in a mountain barrier. Confined by the terrain, gap winds are highly ageostrophic, blowing parallel to the gap from high to low pressure. Reed referred to winds in the Strait of Juan de Fuca as gap winds. Cameron described strong easterly gap winds in the Columbia River Gorge. The climatology of gap winds in the Gorge has recently been described in detail by Sharp and Mass. In summer, northward migration of the Pacific High creates higher pressure offshore. Heating of the Columbia River Basin creates a thermal low pressure east of the gorge. Thus a substantial pressure gradient exists through the gorge, causing consistently westerly flow through the gorge in summer that is regularly exploited by wind surfers near Hood River, Oregon. In winter, conditions are more variable but easterly gap flow is common. With synoptic scale high pressure areas over the interior western United States and Pacific low pressure systems typically to the west, east to west pressure gradients are common. The high pressure to the east is often enhanced by the development of "cold pools" in the Columbia Basin. These cold pools formed by strong radiational cooling are associated with light winds, moisture, and a buildup of pollution in the Columbia Basin. In the gorge, air starts accelerating in response to the along-gorge pressure gradient and becomes generally stronger as it traverses the gorge from east to west. Most acceleration may occur in certain areas but gorge wind data is not complete enough to well define the wind patterns.

To well represent transport and dispersion properties in complex terrain, the terrain must be accurately represented by models. Sharp and Mass concluded that the horizontal grid spacing needs to be about 500 meters in order to have a chance at properly modeling airflow in the Columbia River Gorge. Even with modeling at high resolution, which is time and resource intensive, a good network of measurements is needed to validate the model results. This would ideally include a large network of surface meteorological stations as well as many upper air measurements such as by radar wind profilers, weather balloons, etc. While flow in the gorge is generally from higher to lower pressure, complications arise from the fact that the gorge width

and height change over its extent and airflow in the numerous side canyons entering the gorge adds additional complications. The interaction of airflow "within" the gorge to the prevailing flow above the gorge is also thought to be complex.

The budget for the Columbia River Gorge Air Quality Study did not allow for the intensive meteorological measurements and modeling exercises needed to best represent transport and dispersion of air pollutants in the gorge. It was necessary make due with fewer surface meteorology sites and no upper air data and with models that did not have the resolution needed to best capture the airflow patterns. It is expected that the main features of the flow in the Gorge were captured, although not the details.

iii) Planning and execution of the study

The Columbia River Gorge National Scenic Area straddles the Columbia River between Washington and Oregon and includes parts of six counties; Wasco, Hood River and Multnomah Counties in Oregon and Klickitat, Skamania and Clark Counties in Washington. The air quality in these counties is regulated by the Oregon Department of Environmental Quality for the three counties in Oregon and the Southwest Clean Air Agency for Clark and Skamania Counties in Washington and the Washington Department of Ecology for Klickitat County in Washington. Because of the multi-jurisdictional nature of the regulating agencies, a comprehensive plan involving the three air quality agencies in cooperation with the US Forest Service as the Federal Land Manager was necessary.

An initial study plan was prepared for the nephelometer haze gradient network. Initial funding was provided by the Air Quality agencies in 2002 and 2003. Additional Congressional funding was provided by the US Environmental Protection Agency in subsequent years that allowed for expansion of the nephelometer network to include gaseous pollutant monitoring at three of the monitoring locations in the Gorge. The ambient monitoring network was installed and maintained on a cooperative basis between the Southwest Clean Air Agency and the Oregon Department of Environmental Quality. Data was retrieved both manually and through an electronic data collection system by the two agencies. Special purpose instruments were also installed by the University of California – Davis (UC-Davis) to supplement the existing monitoring network. These special purpose data were extracted and reported by UC-Davis. All monitoring data was transmitted to the Desert Research Institute for compilation and evaluation. This data is summarized in a report titled "Causes of Haze in the Gorge" (CoHaGo). The results from the monitoring program are summarized in Section 3 of this report.

The Redesigned Technical Study Plan called for numerical computer visibility modeling within the Columbia River Gorge to achieve two purposes. The first purpose was to more succinctly identify source regions and source categories contributing to visibility impairment in the Gorge for calendar year 2004. The second purpose was to project visibility conditions for an outyear identified to be 2018. This outyear was selected to be consistent with the Federal Regional Haze Program projections being made for the Class I areas in the Pacific Northwest and across the nation. This second purpose would determine if visibility was worsening, staying the same or getting better in the future year.

Three major tasks were identified in the numerical computer modeling exercise. The first task was the development of an emission inventory for calendar years 2004 and 2018. The second task was development and application of a meteorological model to simulate meteorological

7

conditions across the modeling domain. The third task was the selection and implementation of the computer model that would integrate the meteorology and emissions data with the appropriate chemistry and dispersion algorithms and provide visibility results.

Under task one of the modeling exercise, the Southwest Clean Air Agency and the Oregon Department of Environmental Quality coordinated with the modeling contractor, ENVIRON International and Alpine Geophysics, to develop emission inventories that would be used as model inputs. The 2004 calendar year emission inventory was developed by using the 2002 National Emission Inventory (NEI) data submitted by the States to EPA and updating point and selected area source inventory data to be as current as possible. Because emission inventory development is extremely complex and time intensive, the Technical Team decided to use the inventory developed by the Western Regional Air Partnership (WRAP) for regional haze purposes for the outyear 2018.

The second task involved running the meteorological model (MM5) under various configurations to best characterize meteorological conditions within the Gorge. Under the monitoring task it was clearly identified that two unique conditions existed in the Gorge that represent summer and winter conditions. Because of the uniqueness of these meteorological conditions it was necessary to develop two data sets, one for each summer and winter conditions. This modeling was also performed by ENVIRON International and Alpine Geophysics.

The third task was to integrate the emissions inventory data with the meteorological data in a model that could make visibility projections. Under the original study plan, the project envisioned being able to run two slightly different models. Due to meteorology and emissions inventory complications, budget and schedule constraints limited the modeling activity to execution of only one model. The selected model was identified as Comprehensive Air Quality Model with extensions (CAMx) and ENVIRON International was selected to perform this modeling.

In addition to running the model for calendar year 2004 for summer and winter episodes and the outyear of 2018 for summer and winter episodes, the project also ran five selected sensitivity cases to better understand unique source region and source category contributions to Gorge visibility. The results of the modeling activities are presented in Section 3 (Emissions Inventory), Section 5 (Current Year 2004) and Section 7 (Future Year Projections) of this report.

b) Program Objectives

The Redesigned Technical Study Plan envisioned two main program objectives. These two objectives were: (1) to characterize existing visibility conditions and causes of haze in the Gorge and (2) based on the science and data developed in objective (1), project visibility conditions in a future year to establish a visibility trend that accounts for future growth (population and industry) and emission reductions currently "on the books" that are either planned or not yet fully implemented. Based on the future visibility trend, either improving or not improving, strategies could be identified and/or adjusted to remedy existing and/or future impacts in the Gorge.

Under the Management Plan established by the Gorge Commission in 1992 it was recognized early on that there were several resources that needed protection under the Scenic Area Act. These included scenic, cultural, natural and recreational resources. Specific funding was not

provided under the Management Plan to protect specific resources. The States of Oregon and Washington were also not funded separately to assist with protecting these resources. With the limited funding that ultimately was provided as described earlier, it was recognized that sufficient funding would not be provided to operate a robust program to understand all aspects of each of the identified resources. The Redesigned Study Plan was targeted on assessing visibility as a key metric that can be used as a surrogate for understanding impacts from natural and man-made processes on many of the Gorge resources. The study of visibility conditions can identify pollutants of concern, source regions and potential source categories, and potential strategies that can have varying affects on the different resources within the Gorge. It was not intended, nor was funding available, to provide a comprehensive understanding of all the impacts from natural and man-made activities. By understanding activities that impact visibility much can be learned about the pollutants and activities that affect the other resources. Any strategies developed to improve visibility ultimately result in a reduction in emissions and/or activities which in turn have associated benefits for the other resources. For this reason, visibility was determined to be a general indicator for conditions within the Gorge. In addition, existing air quality and visibility programs could be adjusted with a lesser amount of financial resources in lieu of creating new programs where none existed in the past.

c) Program Approach

i) Original design approach and study plan implemented

In this section we compare the tasks from the original study plan for the Technical Foundation Study (TFS) and the summer and winter intensive study periods to what was actually achieved. None of the measurements listed in the original study plan under supplemental measurements at next and highest funding levels were performed. The measurements listed at higher funding levels included such items as a greatly expanded speciated aerosol network, aircraft measurements, several radar wind profilers, aerosol microphysics (e.g. particle growth) studies, particulate remote sensing with a LIDAR, and tracer studies using artificial tracers or tetroons (altitude controlled balloons).

An air quality modeling plan had not been developed for the original study plan, so emphasis here is on the field measurement program.

Comparison of Redesigned Tasks with the Original TFS Tasks

Original TFS Study Plan Measurement/Task	What it tells us	Cost $ (in 1,000s)	Redesigned Study Comparison
A. Ambient monitoring: Characterization of air quality, chemical processes and basic meteorology			
1. Speciated $PM_{2.5}$, light scatter and surface meteorology within the Gorge - 2 sites. Mt. Zion and Wishram - ongoing	General spatial and temporal characteristics of light scatter and haze producing aerosols within the Gorge.	$164	Fully covered
2. Ambient nephelometers at Wishram, Mt. Zion - minimum 1 year	Light scattering including water growth effects	$48	Fully covered
3. Aethalometers at Wishram, Mt. Zion - minimum 1 year	High time resolution light absorption-impact of local sources, determine if sites are representative. See Portland material moving through.	$42	Fully covered
4. Additional heated nephelometers with surface meteorology horizontally along Gorge (5 minimum e.g., Cascade Locks, another below Hood River, between Hood River and The Dalles) and heated nephelometers with surface meteorology at 3 vertical levels (river, above river, and Gorge rim)	Horizontal light scatter gradient along Gorge. See material moving through Gorge and determine if sites are representative. Vertical mixing/light scatter gradients	$223	Fully covered
5. PM_{10} speciation at Wishram, Mt. Zion. Include NH_4+, SO_2 IMPROVE schedule, 1 year	Speciation for comparison with coarse particle scattering-aerosol neutralization. Supports model evaluation	$100	Not covered.
6. Optical particle sizers at Wishram and Mt. Zion - 1 year	Size resolved high time resolution particle scattering, comparison with $PM_{2.5}$ and PM_{10} speciation data, helps with extinction budget closure.	$50	Partly covered by using size resolved DRUM sampling, (Redesign task # 8), but only done on a seasonal intensive basis and not all species covered.
7. NH_3, HNO_3 (g), SO_2, Noy at two sites (Mt. Zion and Wishram) for one year IMPROVE schedule, 1 day in 6, 4-6 samples per day for NH_3, HNO_3, SO_2. Continuous Noy and low level CO. Add O_3 at Mt. Zion	Determine if atmosphere is ammonia limited- evaluate emissions inventory. Supports modeling (inputs, evaluate, validate, reconcile, etc.). Assessment of ozone levels and risk to environment in western Gorge.	$200	Ammonia limitation question partly covered using cation analysis. (Redesign task # 11). NOx and SO_2 partly covered (redesign task # 7) but only seasonal. Low-level CO and assessment of O_3 in western Gorge not covered.
8. Ozone monitoring at Wishram	Assessment of ozone levels and risk to environment in eastern Gorge	$31	Fully covered
9. Scene Monitoring (Camera). Digital Image Acquisition and Time Lapse Video. Two sites, one western and one eastern Scenic Area	Digital scene images to visually illustrate visibility conditions, and time-lapse video to capture dynamics of formation and movement of haze.	$42	Not Covered. Original task was only of qualitative value and is not needed to support CoHaGo and model evaluation.
B. Enhanced Meteorology: Characterization of physical processes			
10. Portable radar wind profiler and/or tethersonde and ceilometer deployed at key areas - e.g. mouth of Gorge, mid-Gorge, side canyons, and eastern Gorge for exploratory measurements.	Basic information on structure of atmospheric flow in Gorge - depth of flows, side-canyon importance, etc. Help to design more detailed, meteorological measurements. Supports modeling (inputs, evaluate, validate, reconcile, etc.)	$100	Not covered.
11. Radar wind profiler/SODAR/RASS 1 site, 1 year	Vertical wind/temperature profiles. Year round at 1 site. Supports modeling (inputs, evaluate, validate, reconcile, etc.).	$100	Not covered.
C. West of Gorge Sources: Characterization of Emissions			
12. Speciated $PM_{2.5}$ west of Gorge	Regional aerosol species gradient	$60	Partly covered. (Redesign task #

(upwind of Portland). IMPROVE 1 day in 3 schedule.	(transport site.)		9). Will be done on seasonal intensive basis vs. year round. Regional background can be determined using other IMPROVE network sites and Portland speciated $PM_{2.5}$.
D. East of Gorge Sources: Characterization of Emissions			
13. Speciated $PM_{2.5}$ east of Gorge (Columbia Basin). IMPROVE 1 day in 3 schedule.	Regional aerosol species gradient (transport site).	$60	Partly covered (redesign task # 9). Will be done on seasonal intensive basis vs. year round. Regional background can be determined using other IMPROVE network sites and Portland speciated $PM_{2.5}$.
14. Precipitation and fog water sampling and chemical analysis-Boardman power plant area, central Gorge as possible during 45 day period	Determine existing acidic pollutant levels and assess potential risk or impacts to ecosystem and cultural resources	$150	Partly covered. Independent Forest Service measurement program to sample and analyze water chemistry will be conducted in the Gorge, but the second step of assessing potential risk or impact to resources is not covered
E. Emissions Inventory			
15. Complete NW RTC Demo Project inventory, and grid at 5 km resolution	Supports modeling (inputs, evaluate, validate, reconcile, etc.)	$50	Fully covered
F. Modeling Studies			
16. Initial CMB modeling	Help identify general source categories contributing to impacts	$25	Fully covered
17. Initial ISOPART modeling	Help identify chemical processes and evaluate emission inventory	$25	Fully covered
18. Calpuff "footprint" modeling using MM5 data	Help identify potential source regions	$25	Fully covered
19. Limited cases of high-resolution CMAQ + SCAPE (chemical modeling)	Assess NH_3 limitation issue. Define physical processes within Gorge.	$125	Partly covered. (Redesign task # 22). CMAQ and CAMx will be used to model base case for current and future year worst-case haze.
20. Review of applicable 3D modeling practices	Documents pros and cons of various modeling approaches. Candidate models will be identified for overall modeling system	$10	A range of acceptable model types has been defined under other projects.
G. Data QA, Data Analysis, Data Management			
21. QA, analyze, and manage monitoring data to better understand physical/chemical conceptual model		$125	Partly covered, (Redesign task #18), but scaled back a bit. Some of the tasks in a CoHaGo will be done by existing Tech Team staff (e.g., CMB and PMF modeling)
H. Project Management and Reporting			
22. Project management/reporting		$75	Mostly covered, (Redesign task # 23) but scaled back a bit.
	TOTAL	$1,830	

Comparison of Redesign Tasks with the Post -TFS Phases of the Original Study Plan
(Note: The post-TFS phases of the original plan were only suggested at that time. Final design of post-TFS phases would have been done after the original TFS.)

Original one-year expanded measurement program: additional horizontal and vertical gradients in Gorge year-round, in-Gorge vs. out-of Gorge sources			How the Redesigned Study Plan Compares
Additional PM monitoring site collocated with mid-Gorge nephelometer site. Speciated $PM_{2.5}$ and PM_{10}, with NH_+, NH_3, SO_2,	Characterize central Gorge. Compare with measurements at east and west end of Gorge. Some gradient information.	$40K + $80K/yr= $120K 1-year	Partly covered. (Redesign task # 8 and 9). Scaled back number of sample days and species analyzed.
Gas and particle phase speciated organic aerosol using GCMS. 2 sites, one in six days for 1 year	Identification of key organic species in gas and particle phase. Contribution of biogenics, burning, gasoline, diesel, and meat-cooking to organic carbon with CMB	$160K	Partly covered. (Redesign task # 10). Scaled back number of sample days, seasonal intensive vs. year round. Aerosol only.
Radar wind profiler/SODAR/RASS 1 site, 1 year	Vertical wind/temperature profiles	$100K	Not covered.
Speciated $PM_{2.5}$ 2 nephelometer sites along Gorge- IMPROVE schedule, 1 year	Species gradient along Gorge/local city effects	$30K+$80K /yr=$110K	Partly covered, (Redesign task # 8 and # 9), but scaled back number of sites and just seasonal intensive.
DRUM samplers vertical nephelometer sites 1 year, analyze periods of interest	Vertical gradients of species (at least sulfur)	$75K	Partly covered, (Redesign task # 8), but seasonal intensive only.
Speciated $PM_{2.5}$ at nephelometer site at top of Gorge, IMPROVE schedule, 1 year	In Gorge/above Gorge species gradient	$15K+$40K /yr=$55K	Not covered
2 Additional aethalometers either side of City of Hood River – year round	Help determine presence of emissions from Gorge cities, especially winter wood burning	$68K	Not covered
High –time resolution SO_4, NO_3, EC/OC 1-3 sites (Wishram, Mt. Zion, mid-Gorge site) 1 year	Year-round knowledge of chemical species changes in time	$100K/site+ $100K/yr per site= $200-$600K	Partly covered, (Redesign task # 6) but seasonal intensive only
Original summer intensive period studies – effects of Portland/Vancouver Continue measurements as appropriate from TFS and one-year expanded network study and add:			How the Redesigned Study Plan Compares
Nephelometers and surface meteorology upwind (downriver) of Portland (one or more), Portland (3)	Change in light scattering due to Portland urban area	$25K/site 4 sites= $100K	Fully Covered (Redesign task # 4)
Speciated aerosol upwind of Portland (3)/ Portland (3), along Gorge sites (5), top of Gorge (1 or more) Daily for 30 days July-August.	Chemical speciation changes due to Portland urban area – relate to light scattering changes	$140K +$110K/ Month (6 new sites)	Partly covered, (Redesign task # 8 and 9), but fewer sites and days
Radiosondes 4/day for 30 days 2 sites, one mid-Gorge, one mouth of Gorge (e.g., PDX)	Vertical profiles of stability and wind (mixing, transport speed)	$60K	Not covered
High –time resolution SO_4, NO_3, EC/OC Mt. Zion or central Gorge site.	Chemical species change in time –relate to nephelometer data	$140K	Fully covered (Redesign task # 6)
DRUM samplers 5 along Gorge sites 30 days- analyze periods of	High-time res. speciation-Track movement of Portland	$50K	Partly covered (Redesign task # 8), but fewer sites

interest	plume		
Radar wind profilers and sodars 6 sites	Vertical wind profiles	$200K	Not covered
Organic gas and aerosol speciation, at additional sites or times if TFS studies warrant	Spatial pattern of organic speciation	$100K	Not overed.
Extinction cell, photoacoustic absorption, light scattering one site	Extinction budget closure	$70K	Not covered
Original Winter Intensive period studies – Boardman plant, CR Basin sources, in-Gorge, fog water Continue measurements as appropriate from TFS study and add:			**How the Redesigned Study Plan Compares (See Attachment A for details and costs)**
Nephelometers near and away from river either side- eastern Gorge minimum 3 sites	Extent of channeling of emissions eastern Gorge	$10K/site Assumes have equipment $30K 3 sites	Partly covered (Redesign task # 4), but no away from river site
Speciated aerosol near and away from river Eastern Gorge/Hood River drainage/CR Basin- 5 sites 45 days, reporting	Species channeled vs. regional	$35K+$33K /month= $85K 45 days	Partly covered (Redesign task # 8 and 9), but fewer number of sites and days analyzed
Speciated aerosol 5 along Gorge sites, 1 above Gorge site 45 days, reporting	Gradient within Gorge, upwind/ downwind of Gorge cities	$10K+ $51K/month =$86K 45 days	Partly covered (Redesign task # 8 and 9), but fewer number of sites and days analyzed
Radiosondes 4/day for 30 days 2 sites, one mid-Gorge, one east end of Gorge	Mixed-layer depth, vertical wind (transport) structure	$60K	Not covered
Precipitation and fog water sampling and chemical analysis- Boardman power plant area, central Gorge as possible during 45 day period	Determine existing levels of acidity of fog and cloud water. Potential ecosystem and cultural resources effects	$80K	Partly covered. Independent Forest Service measurement program to sample and analyze water chemistry will be conducted in the Gorge, but the second step of assessing potential risk or impacts to resources is not covered
High –time resolution SO_4, NO_3, EC/OC Wishram	Chemical species change in time –relate to nephelometer data	$50K (assumes instruments available)	Fully covered (Redesign task # 7)
Radar wind profilers and sodars 6 sites	Continuous vertical wind structure	$200K	Not covered
Extinction cell, photoacoustic absorption, light scattering one site	Extinction budget closure	$70K	Not covered
Organic gas and aerosol speciation, at additional sites if TFS studies warrant	Spatial pattern of organic speciation	$100K	Not covered.
Ceilometers at 2 wind profiler sites	Cloud base height	$25K	Not covered
	TOTAL	**~$3,044**	

The reader may compare the original and implemented study components to see what items were deleted from the study plan. Some notable omissions are pointed out here:

- No useful upper air measurements were made. This greatly limits our ability to understand the 3-dimensional properties of the atmosphere, how winds aloft may differ from the surface winds. These measurements would have provided very useful data for better understanding pollutant transport patterns and for evaluation of the meteorological model used (MM5).

- Additional speciated $PM_{2.5}$ data would have helped define the spatial particulate patterns and transport of chemical component species (e.g. sulfate) causing haze.

- Speciated organic particulate data was not obtained. We expect that the data would have helped to separate impacts from sources of organic particles such as burning, gasoline vehicles, and other mobile sources.

d) Report Description

i) Purpose and intended readers

The purpose of this report is to summarize the key findings and conclusions from the many technical studies that have been performed for the Gorge Scenic Area. This report will not provide all the background data necessary to develop a complete understanding of the complex processes associated with visibility, air quality modeling, air emission inventories and ambient monitoring activities. The readers are encouraged to refer to the many references provided in the individual report sections to better understand the in-depth processes and evaluations undertaken as part of the Gorge Technical Studies.

The intended readers of this document are the general public and political and government decision makers. This report is intended only to summarize findings and conclusions and the basis for reaching those conclusions. An attempt has been made to reduce a very technical and scientific program to a level where most readers can grasp the concepts involved in the studies and the associated conclusions. There will be readers that are overwhelmed by the science and "technical speak" and there will be readers that need more details to fully comprehend the basis behind each conclusion.

ii) Peer review

The technical study program for the Gorge Scenic Area has utilized knowledgeable and expert staff from many organizations in developing the conclusions presented in this summary report. Peer review of these studies and conclusions has happened in various informal processes. A formal technical process was envisioned at the outset of the program but as the programs and studies developed that formal process was determined to be unnecessary. Each of the three major program activities, ambient monitoring, emission inventory and air quality/visibility modeling was performed by a team and reviewed through a process of technical meetings both in person and by teleconference. The major reports have undergone a technical review and comment process where technical experts have reviewed the individual results and provided comments and recommendations that have been incorporated into the respective documents. Prominent technical staff from various organizations such as the National Park Service (NPS), the US Forest Service (USFS), the National Oceanic and Atmospheric Administration (NOAA), US Environmental Protection Agency (EPA), Washington Department of Ecology (WDOE), Oregon Department of

Environmental Quality (ODEQ), the Southwest Clean Air Agency (SWCAA), the University of Washington (UW), Washington State University (WSU), Indiana University, the Desert Research Institute (DRI), University of California – Davis (UCD) and environmental consultants such as ENVIRON International, Alpine Geophysics, Air Sciences, and Research Triangle Institute (RTI).

This report itself will not undergo a formal peer review process as it represents a culmination and reconciliation of the other individual scientific reports. This document has undergone a formal public review process where the results were presented in a public setting and national experts and the public had an opportunity to challenge and discuss the conclusions and basis for these conclusions. Comments from this review process were incorporated into the final document.

Separate from the Gorge Technical Studies Program, individual scientific investigators involved the program are encouraged and supported to continue to analyze the numerous data collected for this study and to publish scientific and technical papers in trade journals. These papers in turn are subject to a peer review process prior to publication and will continue to provide a basis for any future studies and trends analyses for the Gorge.

2) Ambient Monitoring Program

a) Network Design and Site Description

The Gorge Study added seven new monitoring locations in the Gorge to the existing IMPROVE (Interagency Monitoring of Protected Visual Environments) particle speciation monitoring sites at Mt. Zion and Wishram, to form a nine-site network (see Table 2-1) that was operated from the summer of 2003 through winter of 2005.

Table 2-1. Site name, latitude, longitude, elevation, and approximate elevation above the Columbia River for each site.

Station	Latitude	Longitude	elev meters	Approx Elev above river (m)
Sauvie Island	45.77	-122.77	5	2
Steigerwald	45.57	-122.30	13	10
Mt. Zion	45.57	-122.21	225	210
Strunk Road	45.59	-122.20	380	365
Bonneville Dam	45.65	-121.94	23	2
Memaloose State Park	45.70	-121.34	42	8
Sevenmile Hill	45.64	-121.21	563	540
Wishram	45.67	-121.00	323	270
Towal Road	45.75	-120.63	151	115

Sites are briefly described below:
Sauvie Island – island in the Columbia River close to and downriver from Portland/Vancouver. River axis is north-south at Sauvie Island.
Steigerwald - river level site (10 m above river) at the mouth of the Gorge.
Mt. Zion – somewhat elevated site (about 210 m above river) near west end of the Gorge and close to Steigerwald.
Strunk Road – elevated site (365 m above river) close to Mt. Zion, horizontally further from the Gorge Strunk Road, Mt. Zion and Steigerwald) provides essentially a vertical profile at the west end of the Gorge.
Bonneville Dam – river level site (2m above river) in the heart of the Gorge at Bonneville Dam.
Memaloose State Park – river level site (8 m above river) between Hood River and The Dalles
Sevenmile Hill – elevated site 540 m above (west of) The Dalles horizontally close to the river. Good exposure to higher level flows up and down the Gorge. Note on terminology: In figures, to save space, Sevenmile Hill will be referred to as 7 Mile Hill.
Wishram – slightly elevated (270 m above river) site close to river near to and east of The Dalles.
Towal Road – near river level (115 m above river) site east of Wishram.

b) Monitoring Methodologies

Table 2-2 summarizes the types of air pollutants measured during 2003 to 2005. It is readily apparent from this table that a comprehensive and intensive program was undertaken to understand air quality in the Gorge. Light scattering measurements were made at all of the Gorge Study monitoring sites, meteorological measurements at all but one site, and particle sampling at two sites over the entire study period. During some intensive study periods additional particle sampling and high time resolution particle monitoring were conducted at five of the sites. The following is a summary of the field study measurements.

IMPROVE samplers (http://vista.cira.colostate.edu/improve/) have been operating long-term at Wishram and Mt. Zion. They provide for chemical speciation of $PM_{2.5}$ (particulate matter less than 2.5 microns in diameter) and mass of PM_{10} (particulate matter less than 10 microns in diameter). The IMPROVE samplers operate one day in three so two-thirds of the days in the study period had no data from these samplers. From January 2004 to February 2005 additional ion analysis was done for the Wishram and Mt. Zion IMPROVE samples. This included analysis of cations ($NH4^+$, K^+, Na^+, Mg^{++}, Ca^{++}) as well as anions (in the standard analysis).

Light scattering was measured using Radiance Research M903 nephelometers at nine sites. The Radiance nephelometers are set to maintain relative humidity (RH) of not more than 50%; this is accomplished by heating the inlet air stream. This was done to allow for comparisons of scattering along the Gorge uncomplicated by different amounts of particle growth due to varying RH among sites. Optec NGN-2 nephelometers were operated at Wishram and Mt. Zion; they have been operating long-term at these IMPROVE protocol sites. The Optec nephelometers are unheated and thus represent a more accurate estimate of light scattering, especially under higher RH conditions.

For some days corresponding to IMPROVE sampling days, $PM_{2.5}$ filter samples using the "IMPROVE-like" International Aerosol Sampler (IAS) were collected at Sauvie Island (summer intensive), Bonneville (summer and winter intensives), and Towal Road (winter intensives) and chemically speciated. The IAS unit collected 24-hour time-integrated aerosol samples in the $PM_{2.5}$ mode on three independent channels for analysis of mass, and elemental, ion, and elemental/organic carbon fraction. The IAS collected samples 1 day in 3 to match IMPROVE sampling dates during the Columbia River Gorge Study. Unlike the IMPROVE "module" which contains 3 unique $PM_{2.5}$ samplers, the IAS uses the IMPROVE cyclone to effect a $PM_{2.5}$ cut point and traps the particles on 3 independent filters for analysis. Thus, the flow rate (23 liters/minute) and cyclone, cassette and filter media are identical to the IMPROVE units, but 1/3 the flow (i.e. ~7.7 liters/minute) and consequently one-third as much sample is collected on each filter compared to the IMPROVE sampler.

A Sunset Laboratory carbon analyzer was operated at Mt. Zion during summer-fall 2004, at Bonneville from summer 2004-winter 2005, and at Wishram during winter 2003-2004 and winter 2004-2005. This instrument gave nearly continuous concentrations of organic and elemental carbon (OC/EC) for 2 hour periods (1 hour 45 minutes sampling followed by 15 minutes of analysis time each 2 hours). The analysis uses thermal optical transmittance to

account for pyrolized carbon. This is in contrast to the thermal optical reflectance method used for the filter samples (from the IMPROVE and IAS samplers). Due to the use of transmittance and a different temperature program used, the method is expected to give lower elemental carbon than from the IMPROVE and IAS samples but similar total (organic plus elemental) carbon.

Sulfate and nitrate were measured at the same locations and for approximately the same time periods as the OC/EC measurements. The instrumentation was Rupprecht & Patashnick series 8400S for sulfate and series 8400N for nitrate. Continuous data are available at 10 minute intervals.

As part of the haze gradient study, aethalometers were operated at Wishram and Mt. Zion from July 2003- February 2005. Aethalometers give an estimate of elemental carbon by determining absorption due to particles deposited on a filter. Data is available for 5 minute average time periods, but is generally better when averaged over a longer time interval (e.g. one-hour).

Surface meteorology (wind speed and direction, temperature, and relative humidity) was measured at all nephelometer sites except Memaloose State Park.

Davis Rotating Drum Universal Monitors (DRUM) samplers were operated at Mt. Zion in the summer to fall 2004, at Bonneville from summer 2004 to winter 2004-2005 and at Wishram during winter 2003-2004 and winter 2004-2005. The DRUM sampler allows for analysis of chemical composition of collected particles in 3 hour time increments and 8 different sizes. The 8-Stage Rotating DRUM Impactor Sampler (8-RDI) is a cascade impactor. The analysis used narrow beam techniques (s-XRF) for elements and hydrogen, respectively, and Beta-ray attenuation for mass. Sampling allowed 42-day continuous record in 8 size bins (10-5, 5-2.5, 2.5-1.15, 1.15-0.75, 0.75-0.56, 0.56-0.34, 0.34-0.26, 0.26-0.09 micrometers aerodynamic diameter).

Table 2-2 Summary of the type and dates for monitoring conducted at each of the Gorge Study monitoring sites.

Measurement	Sauvie Is	Steigerwald	Mt. Zion	Strunk Rd	Bonneville	Memaloose	Sevenmile	Wishram	Towal Rd
B_{sp} Optec			7/1/03-2/28/05					7/1/03-2/28/05	
B_{sp} Radiance	8/5/03-2//28/05	7/1/03-2/28/05	7/1/03-2/28/05	7/1/03-2/28/05	8/7/03-2/28/05	8/7/03-2/28/05	8/14/03-2/28/05	7/1/03-2/28/05	7/17/03-2/28/05
Surface Meteorology	8/5/03-2//28/05	7/1/03-2/28/05	7/1/03-2/28/05	7/1/03-2/28/05	8/7/03-2/28/05	none	8/14/03-2/28/05	7/1/03-2/28/05	7/17/03-2/28/05
IMPROVE $PM_{2.5}$ speciation, PM_{10} mass			Every third day 7/1/03-2/28/05					Every third day 7/1/03-2/28/05	
Cation analysis of IMPROVE			Every 3rd day 1/04-2/05					Every third day 1/04-2/05	
International Aerosol Sampler $PM_{2.5}$ speciation	Some days 7/04-11/04				Some days 12/03,2/04, 7/04-1/05				Some days 12/03,2/4, 12/04-2/05
Time resolved EC/OC			6/28/04-11/10/04		6/30/04-2/28/05			12/18/03-3/1/04, 12/1/04-2/28/05	
Time resolved SO_4			7/19/04-11/29/04		1/10/04-3/8/04, 6/28/04-2/28/05			1/4/04-2/12/04, 11/29/04-2/28/05	
Time resolved NO_3			6/30/04-11/29/04		1/30/04-2/20/04, 6/28/04-2/28/05			1/10/04-3/2/04, 11/29/04-2/28/05	
Aethalometer			7/103-2/27/05					7/2/03-2/28/05	
DRUM samplers			6/30/04-8/11/04, 8/19/04-11/2/04		12/4/03-2/24/04, 7/16/04-11/2/04, 12/2/04-2/23/05			12/3/03-1/12/04, 12/2/04-2/23/05	

c) Comparability of Monitoring Techniques

i) Comparisons between filter and high time resolved data

Comparisons between IMPROVE filters and high time resolved data are important because the IMPROVE filters would not be able to identify potential diurnal variations or other short term phenomena that may be present (such as a passing train) and the IMPROVE samplers only operate 1 day every 3 days. High time resolved measurements of SO_4, NO_3, OC, EC, and total carbon (OC+EC) are compared to the 24-hour averaged IMPROVE measurements at Wishram and Mt. Zion and to the 24-hour averaged IAS measurements at Bonneville.

The high time-resolved sulfate tended to be higher than the 24-hour filter sulfate at all sites. There was poor correlation at Wishram and Bonneville, but better correlation ($r^2=0.61$) at Mt. Zion. At Mt. Zion the time-resolved sulfate was about 50% higher than the IMPROVE sulfate.

Nitrate from the time-resolved and filter measurements tended to be of similar overall magnitude; the squared correlation coefficients ranged from $r^2=0.38$ at Wishram to $r^2=0.85$ at Bonneville.

OC concentrations measured by the time-resolved and filter methods were comparable. R^2 ranged from 0.62 at Bonneville to 0.72 at Wishram.

For EC, the time resolved measurements gave about ½ the concentration of the filter based measurements at Mt. Zion and Bonneville and about three-eighths at Wishram. This is expected to result from both the different temperature programs applied to the Sunset Carbon analyzer compared to the IMPROVE temperature program and the use of transmittance rather than reflectance for determining the split between OC and EC. The correlations ranged from $r^2=0.46$ at Bonneville to $r^2=0.62$ at Wishram. For total carbon, at Mt. Zion and Wishram the Sunset analyzer total carbon is about two-thirds the IMPROVE filter carbon. The reason for this is not known. The Sunset analyzer has an organic gas denuder designed to remove organic gases that may absorb onto the sample and cause a positive artifact. The IMPROVE sampler does not have an organic gas denuder; there are considered to be positive artifacts from condensation of organic gases onto the filter and negative artifacts from desorption of particulate organics from the filter. For the Sunset analyzer, desorption of organic particulate is of less concern than for the IMPROVE samples because the analysis is performed every two hours in the field, presumably limiting the loss or organic particulate. On the other hand, perhaps the organic gas denuder removed some organic particulate matter. Consequently, because of the sampling methodologies, the Sunset analyzer may be expected have a lower total carbon concentration than the IMPROVE samplers.

At Bonneville, except for two outliers, the Sunset analyzer has similar total carbon concentrations as the IAS sampler. The outliers contribute substantially to a lowered r^2, low slope, and high intercept.
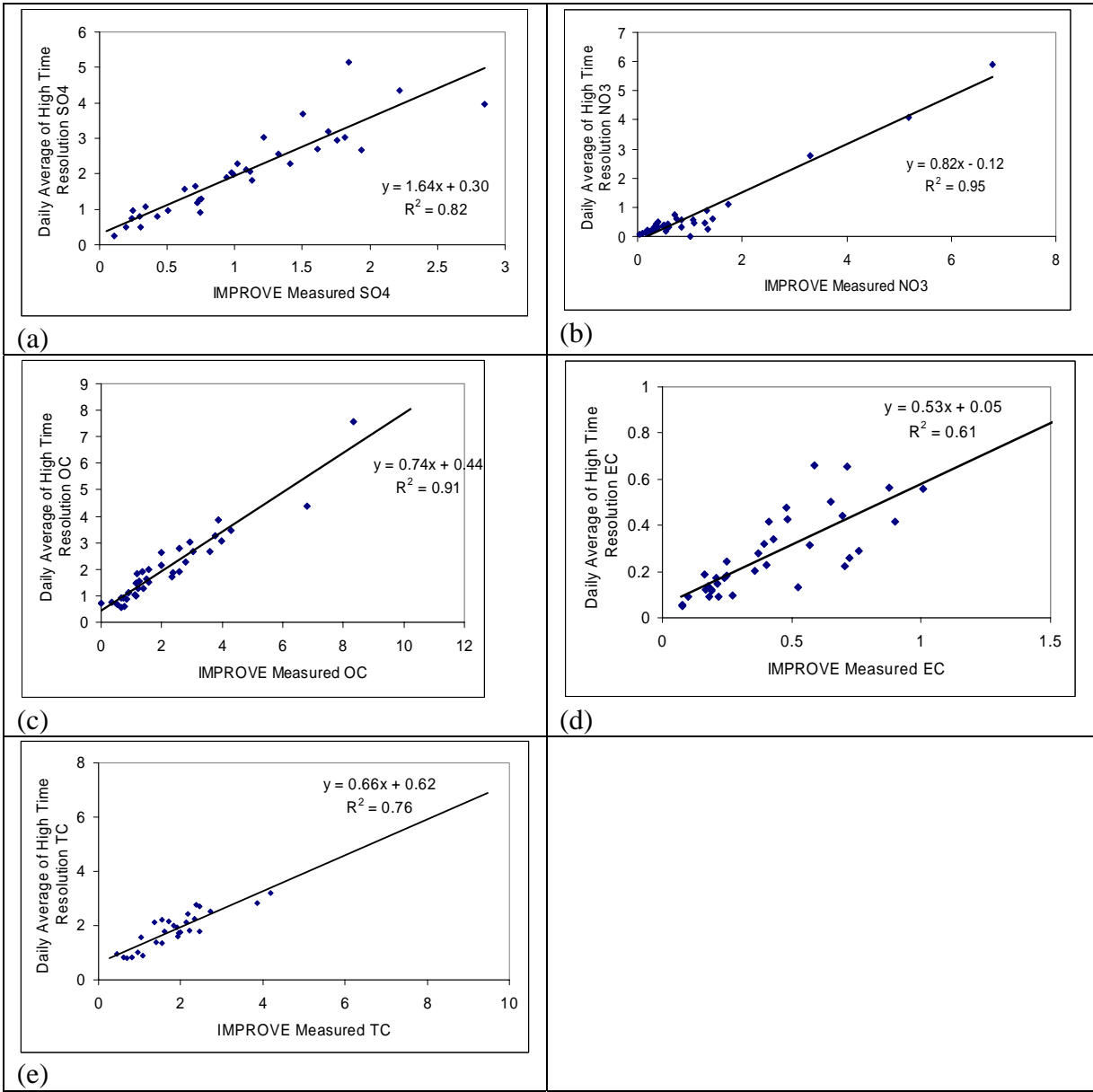
Figure 2-1. Comparison between 24-hour averages of high time-resolved: a) SO_4^{2-}, b) NO_3^-, c) OC, d) EC, and e) TC and measurements and IMPROVE daily filter measurements at Mt. Zion.

Figure 2-2. Comparison between 24-hour averages of high time-resolved: a) SO_4^{2-}, b) NO_3^-, c) OC, d) EC, and e) TC measurements and IMPROVE daily filter measurements at Wishram.
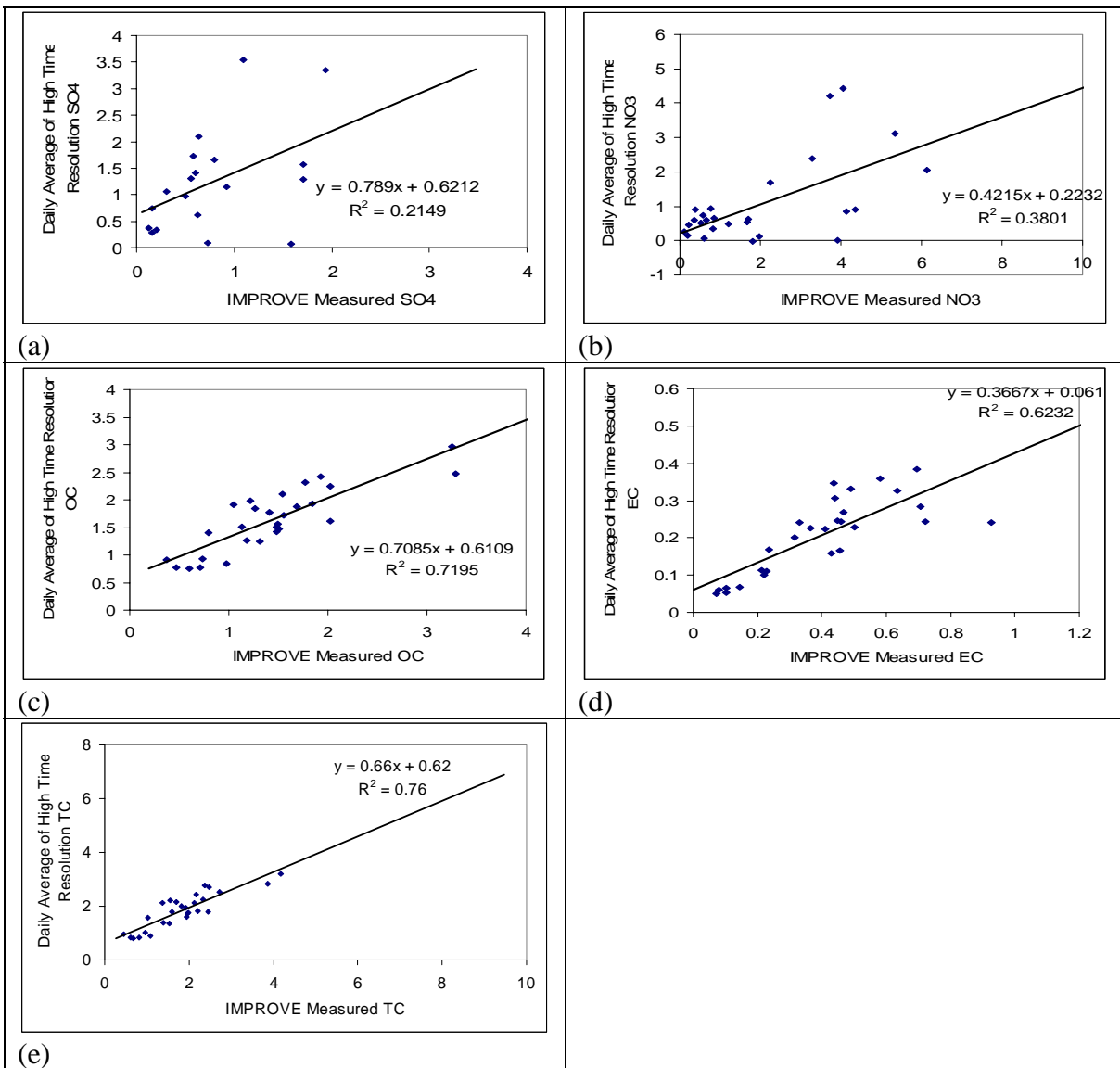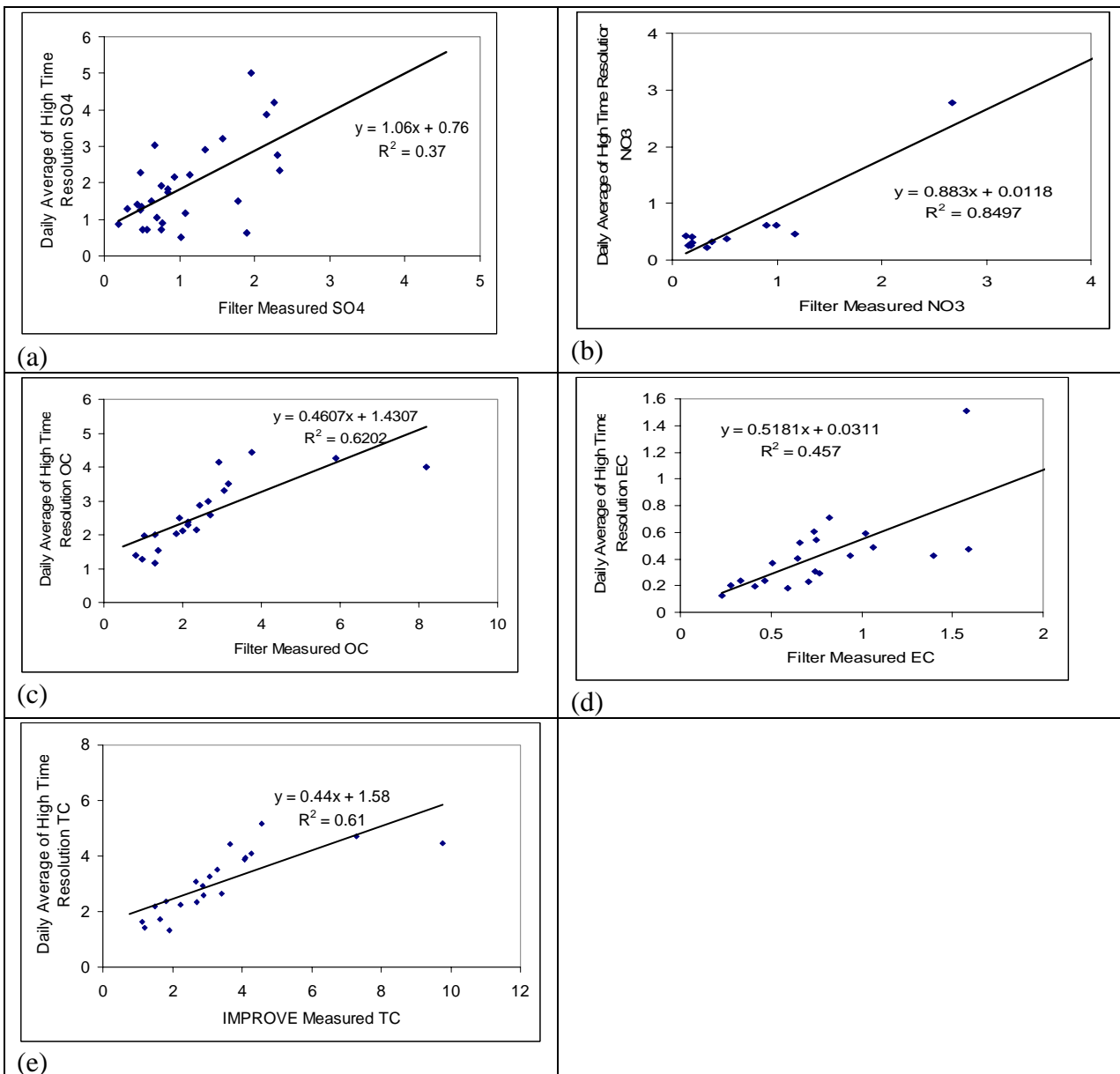
Figure 2-3. Comparison between 24-hour average of high time-resolved: a) SO_4^{-2}, b) NO_3^-, c) OC, d) EC, and e) TC measurements and daily IAS filter measurements at Bonneville.

ii) Comparison of measured and IMPROVE sampler reconstructed light scattering

The Radiance Research and Optec nephelometer data from Mt. Zion and Wishram were compared to the reconstructed light scattering using the IMPROVE data at these sites (see Table 2-4). The standard IMPROVE reconstructed scattering equations (revised 2006) were used. Daily average f(RH) from hourly measurements were used, but were limited to the f(RH) at 50% for comparison to the Radiance nephelometers. Measured and reconstructed scattering compared well for both sites and both types of nephelometers.

Table 2-4 Measured versus reconstructed light scattering by particles (b_{sp}) using IMPROVE aerosol data and Optec and Radiance Research nephelometers is shown below.

Mt. Zion	Regression	r^2
Optec	Reconstructed b_{sp}=0.94*measured + 7.17	0.88
Radiance	Reconstructed b_{sp}= 0.96*measured +8.58	0.87
Wishram	Regression	r^2
Optec	Reconstructed b_{sp}=0.96*measured + 3.96	0.91
Radiance	Reconstructed b_{sp}= 1.02* measured +5.45	0.85

iii) Conclusions regarding quality of data and its appropriate uses

The surface meteorology data, the nephelometer data, and the IMPROVE data are of sufficiently high quality for quantitative use to determine extinction budgets, source-receptor relationships, and to evaluate meteorological and air quality model performance.

The other measurements should be considered more semi-quantitative and are useful for timing of changes in aerosol components and determination of main components contributing to high nephelometer measurements. They are most useful for episode analysis. The high-time resolution data did an adequate job of reconstructing light scattering measured by the nephelometers.

3) Emission Inventory

a) Inventory Approach

An emission inventory (EI) is an itemized list of emission estimates for sources of air pollution in a given area for a specified time period (annual and seasonal emissions). Based on the types and amounts of emissions the EI can be used to develop an understanding of the sources that may impact the Scenic Area. Sources are either man-made or natural sources. The EI includes emissions from point sources (e.g., industry), mobile sources (e.g., motor vehicles, ships, trains, and aircraft), area sources (e.g., woodstoves, outdoor burning, paint and solvent use, and small, non-permitted point sources), and natural sources (e.g., emissions from sources such as vegetation, wild fires, and volcanic activity). As such, judging any source category's contribution to impairment requires that we evaluate emissions, their chemical transformation, and meteorological conditions.

The Gorge Technical Team identified the Western Regional Air Partnership (WRAP) emission inventory and EPA's National Emissions Inventory (NEI) as inventories that would provide a foundation for developing the Gorge EI. The Gorge EI was developed in order to run the Comprehensive Air Quality Model (CAMx) for the assessment of haze in the Gorge. The selected model output years included a 2004 "base year" and a 2018 "future year".

The 2004 base-year emissions inventory (EI) was created for input to CAMx and subsequently the model output concentrations were compared to actual 2004 monitoring data conducted in the Gorge. August and November 2004 were chosen as representative episodes because visibility impairment was at its greatest during those periods. For the "future year" comparison, the Technical Team selected 2018 because the WRAP EI was already projected to that year. It allowed for the Gorge modeling to be compared with the WRAP regional modeling for visibility and regional haze.

For EI analysis and reporting, two specific days were chosen from the episodes for each year to provide a snapshot of the emission inventory (August 18 and November 12). During the analysis, the team learned that the PGE Boardman power plant was shut down on November 9th and 10th, prompting the selection of November 12th for data analysis.

EI Area of Concern
The area included in the emission inventory encompassed sixty-nine Washington and Oregon counties and three Native American reservations. These counties were determined to be most likely to influence visibility in the Scenic Area.

Creating the 2004 Inventory
Oregon and Washington provided 2004 annual emissions data for point sources as these sources are required to report their emissions each year. For area sources and non-road sources such as locomotives, aircraft, and marine vessels, Oregon and Washington grew 2002 NEI emissions to 2004. For all other non-road vehicles and equipment Oregon and Washington ran the EPA NONROAD2005 model to generate daily emissions.

For on-road sources, ENVIRON generated the 2004 emissions by running MOBILE6.2 within CAMx using MOBILE6.2 model inputs provided by Oregon and Washington. This provided hourly and daily emissions data. For the remaining emissions categories where the states could not provide updated 2004 inventory information, Alpine Geophysics took the 2002 WRAP inventory and filled those data gaps by growing the emissions to 2004.

Further adjustments to the 2004 inventory were made, including the reduction of the emissions estimates from residential wood smoke and an increase to ammonia emissions from agricultural operations. The wood smoke reductions were made based upon a recommendation by Oregon DEQ with verification from the Washington Department of Ecology. The increase to ammonia emissions was the result of investigation into more recent EI methodology by Alpine Geophysics and the Oregon DEQ.

Creating the 2018 Inventory
The source of the 2018 EI for the Gorge air quality study was the 2018 EI developed by WRAP. When WRAP developed the 2018 EI, it projected its 2002 base year inventory using EPA's Economic Growth and Analysis System (EGAS) growth factor, US Energy Information Administration (EIA) energy projections, and USDA agricultural projections. Vehicle miles traveled (VMT) growth assumptions for on-road mobile reflect the region's local travel forecast.

Other source categories, such as emissions for wildfires and windblown dust were held constant from 2004 to 2018. Additional adjustments were made to the 2018 WRAP inventory to incorporate expected impacts from EPA rules (including BART) that had been promulgated since WRAP developed its 2018 base inventory.

Projection Anomalies for the 2018 EI
When reviewing early computer modeling output results for reasonableness, the Technical Team discovered a few anomalies in the emission inventory that warranted further investigation. A closer inspection of the inventory revealed that some of the emissions projections for 2018 were inappropriately grown by WRAP and one source was incorrectly located for 2004. The original growth projections developed by WRAP using EPA's EGAS model grew certain industrial point sources to projections that were unrealistic for Pacific Northwest conditions and economic expectations. EGAS generates an EPA Source Classification Code (SCC)-specific growth factor for a specified geographic area using various socio-economic data. More specific county-level growth factors were not applied by WRAP because the county level socio-economic data was not available at the time. Therefore, the EGAS model only generated growth factors at the state level, resulting in default growth factors for source categories and less specific growth information that could be applied if grown by Oregon and Washington themselves. For example, the Technical Team identified an unrealistic increase in emissions from one industrial point source in the In-Gorge region. A secondary aluminum production facility was the source of the increased emissions. [A detailed description on the EI projection, including a representation of what an "adjusted" EI would look like after utilizing new 2018 projections for industrial point sources is provided in the "*Columbia River Gorge Air Quality Study - Emission Inventory Report*".]

Other minor inconsistencies were discovered during the EI analysis. For example, fugitive dust emissions were not accounted for in the East of Gorge region for 2018. Also, an industrial source located in the West of Gorge area had its 2004 emissions incorrectly attributed to the Northwest of Gorge area. In 2018, however, its emissions were correctly attributed to location in the West of Gorge area. While each of these EI projection errors is noted in the EI report, corrections were not incorporated into the modeling due to budget and time constraints. It was also believed that these changes would not significantly change the overall results.

Temporal and Spatial Allocation of Emissions Data within the Domain
Alpine Geophysics processed the emissions inventory data through the Sparse Matrix Operator Kernel Emissions (SMOKE) processing system to convert the data to the resolution needed by the CAMx model. Much of the EI data was in annual form and to conduct model to monitoring analysis, the inputs for CAMx had to be specific to each episode day. As such, SMOKE was used to allocate the data to episode days in August and November.

In an effort to obtain a better understanding of source contribution from specific areas within the modeling domain, the Technical Team divided up the modeling domain into 5 regions: In-Gorge (encompasses the Gorge Scenic Area), Portland (metropolitan Portland and surrounding areas), Northwest of Gorge (Oregon and Washington counties bordering the Columbia River below Multnomah County), West of Gorge (all other areas west of the Gorge area), and East of Gorge (all other areas east of the Gorge area). These regions are referred to as PSAT regions since analysis of these regions was further conducted using the CAMx PM Source Apportionment Technology (PSAT) modeling tool. Alpine Geophysics processed the emissions estimates through SMOKE to allocate the data to PSAT regions.

b) Emissions Inventory Summary

To help obtain a better understanding of source contributions within the Gorge modeling domain, Figure 3-1 shows the emissions by pollutant for the five PSAT regions. The reader should refer back to Figure ES-2 on Page iv to remember the geographical coverage of each of these five PSAT regions.

The contribution of pollutants from In-Gorge, Portland, and Northwest of Gorge is relatively small compared to West of Gorge and East of Gorge emissions. In particular, the In-Gorge contribution is very small in comparison to all the other regions. One reason for the significant emissions from the other areas is primarily due to the larger areas that the West of Gorge and East of Gorge regions encompass. Emissions from the Puget Sound area (Seattle, Tacoma, Olympia) and the Southern Willamette Valley (Salem, Eugene, Corvallis) are included in West of Gorge emissions. The East of Gorge region covers vast areas of Eastern Oregon and Washington.

As Figure 3-1 below shows, VOC emissions comprise the largest pollutant category at 5,000 tons/day. While VOC emissions contribute to the formation of ozone, the primary pollutants impacting visibility in the Gorge are organic carbon (a component of $PM_{2.5}$), nitrogen and sulfur oxides. These pollutants all have the ability to absorb or scatter light, affecting visibility. $PM_{2.5}$ and NOx contribute the second largest amount of pollutants on average for each region, with 1,500 tons/day and 1,100 tons/day respectively.
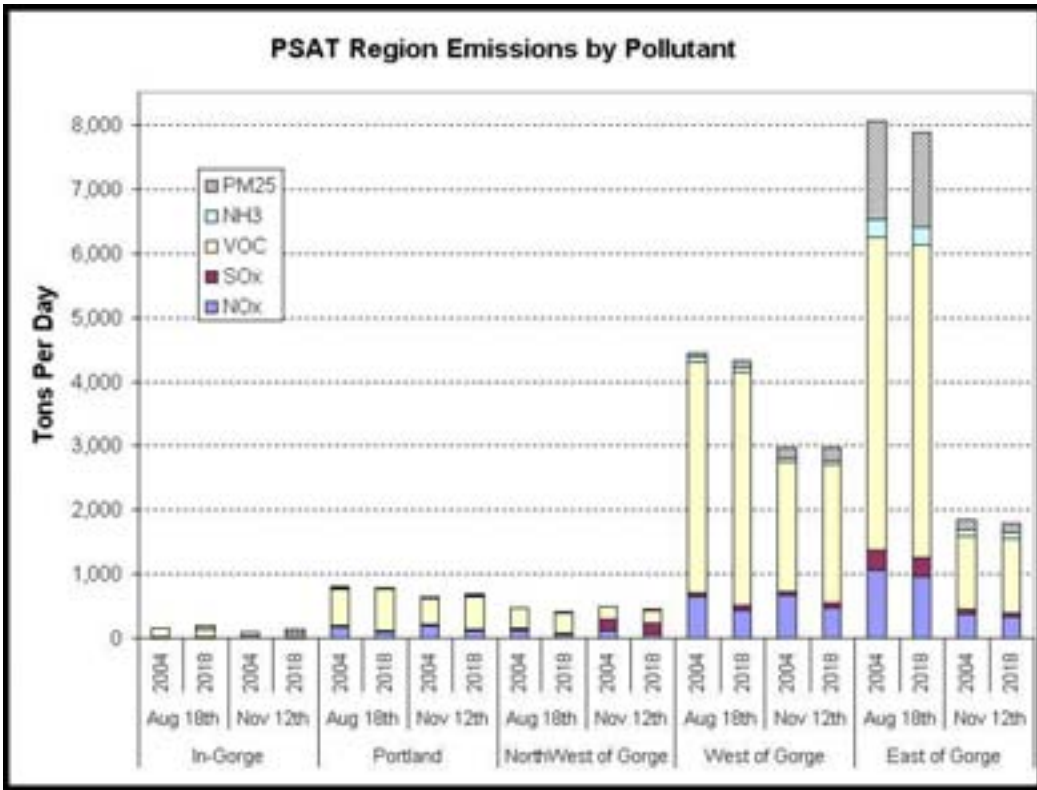

Figure 3- 1: PSAT Region Emissions by Pollutant

In understanding the types of emissions being contributed to the Gorge Scenic Area, Figure 3-2 provides a comparison of natural and man-made sources. The amount of natural source contribution to the Gorge accounts for most of pollutant emissions in comparison to man-made emissions. The natural source contribution comes from a number of sources including vegetation (a significant component of the VOC pollutant emissions) and wildfires (responsible for $PM_{2.5}$ emissions). Natural sources and wildfires comprise 66% of the emissions shown in Figure 3-2. In August, with the prevalence of wildfires, these sources comprise 77% of emissions.
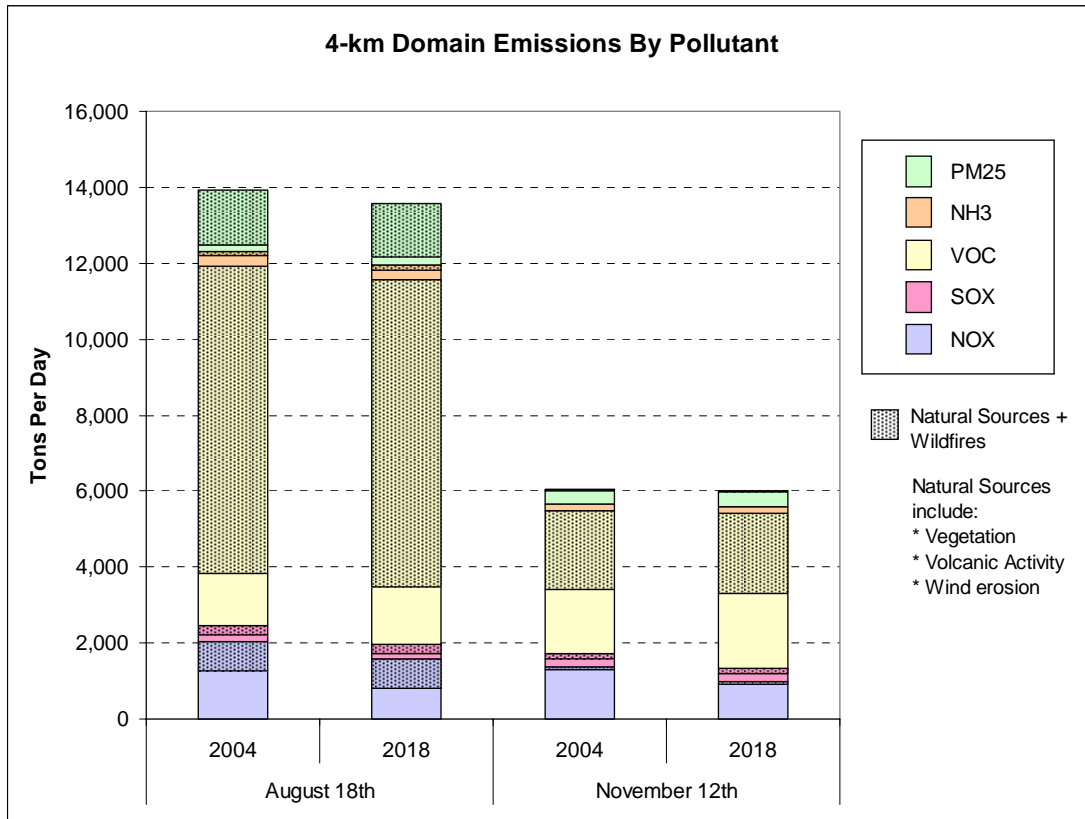

Figure 3- 2: Natural Source vs. Man-Made Source Pollutant Contribution (Domain-Wide)

To put forest fire emissions into perspective, Table 3-1 below shows the magnitude of wildfire emissions compared to PSAT region non-wildfire emissions. On August 18th 2004, wildfires emitted 81 times the amount of $PM_{2.5}$ as all other sources within the Portland region.

Table 3-1. August 18th 2004 Magnitude of Wildfire Emissions Comparison

Wildfire, Tons Per Day					
	VOC	SOX	NOX	NH3	PM25
4-km Domain	1,356	247	559	117	1,375

4 km Domain, Non-Wildfire, Tons Per Day					
Region	VOC	SOX	NOX	NH3	PM25
In-Gorge	120	3	26	2	4
Portland	564	16	184	15	17
NorthWest of Gorge	309	43	111	5	9
West of Gorge	3,596	46	653	76	60
East of Gorge	3,515	67	512	163	160

Wildfire Tons Per Day Divided by the Non-Fire Tons Per Day: Magnitude of Wildfire Emissions Compared to Non-Wildfire Emissions by Region					
Region	VOC	SOX	NOX	NH3	PM25
In-Gorge	11	98	22	56	352
Portland	2	15	3	8	81
NorthWest of Gorge	4	6	5	23	156
West of Gorge	0	5	1	2	23
East of Gorge	0	4	1	1	9

Figures 3-3 through 3-7 show the NH$_3$, NOx, PM$_{25}$, SOx, and VOC emissions inventory data in tons per day for the 4-km modeling domain, episode days of August 18th and November 12th, for base and future year episodes. Figure 3-3 shows the emissions for NH$_3$. The primary source of emissions is from area sources, in particular agriculture and livestock emissions. Wildfire emissions also contribute to the August episodes.

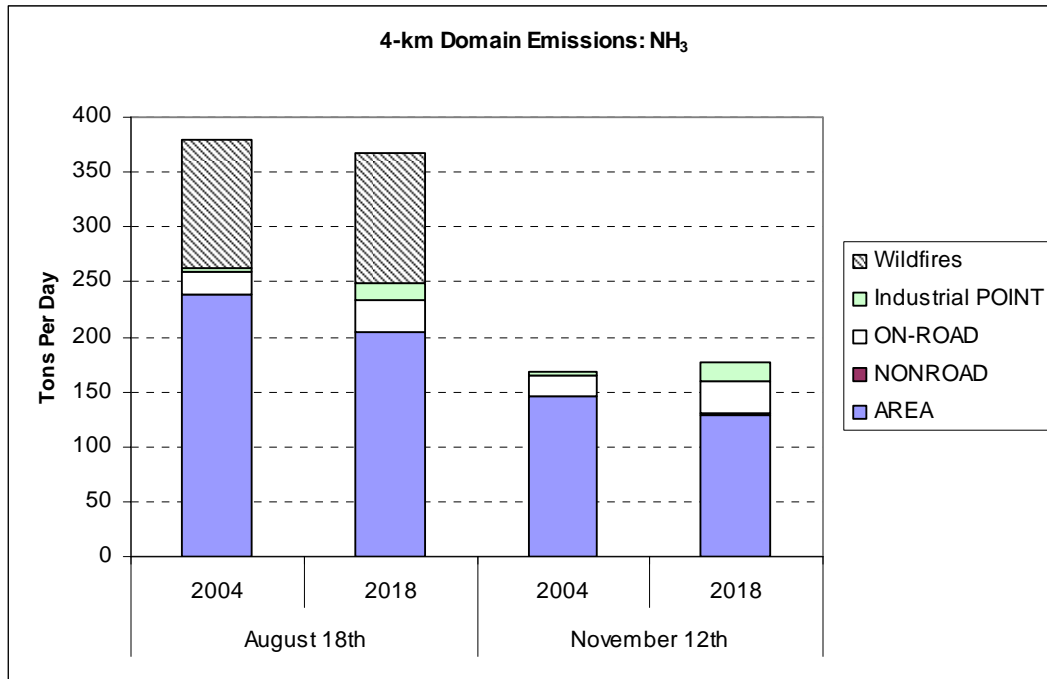**Figure 3-3.** Ammonia emission inventory data

Figure 3-4 shows the NOx emissions for the 4-km modeling domain. For the August episode, wildfires and on-road sources (such as automobiles) are the main contributors of NOx emissions. In November, both on-road sources and non-road sources (locomotives, and commercial marine vehicles) dominate.
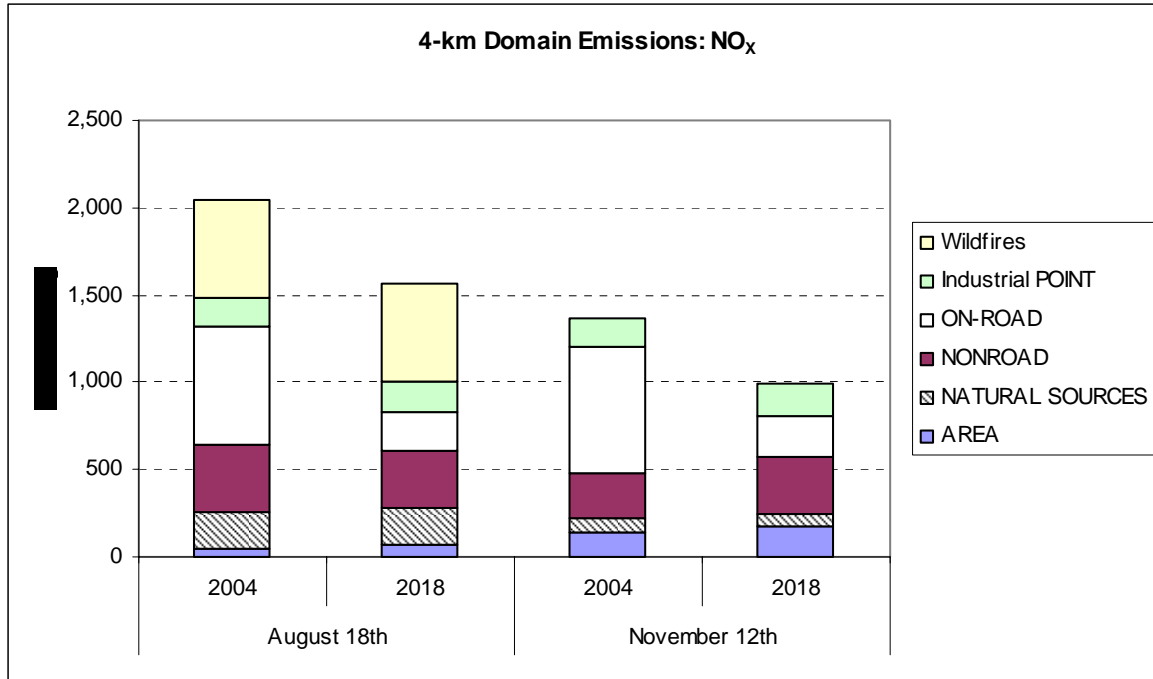
Figure 3-4. Nitrogen oxide emission inventory data

In Figure 3-5, the PM$_{2.5}$ emissions are shown for the 4-km modeling domain. Wildfires are the dominant source for the August episode, comprising over 75% of the overall emissions. In November, area sources contribute the most emissions, primarily from residential wood burning.

Figure 3-5. PM$_{2.5}$ emission inventory data

Figure 3-6 shows VOC emissions for the 4-km modeling domain. Wildfires dominate both the August and November episodes.

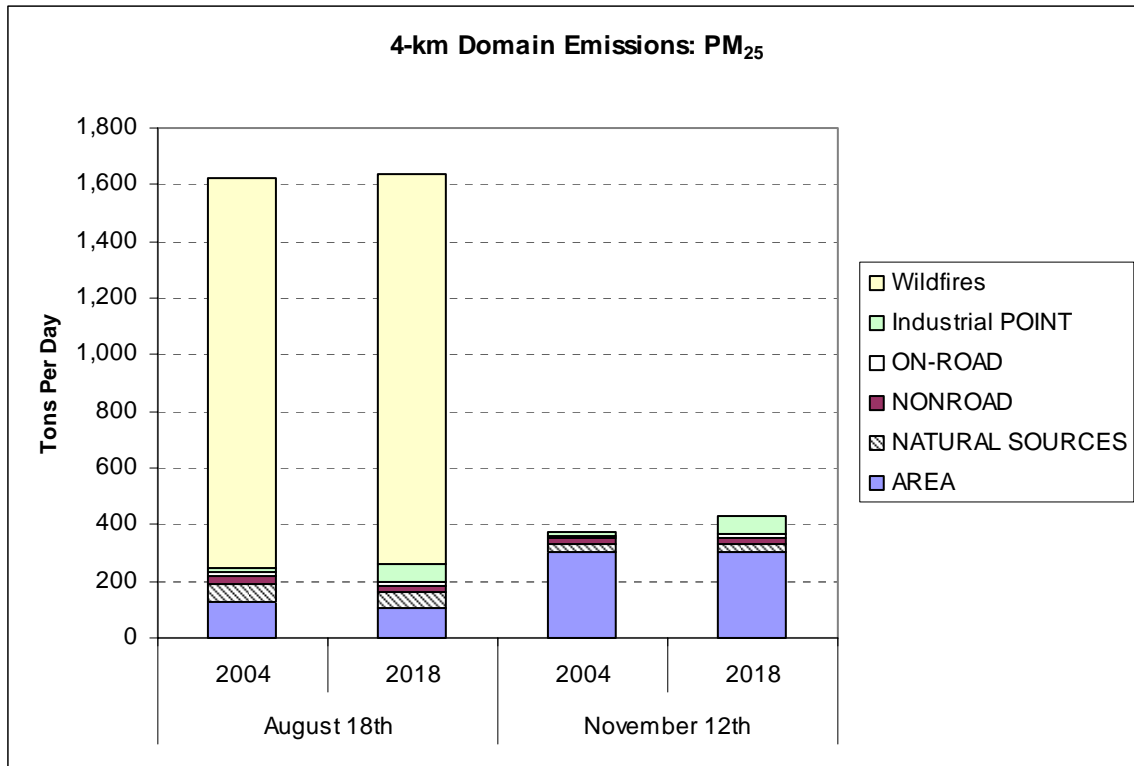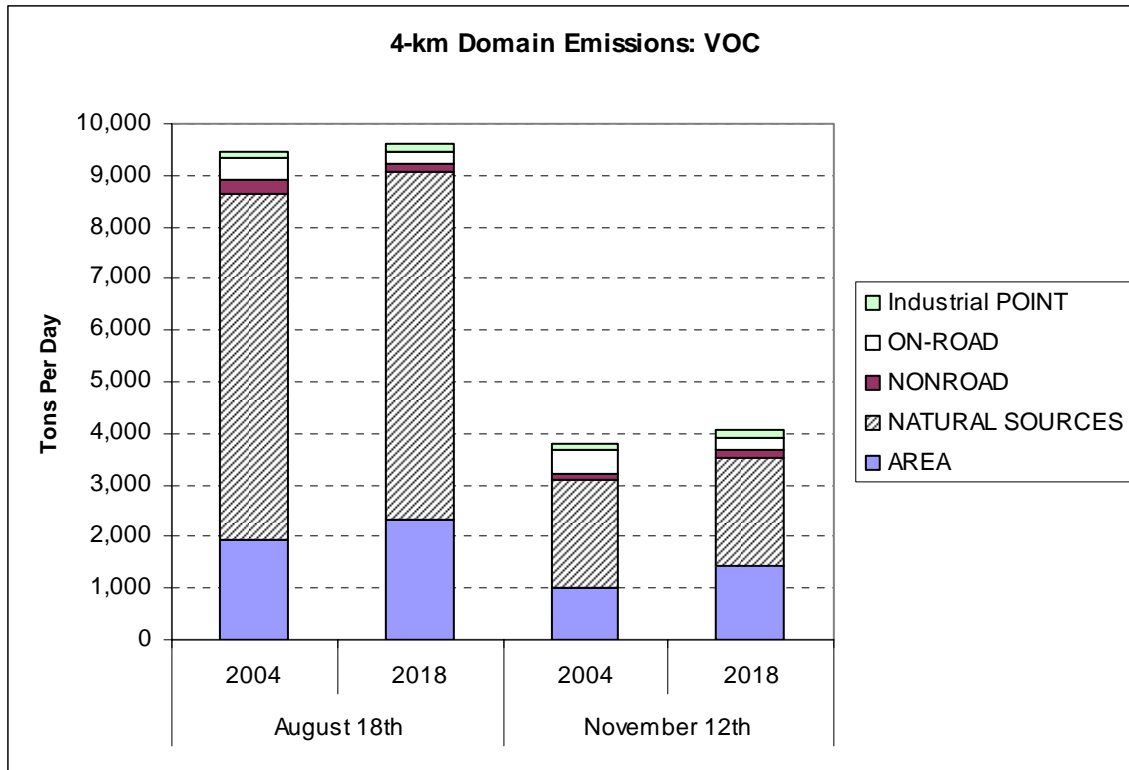**Figure 3-6.** Volatile organic compound emission inventory data

In Figure 3-7, SOx emissions are shown for the 4-km domain. Natural sources, such as wildfires continue to dominate the emissions contribution in August and volcanic activity contributes to the November episode.
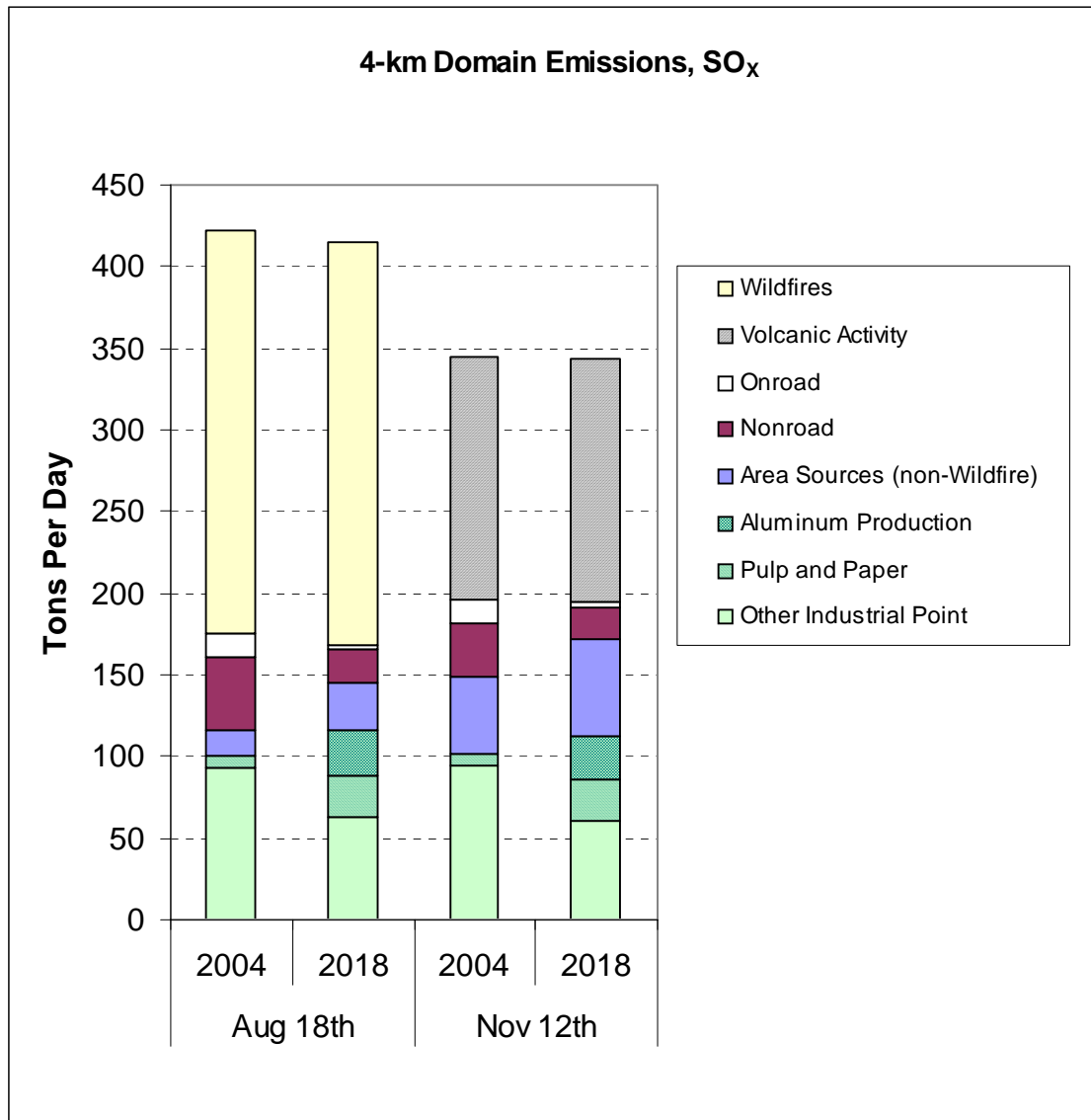
Figure 3-7. Sulfur oxide emission inventory data

As previously discussed in the Projection Anomalies section of this chapter, the pulp and paper and aluminum production growth is considered to be incorrectly estimated in the WRAP 2018 inventory. The incorrect growth is made apparent in Figure 3-7. The incorrect growth accounts for on average 12% of the domain SOx emissions.

Though much can be determined from EI analysis, a complete picture of which sources contribute to visibility impairment in the Gorge is more accurately obtained from monitoring and modeling data, as described in Chapters 2, 4, 5 and 7.

4) Characterization of Gorge Meteorology, Air Quality, and Haze

a) Meteorological Regimes and Associated Haze

Material in this section is presented in much more detail in the Final Report for the Columbia River Gorge Haze Gradient Study.

Winds within the Columbia River Gorge are highly channeled and blow from high to low pressure. In summer, northward migration of the Pacific High creates higher pressure offshore. Heating of the Columbia River Basin creates a thermal low pressure east of the gorge. Thus a substantial pressure gradient exists through the gorge, causing consistently westerly flow through the gorge in summer. In winter, conditions are more variable but easterly flow is common. With synoptic scale high pressure areas over the interior western United States and Pacific low pressure systems typically to the west, east to west pressure gradients are common. The high pressure to the east is often enhanced by the development of "cold pools" in the Columbia Basin. These cold pools formed by strong radiational cooling are associated with light winds, moisture, and a buildup of pollution in the Columbia Basin. In the gorge, air accelerates in response to the along-gorge pressure gradient and becomes generally stronger as it traverses the gorge from east to west.

In order to organize the approximately 600 day study period (July 1, 2003 to February 28, 2005), a cluster analysis was done to obtain a small number of clusters for which common diurnal wind patterns were observed. It was hypothesized that days with similar winds at each monitoring site, including their diurnal variation, should be similarly affected by transport from sources.

Five basic wind patterns were identified and named as follows: strong westerly; moderate westerly; light westerly; light easterly; and winter easterly. Winter easterly was named as such because it occurred mainly in winter and never between May and September. Figure 4-1 shows the daily average westerly wind component at each site for the five wind patterns.

All sites show a consistent decrease in average westerly wind speed from strong westerly to winter easterly. Strong westerly, moderate westerly, and light westerly increase in speed with distance eastward into the gorge until Towal Road, which has lower speeds than Wishram. Winter easterly is light at the east end of the gorge and generally increases in speed toward the western gorge. At the easternmost sites, weak easterly had weak net westerly flow with periods of easterly flow and a diurnal change in flow direction. At western and central gorge sites weak easterly had easterly flow all hours of the day. Figure 4-2 shows the frequency of each wind pattern by month. March though June had data only from one year (2004); all other months had data from two years.
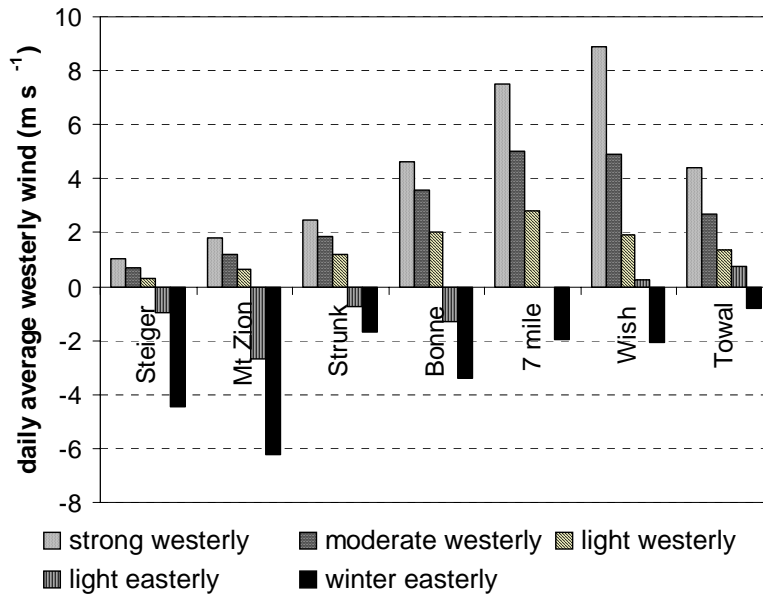
Figure 4-1. Daily average westerly wind component (m sec^{-1}) by monitoring site.
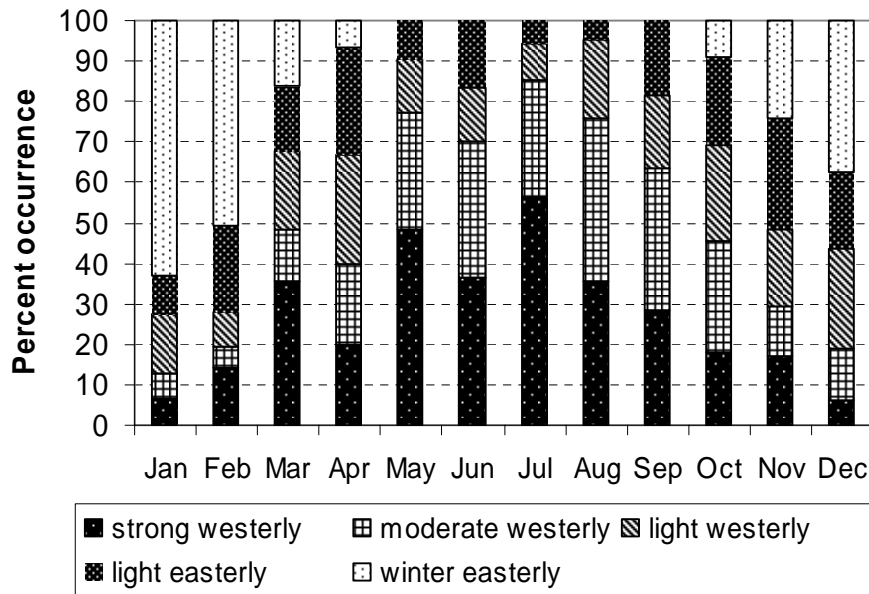
Figure 4-2. Frequency of wind pattern type by month.

Strong westerly occurs mainly in summer, peaking in frequency in July. Moderate westerly peaks in the late summer to early fall (August-October). Light westerly occurs throughout the year, with a peak in the transition months April and October. Light easterly is another transition pattern, peaking in April and November. Winter easterly is a winter-time pattern and never occurred from May – September.

Figure 4-3 gives daily average b_{sp} at each site for each wind pattern. The following observations are noted:

1)   For all sites except Steigerwald, winter easterly has the highest average b_{sp} of all clusters. As the highest b_{sp} levels are at the easternmost site, it suggests that sources to the east of the gorge are the main sources responsible for the haziest days. For all sites, strong westerly has the lowest average b_{sp}. Thus, the most typical summer pattern and most typical winter pattern have the lowest and highest b_{sp}, respectfully for nearly all sites.
2)   The eastern sites (from Memaloose east) have much larger variations in average b_{sp} between clusters than do the other sites (Steigerwald, Mt. Zion, Strunk, and Bonneville).
3)   For the four eastern gorge sites, average b_{sp} is inversely proportional to the westerly flow component.
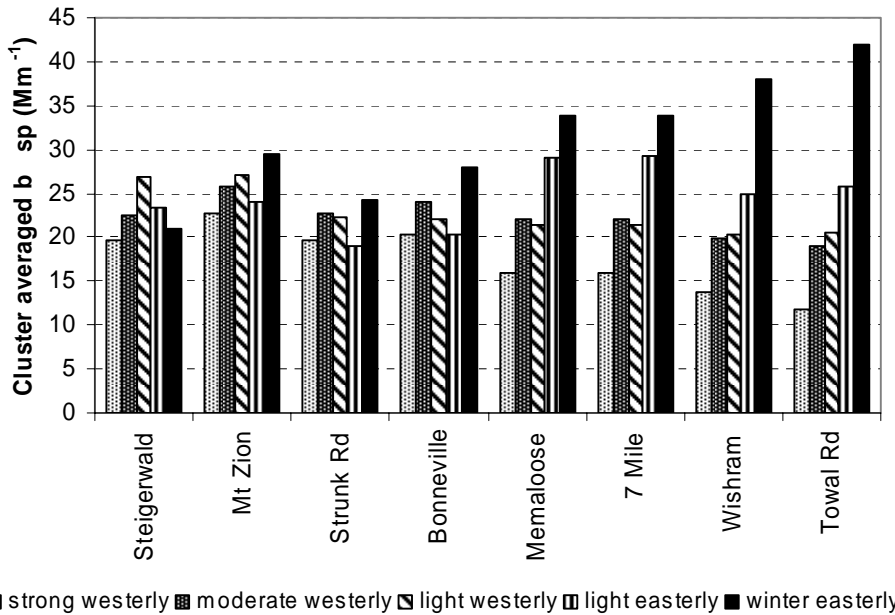
Figure 4-3. Daily average b_{sp} (Mm^{-1}) for each wind pattern type.

Figure 4-4 shows the average b_{sp} by time of day for four sites in the western and central gorge for June through August. Winds in June through August are nearly always westerly, typically increasing in speed during mid- morning to early afternoon in the western and central gorge. As winds increase from the Portland/Vancouver urban area, b_{sp} increases first at the westernmost gorge site of Steigerwald and then at Mt. Zion and Strunk Road, and finally at Bonneville. This pattern suggests transport of a pulse of hazy air from the urban area through the gorge. Later in the day as winds and vertical mixing increase and the air spends less time over the urban area b_{sp} levels decrease.
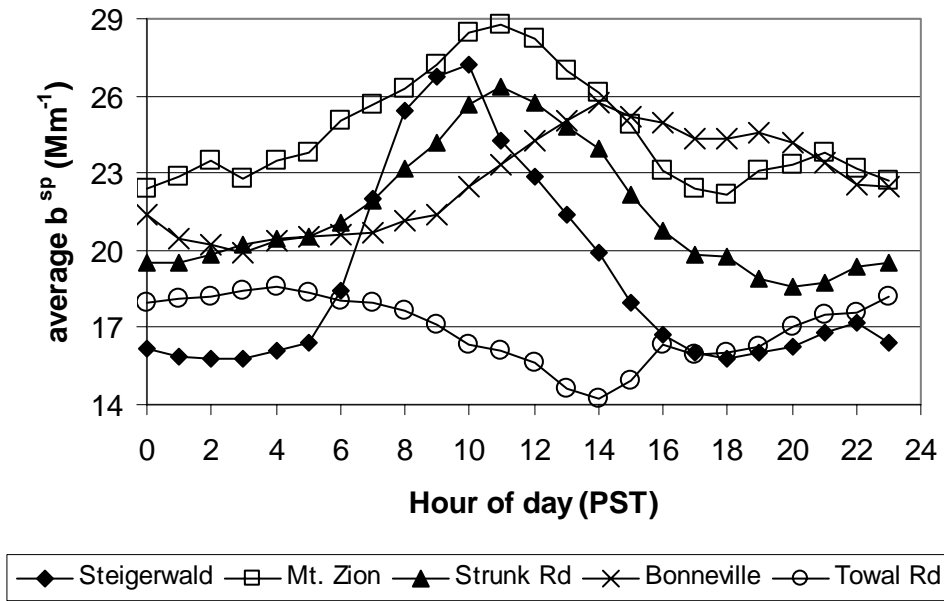
Figure 4-1. Diurnal variation in b_{sp} for four western and central gorge sites and one eastern gorge site, summer (June-August). Note the eastern propagation of higher b_{sp} levels late morning to early afternoon at the western and central gorge sites.

Light easterly showed an increase in b_{sp} from Wishram to Sevenmile Hill and Memaloose, suggesting impact from The Dalles area. Bonneville shows diurnally consistent easterly flow for light easterly, while Sevenmile Hill, Wishram, and Towal Road showed diurnal variation in flow direction (westerly and easterly both) during light easterly days. Figure 4-5 shows the diurnal variation in westerly wind component and b_{sp} at Sevenmile Hill for light easterly days. At 7 am the wind direction changed from westerly to easterly and average b_{sp} increased over the next few hours from about 29 Mm^{-1} to 38 Mm^{-1}. Sevenmile Hill is located nearly directly above The Dalles. As the wind changes direction and comes from The Dalles, b_{sp} increases. This increase suggests contributions to haze from local sources in the area of The Dalles.
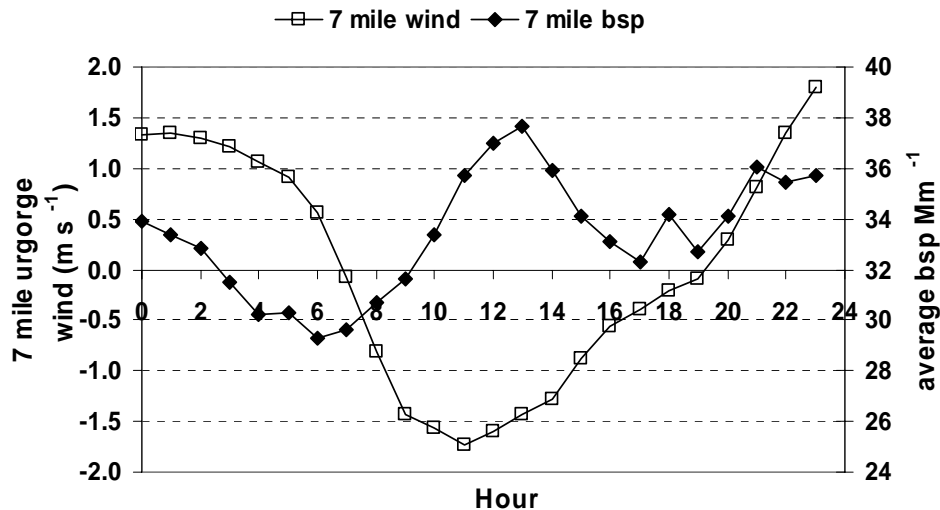
Figure 4-2. Sevenmile Hill westerly wind component and b_{sp} for the light easterly pattern.

The effect of precipitation on b_{sp} was considered by using precipitation data for Portland and The Dalles. With some exceptions, days without precipitation have considerably higher b_{sp} than days with precipitation at one or both sites. In most cases, days with precipitation at The Dalles have the lowest b_{sp}. Most days that had precipitation at The Dalles also had precipitation at Portland; this implies widespread precipitation resulting in scavenging of aerosol by precipitation throughout the Gorge.

b) Temporal Variation of Aerosol Components and Light Scattering Over the Entire Study Period

Here we consider the variation in aerosol component concentrations and measured and reconstructed light scattering over the study period. Figure 4-3 shows the reconstructed fine mass at Mt. Zion from July 2003- December 2004. Figure 4-4 shows the same for Wishram. Figure 4-5 and Figure 4-6 show reconstructed extinction by aerosol component for Mt. Zion and Wishram, respectively. Figure 4-7 shows the daily averaged measured particle light scattering by site (from the Radiance Research RH controlled nephelometers). Daily average scattering tracks well among the nine nephelometer sites. Values tend to be relatively low in spring and summer and higher in autumn and winter.

The reconstructed fine mass and reconstructed extinction by aerosol component stack bar plots for the two sites (Figures 4-6 to 4-9) reveal several broad patterns. Ammonium sulfate tends to be highest in summer and lower in winter and is generally higher at Mt. Zion than at Wishram. The occasional high winter sulfate concentration tends to be on days with high ammonium nitrate concentration. Ammonium nitrate is highest in the winter months (November to March) and is generally higher at Wishram than at Mt. Zion. Organic mass tends to be highest in the late summer and fall (July to December) and occasionally has large peaks that are seen at both Gorge monitoring sites.

Compared to organic mass contributions, the relative sulfate, nitrate and elemental carbon contributions to light extinction are enhanced while the contribution by fine soil is diminished. This is due solely to the higher extinction efficiency of the sulfate and nitrate at elevated relative humidity (above ~60%) and to the higher extinction efficiency of elemental carbon and lower extinction efficiency of fine soil regardless of humidity compared to the extinction efficiency of organic carbon. As a result during winter, the season of highest relative humidity, nitrates and sulfate are much more important to light extinction than they are to the fine mass concentration.
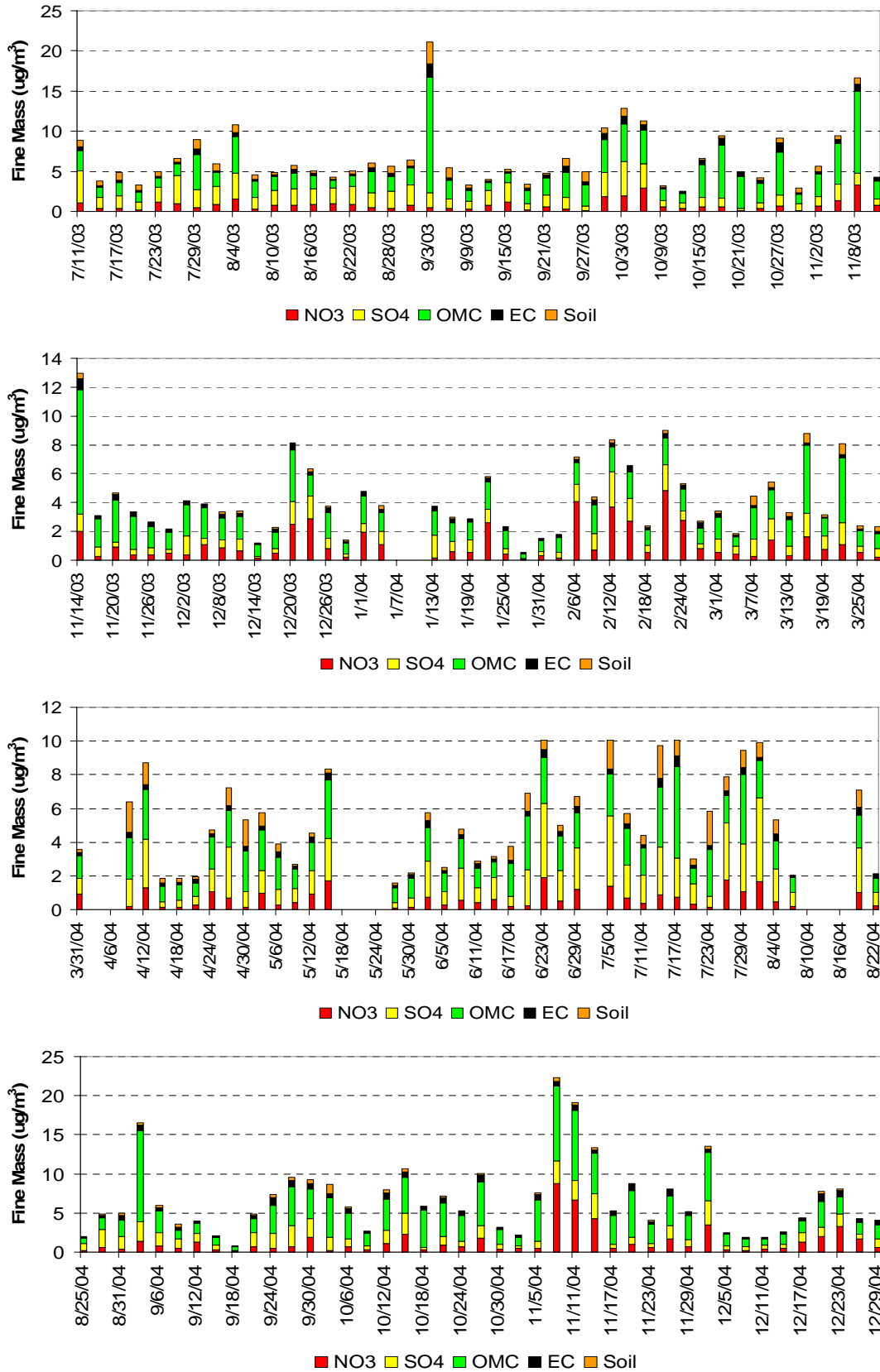
Figure 4-3. Fine mass major components, Mt. Zion July 2003 – December 2004.
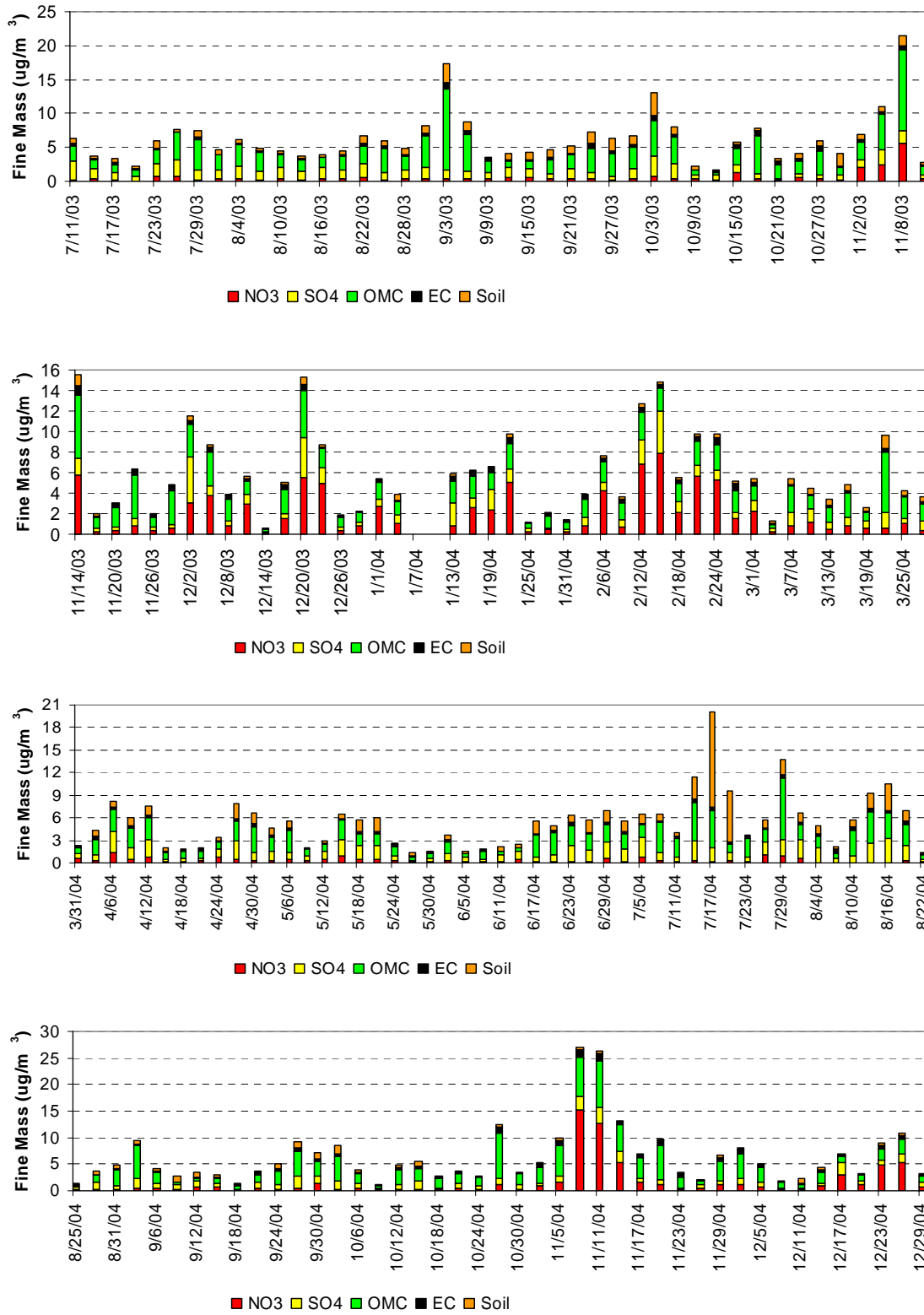
Figure 4-4. Fine mass major components, Wishram July 2003 – December 2004.
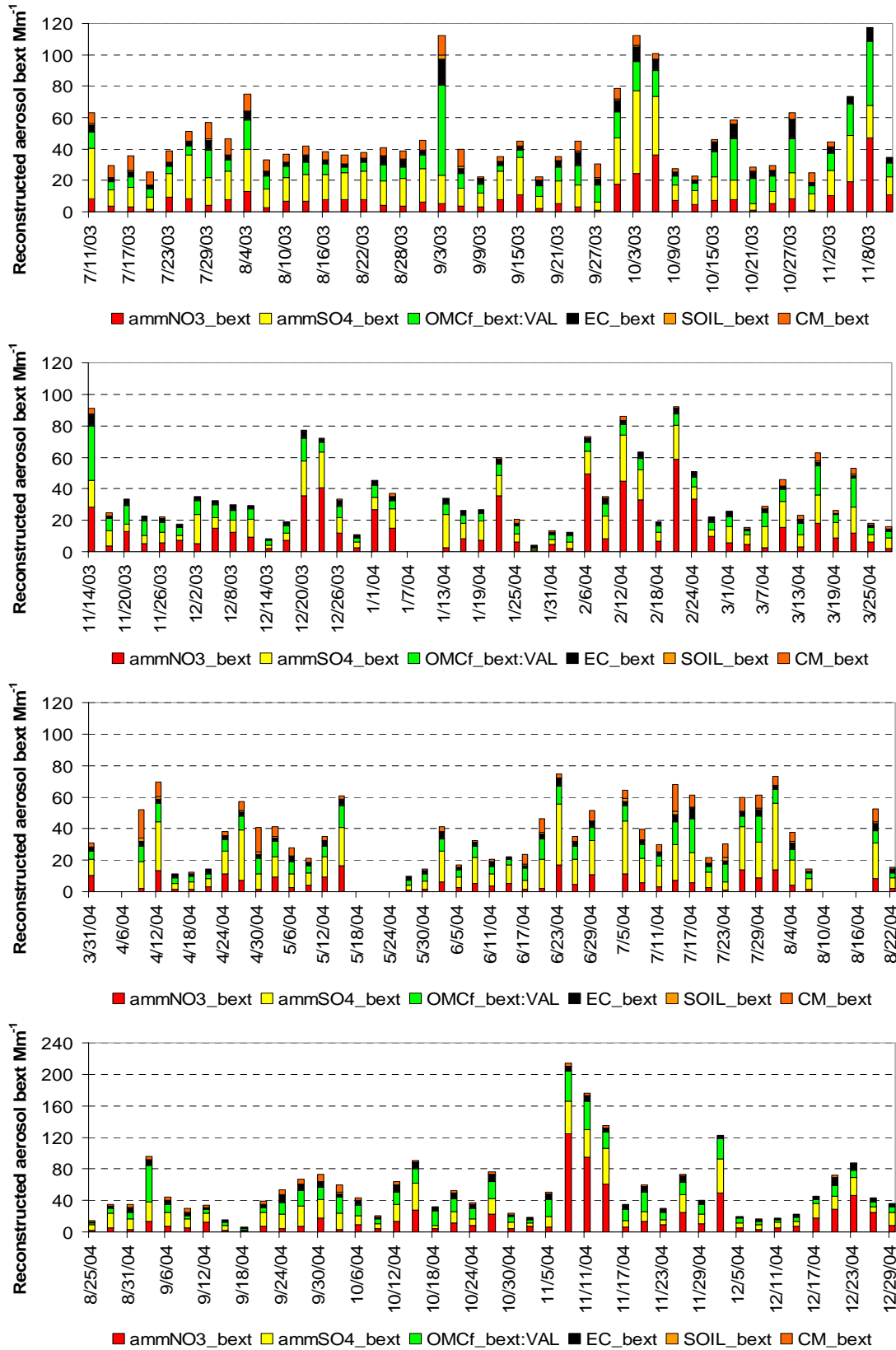
Figure 4-5. Reconstructed light extinction at Wishram, July 2003 – December 2007.
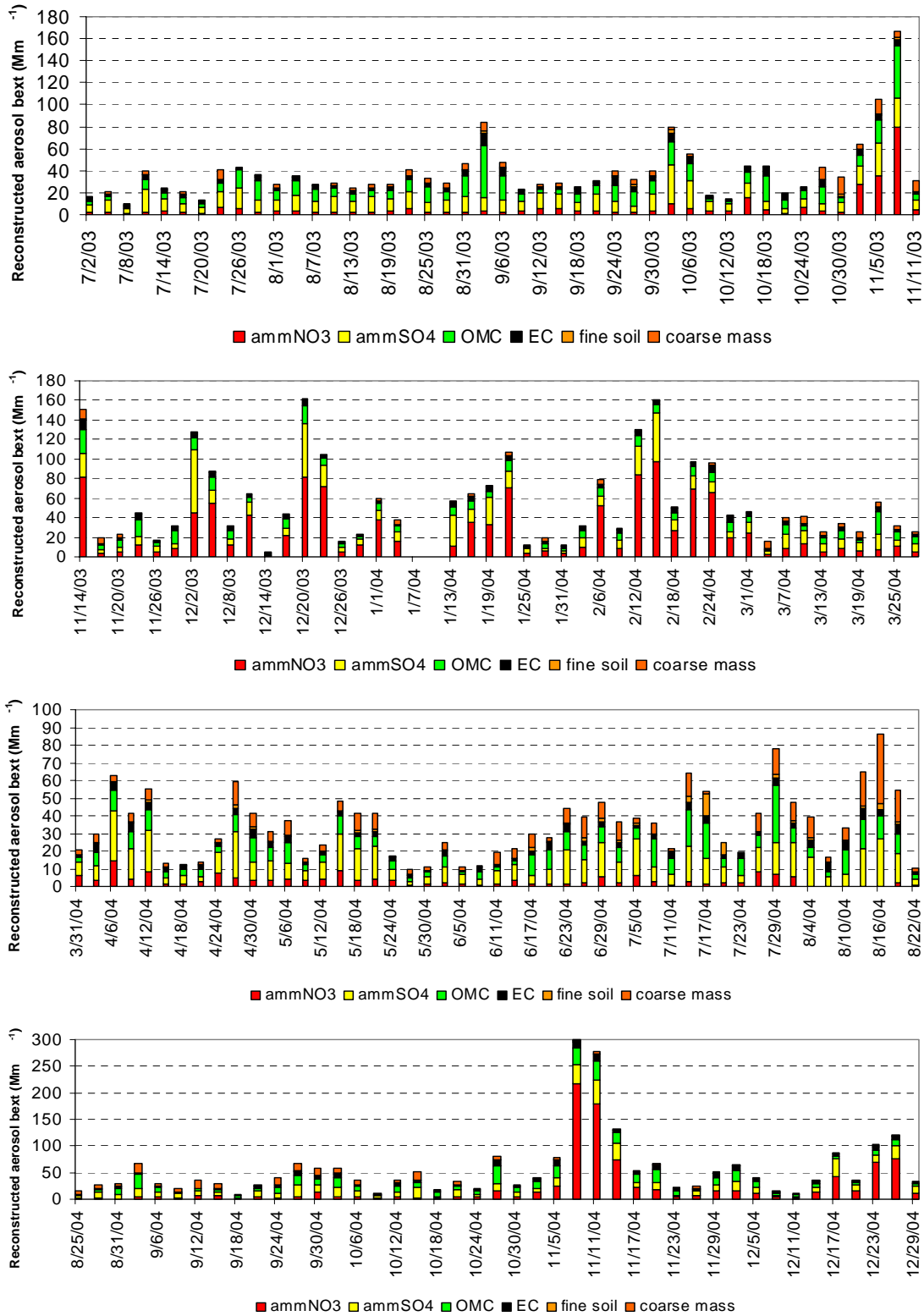
Figure 4-6. Reconstructed light extinction at Mt. Zion, July 2003 – December 2004**.**

The particle light scattering measured by the relative humidity controlled nephelometers at the sites in the Gorge (Figure 4-7) confirms the pattern of greatest haze levels during the winter months. It also demonstrates that the high correlation among the sites throughout the length of the Gorge. While there are haze gradients across the length of the Gorge with the east end hazier in the winter and the west end hazier in the summer, the values at all of the sites tend to rise and fall together.

46
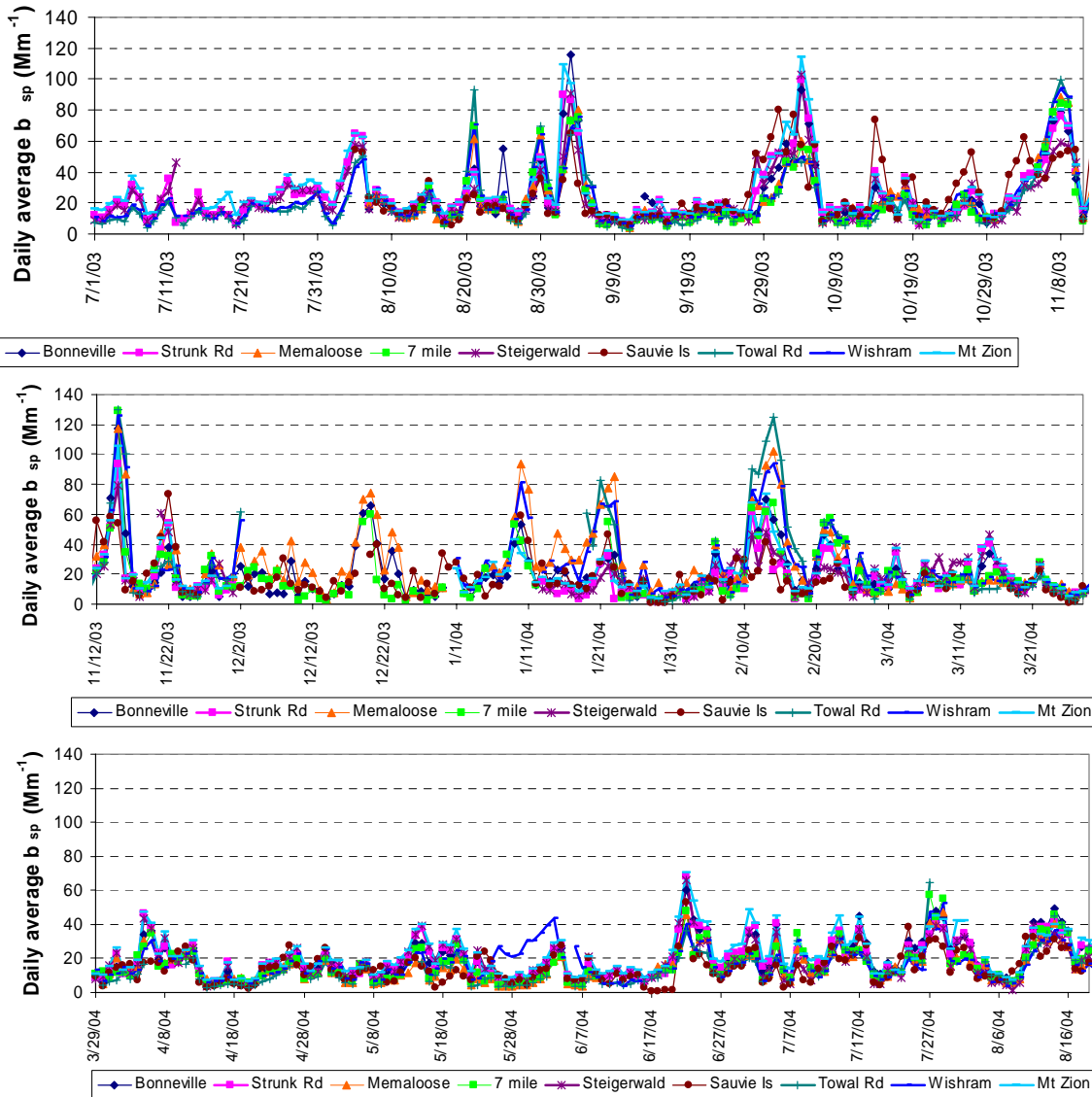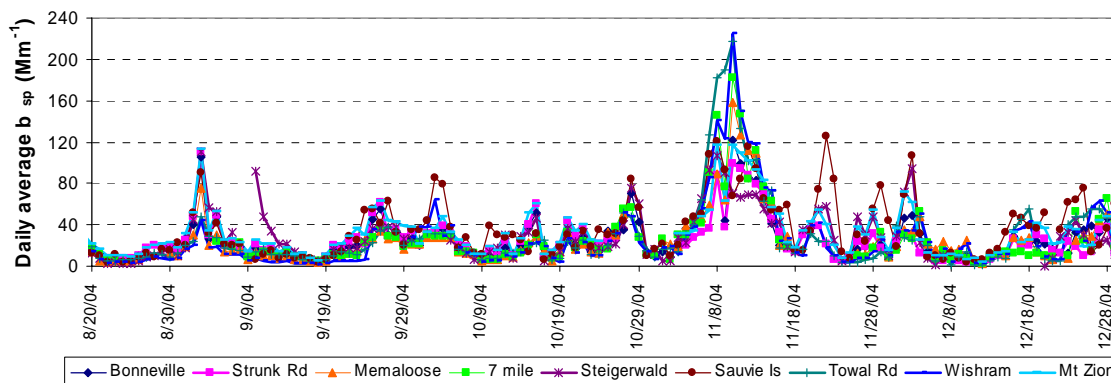
Figure 4-7 Measured daily averaged b_{sp} (Mm^{-1}) from RH controlled nephelometers.

c) Observation Based Analysis of Modeled Episodes

Regional air quality modeling conducted as part of the Gorge Study (Chapter 5) was done for two episodes, one each for the characteristic summer and winter seasonal air quality conditions typical in the Gorge. The episodes were chosen for periods with seasonally high haze levels and with a relatively high fraction of ambient monitoring data available. This section describes air quality, haze and meteorological conditions measured during the two selected episodes in greater detail.

i) November 4-November 18, 2004 episode

An extended episode of high b_{sp} (i.e., poor visibility) at all sites occurred during early-mid November 2004. Daily averaged b_{sp} for all nephelometers (Radiance Research RH controlled nephelometers) is shown in Figure 4-8. Unless noted otherwise all nephelometer data in the episode analysis section is from the Radiance Research nephelometers heated to limit RH to 50%. Also shown is the wind pattern type based on the cluster analysis discussed above, which shows that the winds switched from light and variable (cluster 3 & 4) to strong down-gorge (cluster 5) when haze levels were high, then back to light and variable after the haze levels subsided. National Weather Service sites in eastern Washington and eastern Oregon (Walla Walla, Pasco, and Pendleton) reported light winds, high RH and smoke/haze and fog leading up to and during the episode. The episode started as light westerly flow on November 6 turned to light easterly flow on November 7-8. B_{sp} levels dipped slightly with light upgorge flow on November 9 then rose with easterly flow on November 10, which continued for a few days with a gradual reduction in daily average bsp. All sites except Sauvie Island and Steigerwald had daily average b_{sp} peaking on November 10. Towal Road and Wishram had daily average b_{sp} of over 200 Mm^{-1} on November 10, and b_{sp} on that date generally decreased from east to west. Time resolved sulfate (SO_4), nitrate (NO_3), and OC/EC were available for Bonneville and Mt. Zion for this period (although Mt. Zion OC/EC was only available for the early part of the episode). Hourly averaged b_{sp}, SO_4, NO_3, and OC at Bonneville and Mt. Zion for November 7- November 15 are shown in Figure 4-10.

This episode had elevated concentrations of sulfate, nitrate, and organic carbon. Sulfate concentrations were as high as 10 µg/m^3 at Mt. Zion and 8 µg/m^3 at Bonneville. Nitrate

reached hourly average concentrations of over 9 μg/m³ at both locations. Peak OC concentrations were about 8 μg/m³ at Bonneville and 7 μg/m³ at Mt. Zion and concentrations were generally higher at Bonneville than at Mt. Zion.

Daily average b_{sp} November episode
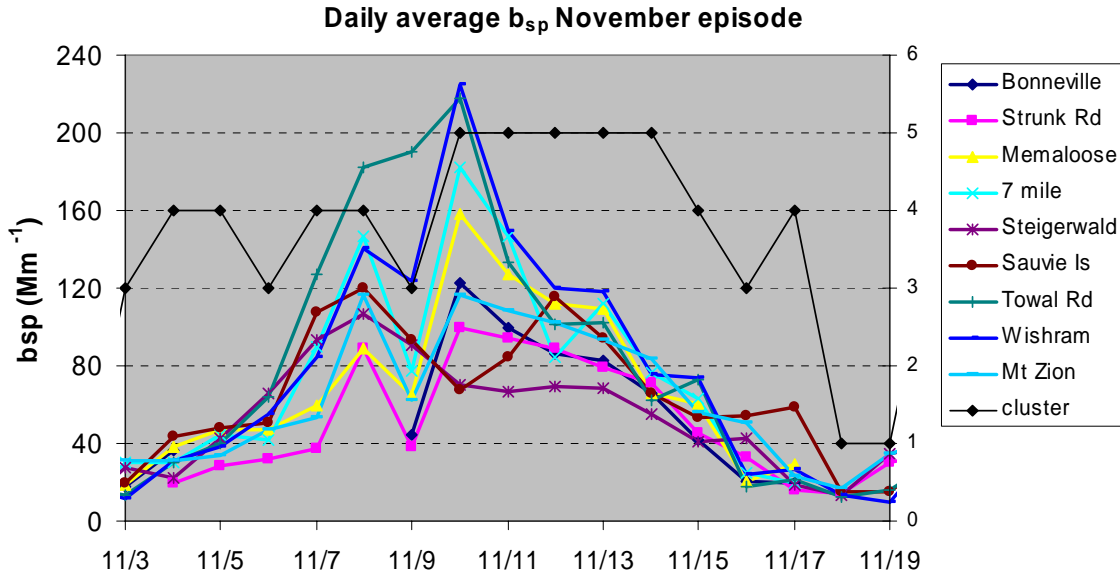
Figure 4-8. Daily average particle light scattering for the November 2004 episode. Also shown is wind pattern type where 1 is strong westerly to 5 being strong (winter) easterly.

Figure 4-9 shows measured versus reconstructed scattering at Bonneville for the November episode. Reconstructed scattering is a sum of the scattering from Organic compounds, sulfates, and nitrates from the high time resolved data. The square correlation coefficient is 0.97 showing that the high-time resolved measurements are accurately capturing the trends. The slope is a bit low at 0.7 but does not include contributions from coarse mass, fine soil, or sea salt.

Bonneville November episode
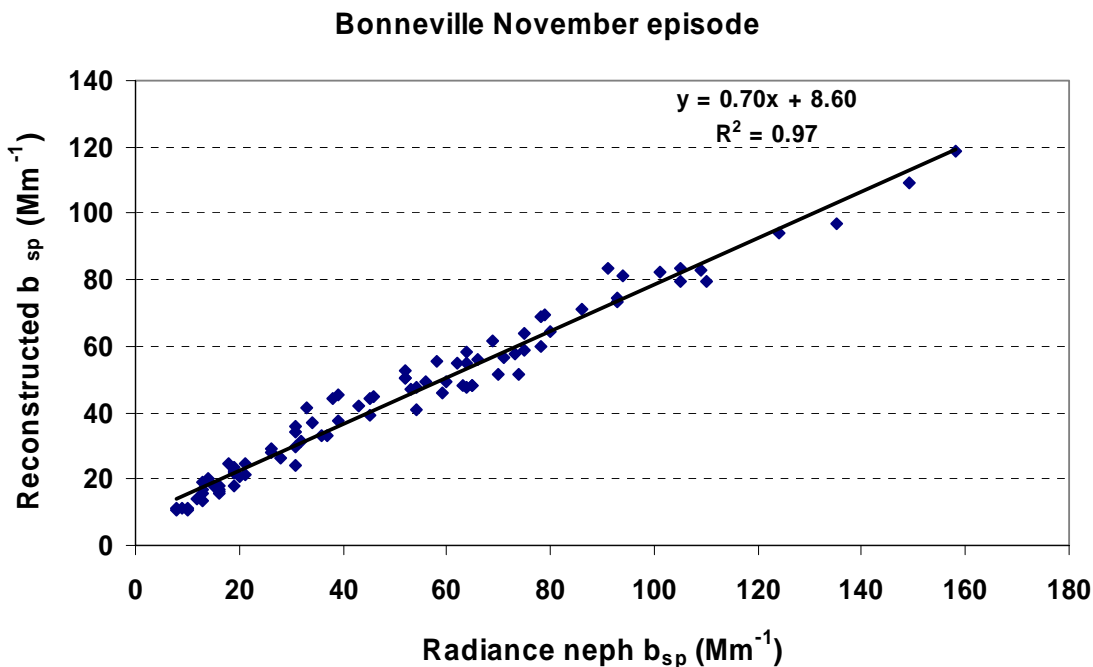
Figure 4-9. Scatterplot of reconstructed particle light scattering versus Radiance nephelometer particle light scattering at Bonneville for the November 2004 episode.

Figure 4-10 shows time series of b_{sp}, SO_4, NO_3, and organic carbon at Bonneville and Mt. Zion for the November episode. Light scattering (b_{sp}) and nitrate concentrations are much more highly correlated at both sites with sharp peaks midday during the latter half of the episode, while organic carbon has little diurnal variations and sulfate seems to share some of nitrates variations and some of the slow variations of organic carbon. This is consistent with some of the sulfates being associated with both nitrate source regions and atmospheric processing while organic carbon sources also emitting sulfur.

(a) Bonneville
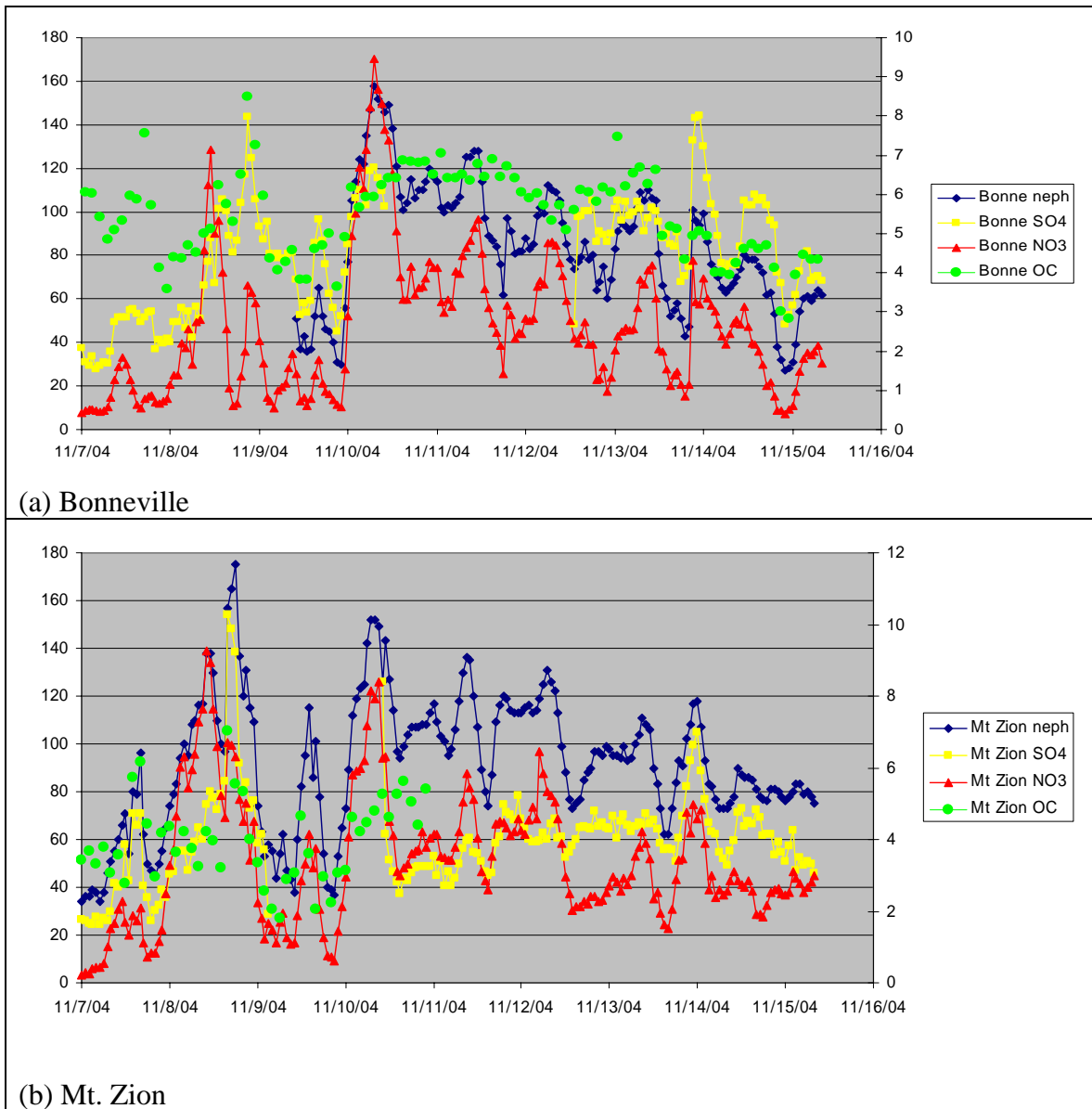
(b) Mt. Zion

Figure 4-10. Particle light scattering (Mm^{-1}) on the left vertical axis and high time-resolved sulfate, nitrate, and organic carbon concentrations ($\mu g/m^3$) on the right vertical axis at: a) Bonneville and b) Mt. Zion for the November 2004 episode.

Figure 4-11 compares Mt. Zion and Bonneville NO_3 during the episode. Mt. Zion experienced peak nitrate on November 8, Bonneville on November 10. The nitrate concentrations for the two sites are generally well correlated and about the same magnitude, though there are a number of periods when the Bonneville nitrate concentration is lower. It is unclear whether this represents a vertical (Mt. Zion is at higher elevation than Bonneville) or a horizontal concentration gradient.
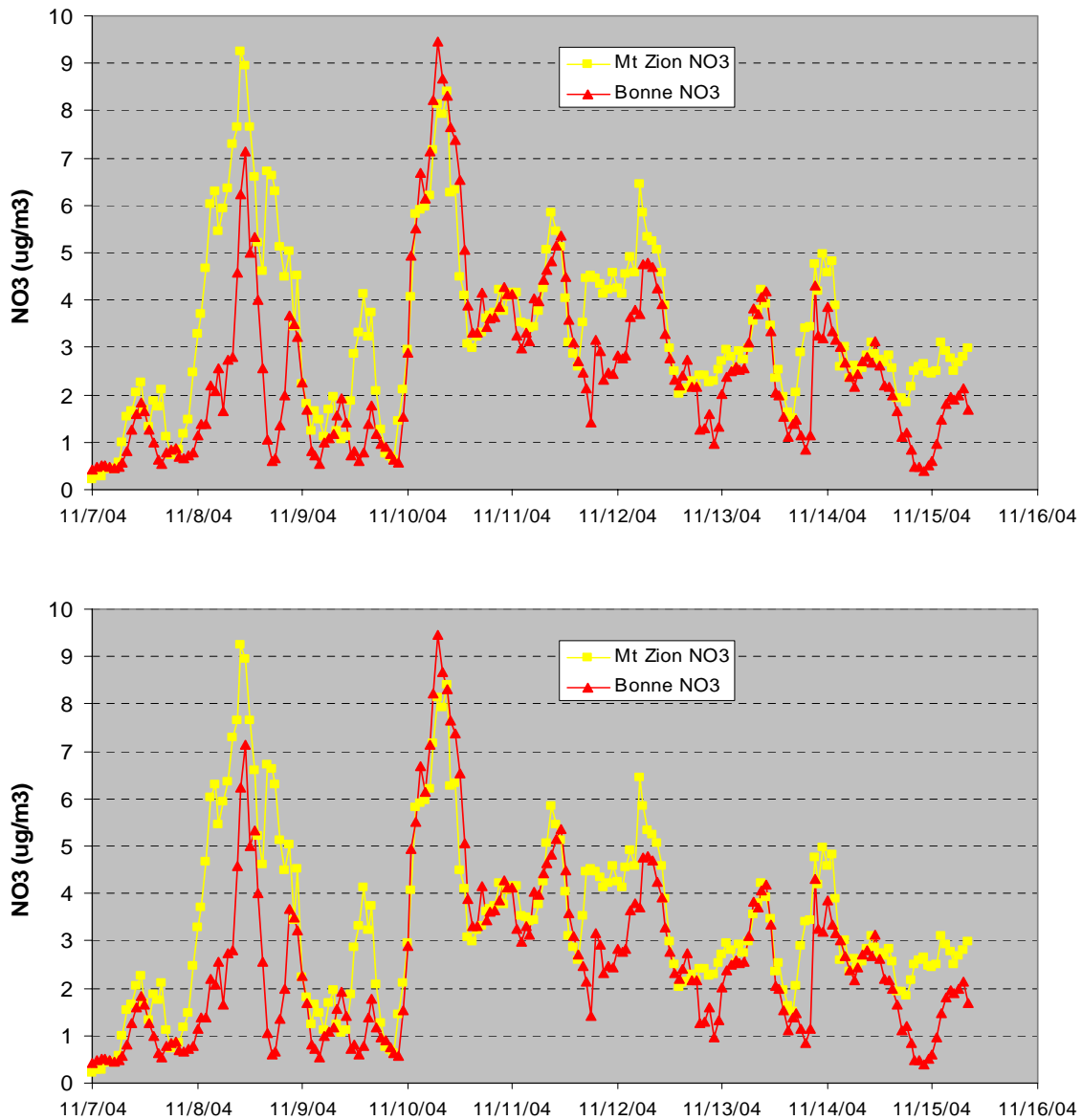
Figure 4-11 Time series of high time-resolved nitrate at Mt. Zion and Bonneville for the November 2004 episode.

Next we will compare westerly wind component with b_{sp} at the sites. Figure 4-12 uses the Sevenmile Hill site as an example for trends in b_{sp} and winds over the episode. Light westerly winds during November 5-6 transitioned to light easterly winds during November 7-8. A steady rise is b_{sp} was associated with this wind shift. Late in the day on November 8, winds briefly became from the west at about 10 mph. Concurrent with this wind shift was a large drop in b_{sp} from over 180 Mm^{-1} to less than 40 Mm^{-1}. After about 12 hours of westerly flow, winds became easterly near midday on November 11. Concurrent with the shift was a rapid rise in b_{sp} to over 200 Mm^{-1}. B_{sp} remained high but gradually decreased under continued light easterly flow over the next few days then dropped rapidly to under 20 Mm^{-1} on November 15 as winds became westerly at 10-15 mph. This wind/b_{sp} pattern was common at other sites and indicates sources to the east of the Gorge as being sources of the high b_{sp}. As levels of b_{sp} decreased from east to west, this suggests that most impact was due to sources east of the Gorge rather than within the Gorge.
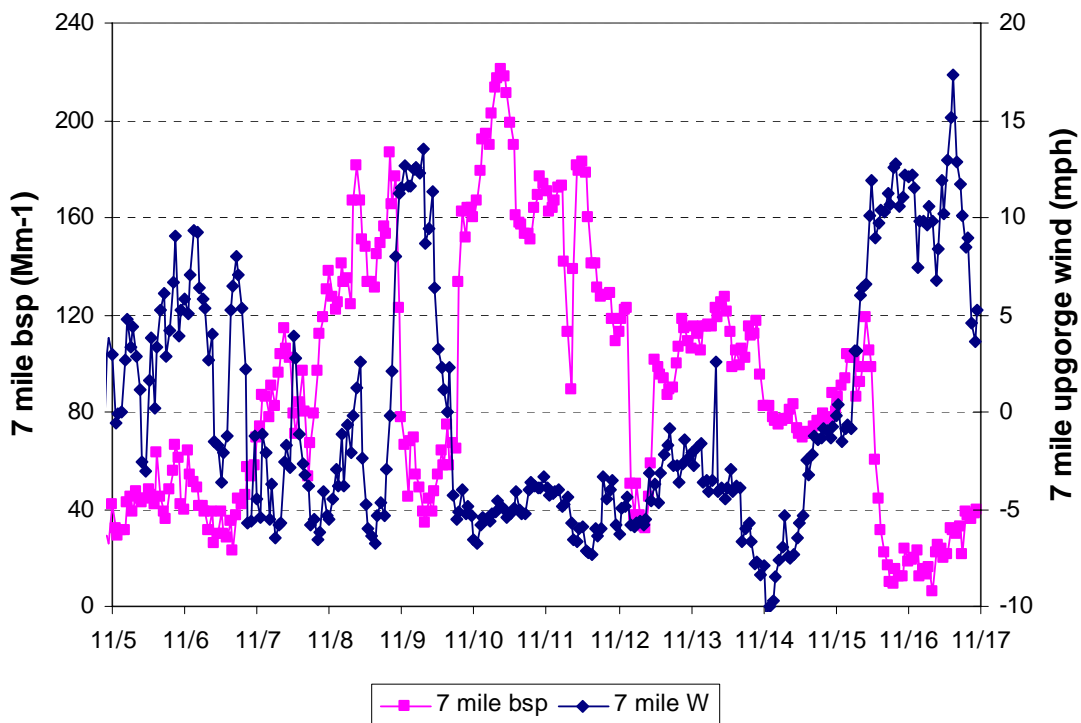
Figure 4-12. Time series of b_{sp} and westerly wind component at Sevenmile Hill during the November 2004 episode.

PMF results for episode

Positive Matrix Factorization (PMF) is a receptor modeling technique that uses particle composition data for many sample periods to identify groups of similarly varying components that can be interpreted as specific emission sources or source categories. The contribution to the fine mass for each of these PMF source categories can be determined for each sample period. PMF analyses were conducted on the data available for Wishram and Mt. Zion. Table 4-1 gives the percentage of fine mass apportioned to each source averaged

over the peak episode days with IMPROVE samples (November 8, November 11, and November 14).

Table 4-1. Percentage of fine mass apportioned by PMF to each source factor at Wishram and Mt. Zion (for the samples on November 8, 11, and 14, 2004).

	Sulfate rich	**Biomass burning**	**Mobile**	**Dust**	**Nitrate rich**	**Oil combustion**	**Paper mill**
Mt. Zion	9.8	41.1	3.1	3.3	37.4	1.2	4.1
Wishram	2.4	43.3	7.4	1.6	45.3	NA	NA

The bulk of the fine mass was attributed to the biomass burning and nitrate-rich secondary factors.

ii) August 10-22, 2004 episode

The August 2004 episode had several days of continuously elevated b_{sp} at the nephelometer sites. Figure 4-13 shows time series of b_{sp} at representative sites. B_{sp} tended higher at the western sites and Bonneville than at the eastern sites.

August 2004 episode hourly bsp at selected sites
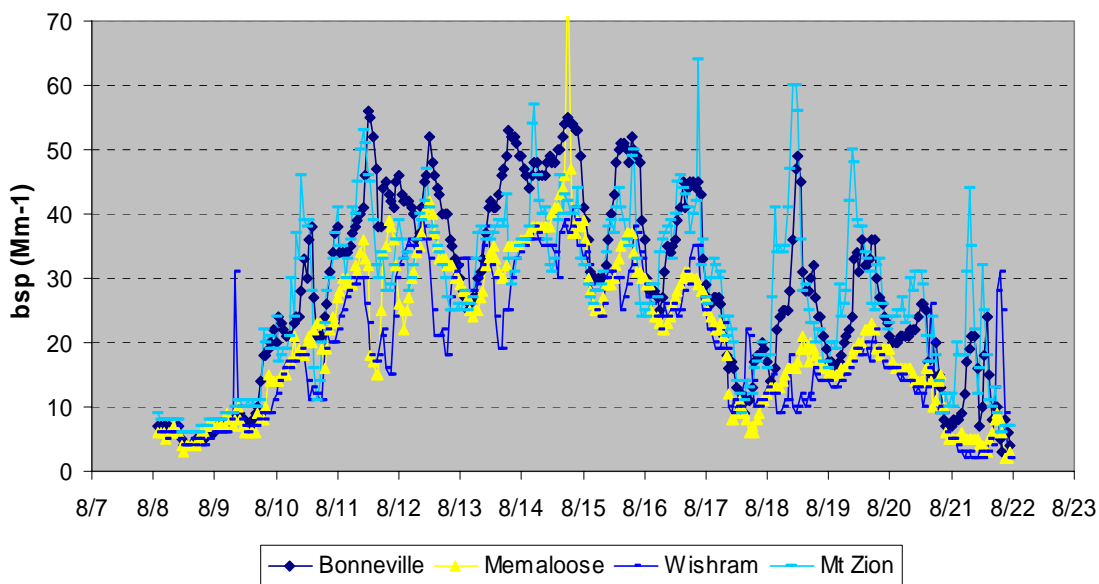
Figure 4-13. Time series of b_{sp} at selected sites for the August 2004 episode.

August 8 and 9 had light easterly flow and low b_{sp}. From August 10-14, the height of the episode, light westerly flow prevailed. The pressure gradient was east-west at the beginning of the episode, explaining the light easterly flow observed. During August 10, the pressure gradient and flow became light westerly and the b_{sp} increased.

Figure 4-14 shows a time series of b_{sp}, reconstructed b_{sp}, and estimated b_{sp} due to sulfate, nitrate, and organic carbon at Bonneville for the episode. Measured and reconstructed scattering compare well both in magnitude and trend. Reconstructed b_{sp} was due about equally to sulfate and organic carbon, with a very minor contribution from nitrate.

Figure 4-15 shows a scatter plot of the reconstructed versus measured particle light scattering at Bonneville during the August 2004 episode. The r^2 of 0.88 gives confidence in the ability of the high-time resolution measurements of carbon, nitrate, and sulfate to accurately capture short-term trends in these compounds. The slope of 0.77 seems reasonable as other components of the scattering budget (e.g. fine soil, coarse mass, and sea-salt) are not included here.
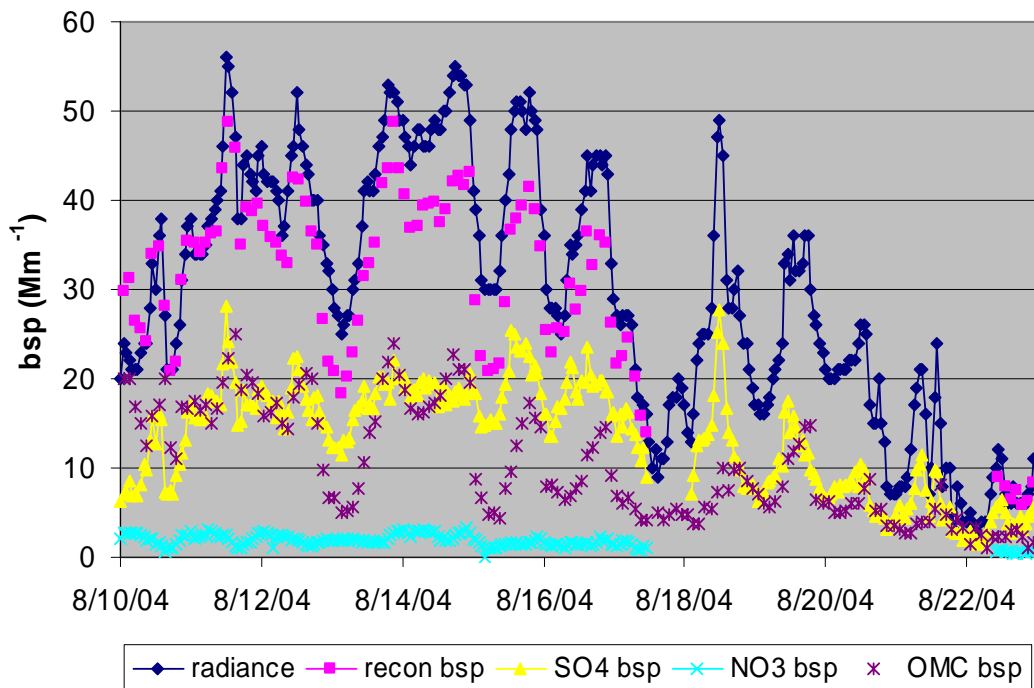
Figure 4-14. B_{sp}, reconstructed b_{sp}, and estimated b_{sp} due to sulfate, nitrate, and organic carbon at Bonneville during the August 2004 episode.

Bonneville August episode
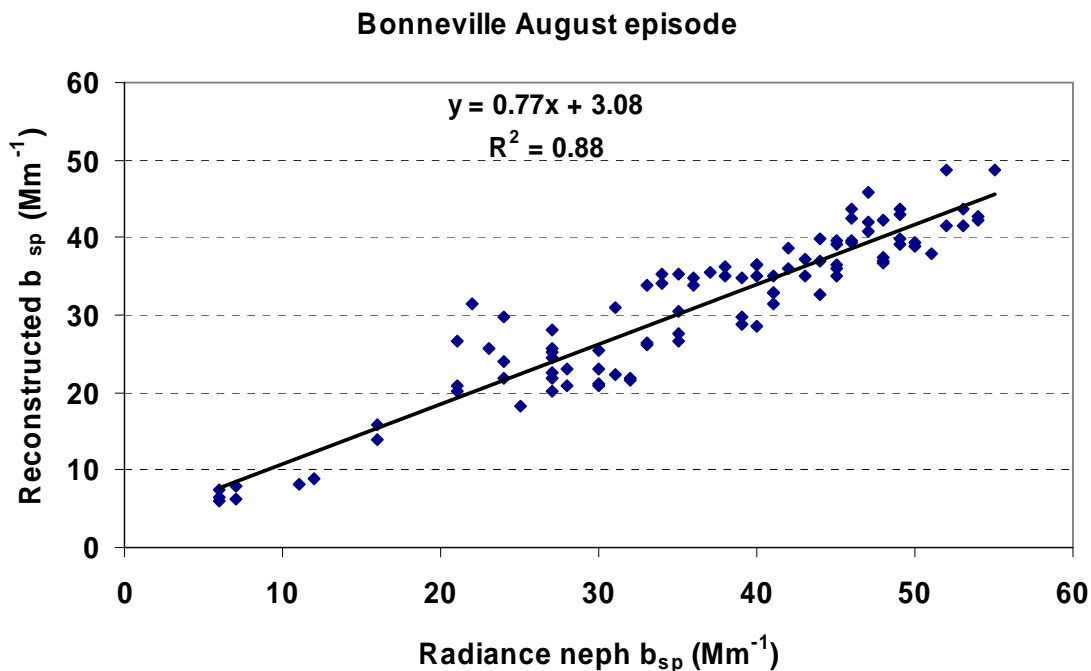
Figure 4-15. Scatterplot of reconstructed particle light scattering versus Radiance nephelometer particle light scattering at Bonneville for the August 2004 episode.

OC concentrations for IMPROVE sites in Washington, Idaho, and Oregon for August 13, 2004 were generally between 2 and 4 $\mu g/m^3$, with over 8 $\mu g/m^3$ at Sawtooth Wilderness Area. This suggests impacts from fires in the region. The Wishram and Mt. Zion IMPROVE samples are not available for this date. Increased levels of sulfate on August 16 were measured at IMPROVE sites in Washington and Oregon in the central and northern Cascades, Puget Sound and Olympic National Park (missing data at Wishram and Mt. Zion). The high-time resolution sulfate monitor at Mt. Zion (data not shown) gave much lower values than the one at Bonneville, possibly due to a problem with the monitor at Mt. Zion.

d) Quantitative Receptor Modeling Analysis

The Positive Matrix Factorization (PMF) receptor model was applied to the 24-hr integrated aerosol chemical composition data obtained from the Mt. Zion and Wishram IMPROVE sites during the years 2003-2004. PMF was applied to each site to generate profiles of source factors. Normalized source profiles and the quantitative source contributions for each resolved factor were calculated. The major sources that contribute to the aerosol loadings and light extinction in the Columbia River Gorge were identified.

PMF is a statistical method that identifies a user specified number of source profiles (i.e. relative composition particle species for each source) and source strengths for each sample period that minimizes the difference between measured and PMF fitted mass concentration.

i) PMF results for Mt. Zion

A total of 220 samples collected in 2003 and 2004, and 33 species were used in the PMF modeling for Mt. Zion. A good relationship (slope = 0.92, R^2 = 0.98) was found between the daily reconstructed fine mass contributions from all PMF resolved sources and measured fine mass concentrations, which indicates that the resolved sources effectively account for most of the variation in the particle mass concentration. Figure 4-16 illustrates the major source factors resolved by PMF based on $PM_{2.5}$ chemical speciation data from the IMPROVE site. Seven source factors are identified. A factor with significant amount of Na, Cl and K is identified as from Kraft paper mill emissions. Emissions from Kraft recovery boilers have been shown to consist largely of sodium and sulfate particles (i.e. Na_2SO_4) with lesser but significant amounts of Chlorine and Potassium. Vanadium and Nickel, which are associated with oil combustion sources are used as the signatures of the oil combustion source factor. The biomass smoke factor is dominated by OC/EC (with the presence of K), while secondary sulfate and nitrate factors are dominated by sulfate and nitrate, respectively. A mobile emission factor is identified with large fraction of EC1, EC2, and Zn. Major dust components such as silicon, calcium, iron, and potassium are present in the dust factor. Figure 4-17 shows the average contribution of each source factor to $PM_{2.5}$ mass. Smoke from biomass burning is the largest contributor to $PM_{2.5}$ at Mt. Zion, with a contribution of 31%. It is worth pointing out that the mobile contribution shown here is mostly primary emissions. Considerable amounts of nitrate and sulfate rich secondary aerosols (which are shown as separate factors) may also result from mobile sources. The uncertainty which represents the average of one standard deviation of the PMF calculated source contributions for each factor is ~ 5-13% of the estimated contribution. Time series of contributions of each source to $PM_{2.5}$ mass during the years 2003-2004 indicates that oil combustion and sulfate factors contribute most during the summer season, while nitrate has the highest contribution in the winter. Smoke and dust are more episodic with large peaks during dust and fire pollution events (smoke is most significant in October and November, contributing to >50% of the $PM_{2.5}$ mass according to the PMF analysis). Conversely, the contributions of mobile and paper mill emissions are relatively constant throughout the year.

Figure 4-16. Source profiles for PMF factors at the Mt. Zion IMPROVE site. Y-axis is the fraction of PM$_{2.5}$ mass for each factor associated with each chemical compound.
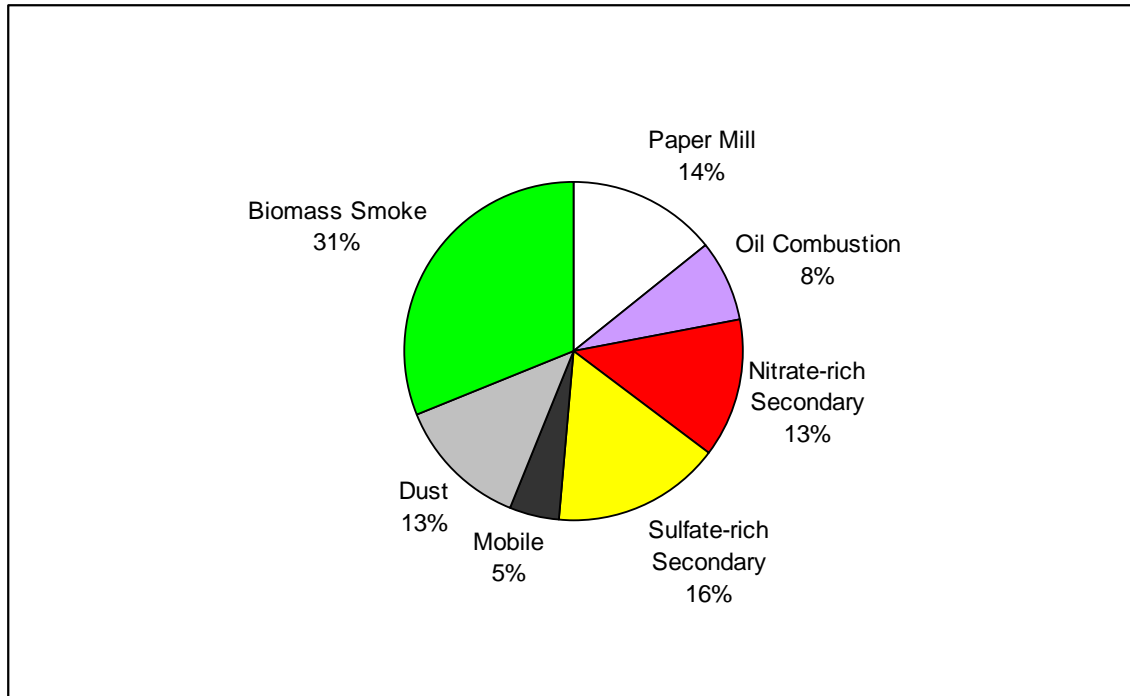
Figure 4-17. Percentage of PM$_{2.5}$ mass associated with each PMF source factor at Mt. Zion

ii) PMF results for Wishram

A total of 237 samples collected in 2003 and 2004, and 33 species were used in the PMF modeling for Wishram. Good agreement (slope = 0.94, R^2 = 0.98) was also found between the daily reconstructed fine mass contributions from all PMF resolved sources and measured fine mass concentrations. Figure 4-18 illustrates the major source factors resolved by PMF based on PM$_{2.5}$ chemical speciation data. Five source factors are identified for Wishram. As with Mt. Zion, a biomass smoke factor, a dust factor, a mobile emission factor, is identified as dominated by OC/EC (with the presence of K), and secondary sulfate-rich secondary factor, and a nitrate-rich secondary nitrate factor are resolved by PMFs are dominated by sulfate and nitrate, respectively. As shown in Figure 4-20 and Figure 4-22, the source profiles of the five common source factors identified by PMF in Wishram and Mt. Zion are very similar. The only significant differences are that some more dust components such as Si, K and Ca present in the sulfate-rich secondary factor, and some more nitrate exists in the dust source factor at Wishram. A mobile emission factor is identified with large fraction of EC1/EC2 and organics, as well as Zn and Pb. A dust factor dominated by mineral components silicon, calcium, iron, and potassium is identified. Paper Mill and Oil Combustion factors were not identified in Wishram, which may be blended with other factors and cannot be separated out at Wishram. Figure 4-19 shows the average contribution of each source factor to PM$_{2.5}$ mass at Wishram. Smoke from biomass burning is the largest contributor to PM$_{2.5}$ at Wishram, with a contribution of 29%, followed by secondary sulfate and nitrate. Time series of PMF factor scores indicates that the sulfate factor contributed most during the summer season, while nitrate contributed most in the winter. Smoke and

dust were episodic sources with large peaks during dust and fire pollution events, while the contribution of mobile sources was relatively constant throughout the year.
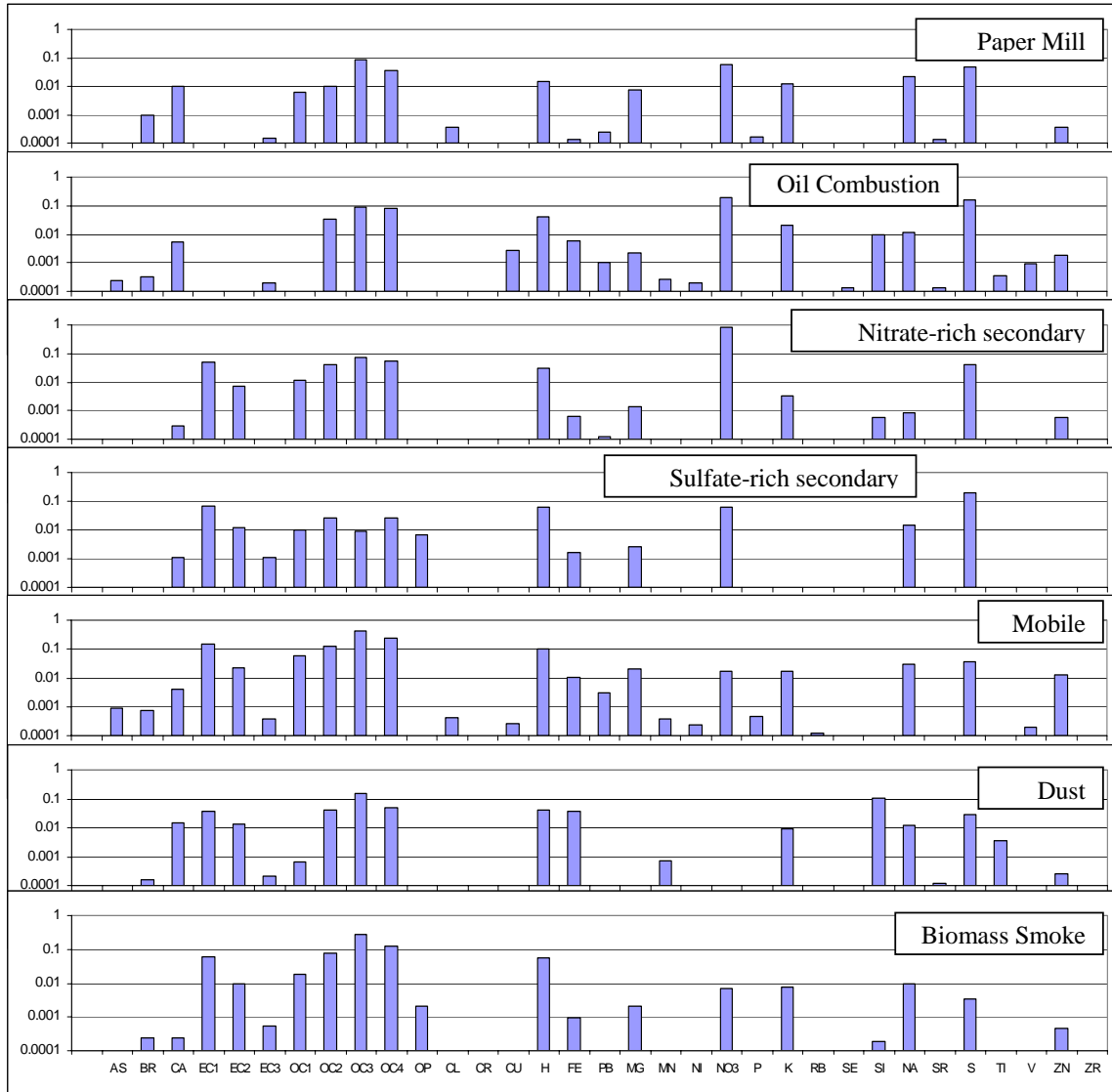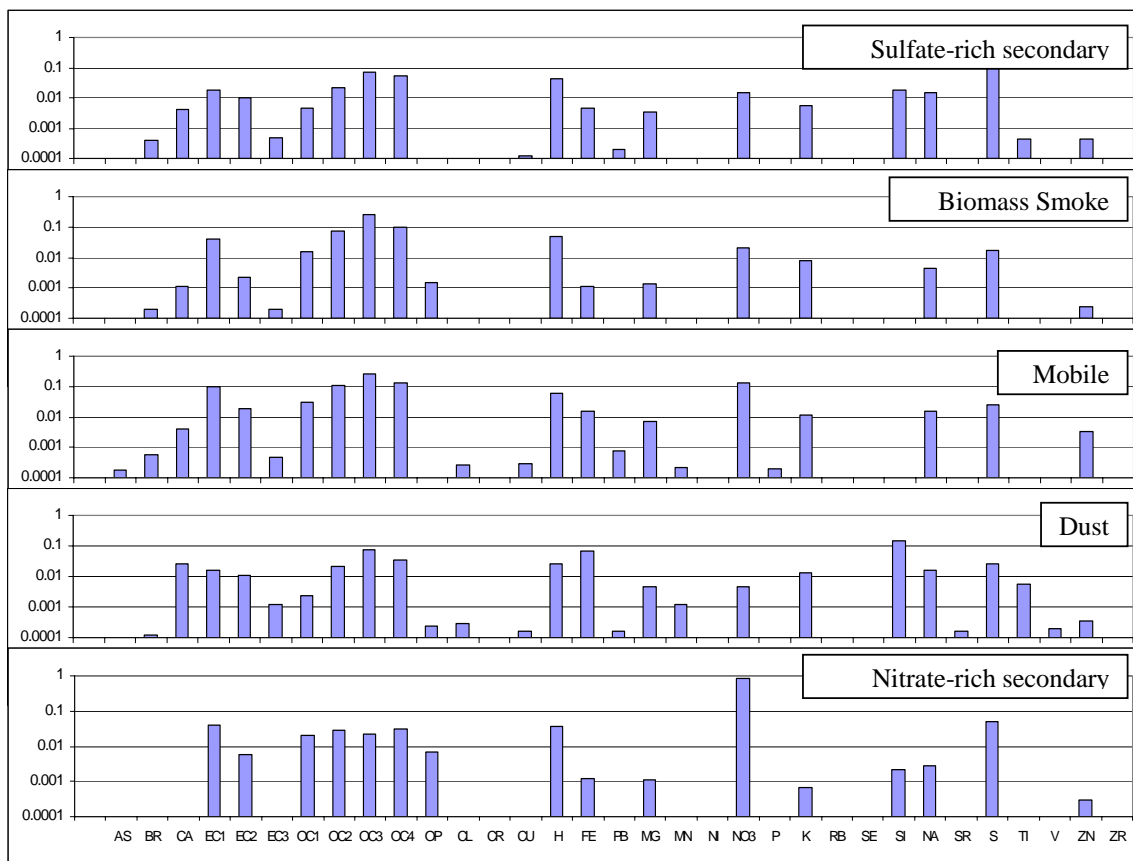

Figure 4-18. Source profiles for PMF factors at the Wishram IMPROVE site. Y-axis is the fraction of $PM_{2.5}$ mass for each factor associated with each chemical compound.
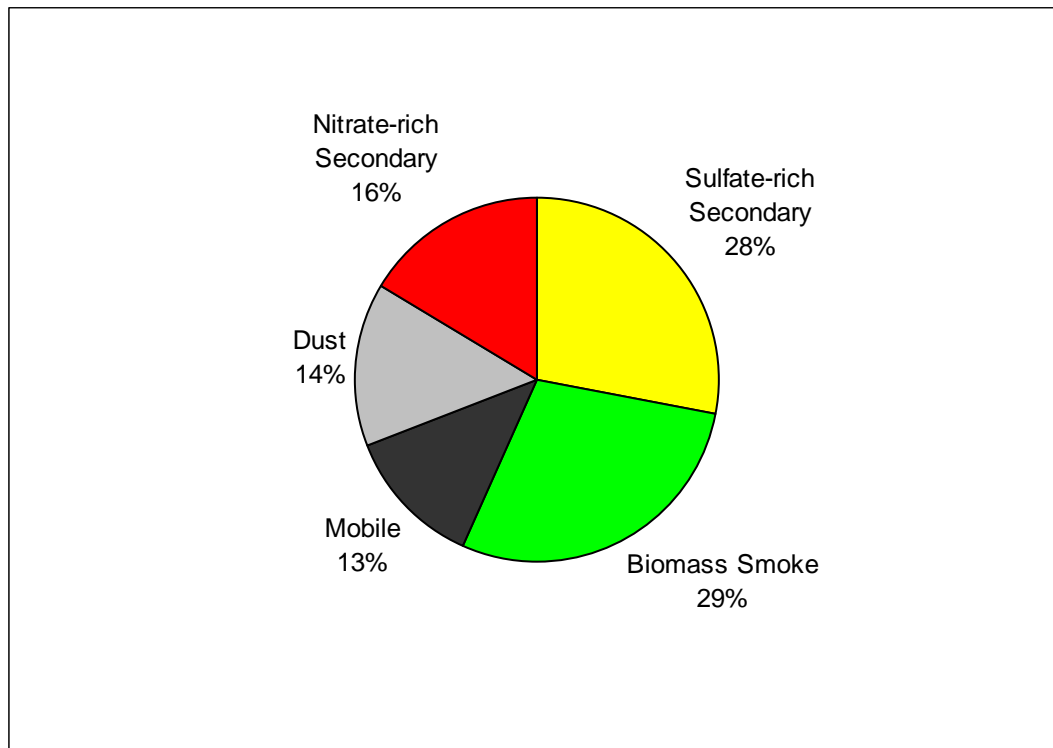
Figure 4-19. Percentage of PM$_{2.5}$ mass associated with each PMF source factor at Wishram.

iii) PMF attribution by chemical compound and to light extinction

In the previous section we presented attribution of fine mass concentration by PMF source factor. Here we present the PMF attribution to the main chemical components of haze in the gorge- organic compounds, sulfate, and nitrate. We also use the results to generate the contribution of each factor to reconstructed light extinction (haze) at Mt. Zion (Figure 4-20) and Wishram (Figure 4-21). In general, the reconstructed aerosol light scattering coefficients are in very good agreement with the Optec Nephelometer measured light scattering coefficients at the ambient RH (Slope ~ 0.94 at Mt. Zion and 0.96 at Wishram, R^2 ~ 0.9 at both locations).

About half of the organic mass was attributed to biomass smoke at both sites, with mobile being the next largest contributor. Sulfate rich contributed half the sulfate at Mt. Zion and 62% at Wishram. The oil combustion and paper mill factors were the next largest contributors to sulfate at Mt. Zion. Nitrate-rich contributed about 16% of the sulfate at Wishram, suggesting a linkage between sulfate and nitrate sources at Wishram. The nitrate-rich secondary factor accounted for 75% of the nitrate at Mt. Zion and 84% at Wishram. The only other factors contributing significantly to nitrate were oil combustion (10%) at Mt. Zion and mobile sources (10%) at Wishram.

For reconstructed extinction, chemical component mass contributions for each factor were multiplied by the IMPROVE default extinction efficiencies and relative humidity growth factors. Because RH measurements were only available for about half of the IMPROVE sampling days during 2003 – 2004, we did not use the measured RH values to calculate the

60

reconstructed light extinction coefficients in this paper. Instead, the default IMPROVE relative humidity growth factors, which are based on the month-specific climatological mean RH values for Mt. Zion and Wishram, were used following the Regional Haze Rule. Reconstructed light extinction based measured RH were also calculated and reported in the Causes of Haze in the Gorge (CoHaGo) Final Report. Coarse mass was not used in the PMF analysis so the coarse mass concentrations for each sample period were multiplied by the IMPROVE default value of 0.6 m^2g^{-1}. The nitrate-rich secondary factor was the greatest contributor to reconstructed light extinction at both sites. Sulfate-rich was the second highest at both sites and biomass smoke third highest. Coarse mass plus dust was 14% of reconstructed extinction at Mt. Zion and 15% at Wishram. Oil combustion was 10% at Mt. Zion, paper mill 7% and mobile 5%. Mobile was 12% at Wishram.
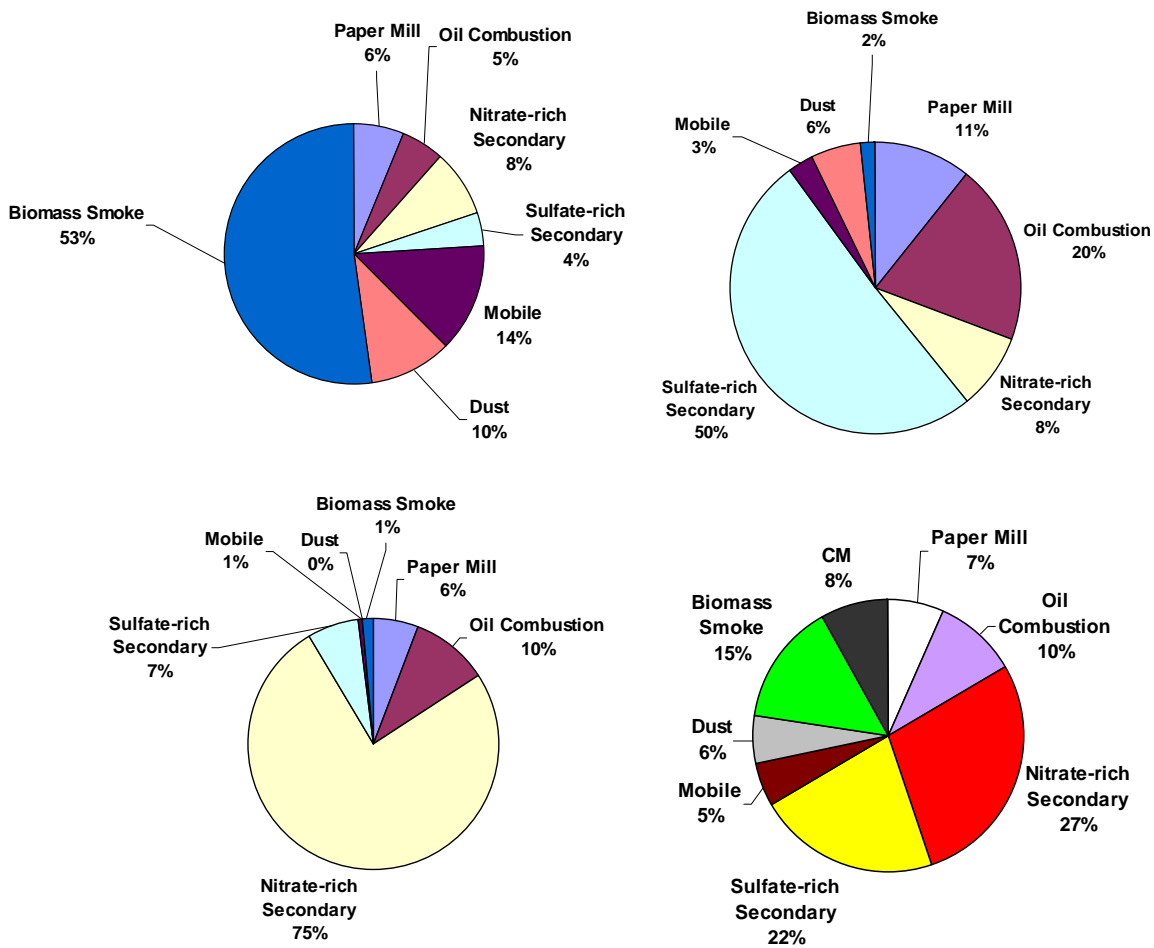
Figure 4-20. Percentage contribution of each PMF source factor at Mt. Zion to: a) organic carbon; b) sulfate; c) nitrate; and d) reconstructed particle light extinction.
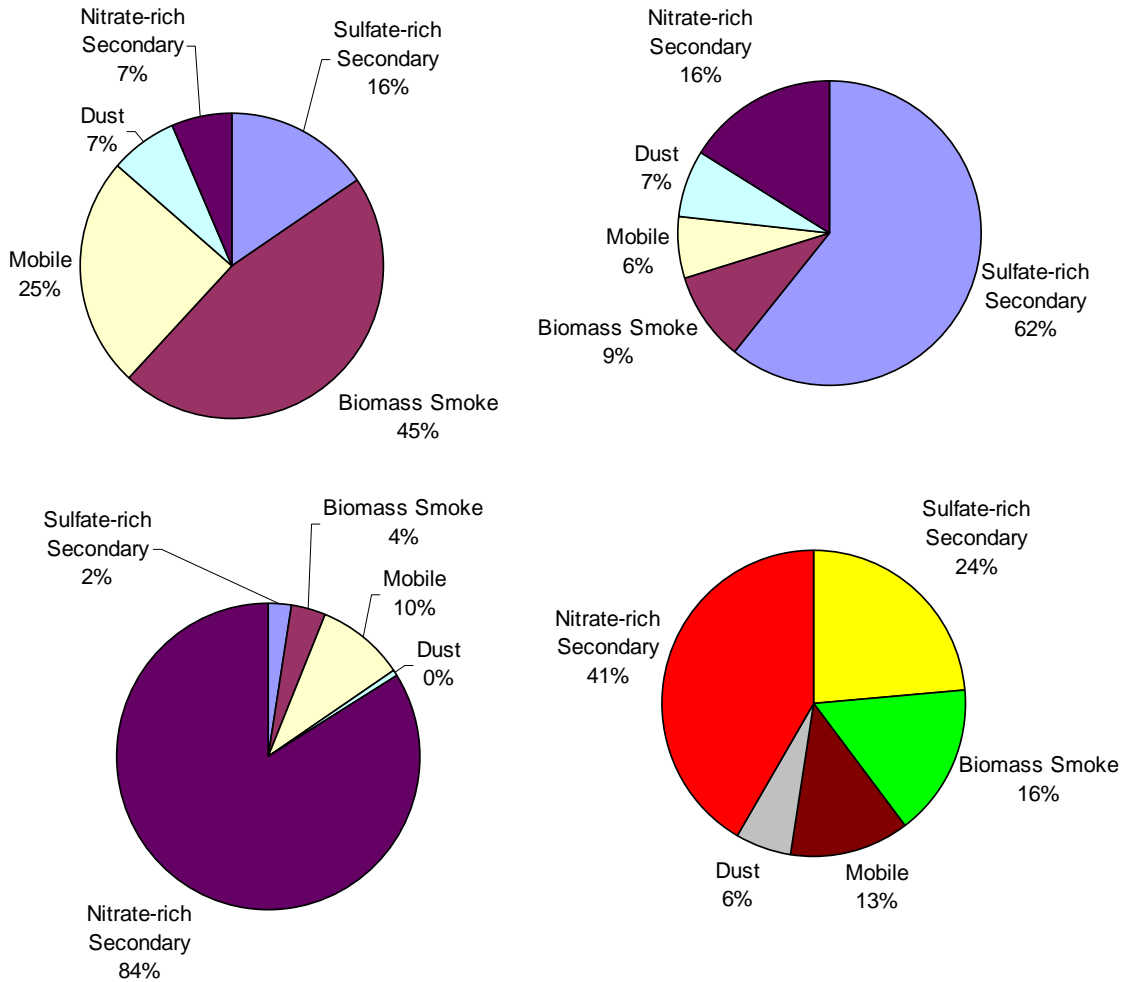
Figure 4-21. Percentage contribution of each PMF source factor at Wishram to: a) organic carbon; b) sulfate; c) nitrate; and d) reconstructed particle light extinction

iv) PMF analysis results by wind pattern

The percentage of PM$_{2.5}$ mass attributed to each source factor by wind pattern type (cluster) at Wishram and Mt. Zion is shown in Table 4-2 and Table 4-3. At Wishram, sulfate-rich secondary particulate is the most important factor for the 3 upgorge patterns and is minor for the winter downgorge. Biomass smoke is the largest contributor to the light downgorge pattern, and is about 30% of PM$_{2.5}$ mass for the light and moderate upgorge and winter downgorge patterns. The mobile factor is most important for light upgorge and light downgorge. The dust factor is highest for the usually summertime moderate and strong upgorge patterns. Nitrate rich secondary particulate is the largest factor for the winter downgorge pattern, is also substantial for light downgorge, and is minor for the upgorge patterns. An interesting finding is that for winter downgorge, over one-half of the sulfate at Wishram is attributed to the secondary-nitrate factor. This suggests that the source or

sources contributing to secondary nitrate also have substantial sulfate associated with them. It should be noted that the upgorge wind patterns have slightly higher $PM_{2.5}$ mass at Mt. Zion than Wishram and the downgorge patterns have higher PM mass at Wishram- thus a higher percentage at one site may or may not imply a higher concentration of $PM_{2.5}$ mass. This summary implies that most sulfate at Wishram is from the west, most nitrate is from the east, and biomass smoke comes from both east and west.

Table 4-2. Percentage of $PM_{2.5}$ mass attributed to each source factor by wind pattern type (cluster) at Wishram.

Percentage of $PM_{2.5}$	Strong upgorge	Moderate upgorge	Light upgorge	Light downgorge	Winter downgorge
Sulfate-rich secondary	44	33	33	16	9
Biomass smoke	19	28	31	37	33
Mobile	10	12	17	16	9
Dust	22	22	15	12	6
Nitrate-rich secondary	5	5	5	19	44

Table 4-3. Percentage of $PM_{2.5}$ mass attributed to each source factor by wind pattern type (cluster) at Mt. Zion.

Percentage of $PM_{2.5}$	Strong upgorge	Moderate upgorge	Light upgorge	Light downgorge	Winter downgorge
Paper Mill	19	15	14	10	6
Oil Combustion	14	14	8	3	1
Nitrate-rich secondary	9	7	10	12	34
Sulfate-rich secondary	16	13	17	10	19
Mobile	5	4	5	5	3
Dust	12	18	14	16	5
Biomass smoke	25	29	32	43	32

At Mt. Zion, the biomass smoke factor has the largest contribution to $PM_{2.5}$ mass for all wind patterns except winter downgorge, where nitrate-rich secondary is slightly higher. The paper mill factor is highest for the upgorge types, which is reasonable because multiple paper mills are west of Mt. Zion. Sulfate-rich secondary ranges from 10-19 percent, is associated with both upgorge and downgorge flow, and is marginally highest for winter downgorge. This result appears to conflict with the result for Wishram for which winter downgorge has the lowest sulfate factor contribution. However it could be that sources between Wishram and Mt. Zion are contributing to higher sulfate there for wind type 5 or that emissions of SO_2 upwind of the gorge have not converted a large fraction of the SO_2 to sulfate by the time the emissions reach Wishram (but convert more during transport to Mt. Zion). The oil combustion factor is highest for moderate and strong upgorge and near zero for the

downgorge wind patterns. The dust factor is significant for all but the winter downgorge (winter only) factor. The mobile factor is small for all wind patterns. The nitrate factor is important in the wintertime, especially with downgorge flow.

e) Gorge Air Quality in Context

To investigate whether the Gorge Study monitoring period is representative of typical air quality conditions in other years, five years of data from two sites within the Gorge, Mt. Zion and Wishram, that are operated as part of a national-scale monitoring PM speciation network (IMPROVE) were examined. Another IMPROVE site, the Mt Hood site, is geographically near to these two in-Gorge sites (~45 km south of the Columbia River) but at higher elevation (1531 m). Comparison of data between the Mt. Hood and the two Gorge sites provides a way to examine regional air quality and contrast it to the distinct characteristics of in-Gorge air quality. Data from these three sites were examined for the 5-year period, January, 2000 through December, 2004.

The largest components that contributors to the $PM_{2.5}$ mass concentrations at these sites are ammonium nitrate, ammonium sulfate and organic mass. Time plots with smoothed concentration (30-day moving averaged values) show the seasonal behavior and interannual variability of these major particle species (Figure 4-22). Ammonium nitrate concentrations in the Gorge have an annual cycle with high concentrations every winter (November through February) and generally low concentrations for the remaining months of the year. Nitrates tend to be higher at Wishram on the east end of the Gorge than at Mt. Zion during the winter and the reverse during the summer. By comparison, Mt. Hood has relatively low concentrations all year. In a separate analysis it was shown that periods of fog over the Columbia River Basin as evidence by fog observed at the Hanford Meteorological Station 25 miles northwest of Richland, WA only occurred during the months (i.e., November through February) that include nearly all of the days with high concentrations of ammonium nitrate in the Gorge, and that the Hanford fog tended to be associated with days of higher Wishram ammonium nitrate concentrations during the four winter months (5-year mean values for fog days of $3.2ug/m^3$ compared to $2.6ug/m^3$ during fog-free days). The Gorge Study year (2004) is similar to the four other years with respect to the seasonal behavior of nitrate events, though the concentrations at Wishram tend to be somewhat below averaged values for the earlier years.

Ammonium sulfate concentrations at the Mt. Hood site show a characteristic ramping up of concentrations from spring through late summer, followed by a drop during the winter months. This behavior is common to most monitoring sites throughout the country as a result of the higher temperatures and longer daylight hours that enhance the chemical conversion of SO_2 to particulate sulfate. The two Gorge sites also have increasing ammonium sulfate concentrations between mid-spring and summer, but during the winter months their concentrations do not decrease to the same extent as at Mt Hood. In fact during some winters there are peak ammonium sulfate concentrations that are higher than typical summer concentrations. Sample periods with high winter ammonium sulfate concentrations tend to occur during high ammonium nitrate concentrations and like the nitrate may be associated with fog events. Just as with ammonium nitrate, the eastern end of the Gorge has higher ammonium sulfate during the winter than at the western Gorge site, and the opposite sulfate

concentration gradient is apparent during the summer. Notice that the Gorge Study year (2004) has a somewhat flatter smoothed ammonium sulfate time-series compared to the four other years with respect to the seasonal behavior and as with the nitrate, the concentrations at Wishram tend to be somewhat below the averaged values for the earlier years.
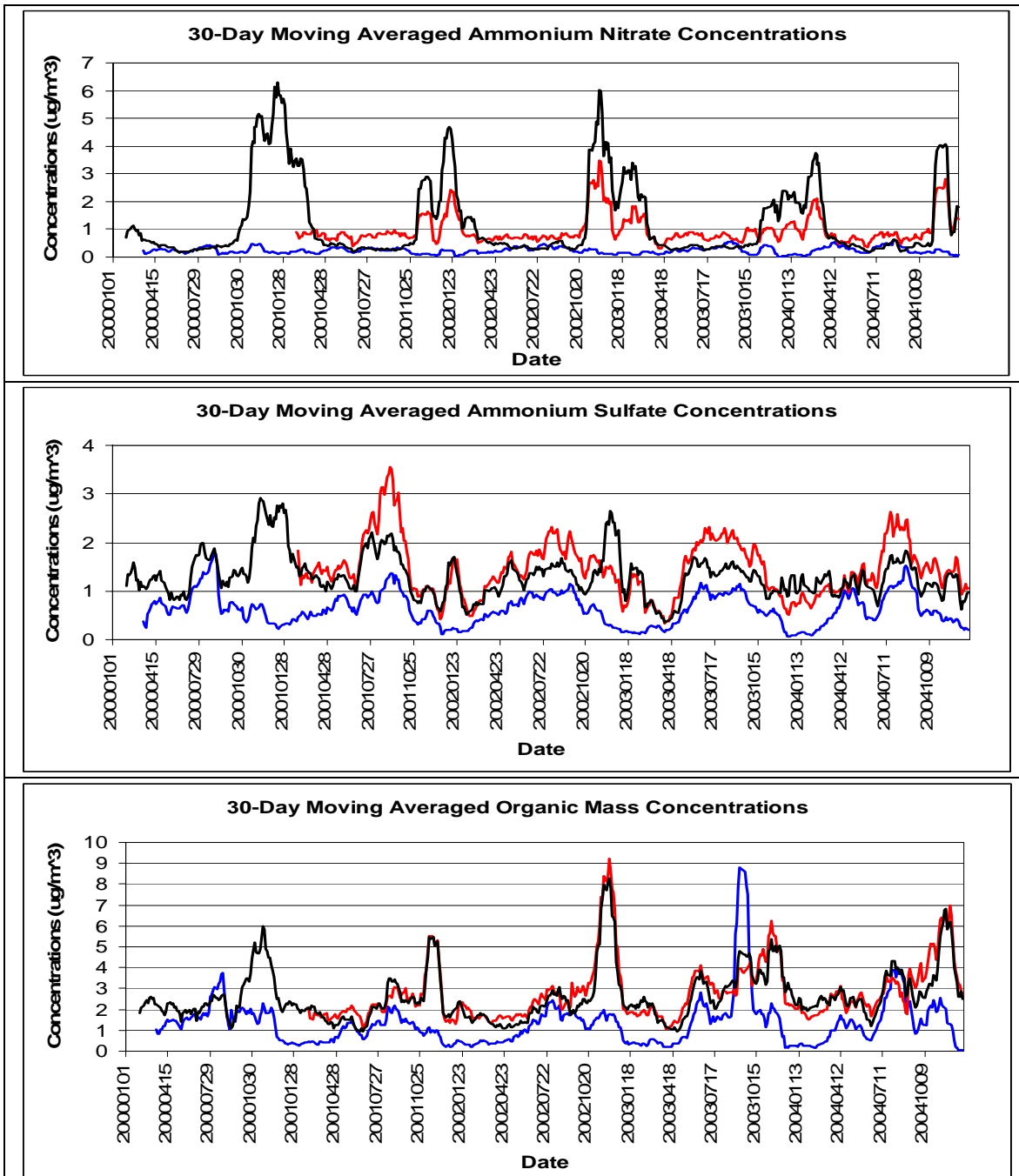
Figure 4-22. Thirty-day moving averages of ammonium nitrate (top), ammonium sulfate (center), and organic mass (bottom) concentrations for the Mt. Hood (blue), Mt. Zion (red), and Wishram (black) monitoring sites based on IMPROVE particle speciation data. Dates are shown numerically as year-month-day. Date shown is the end of the 30-day averaging period.

The organic mass concentration for the two in-Gorge monitoring sites is highly correlated and with similar concentrations regardless of the season, unlike the ammonium nitrate and ammonium sulfate where the concentration gradient is high at the predominately upwind side of the Gorge (west in summer and east in winter). Some years in the summer and early fall organic mass concentrations are similar in-Gorge and at the Mt. Hood monitoring site, and during one period in fall of 2003 the Mt. Hood concentrations exceeded those in the Gorge. The in-Gorge organic mass concentrations are larger than at the Mt. Hood site during the colder winter months (October through March), perhaps a result of wood burning for home heating plus a buildup of all sources during winter stagnation periods. The Mt. Hood seasonal distribution of organic mass tends to peak in late summer, while the in-Gorge concentrations tend to be highest several months later in mid to late fall. The Gorge Study year (2004) had organic mass concentrations in the Gorge and at Mt. Hood that are similar to those of the preceding four years.

Estimates of the particle light extinction (a measure of the amount of haze) contributed by each of the major particulate species for every sample period using the IMPROVE algorithm for each of the three site for the entire 5-year period. Mean values for all months and for the summer and winter months for the 5-year period as well as for the 2004 Gorge Study year are displayed in Table 4-4. Notice that the total light extinction is higher in winter than in summer for the in-Gorge sites, principally due to much higher ammonium nitrate contributions to haze, while at the Mt. Hood site the summers are the seasons of greatest haze because of the greater contributions by sulfate and organic mass. The total haze levels are higher at Wishram than at Mt. Zion in the winter, due to higher nitrate and sulfate contributions to haze. In summer the haze levels are higher at Mt. Zion than at Wishram, again mostly due to higher sulfate and nitrate contributions to haze at the predominately up-wind site. As suggested by the smoothed concentration time plots, Table 4-4 shows that the haze levels during the Gorge Study year (2004) are similar to the 5-year averaged values at all three sites. With few exceptions the contributions to haze by all of the components during the 2004 Gorge Study year are within 10% of the corresponding 5-year averaged values.

Table 4-4. Mean particle light extinction budget estimates calculated using the revised IMPROVE algorithm for all months, the summer months (May to Aug.), and the winter months (Nov. to Feb.) for the 5-year period from 2000 through 2004, and in parentheses for the 2004 Gorge Study year at Mt. Zion, Wishram, and Mt. Hood.

Mt. Zion								
Light Extinction (Mm-1)	Nitrate	Sulfate	Elemental Carbon	Organic Mass	Fine Soil	Coarse Mass	Sea Salt	Total
All Months	11.6 (13.0)	13.8 (13.3)	3.3 (3.4)	10.3 (11.7)	0.4 (0.4)	3.2 (3.2)	1.3 (1.8)	44.0 (46.7)
May to Aug.	6.1 (5.7)	15.8 (14.5)	3.2 (2.9)	8.6 (8.7)	0.6 (0.6)	4.5 (4.6)	0.6 (1.1)	39.5 (38.0)
Nov. to Feb.	21.8 (24.8)	12.7 (13.5)	3.4 (3.6)	12.6 (12.0)	0.2 (0.1)	1.4 (1.2)	1.8 (2.2)	53.9 (57.5)

Wishram								
All Months	17.9 (17.1)	13.2 (11.6)	3.4 (3.6)	9.4 (10.6)	0.9 (0.8)	4.0 (5.2)	0.8 (1.1)	48.3 (49.5)
May to Aug.	2.7 (2.8)	11.3 (10.3)	2.6 (2.7)	8.3 (9.7)	1.2 (1.4)	6.6 (7.4)	0.2 (0.4)	33.0 (32.5)
Nov. to Feb.	45.2 (42.9)	18.0 (14.5)	4.4 (5.0)	11.7 (12.2)	0.5 (0.3)	1.7 (2.1)	1.0 (1.5)	76.6 (78.4)
Mt. Hood								
All Months	2.4 (2.6)	5.6 (5.5)	1.2 (1.1)	4.7 (4.6)	0.3 (0.2)	0.9 (0.8)	0.4 (0.5)	15.5 (15.3)
May to Aug.	2.6 (2.7)	7.1 (6.7)	1.7 (1.5)	7.0 (7.0)	0.3 (0.3)	1.3 (1.4)	0.1 (0.3)	20.1 (19.9)
Nov. to Feb.	2.4 (1.9)	3.8 (3.0)	0.8 (0.6)	2.2 (1.5)	0.1 (0.0)	0.3 (0.1)	0.5 (0.6)	10.0 (7.8)

5) Current Year Meteorological, Emissions, and Air Quality Modeling

This section summarizes the current year meteorological, emissions and air quality modeling conducted as part of the Columbia River Gorge National Scenic Area Air Quality Study (Gorge Study) with details provided in the modeling report (Emery, et al., 2007). Chemical transport modeling was performed using the Comprehensive Air Quality Model with extensions (CAMx), in combination with emission inputs from the U.S Environmental Protection Agency's (EPA) Models-3 Sparse Matrix Operating Kernel Emissions (SMOKE) system, and meteorological inputs from the Pennsylvania State University / National Center for Atmospheric Research (PSU/NCAR), Fifth Generation Mesoscale Model (MM5). The general approach for the Gorge Study modeling was to leverage the considerable regional visibility modeling work already conducted by the Western Regional Air Partnership (WRAP) Regional Planning Organization (RPO) that addresses the requirements of the federal Regional Haze Rule (www.wrapair.org).

a) Overview of Approach

Following the WRAP modeling methodology, the Gorge Study modeling component employed CAMx to simulate two season-representative high PM/extinction episodes with a wide array of sensitivity tests and Probing Tool applications for both a 2004 base year (discussed in this Section) and the 2018 future year (discussed in Section 7). Based on visibility measurements during the 2003-2005 enhanced monitoring periods, two multi-day seasonal episodes in 2004 were selected for the Gorge Study modeling: a summer period over August 10-22, and an autumn period over November 3-18. A 10-day "spinup" period was added before each episode to reduce the influence of initial conditions. Modeling was conducted on a series of telescoping nested grids, with the finest high-resolution grid focusing on the Gorge area:

- A 36-km resolution grid covering the continental U.S., most of Canada and Mexico;
- A 12-km resolution grid covering the Pacific Northwest including Idaho, Oregon, and Washington and portions of surrounding states and Canada;
- A 4-km resolution grid covering most of Oregon and Washington.

The boundary conditions (BCs) for the 36-km continental U.S. domain were based on the GEOS-CHEM global chemistry model.

The Gorge Technical Team expended significant effort developing refined episode-specific emissions for the two 2004 modeling episodes on the 4-km Oregon/Washington grid. The 2002 WRAP emission inventory was adjusted to 2004 and used for areas outside the 4-km grid. Base case air quality model performance was evaluated for the two specific episodes simulated using operational and diagnostic techniques.

The CAMx PM Source Apportionment Technology (PSAT) probing tool was used to assess source category and region-specific attribution to sulfate, nitrate, carbonaceous, and primary particulates at several monitoring sites within the Gorge.

Overall the MM5/SMOKE/CAMx modeling system properly replicated the extensive set of PM and light scattering data that was collected as part of the Haze Gradient and "CoHaGo" field studies in 2004. The modeling system performed well in characterizing the distributions of individual PM species concentrations that were important in contributing to visibility-impairing haze over each episode. This further translated to a proper characterization of light scattering levels measured at each site and each episode. Results are as good, and in many ways better, than regional modeling results in the Pacific Northwest area as conducted by the WRAP to address regional visibility/haze rules. The in-depth analyses undertaken in this modeling project have established confidence that the modeling system appropriately projects the individual PM constituent concentrations and resulting visibility impacts into the 2018 future year (according to the WRAP 2018 inventory projections), from which we have constructed visibility trend lines.

As with any modeling exercise, the results and conclusions reached as documented in this report are subject to the specific uncertainties associated with the methodology and datasets applied in this project.

i) Meteorological modeling

MM5 version 3.63 was used for the Gorge Study modeling system. Six MM5 simulations were performed and compared in this study for both the August and November 2004 episodes. Two of the MM5 model configurations were taken from previous modeling efforts conducted in this region: the University of Washington (UW) forecasting system ("Run 3"), and the Portland Ozone State Implementation Plan (SIP) ("Run 4").

Significant effort was expended to determine the best performing options in MM5 for the Gorge study. None of the MM5 configurations met all of the commonly accepted benchmarks for statistical performance, meaning that MM5 did not perform as well as it has historically performed in other air quality applications around the country[2]. It is important to note that these benchmarks were established according to a wealth of meteorological modeling applications for mostly urban and regional summertime ozone modeling. The Gorge Study area contains more complex terrain than most other areas modeled to date for air quality applications, and thus the monitors are more likely to be influenced by local and small-scale forcings. Both Gorge Study modeling episodes exhibited rather weak synoptic forcing; MM5 traditionally performs better under stronger forced conditions, such as storm systems. Another point to consider is that the Gorge Study region includes fewer sites than were used to develop the benchmarks; statistics based on fewer pairings tend to yield poorer statistics. Nevertheless, MM5 performed well in capturing the August up-gorge flow

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[2] Note that MM5 modeling undertaken by WRAP for the year 2002 also did not meet all of the performance benchmarks in the Pacific Northwest region; specifically MM5 suffered from under prediction tendencies for temperature, and over prediction tendencies for humidity and rainfall. In our experience, as well as the experience of many other air quality modelers throughout the country, this is a common trait of MM5 that is very difficult to resolve.

patterns and the November down-gorge flow patterns, to the extent that such flows were characterized by sites along the Gorge itself. For the November 2004 episode which was characterized by stagnation and fog, the MM5 model failed to adequately simulate the presence of fog in the Gorge and eastern Washington that adversely affected the chemical transport model performance. Ultimately fog was added to the meteorological fields based on satellite observations that improved the chemical transport model performance.

ii) Emissions processing

The emission inventory is a key component of an air quality modeling exercise. Spatially and temporally resolved estimates of sulfur dioxide (SO_2), volatile organic compounds (VOC), nitrogen oxides (NOx), carbon monoxide (CO), ammonia (NH_3), PM and other chemicals from sources such as electric generating utilities (EGUs), pulp mills, automobiles, commercial marine shipping activities, railroad locomotives, and even natural vegetation (biogenic), to name a few sources, are critical inputs to an air quality model.

A separate Emission Inventory report prepared by ODEQ provides a detailed breakdown and comparison of the resulting episodic emissions by source category and region that is summarized in Section 3.

2004 Base Year Emissions

The Southwest Clean Air Agency (SWCAA) and the Oregon Department of Environmental Quality (ODEQ) provided local 2004 annual stationary, area, and non-road mobile source emissions estimates (projected from the 2002 National Emissions Inventory [NEI]) for counties in Washington and Oregon. SWCAA and ODEQ also provided wildfire and prescribed fire activity data that were used to estimate fire emissions. Finally, SWCAA and ODEQ provided day-specific emissions estimates for the Portland General Electric (PGE) Boardman power plant and the Georgia Pacific Camas Mill wood pulping facility. For all other counties within the modeling domain, the SMOKE emissions processing system as configured for the WRAP study was used as a starting point, which included projecting the 2002 WRAP county-level annual stationary and non-road emissions to 2004. Additionally, all temporal and speciation profiles and cross-reference data were taken from the WRAP emission processing efforts. Spatial allocation of the emissions to the 4-km and 12-km modeling grids was based on profiles and surrogate factors developed specifically for this project using population and landuse/landcover distributions provided by EPA (and as used in the WRAP modeling). Special attention was given to the development of high resolution surrogate distributions in the OR/WA region and within the Gorge itself, especially as they related to commercial marine shipping.

MM5 temperature and wind fields were used to generate day- and grid-specific biogenic, wind-blown dust, and agricultural ammonia emissions for the Gorge modeling episodes. The EPA national landuse/landcover dataset used to develop spatial surrogates was also used in the estimation of agricultural ammonia emissions. The processing of on-road mobile sources required the use of OR/WA-specific and/or WRAP activity data (roadway locations, vehicle miles traveled (VMT), speed distributions, vehicle fleet mix, etc.).

Volcanic emissions from Mt. St. Helens were estimated for SO_2, based on measurements taken in November 2004. This was a period of increasing geologic activity that resulted in escalating emissions from Mt. St. Helens. Based on conversations with scientists at the United States Geological Survey (USGS), there was no volcanic activity during August 2004; hence, volcanic emissions for this episode were set to zero. The USGS does not estimate emissions of ash, which could be used as a surrogate for primary PM. However, given that there was no ash plume activity reported in either November or August 2004, primary PM emissions were considered nonexistent. Therefore, only the SO_2 emission estimates were used in this effort.

SMOKE was configured to generate model-ready point, area, non-road mobile, on-road mobile, and fire source emissions for the 36/12/4-km grid system; criteria pollutant emissions were speciated according to the Carbon Bond IV (CB4) chemical mechanism with PM. Certain emission subcategories, such as electric generating units (EGU), on-road mobile sources, fires, etc., were processed through the SMOKE system in separate streams in order to support PSAT applications and to allow maximum flexibility in developing and applying alternate strategies in the modeling. Specialized processing was conducted for certain source categories to provide updated and/or day-specific emission estimates for the episodic conditions modeled in this study: large industrial point sources, wildfires, some prescribed fires, on-road mobile, biogenics, wind-blown dust, and agricultural ammonia.

Upon review of the resulting model-ready emission inventory, several major issues were identified and rectified:

> Reduction in Residential Wood Smoke: Annual fine PM emissions from residential wood combustion in Oregon and Washington were found to be overstated by a factor of two, based upon an improper interpretation of a 1999 fireplace survey conducted in both states. A 50% reduction to the 2004 annual residential wood combustion categories was thus applied for both states. Furthermore, since the WRAP 2018 projections for residential wood combustion were found to be too large relative to the revised 2004 estimates, the 2018 emissions for this category were derived from the revised 2004 estimates by applying a 4% growth rate based on published population projections in Oregon and Washington.

> Increase in Agricultural Ammonia: Based on a detailed scrutiny of the Oregon and Washington ammonia inventories against recent emission factors published in the literature, two major issues were identified: (1) ammonia emissions from confined animal feeding operations (CAFO), such as dairies, were understated by factors of 1.5 to approximately 4; and (2) ammonia emissions from fertilizer application were understated by factors of 2.5 to 3. Ammonia emissions in Oregon and Washington were thus increased on a facility-type (CAFO) and application-type (fertilizers) basis.

> Application of Canopy Escape Factors: It is well known in the air quality modeling field that the impact of fugitive dust sources (such as unpaved and paved road dust; roadway, commercial, and residential construction; and agricultural tilling) on air quality is substantially lower than emissions inventories suggest, often by as much as an order of magnitude. Numerous studies suggest that removal of fugitive dust

occurring near the source, on a scale of tens to hundreds of meters, is beyond the
capability of current Eulerian air quality models (e.g., CMAQ, CAMx, etc.) that
address scales of 1-10 km. The county-specific transport factors of Pace were applied
to the fugitive dust categories. This reduced the amount of fugitive dust that the air
quality model "sees" by approximately 75%.

b) CAMx Base Case Performance Evaluation

i) August 2004 performance

Nine individual CAMx simulations were undertaken for the August 10-22, 2004 modeling
episode. More than half of these runs addressed improvements in the input emission
inventory or the treatment of biogenic secondary organic aerosol (SOA). The remaining runs
tested model sensitivity to various input changes that from our experience are associated with
the largest uncertainty and have the largest potential impact on the air quality results.

August model performance against Gorge field study measurements was not sensitive to
changes in wild fire emissions, or to increases in ammonia emissions. The simulated wild
fire emissions occasionally contributed to the performance at the Gorge monitors as the
plume edges wafted over the eastern-most sites. The August modeling was also not sensitive
to increased ammonia emissions. This was due to the fact that the period was warm and dry,
and so the ammonium nitrate formation was thermodynamically limited by the
meteorological conditions, as opposed to being limited by available ammonia.

After undertaking several diagnostic and sensitivity tests for the August modeling episode,
from which several emission problems were ameliorated, we were able to achieve an
acceptable base case replication of the PM components and light scattering/extinction that
were measured along the Columbia River. When model performance was quantitatively
gauged against 24-hour average measurements, it was found to meet or beat performance
goals and criteria for the most critical PM components observed during the period (organic
aerosol and sulfate), and for total light scattering and extinction. Those components that did
not meet the performance criteria (nitrate, fine and coarse primary PM) were either both
predicted and measured to be very low in concentration (the case for nitrate that was below 1
$\mu g/m^3$), or did not contribute significantly to light extinction due to low scattering efficiency
(the case for fine and coarse primary PM). CAMx performance in replicating the range of
24-hour light scattering among all nine Gorge Study dry nephelometer sites was quite good,
indicating a near zero bias tendency with a moderate degree of scatter about the 1:1 line (see
Figure 5-1). This level of performance is comparable to some of the best performance results
achieved by WRAP.

When hourly predictions were compared to limited hourly measurements taken at two Gorge
Study sites, Mt. Zion and Bonneville, the model demonstrated a basic ability to replicate the
inter-daily trends in PM component concentrations and light scattering during this episode,
but the model over stated the diurnal variation of carbonaceous components, and thus total
light scattering as well. Overall, the model performed very well in replicating the temporal

and spatial variation of key PM species concentrations and light extinction levels that were observed during this episode.

ii) November 2004 performance

Eight individual CAMx simulations were undertaken for the November 4-18, 2004 modeling episode, which paralleled the run configurations made for August. Most of these runs addressed improvements in the input emission inventory or the treatment of biogenic SOA.

The carbonaceous components tended to be over predicted and were dominated by wood smoke, which was especially concentrated in the Portland area. Over predictions in primary fine/coarse PM were due to over stated emission factors and the application of seasonal profiles in the modeling inventory that do not account for the suppressive effects of episode-specific precipitation events on such categories as road dust and construction and agricultural fugitive dust. Reducing the dust components to near zero to account for specific precipitation events would dramatically improve model performance for primary PM; this would require the development of day-specific dust emission fields (not done in this study).

Sulfate, nitrate and associated ammonium were appropriately predicted to be much higher during this episode, with nitrate exceeding 10 $\mu g/m^3$ in both measurements and predictions. This was due to the fact that the period was much cooler, wetter, and stagnant than the August episode, which are prime conditions for the formation of secondary sulfate and nitrate PM salts. Cloud water is an important heterogeneous chemical pathway for sulfate and nitrate, while high humidity and cool temperatures are critical for correctly characterizing the balance between sulfate, nitrate and ammonium. Nitrate aerosols are formed from the neutralization of nitric acid gas (which is produced by the atmospheric oxidation of NOx emissions) by cations such as ammonium, sodium, calcium, and potassium. Ammonium is by far the most abundant cation available away from oceans, so ammonium nitrate is the most abundant form of nitrate particles. On the other hand, sulfate (which is produced by the atmospheric oxidation of SO_2 emissions) exists as an aerosol regardless of its state of neutralization by the same cations. Thus, there is a "competition" between sulfate and nitrate to react with available cations; the process is complex and dependent on atmospheric conditions and the mix of chemicals. In very simple terms, ammonia preferentially reacts with sulfuric acid aerosols, and any excess is then available to form nitrate particles.

Our tests with CAMx indicated that ammonium nitrate formation during the November 2004 episode was limited by available ammonia. Indeed, nitrates and ammonium were much higher in tests that doubled ammonia emissions, especially around major urban areas such as Portland and along the Interstate 5 route up through Seattle. Sulfate was not significantly impacted by the doubling of ammonia, as the chemical process described above would suggest. So the doubling of ammonia emissions likely went into neutralizing more sulfate (which would not lead to an obvious change in total sulfate concentrations output by the model), and any excess ammonia went to neutralizing more available nitrate. In other words, even more ammonia emissions would probably lead to additional PM nitrate (i.e., an ammonia-limited system). Higher ammonium nitrate concentrations resulted in the largest increases in light scattering in the western Columbia River Gorge area early in the episode, while eastern Gorge sites showed a more modest increase later in the episode.

Several diagnostic and sensitivity tests for the November modeling episode were successful in allowing us to identify problems in the November 2004 emission inventory and to improve certain performance issues associated with the meteorology of the period. Incremental improvements at each step of the process brought model performance for light scattering and most PM constituents to acceptable levels. Model performance was qualitatively gauged for 24-hour average PM, and found to continually exhibit over prediction tendencies for primary PM components along the western portion of the Columbia River (carbonaceous and fine dust), as described above. Overall, sulfate and secondary organic aerosols (SOA) were well predicted, although sulfate exhibited an over prediction tendency. On an episode-average basis, nitrate concentrations were well modeled with very small bias, but nitrate performance on a day-to-day basis was not well correlated with observations.

Performance for light scattering indicated a "bifurcated" pattern: light scattering was over predicted in the Portland area and along the western portion of the Columbia River, while it was under predicted along the eastern portion of the river (see Figure 5-1). MM5 model performance suffered from a lack of humidity and clouds during the November episode. As discussed above, the ability to generate the correct amount of nitrate is particularly sensitive to the accuracy of humidity and temperature fields. The MM5 cloud field predictions were improved by simply assigning fog to areas of the air quality modeling grid according to available visible satellite imagery. This was found to help the under predictions in sulfate and nitrate significantly, and improved modeling performance in replicating the observed light scattering in the Gorge. However, we identified other issues associated with how the "dry" nephelometer instruments employed during the Gorge field study over estimated PM light scattering during the very high humidity conditions that occurred over the core November period. This instrument artifact contributed to some uncertainty in our model-observation comparisons for light scattering.
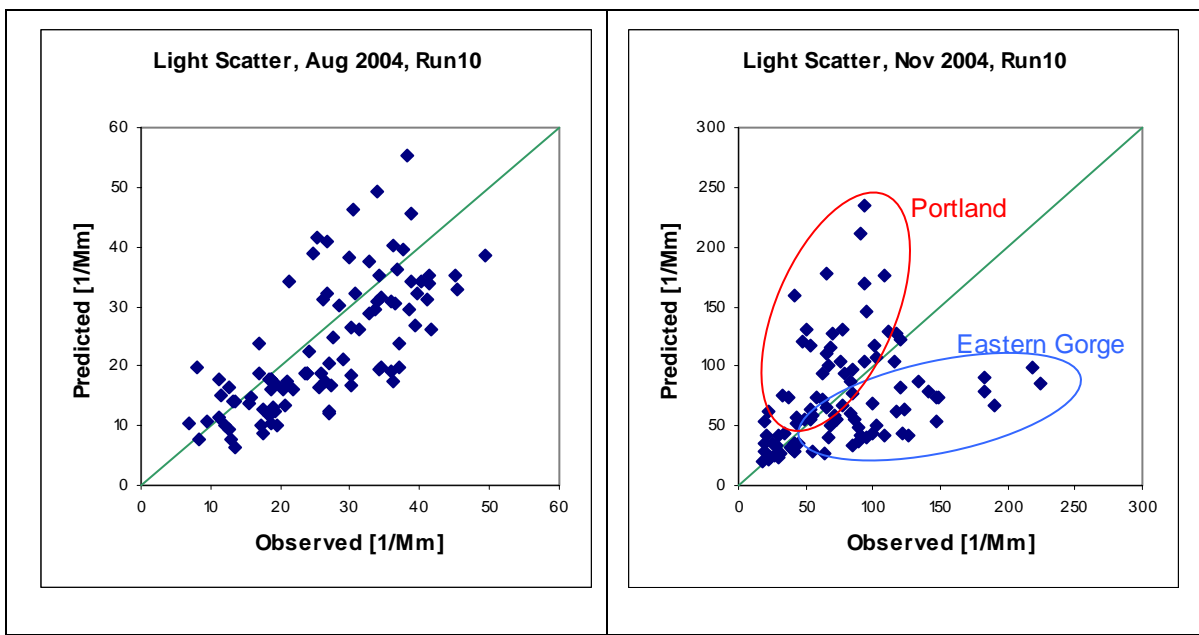
Figure 5-1. Scatter diagram comparing 24-hour average light scattering predicted by CAMx against "dry" nephelometer measurements from nine Gorge Study sites along the Columbia River.

Units are inverse megameters; results are from CAMx "Run 10" for the August 2004 (left) and November 2004 (right) episodes.

In summary, CAMx performed well in replicating the much higher concentrations of ammonium sulfate and ammonium nitrate along the Columbia Gorge during the cool, foggy, stagnant conditions of the November 2004 episode. The thick haze that formed during the period was observed to be dominated by these secondary salts, as well as from carbonaceous PM from (mostly) wood smoke. The air quality model simulated the elevated concentrations of all of these key species adequately well, allowing us to have confidence that the model provides the correct conclusions regarding source apportionment and impacts from emission changes under such extreme haze conditions.

c) Base Year Source Apportionment Modeling

The CAMx PM Source Apportionment Tool (PSAT) was applied to the August and November 2004 modeling episodes to quantify source attribution at the Mt. Zion and Wishram monitoring sites for the 2004 Base Case scenario. A full description of PSAT is provided in the CAMx User's Guide. In PSAT, the emissions of PM and gas precursors are stratified by source category and by source region; tracers are used to tag emissions from each category-region pair and track transport, chemical evolution from gas to PM, and deposition. Tracers can be run, separately or in combination, for a sulfur group, a nitrogen group, an organic group, and a primary PM group.

In the PSAT application run for the Gorge Study, twelve source categories and six source regions were defined. The CAMx input emission inventory files were split into ten source categories for the PSAT application. Two additional categories (initial conditions and boundary conditions) are automatically added internally by CAMx. The ten emission categories consisted of nine categories within the 4-km grid, and the tenth category for all sources outside the 4-km grid:

1. On-road mobile sources;
2. Non-road mobile sources (railroad, marine shipping, construction, lawn/garden equipment, etc.);
3. Ammonia sources (livestock operations, agricultural fertilizer application, waste treatment);
4. Other area sources (residential, commercial, industrial, etc. not included above);
5. Point source electric generating units (EGU);
6. Point source pulp mills;
7. Wildfires;
8. Other fires (prescribed and agricultural burns, structural fires)[3];
9. Other point sources (not included in the above);
10. All emissions outside the 4-km grid.

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[3] The "other fires" category does not include residential wood smoke; that is contained in "other area sources."

Figure 5-2 displays the five PSAT source regions in the 4 km grid: (1) within the Columbia River Gorge from east of Portland to Wishram; (2) the Portland Metropolitan area; (3) the western portion of the Columbia River northwest of Portland; (4) the remaining portions of Oregon and Washington west of the Cascade crest; and (5) the remaining portions of Oregon and Washington east of the Cascade crest.

PSAT was run for the sulfur, nitrogen, and primary PM families of tracers. The secondary organic aerosol (SOA) group was not run; the main issue concerning SOA is the relative amount of SOA formed from biogenic vs. anthropogenic VOC emissions. Since the core SOA module in CAMx generates a biogenic/anthropogenic attribution by design (without the need for PSAT), and biogenic SOA was seen to dominate 24-hour PM predictions across the 4-km grid, it was determined that relying on the biogenic/anthropogenic split provided by the core CAMx model was sufficient and was in fact needed to reduce the computer burden. However, this approach does not provide a source region attribution for anthropogenic SOA.
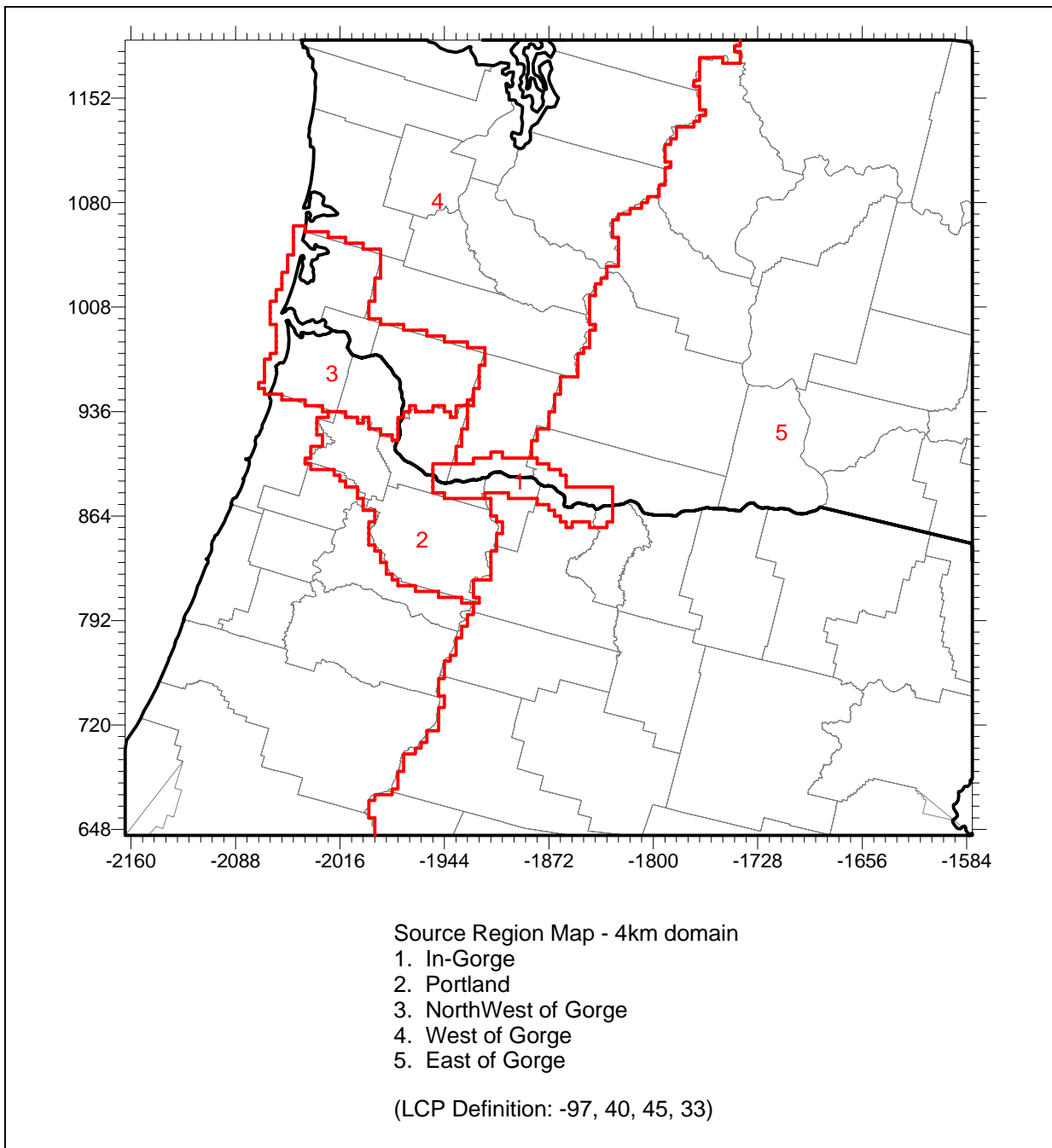
Figure 5-2. Breakdown of the 4-km modeling grid into 5 source regions for use in the CAMx PSAT application. A sixth region was defined for all areas outside the 4-km grid (i.e., within the 12-km grid).

i) PSAT Results for August 2004

At Mt. Zion, areas outside the 4-km domain contribute to the bulk of sulfate during this episode. Portland and areas along the westernmost area of the Columbia River (i.e., PSAT regions 2 and 3) are the largest local source areas of sulfate, which agrees with the general west-to-east transport direction during this period. A variety of source types in these western areas contribute to sulfate, including non-road sources (heavily dominated by diesel engines), electric generating units (EGUs), pulp mills, and other point sources. Nitrate is primarily attributed to similar local upwind regions from on-road, non-road, and EGU sources. Not surprisingly, ammonium is attributed to mainly local ammonia-specific sources in the Gorge and in Portland (PSAT regions 1 and 2). Primary carbonaceous components come mostly from upwind and local areas from mobile and area sources (particularly non-road), suggesting diesel activity. Other carbon sources include area sources and fires. The vast majority of SOA is derived from biogenic sources. Dust (coarse and fine) is nearly entirely from local on-road sources (road dust). Other fine/coarse fractions of primary PM are mostly from local area sources.

The PSAT application revealed that a large fraction of visibility impairment at Mt. Zion during the August 2004 episode was caused by natural sources, including secondary organic aerosols (SOA) from biogenic emissions (~30%). Table 5-1 ranks the contributions to light extinction at the Mt. Zion monitoring site averaged over the August 2004 episode stratified by species, source regions and source category that accounts for roughly 90% of the non-biogenic extinction (~60% of total extinction). Table 5-2 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze at Mt. Zion during the August 2004 episode are:

1. **Sulfate from super-regional sources (i.e., the Boundary Conditions) outside the 12-km Pacific Northwest grid (12%);**
2. **Elemental carbon from Portland non-road sources (5%);**
3. **Sulfate from regional sources outside the 4-km OR/WA grid (5%);**
4. **Elemental carbon from local Gorge non-road sources (3%); and**
5. **Sulfate from EGU sources northwest of Portland (2%).**

Table 5-1. Top-ranked list of source region/categories contributing to visibility-impairing haze over the August 2004 episode at Mt. Zion. Source regions/categories shown account for roughly 60% of the total episode-average light extinction.

Species	Region	Source	ug/m^3	Mm^{-1}	Contribution
Sulfate	BC		0.38	4.40	12%
EC	Portland	Non-road	0.19	1.93	5%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.15	1.78	5%
EC	Gorge	Non-road	0.10	1.03	3%
Sulfate	NW of Gorge	EGUs	0.08	0.89	2%
POA	East of Gorge	Wildfires	0.21	0.86	2%
Nitrate	Portland	On-road mobile	0.07	0.74	2%

EC	Portland	On-road mobile	0.07	0.68	2%
EC	NW of Gorge	Non-road	0.07	0.65	2%
Nitrate	Portland	Non-road	0.06	0.63	2%
Nitrate	BC		0.05	0.59	2%
POA	Portland	Other area	0.13	0.52	1%
EC	East of Gorge	Wildfires	0.05	0.47	1%
Sulfate	NW of Gorge	Other points	0.04	0.45	1%
Sulfate	NW of Gorge	Non-road	0.04	0.43	1%
Nitrate	NW of Gorge	EGUs	0.04	0.43	1%
POA	Portland	Non-road	0.10	0.40	1%
Nitrate	West of Gorge	On-road mobile	0.04	0.39	1%
Sulfate	NW of Gorge	Pulp mills	0.03	0.38	1%
POA	Gorge	Other area	0.08	0.32	1%
Fine Other	Portland	Other area	0.32	0.32	1%
Sulfate	Portland	Non-road	0.03	0.30	1%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.03	0.29	1%
Sulfate	Portland	Other area	0.02	0.28	1%
Sulfate	East of Gorge	Wildfires	0.02	0.27	1%
Nitrate	NW of Gorge	Non-road	0.02	0.27	1%
POA	Portland	On-road mobile	0.06	0.24	1%
POA	Gorge	Non-road	0.06	0.24	1%
Sulfate	Portland	Pulp mills	0.02	0.24	1%
EC	West of Gorge	Non-road	0.02	0.21	1%
POA	BC		0.05	0.20	1%
EC	Gorge	On-road mobile	0.02	0.20	1%
EC	Portland	Other area	0.02	0.20	1%
Nitrate	NW of Gorge	On-road mobile	0.02	0.20	1%
Coarse Other	Portland	Other area	0.32	0.19	1%
Nitrate	NW of Gorge	Other points	0.02	0.17	0%
EC	Outside 4 km domain	Outside 4 km domain	0.02	0.16	0%

Table 5-2. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the August 2004 episode at Mt. Zion. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm^{-1}	Contribution
BC/Outside 4 km domain	7.81	22%
Portland	7.10	20%
NW of Gorge	4.37	12%
Gorge	2.29	6%
East of Gorge	1.64	4%
West of Gorge	1.18	3%
Biogenic SOA	12.00	33%

At Wishram, areas outside the 4-km domain (but within the 12-km domain) contribute to the bulk of sulfate during this episode. However, there is a stronger influence from wildfires in the eastern portion of the 4-km grid, and a smaller influence from Portland and the western areas. Nitrate is primarily attributed to local and upwind regions to the west, from on-road and non-road sources. Ammonium has a strong source locally in the Gorge and in the

eastern area from ammonia-specific sources, which are dominated by agricultural activities. Primary elemental and organic carbon components indicate a rather strong contribution from wildfires occurring in north-eastern Washington during this episode; elemental carbon further shows a large contribution from in-gorge non-road sources, which implicate diesel emissions from railroads, barges, and off-road equipment. Again, nearly all SOA generated by CAMx is from biogenic sources, but there is less total SOA simulated at this site than at the Mt. Zion site, probably due to drier and non-forested conditions along the eastern end of the Gorge. Coarse and fine dust are nearly entirely from in-gorge on-road and area sources, while other fine/coarse fractions of primary PM are mostly from area sources (again, mostly agricultural activities) and more uniformly apportioned across several regions.

The PSAT application revealed that the majority of visibility impairment at Wishram during the August 2004 episode was caused by natural sources, including SOA from biogenic emissions (30%) and carbonaceous aerosols from wildfires (20%). Table 5-3 ranks the contribution to light extinction at Wishram averaged over the August 2004 episode that accounts for roughly 90% of the non-biogenic extinction (~60% of total extinction). Table 5-4 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

Of the non-SOA fraction tracked by PSAT, the top five ranked non-biogenic sources contributing to haze included:

1. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (12%);**
2. **Primary organic carbon from eastern OR/WA wildfires (12%);**
3. **Elemental carbon from eastern OR/WA wildfires (6%);**
4. **Sulfate from regional sources outside the 4-km OR/WA grid (5%); and**
5. **Elemental carbon from local Gorge non-road sources (5%).**

Table 5-3. Top-ranked list of source region/categories contributing to visibility-impairing haze over the August 2004 episode at Wishram. Source regions/categories shown account for roughly 60% of the total episode-average light extinction.

Species	Region	Source	ug/m^3	Mm^{-1}	Contribution
Sulfate	BC		0.31	3.49	12%
POA	East of Gorge	Wildfires	0.85	3.42	12%
EC	East of Gorge	Wildfires	0.177	1.77	6%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.12	1.39	5%
EC	Gorge	Non-road	0.133	1.33	5%
Sulfate	East of Gorge	Wildfires	0.07	0.80	3%
Sulfate	NW of Gorge	EGUs	0.03	0.33	1%
Nitrate	West of Gorge	On-road mobile	0.029	0.30	1%
Nitrate	BC		0.026	0.28	1%
EC	West of Gorge	Non-road	0.026	0.26	1%
Nitrate	Portland	On-road mobile	0.022	0.23	1%
EC	Outside 4 km domain	Outside 4 km domain	0.021	0.21	1%
Coarse Dust	Gorge	Other area	0.3467	0.21	1%
EC	West of Gorge	On-road mobile	0.020	0.20	1%

POA	Outside 4 km domain	Outside 4 km domain	0.05	0.20	1%
POA	BC		0.05	0.20	1%
POA	Gorge	Non-road	0.05	0.20	1%
EC	BC		0.018	0.18	1%
EC	Portland	Non-road	0.016	0.16	1%
POA	West of Gorge	Other area	0.04	0.16	1%
Nitrate	Gorge	Non-road	0.014	0.15	1%
Nitrate	Portland	Non-road	0.013	0.14	1%
Sulfate	NW of Gorge	Other points	0.01	0.14	0%
Sulfate	West of Gorge	Non-road	0.01	0.14	0%
Sulfate	NW of Gorge	Non-road	0.01	0.13	0%
EC	Gorge	On-road mobile	0.013	0.13	0%
Nitrate	NW of Gorge	EGUs	0.012	0.12	0%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.011	0.12	0%
Sulfate	West of Gorge	Other points	0.01	0.11	0%
Sulfate	East of Gorge	EGUs	0.01	0.10	0%
Sulfate	Gorge	Non-road	0.01	0.10	0%
Sulfate	Portland	Non-road	0.01	0.10	0%

Table 5-4. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the August 2004 episode at Wishram. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm^{-1}	Contribution
East of Gorge	6.44	23%
BC/Outside 4 km Domain	6.26	22%
Gorge	2.58	9%
West of Gorge	1.63	6%
NW of Gorge	0.97	4%
Portland	0.81	3%
Biogenic SOA	9.44	33%

ii) PSAT results for November 2004

A very different PM environment is characterized in the November episode, with secondary sulfate/nitrate/ammonium salts dominating the mass budgets. At Mt. Zion, almost 3 µg/m^3 is predicted for episode-average sulfate, and the largest contributor is EGU emissions in the eastern portion of the modeling domain. However, a wide array of source types and areas contribute to the Mt. Zion sulfate, including areas outside the 4-km domain (but within the 12 km grid), which indicates the regional nature of this secondary pollutant. Nitrate is also rather high (over 2 µg/m^3), with large contributions from on-road and non-road NOx sources mainly from Portland and areas to the west and along the Gorge. Ammonium is attributed to specific ammonia sources (mostly agricultural activities such as animal feed lots and fertilizer applications). Again, a vast area of emissions contributes to ammonium, but the most comes from the eastern Gorge area where there are some large agricultural sources. Both elemental and organic carbon show large contributions from on-road and non-road sources within the Gorge and from Portland, and the POA is apportioned in large measure to area sources (residential wood smoke). Elemental carbon in particular has a large non-road component, likely due to heavy duty diesel engines on off-road equipment, barges, and railroads. Coarse/fine dust are mostly locally generated, and given the wetter nature of the November episode, are likely overstated since the modeling emissions inventory does not account for local day-specific rainfall patterns. Most sources of primary fine/coarse PM are very local in origin and are from fugitive and wind-blown dust sources.

The PSAT application revealed that the vast majority of visibility impairment at Mt. Zion during the November 2004 episode was caused by anthropogenic sources (~90%). Secondary organic aerosols from biogenic emissions contributed ~40% of the episode-average total organic carbon concentration, but only 11% of episode-average light extinction. Table 5-5 ranks the contributions to light extinction at Mt. Zion for the November 2004 episode that accounts for roughly 90% of the non-biogenic extinction (~80% of total extinction). Table 5-6 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze are:

1. **Sulfate from eastern OR/WA EGU sources (10%);**
2. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (10%);**
3. **Nitrate from Portland on-road sources (9%);**
4. **Nitrate from western OR/WA on-road sources (4%); and**
5. **Nitrate from super-regional sources outside the 12-km Pacific Northwest grid (4%).**

Table 5-5. Top-ranked list of source region/categories contributing to visibility-impairing haze over the November 2004 episode at Mt. Zion. Source regions/categories shown account for roughly 80% of the total episode-average light extinction.

Species	Region	Source	ug/m³	Mm⁻¹	Contribution
Sulfate	East of Gorge	EGUs	0.62	12.07	10%
Sulfate	BC		0.58	11.33	10%
Nitrate	Portland	On-road mobile	0.54	9.86	9%
Nitrate	West of Gorge	On-road mobile	0.28	5.08	4%
Nitrate	BC		0.25	4.52	4%
Sulfate	Portland	Other area	0.23	4.48	4%
Sulfate	NW of Gorge	Other points	0.18	3.60	3%
Sulfate	Gorge	Non-road	0.17	3.36	3%
Nitrate	Portland	Non-road	0.17	3.17	3%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.15	3.00	3%
POA	Portland	Other area	0.71	2.84	2%
Sulfate	Portland	Non-road	0.14	2.73	2%
POA	Gorge	Other area	0.56	2.23	2%
Sulfate	NW of Gorge	EGUs	0.11	2.18	2%
Nitrate	Gorge	Non-road	0.11	1.99	2%
Nitrate	NW of Gorge	EGUs	0.11	1.92	2%
EC	Gorge	Non-road	0.16	1.64	1%
Nitrate	Gorge	On-road mobile	0.08	1.54	1%
Nitrate	Portland	Other area	0.08	1.50	1%
Sulfate	Portland	Other points	0.07	1.42	1%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.08	1.42	1%
Sulfate	West of Gorge	Other points	0.07	1.38	1%
Sulfate	Portland	On-road mobile	0.07	1.31	1%
EC	Portland	Other area	0.13	1.30	1%
Sulfate	West of Gorge	Other area	0.07	1.30	1%
Nitrate	East of Gorge	On-road mobile	0.07	1.27	1%
Nitrate	West of Gorge	Non-road	0.07	1.22	1%
EC	Gorge	Other area	0.10	1.04	1%
EC	Portland	Non-road	0.10	1.01	1%

Table 5-6. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the November 2004 episode at Mt. Zion. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm⁻¹	Contribution
Portland	32.00	28%
BC/Outside 4 km domain	22.16	19%
East of Gorge	15.31	13%
Gorge	14.96	13%
West of Gorge	10.30	9%
NW of Gorge	7.72	7%
Biogenic SOA	13.35	11%

The Wishram site experiences even more episode-average sulfate than Mt. Zion, with nearly a 5 μg/m^3 episode average. Again the single largest contributor is EGU emissions in the eastern portion of the modeling domain. Unlike Mt. Zion, very little contribution is shown for other sources, since this site is much farther from large sources such around the Portland area and transport winds are generally easterly from remote areas of eastern Oregon and Washington. Nitrate is also higher at Wishram (almost 5 μg/m^3), with contributions primarily from on-road, non-road, area, and EGU NOx sources in the eastern area. NOx sources outside the 4-km grid (mostly well to the east) also contribute to nitrate. Ammonium in nearly entirely attributed to local sources in the eastern area of the domain; large ammonia sources in the area of Wishram are causing a local formation of particle ammonium nitrate as aged nitric acid plumes move into the area from the east, mix with the ammonia, and condense into PM nitrate in the cool humid environment. Carbonaceous PM is much lower than the secondary salts, although episode-average elemental carbon (EC) concentrations of nearly 1 μg/m^3 are rather high compared to many other IMPROVE sites in the western US. Most EC stems from local non-road sources in the Gorge and in the eastern area, which suggests a large contribution from diesel exhaust. POA at Wishram is lower than at Mt. Zion, given it's distance from Portland, and has local origins from non-road, area (residential wood combustion), and fires. Like Mt. Zion, coarse/fine dust is mostly locally generated in Gorge and in the eastern area, with mostly area and on-road sources contributing.

The PSAT application revealed that the vast majority of visibility impairment at Wishram during the November 2004 episode was caused by anthropogenic sources (95%). SOA from biogenic emissions contributed ~50% of the episode-average total organic carbon concentration, but only 5% of episode-average visibility impairment. Table 5-7 ranks the contributions to light extinction at Wishram for the November 2004 episode hat accounts for roughly 90% of the non-biogenic extinction (~85% of total extinction). Table 5-8 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze are:

1. **Sulfate from eastern OR/WA EGU sources (27%);**
2. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (7%);**
3. **Nitrate from eastern OR/WA on-road sources (7%);**
4. **Nitrate from super-regional sources outside the 12-km Pacific Northwest grid (6%); and**
5. **Nitrate from eastern OR/WA non-road sources (6%).**

Table 5-7. Top-ranked list of source region/categories contributing to visibility-impairing haze over the November 2004 episode at Wishram. Source regions/categories shown account for roughly 85% of the total episode-average light extinction.

Species	Region	Source	ug/m^3	Mm^{-1}	Contribution
Sulfate	East of Gorge	EGUs	2.64	51.64	27%
Sulfate	BC		0.72	14.15	7%
Nitrate	East of Gorge	On-road mobile	0.75	13.68	7%
Nitrate	BC		0.65	11.93	6%
Nitrate	East of Gorge	Non-road	0.62	11.44	6%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.56	10.35	5%
Nitrate	East of Gorge	EGUs	0.53	9.64	5%
Nitrate	East of Gorge	Other area	0.43	7.85	4%
Sulfate	East of Gorge	Non-road	0.31	5.97	3%
Sulfate	Gorge	Non-road	0.28	5.40	3%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.26	5.08	3%
Nitrate	Gorge	Non-road	0.21	3.89	2%
EC	Gorge	Non-road	0.310	3.10	2%
Nitrate	Portland	On-road mobile	0.15	2.77	1%
Sulfate	NW of Gorge	Other points	0.13	2.49	1%
Nitrate	West of Gorge	On-road mobile	0.11	2.08	1%
Nitrate	Gorge	On-road mobile	0.11	1.96	1%

Table 5-8. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the November 2004 episode at Wishram. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm^{-1}	Contribution
East of Gorge	108.50	57%
BC/Outside 4 km domain	44.01	23%
Gorge	18.02	10%
Portland	4.59	2%
NW of Gorge	3.25	2%
West of Gorge	2.24	1%
Biogenic SOA	9.58	5%

6)   Uncertainty Assessment and Attribution Reconciliation

This section compares the results of the PMF analysis discussed in Section 4 of this report with the results of the numerical source modeling provided in Section 5. This summary section highlights areas of agreement and disagreement and provides explanations for any differences.

a) November Episode PSAT/PMF Comparison

For the November 2004 episode the PSAT results summarized contributions to particle light extinction for the high impact days of the episode. There are 5 days with IMPROVE samples for the November episode, but the days of November 8, 11, and 14 were much more impacted than the other episode sample days of November 5 and November 17. So we can compare the average PMF factor contributions to light extinction for the three hazy sample days to the source modeling PSAT results. Because PMF determines factor contributions based on many sampling days, it is generally considered to be more applicable for average contributions than individual day contributions. Similarly for source modeling results used by PSAT, there is more confidence in longer term averages than short-term averages. Effects of random errors in wind fields, location of clouds, etc. will tend to balance out over longer modeling periods, but result in more uncertainty over shorter term periods such as the two episodes modeled for this study. Below we give results separately for Wishram and Mt. Zion.

Wishram

The reconstructing particle light extinction from the IMPROVE samples apportioned by PMF averaged 236 Mm^{-1} at Wishram for the 3 high IMPROVE days during the episode. Reconstructed particle light extinction from the source modeling apportioned by PSAT for the peak days averaged 190 Mm^{-1}.

PMF Results Summary for Wishram for November 2004

The PMF factor average contributions to haze at Wishram for the November 2004 episode (Nov. 8, 11, and 14)) were:

Nitrate-rich secondary 75.6%
Biomass burning 15.8%
Mobile sources 5.0%
Sulfate-rich secondary 1.7%
Coarse mass 1.5%
Dust 0.5%.

(Note that coarse mass (CM) was not included in the PMF modeling but the light extinction due to it was added based

PMF Wishram Nov 2004

- Nitrate-rich secondary
- biomass burning
- mobile sources
- sulfate-rich secondary
- coarse mass
- dust
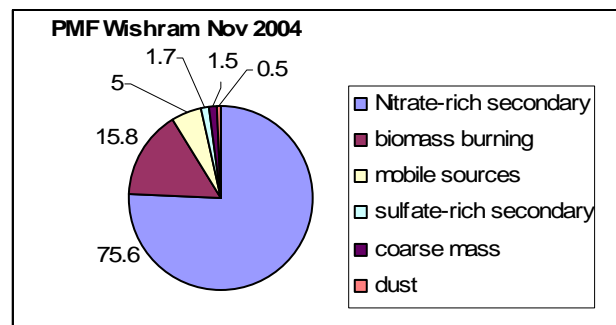
on CM concentration). The sulfate-rich secondary factor seems low, but remember that the nitrate-rich secondary factor was fairly rich in sulfate as well as nitrate (73% nitrate, 14% sulfate). If sources of nitrate are also sources of sulfate (such as electric generating units (EGUs), it may be difficult for PMF to separate them.

PSAT Results Summary for Wishram for November 2004

The PSAT average contributions to haze at Wishram for the November 2004 episode included:

Sulfate and nitrate from EGUs east of gorge 32.2%
Non-road mobile source sulfate, nitrate, and EC from the gorge and east of gorge 15.7%
On-road mobile source nitrate 10.8%
Sulfate and nitrate from boundary conditions and outside the 4-km grid 21.8%
Sulfate and nitrate from misc. point and area sources 5.4%
Biogenics 5.0%
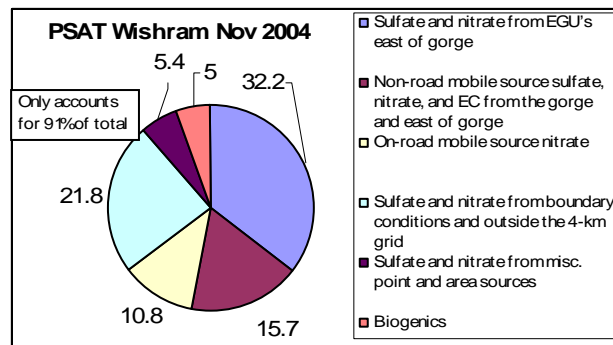
Comparison of Gross Results PMF to PSAT for Wishram for November 2004

Adding sulfate-rich secondary and nitrate-rich secondary PMF results gives 77.3% of the particle light extinction from theses factors. Adding sulfate and nitrate from EGUs, BC's, outside of 4km domain plus other point and area sources gives 59.4% from the source modeling. PMF attributes 5% to mobile and 15.8% to biomass burning while PSAT attributes 26.5% to mobile sources and 5% to biogenic. The main difference here is the much larger attribution to mobile sources by PSAT compared to PMF. However the sum of mobile and biogenic shows 31.5% by PMF while the sum of mobile and biomass burning is 20.8% by PMF. It is suspected that PMF may be attributing some of the mobile sources to the biomass burning factor. Overall the results of the 2 methods do not differ dramatically. The PSAT shows the biggest source to be EGUs east of the gorge and the PMF result of high impacts from sulfate and nitrate rich secondary factors supports that result. The largest differences in results are the much lower attribution to mobile sources by PMF compared to PSAT and the significant attribution to biomass burning by PMF.

Mt. Zion

PMF attribution to particulate light extinction by factor for Mt Zion for November 2004:

Nitrate-rich secondary 64.3%
Sulfate-rich secondary 12.5%
Biomass burning 14.3%
Mobile sources 2.5%
Paper mills 1.8%
Oil combustion 1.5%
Dust 1.2%
Coarse mass from measurements 1.8%

PMF Mt Zion Nov 2004

1.5 1.2
1.8 1.8
2.5
14.3
12.5
64.3

☐ Nitrate-rich secondary
☐ Sulfate-rich secondary
☐ Biomass burning
☐ Mobile sources
☐ Paper mills
☐ Oil combustion
☐ Dust
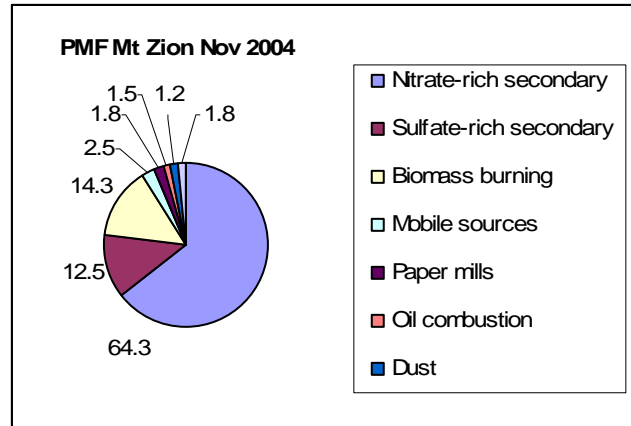
PSAT attribution to particulate light extinction by factor for November 2004:

Boundary conditions and Outside 4 km domain 17.6%
On-road mobile 16.6%
Non-road mobile 13.1%
EGUs 14.1%
Other area 12.8%
Other point 5.6%
Biogenic 11.6%
Miscellaneous other 9%

PSAT Mt Zion Nov 2004

9   17.6
11.6
5.6   16.6
12.8
14.1   13.1

☐ Boundary conditions and Outside 4 km domain
☐ On-road mobile
☐ Non-road mobile
☐ EGUs
☐ Other area sources
☐ Other point sources
☐ Biogenic sources
☐ Miscellaneous other
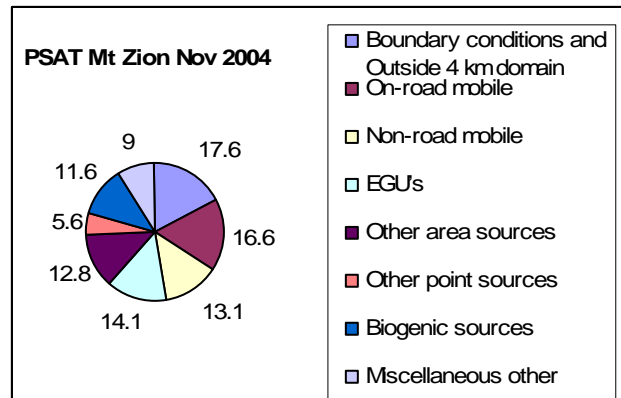
Comparison of gross results PSAT and PMF for Mt Zion for November 2004

PMF attributes 77% to sulfate and nitrate-rich secondary. PSAT attributes about 50% to like sources including EGUs, boundary conditions, sources outside the 4km domain, other point and other area sources. PSAT attributes 29.7% to on-road sources and non-road mobile sources while PMF only has 4% for mobile plus oil combustion. PMF has 14.4% for the biomass burning factor which may account for part of the difference between the PSAT and PMF mobile sources (PMF may be attributing a large portion of mobile source impacts to biomass burning instead).

b) August Episode PSAT/PMF Comparison

IMPROVE samples were not available for the high haze days of the August episode. Instead we compare PSAT results for the episode to August average PMF attributed reconstructed light extinction. The samples used are from August 2003 and August 2004. The PSAT results for the episode then are compared to PMF results that might be typical for August rather than for the specific period. As fires were reported to affect the area the August average PMF results may underestimate the biomass burning compared to the actual conditions during the episode. Overall over the 2 Augusts, PMF biomass burning impacts were similar to PSAT wildfire impact during the August 2004 episode. Notably, both showed much higher impacts in the eastern Gorge (Wishram) than the western Gorge (Mt. Zion).

Mt. Zion

The PMF attribution to haze by factor for Mt Zion averaged over all August 2003/2004 samples is:

Paper mill 5.7%
Oil combustion 22.7%
Nitrate-rich secondary 8.8%
Sulfate-rich secondary 28.5%
Mobile 3.8%
Dust 9.1%
Biomass burning 8%
Coarse mass (from observations, not PMF) 13.4%
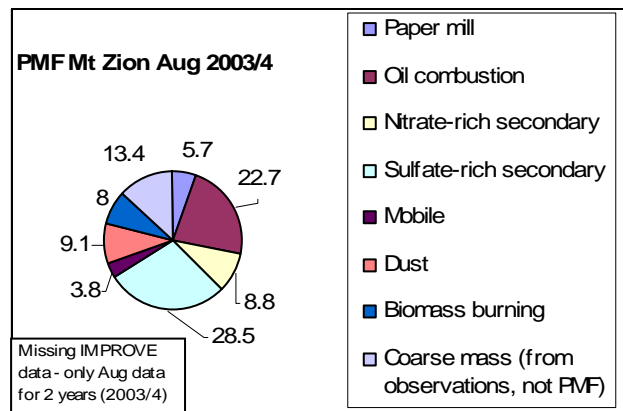
The PSAT attribution to haze for Mt Zion by category for August 2004 is:

Biogenic 33%
Boundary conditions 14.4%
Outside 4 km domain 6.2%
Non-road mobile 16.9%
On-road mobile 6.8%
Other area 5.1%
Wildfires 4.4%
EGUs 3.7%
Pulp & paper mills 1.7%
Other point 1.7%
Miscellaneous other 5.7%
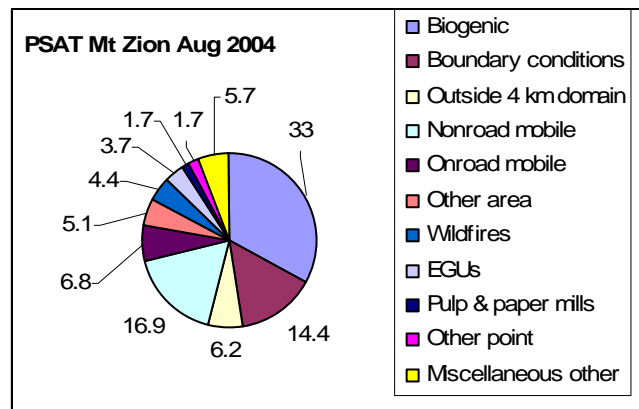
Comparison of PMF and PSAT results for Mt Zion for August 2004

Combining oil combustion (shipping) and mobile from PMF gives 26.5%.
Combining on-road mobile and non-road mobile from PSAT gives 23.7%.
Unlike the November episode, this indicates good agreement from the two methods for mobile sources.

Combining nitrate-rich secondary and sulfate-rich secondary from PMF gives 37.3%.
Combining a variety of sources rich in secondary sulfate and nitrate from PSAT gives 31.1% (boundary conditions, outside 4km grid, EGUs, other point, other area). This is also reasonable agreement.

Some difference is notable in pulp and paper mill effects: 5.7% from PMF and 1.7% from PSAT. However, as we don't have all IMPROVE samples for the period it is unknown whether PMF would give a similar value for this period or not. The DRUM sampler at Mt. Zion showed frequent direct impact of paper mill emissions at Mt. Zion. Unfortunately, the DRUM sampler was turned off early on August 10 at the very beginning of the episode. As a large mill close to the Mt. Zion site, the MM5 model may have difficulty correctly modeling transport winds between the source and Mt. Zion.

Biomass burning from PMF was 8% compared to 4.4% from PSAT wildfires. PSAT had 33% from biogenic emissions which was not a source category from PMF. The IMPROVE data showed an average of 13.4% from coarse mass, while PSAT had 1% coarse mass under other area sources.

Wishram

The PMF particle light extinction attribution to haze by factor averaged over all August 2003/2004 IMPROVE samples for Wishram for each factor is:

Nitrate-rich secondary 5.6%
Biomass burning 16.8%
Mobile sources 9.2%
Sulfate-rich secondary 44.6%
Coarse mass 17.1%
Dust 6.8%
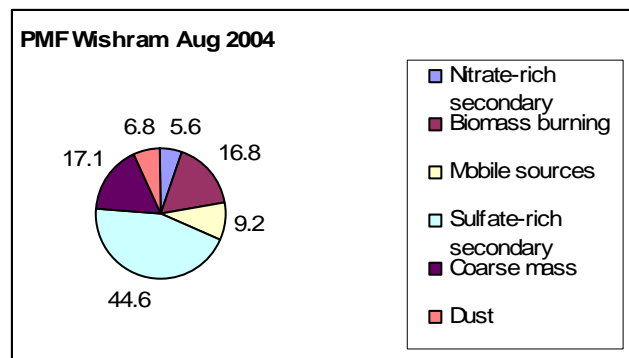
The PSAT attribution to haze by category for Wishram for August 2004 is:

Biogenic 33%
Wildfires 21.4%
Boundary conditions 14.8%
Outside 4 km domain 6.9%
Non-road mobile 9.7%
On-road mobile 2.4%
EGUs 2%
Other area (includes coarse dust) 1.3%
Other point 0.9%

PSAT Wishram Aug 2004

1.3 0.9
2.4 2
9.7
33
6.9
14.8
21.4

Only accounts for 92.4% of total

- Biogenic
- Wildfires
- Boundary conditions
- Outside 4 km domain
- Non-road mobile
- On-road mobile
- EGUs
- Other area (includes coarse dust)
- Other point
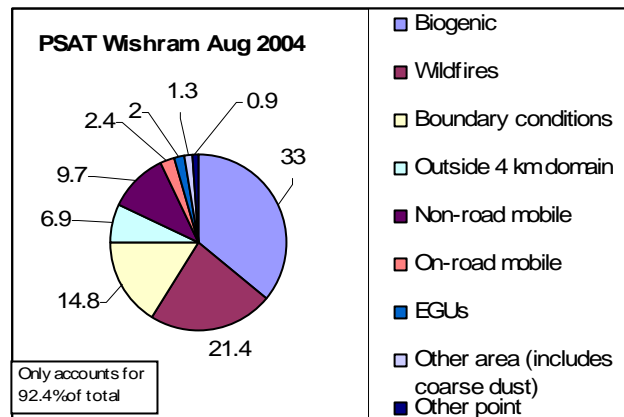
Comparison of PMF and PSAT Results for Wishram for August 2004

As with Mt. Zion for August we are comparing average August PMF attribution with episode attribution from PSAT. PMF biomass burning 16.8% and PSAT wildfire of 21.4% compare well.

PMF mobile of 9.2% and PSAT on-road and non-road mobile of 12.1% compare favorably also.

The PMF sulfate rich and nitrate rich factors combined result in 50% attribution. This is far higher than the sum of similar factors from PSAT- adding boundary conditions, outside of 4 km domain, EGUs and other point sources (all high in sulfate and nitrate) gives 25%. PSAT has 33% from biogenics which does not have a category by PMF. However, the PMF sulfate-rich secondary category is 26% organic by mass and the nitrate-rich secondary is 10% organic by mass. It could be that since biogenic emissions would be present whenever sulfate or nitrate is present, PMF cannot separate them and they are lumped into the secondary sulfate and nitrate factors. This could account for about 12% out of the 50% sulfate-rich and nitrate rich factors. The data show for August averages coarse mass is about 17% of particulate light extinction at Wishram. PSAT shows about 1%.

7)   Model Projections of Future Haze Levels

A 2018 future year was simulated for both episodes to project future year visibility conditions at the Gorge monitoring sites. With two exceptions, the WRAP 2018 emission projections were used as is for this estimate for all grids. The two exceptions were additional emission reductions that were applied to two specific large sources by 2018: the Boardman power plant near the eastern end of the Gorge; and the Camas pulp mill at the western end of the Gorge. Note that this is in contrast to the 2004 emissions modeling that used a 2004 inventory for Oregon and Washington provided by the SWCAA and ODEQ.

a) 2018 Future Year Emissions

Similar to the 2004 base case discussed in Section 5, the SMOKE emissions model was configured to generate model-ready point, area, non-road mobile, on-road mobile, and fire source emissions for the 36/12/4-km grid system for the August and November 2004 episodes and a 2018 base case emissions scenario. The 2018 emission estimates were taken entirely from the WRAP 2018 Base B On-the-Books database. However there are several upcoming federal programs that will have substantial emission reductions that were not included in this inventory. In addition, each of the WRAP states continues to make refinements to their inventories for 2018. The WRAP 2018 emissions estimates were modified for the following sources: the PGE Boardman power plant; the Georgia Pacific Camas Mill pulping plant; and residential wood smoke.

The presumptive Best Achievable Retrofit Technology (BART) limits for NOx and SO_2 were used to model emissions from the Boardman coal-fired power plant. For NOx, the BART limit is 0.23 lbs NOx/million Btu or 1,323 lbs NOx/hour. For SO_2, the BART limit is 0.15 lbs SO_2/million Btu or 863 lbs SO_2/hour. Primary PM emissions were left unchanged from 2004 levels, although it is anticipated that the PM emissions will decrease once multi-pollutant controls are installed. This resulted in an over 70% reduction in SOx emissions in Morrow County where the Boardman Power Plant resides from 2004 (~45 tons per day, TPD) to 2018 (~12 TPD).

The Air Agencies provided a spreadsheet of hourly NOx, SO_2, CO, and PM emissions estimates to be used to represent the Camas Mill facility. These estimates are based on the presumptive BART limits and represent a worst case day. As discussed in Section 5, errors were found in the 2004 base case emissions estimates for residential wood combustion, which carried over to the 2018 WRAP data base. The 2004 base case emissions estimates were revised and a growth factor of 4%, representing the expected OR/WA population growth to 2018, was applied to estimate the 2018 emissions for this source category.

The 2004 volcanic, biogenic, wind-blown dust, agricultural ammonia source, wildfire, and other fire emission estimates were used in place of the WRAP 2018 emissions estimates. This is standard practice to hold "natural" sources constant from the current (2004) to future (2018) years. As Mt. St. Helens showed no activity in August 2004, no SO_2 emissions for the volcano were incorporated in the 2018 modeling of the August episode so that a

consistent anthropogenic projection to 2018 could be made for visibility. The November 2004 Mt. St. Helens SO_2 emissions were used in the 2018 modeling of the November episode, again to remain consistent in the visibility projection. Following the approach used in WRAP, we assumed zero growth in agricultural ammonia emissions.

As with the 2004 base case emissions, certain emission subcategories, such as EGUs, on-road mobile sources, fires, etc., were processed through the SMOKE system in separate streams in order to support the application of CAMx/PSAT and to support additional quality assurance of the emissions estimates.

b) Future Year Projections and Trend Lines

CAMx was run for both the August and November modeling episode in exactly the same manner as performed for the final 2004 Base Case application ("Run 10"). The only change to the model inputs included use of the 2018 episode-specific modeling emission inventories. All grid configurations, model options, meteorological and other environmental inputs (including "natural" emissions such as wild fires, prescribed burns, wind-blown dust, ammonia and biogenics) were maintained to be consistent with the Run 10 2004 Base Case simulations. Hence, the future year applications performed for the August and November modeling episodes reflect only changes in the projected 2018 anthropogenic emission inventories via anticipated growth in population and industrial, commercial, and vehicular activity, as well as emission controls that were reflected in the 2018 WRAP inventories and some additional adjustments applied specifically for this project, as described earlier.

The results of the future year CAMx simulations were used to prepare visibility trend lines (or rates) from 2004 to 2018. Trends were calculated for two IMPROVE sites – Mt. Zion and Wishram – in order to remain consistent with the PSAT and model performance evaluations for total light extinction and visibility discussed in Section 5. Keep in mind that the inventory data projected for 2018 is just that, a projection, and that the air quality model has some bias. Therefore the reader should not use these values in an absolute sense. While we have made the best effort to replicate the monitored values for 2004 as closely as possible, the model and the science are not perfect. Furthermore, it will be of little value to attempt to predict what the actual absolute future year visibility measurements will be at specific monitors in the Gorge because ultimately the emissions mix and meteorology will be different (as compared to what we have simulated). Instead, the outcome of this modeling exercise is to better understand the likely relative impacts of all the emissions increases (due to population growth for example) and decreases (due to implementation of currently mandated emission reduction strategies) on future year visibility; this is the trend that were are determining in this exercise. The source apportionment information and emission inventory data helps us understand better who is contributing and how much.

Trend lines for 2004-2018 total extinction and deciview were calculated from peak episode-average conditions, which were determined by averaging the 24-hour extinction values on just the "high" PM days identified from the modeling results in each episode. Trend lines and rates were simply determined from the difference in the 2004 and 2018 episode averages.

At both Mt. Zion and Wishram, little change in total extinction was seen on each day for the August episode (Figure 7-1). However, some minor reductions in sulfate and nitrate were noticeable. In general, the lack of extinction response for this episode was tied mostly to the fact that the inventory is dominated by "natural" emissions such as biogenic SOA and wild fires that cannot be directly controlled, and which were carried over from the 2004 inventory development efforts. For the November episode, reductions in nitrate (NOx) and sulfate (SO$_2$) resulted in more significant reductions in total PM extinction, especially on the worst visibility days (Figure 7-2). The cleaner days indicated little change in 2018. Little change to other species (carbonaceous and primary PM) was seen in the 2018 out year.

In summary, Mt. Zion was simulated to show just a slight improvement in worst-day extinction out to 2018 for the August episode while the Wishram site actually shows a very slight degradation (Table 7-1). Nevertheless, these changes were not perceptible according to the 1 Deciview (dv) threshold for perceptible visibility changes. In the November episode, a perceptible improvement was simulated for worst-day visibility at both sites (-1.0 and -1.3 dv), with reductions in total extinction of over 10% and dv reduction of about 1 (Table 7-2).

These trends were compared to recent results from the WRAP 2002 and 2018 Base B modeling that estimated visibility improvements for the Mt. Hood and Mt. Adams Class I areas over a similar time horizon (2004 – 2018) of -0.82 dv and -0.77 dv, respectively. Note that WRAP did not calculate visibility trend lines for Mt. Zion or Wishram IMPROVE sites as they are not located in Federal "Class I" areas. Since WRAP conducted modeling over the entire 2002 year, the trend lines are determined from the average of the 20% worst visibility days over the annual simulation. Haze conditions on such days in the WRAP 2002 modeling would be consistent with the hazy episode days in 2004 selected for modeling in the Gorge Study. The WRAP simulated projections are very similar and in between what we calculated for Mt. Zion and Wishram during the August and November 2004 episodes. This result provides additional certainty that the Gorge model is working consistently.

Figure 7-1. Changes in daily light extinction (Mm^{-1}) between the 2004 Base Case (left bar for each day) and 2018 Future Projection (right bar for each day) at Mt. Zion (top) and Wishram (bottom) over the August episode. Contributions from ammonium sulfate ([NH$_4$]2SO$_4$), ammonium nitrate ([NH$_4$]NO$_3$), total organic carbon (OC), elemental carbon (EC), fine PM, coarse PM, and sea salt (NA+PCL) are shown.

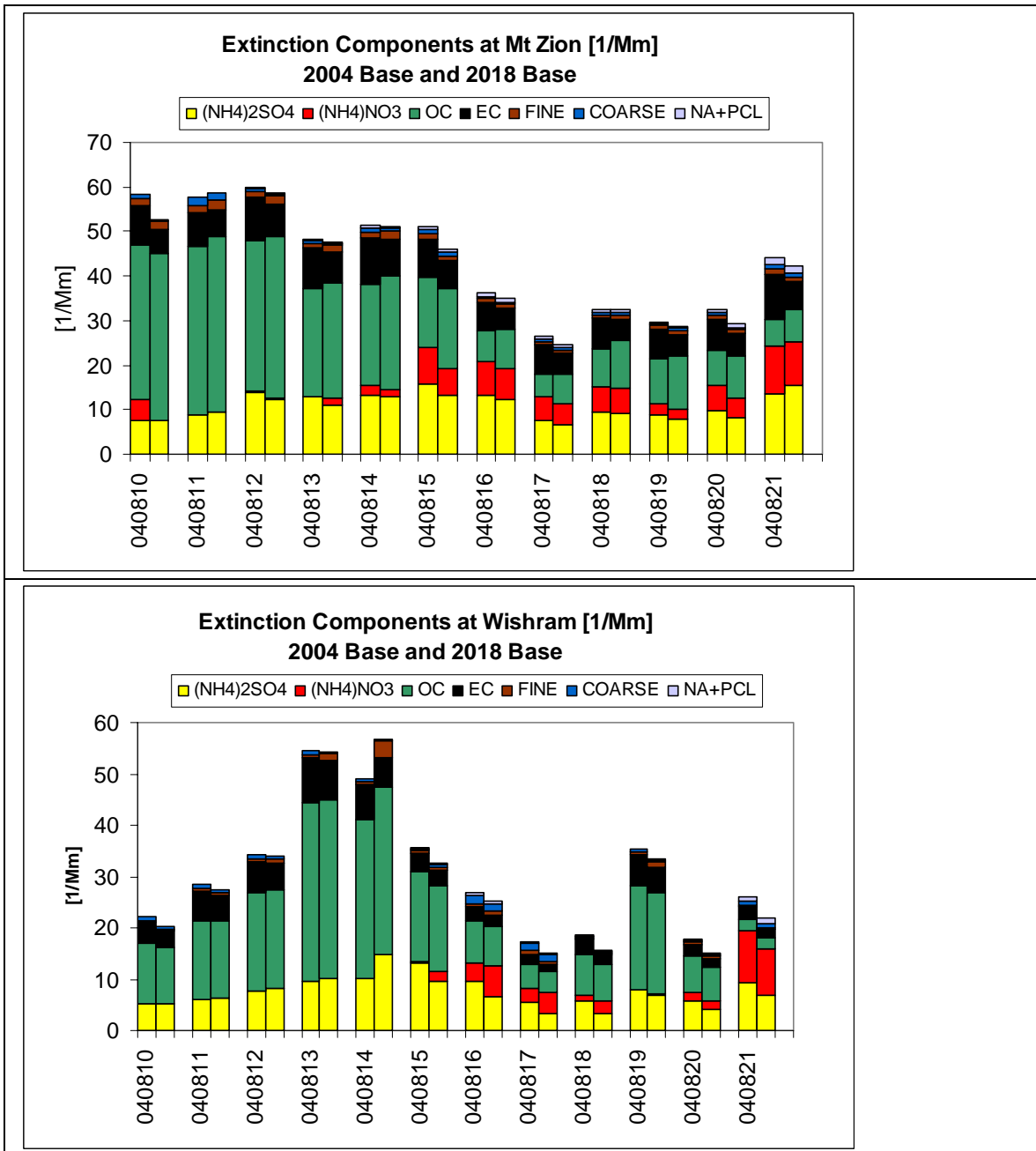**Figure 7-2.** Changes in daily light extinction (Mm[-1]) between the 2004 Base Case (left bar for each day) and 2018 Future Projection (right bar for each day) at Mt. Zion (top) and Wishram (bottom) over the November episode. Contributions from ammonium sulfate ([NH4]2SO4), ammonium nitrate ([NH4]NO3), total organic carbon (OC), elemental carbon (EC), fine PM, coarse PM, and sea salt (NA+PCL) are shown.
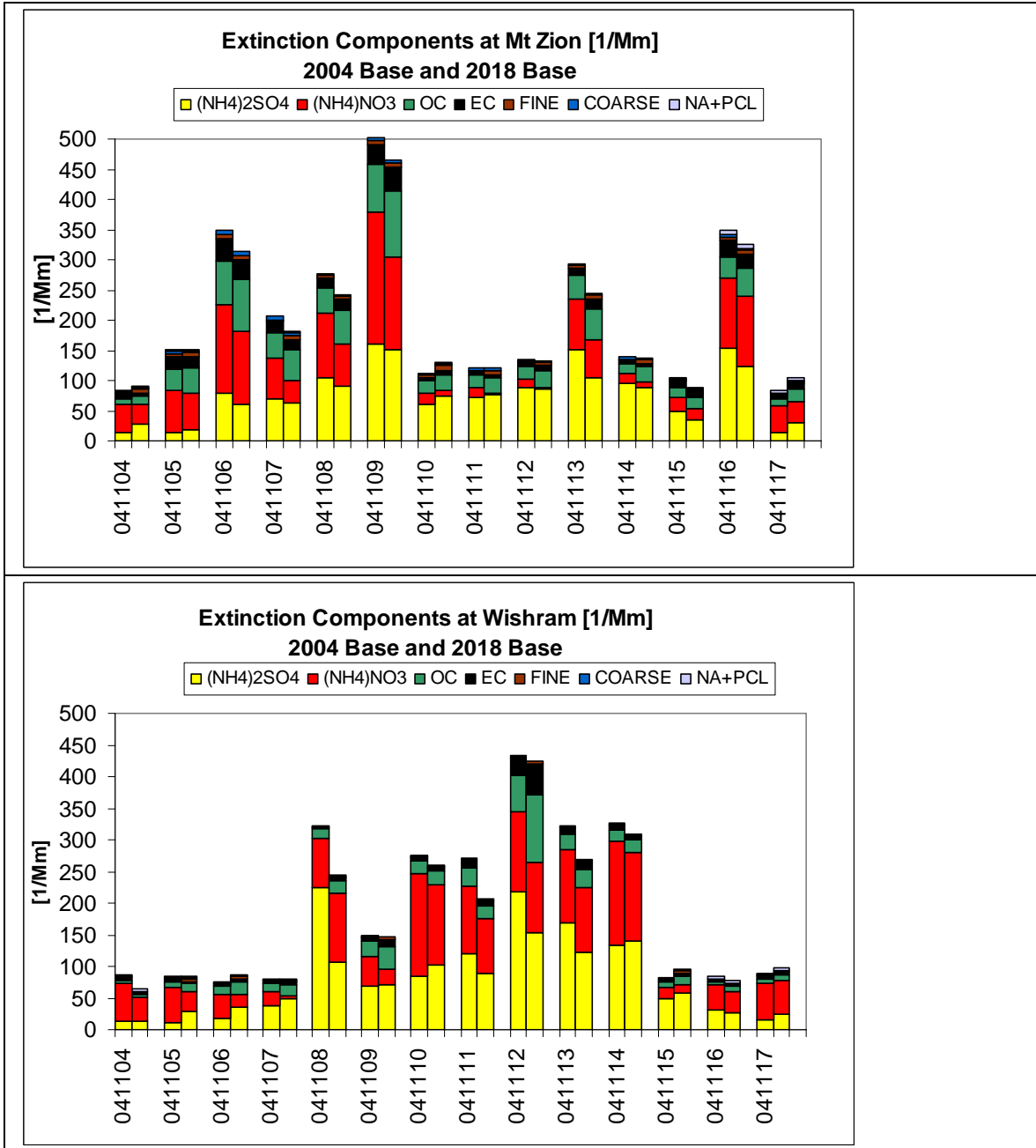
Table 7-1. Episode-average trends for extinction and visibility from "high" PM extinction days during the August 2004 episode.

	Mt. Zion	Wishram
Total Extinction Change	-1.9 Mm^{-1} (-3%)	0.4 Mm^{-1} (1%)
Extinction Annual Rate	-0.13 Mm^{-1}yr^{-1}	0.03 Mm^{-1}yr^{-1}
Total Dv Change	-0.3 (not perceptible)	0.08 (not perceptible)
Dv Annual Rate	-0.02 yr^{-1}	0.006 yr^{-1}

Table 7-2. Episode-average trends for extinction and visibility from "high" PM extinction days during the November 2004 episode.

	Mt. Zion	Wishram
Total Extinction Change	-35 Mm^{-1} (-10%)	-40 Mm^{-1} (-12%)
Extinction Annual Rate	-2.5 Mm^{-1}yr^{-1}	-2.8 Mm^{-1}yr^{-1}
Total Dv Change	-1.0 (perceptible)	-1.3 (perceptible)
Dv Annual Rate	-0.07 yr^{-1}	-0.09 yr^{-1}

c) Future Year "What If" Scenarios

Five "what-if" scenarios were run for the 2018 Future Case to estimate the impacts of certain sources on visibility over the two modeling episodes. The purpose in developing "what-if" scenarios was to proactively address several questions that were likely to be raised by the general public during the public comment process. These scenarios were based on a survey performed by the Clean Air Agencies. The most common scenarios were:

- Case 1: Zero Boardman power plant emissions.
- Case 2: Zero ammonia emissions in PSAT region 5 (east of Gorge; see Figure 5-2).
- Case 3: Zero on-road mobile source emissions in PSAT region 2 (Portland and Vancouver).
- Case 4: Zero major point source emission for PSAT region 2 (Portland and Vancouver).
- Case 5: Zero major point source emissions for PSAT region 1 (in Gorge).

As seen in Figures 7-3 and 7-4, very little sensitivity to any of the what-if scenarios was seen at both of the monitoring sites. Since major SO_2 and NOx emission reductions at the Boardman Power Plant are already reflected in the 2018 inventory (i.e., presumptive BART controls), practically zero sensitivity to Case 1 is seen. Some increases and decreases in sulfate and nitrate are seen for some cases (e.g., Case 5, in which all point sources in the Gorge were removed). This mixed effect is possible depending upon how the chemical conditions set up for a specific episode. There are two possible non-linear effects at play here:

(1) The amount of ambient NOx relative to organic gases can lead to ozone (oxidant) production or ozone destruction. In NOx-lean conditions (such as in remote rural

locations), controls on NOx can lead to less oxidants that ultimately form less sulfate, while in NOx-rich conditions (e.g., urban areas such as Portland), controls on NOx can lead to more oxidants (less ozone inhibition) and thus more sulfate formation.

(2) The amount of particulate nitrate and sulfate that can form depends on the amount of available ammonia that neutralizes these acids. It is very common to see nitrate increases when SO_2 emissions are reduced while NOx and ammonia emissions are held constant. Since ammonium preferentially neutralizes sulfate, with any excess then available for neutralizing nitrate, a reduction in SO_2 leads to a reduction in sulfate, and thus more ammonium is available to form more particulate nitrate (this phenomena has been termed nitrate replacement).

As we have seen in both the 2018 projection (relative to the 2004 base case) and a few of the "what-if" scenarios, the modeled sulfate and nitrate estimates response to changes in emissions is mixed reflecting the complex chemistry processes involved. Again, the August episode is dominated by "natural" emissions that were not removed in any of these scenarios. The less obvious signals stemming from the what-if scenarios should be examined in further modeling efforts; but overall these effects are not significant to the overall conclusions of this study.

Somewhat more influence from each what-if scenario is seen on the worst PM days of the November episode, especially Cases 2 and 3 at Mt. Zion, which removed eastern Gorge ammonia and Portland on-road mobile sources, and Cases 1 and 5 at Wishram, which removed major point sources from the in-Gorge area.

Figure 7-3. Daily speciated and total extinction between the 2018 Future Year case (left-most bar) and five "what-if" scenarios at Mt Zion (top) and Wishram (bottom) over the August 2004 episode.

Figure 7-4. Daily speciated and total extinction between the 2018 Future Year case (left-most bar) and five "what-if" scenarios at Mt Zion (top) and Wishram (bottom) over the November 2004 episode.
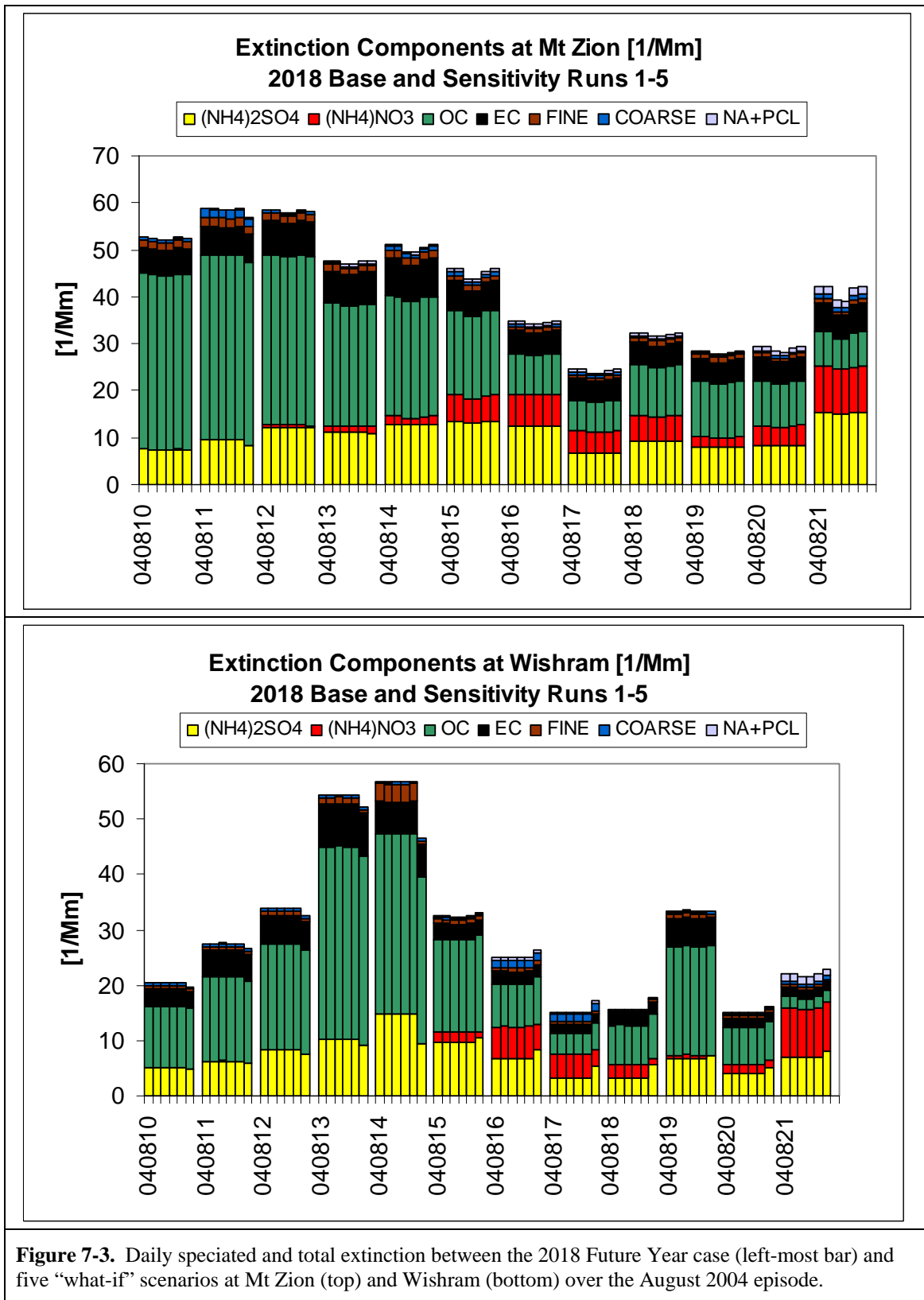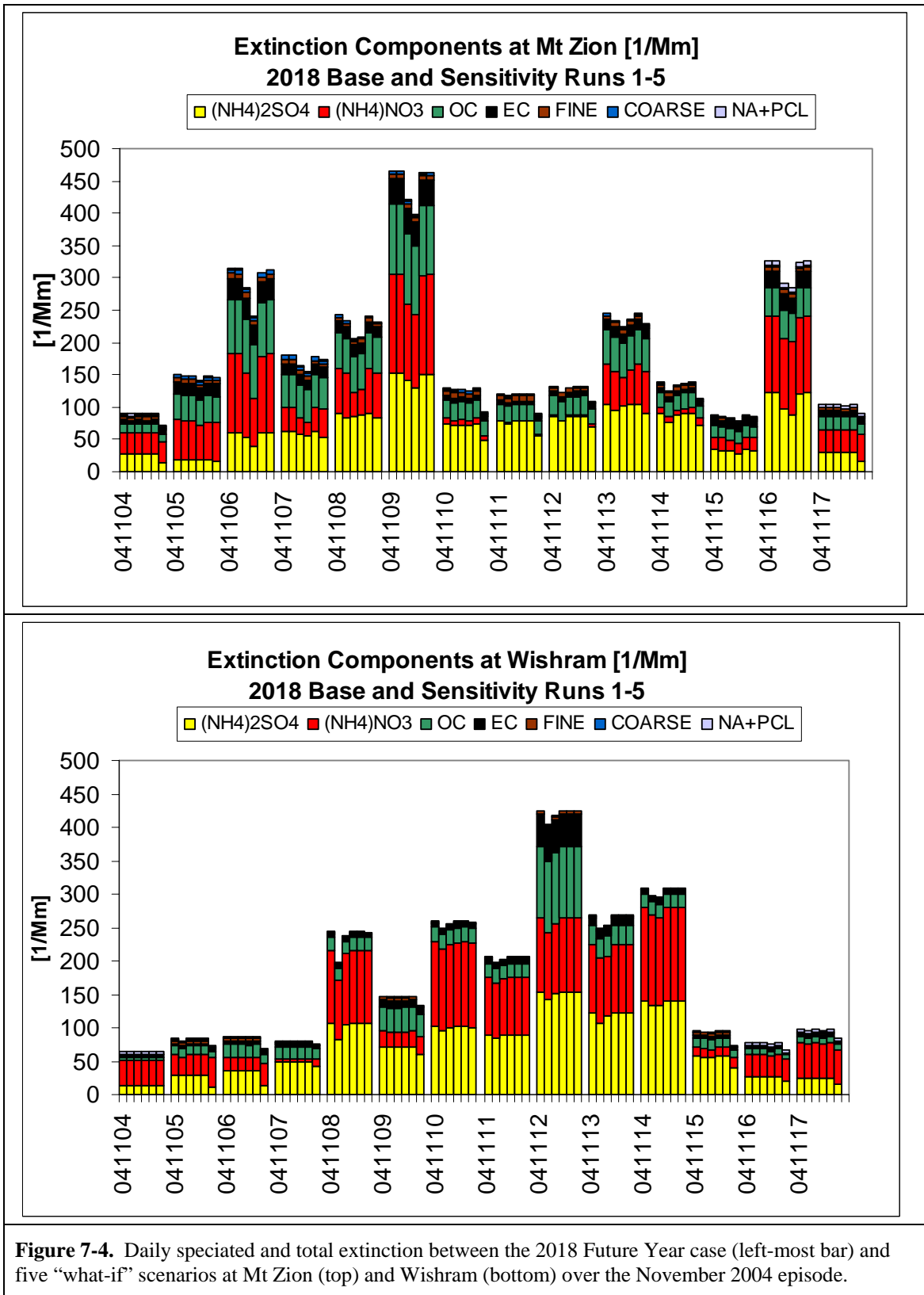
d) Future Year Source Apportionment Modeling

The CAMx PSAT Probing Tool was applied to the August and November 2004 modeling episodes to quantify source attribution at the Mt. Zion and Wishram monitoring sites for the 2018 Future Year scenario. The PSAT application for the Future Year scenario was run in exactly the same manner as the PSAT application for the 2004 Base Case, only it was based on the 2018 emissions (see Section 6 for more discussion of PSAT source regions and categories).

i) 2018 PSAT results for the August episode

At Mt. Zion, areas outside the 4-km domain continue to contribute the bulk of sulfate during this episode. Portland and areas along the westernmost area of the Columbia River are the largest local source areas of sulfate, which agrees with the general west-to-east transport direction during this period. A variety of source types in these western areas contribute to sulfate, including non-road sources (heavily dominated by diesel engines), EGUs, pulp mills, and other point sources. Nitrate is primarily attributed to similar local upwind regions from on-road, non-road, and industrial sources. Ammonium is attributed to mainly on-road and local ammonia-specific sources in the Gorge and in Portland. Primary carbonaceous components come mostly from upwind and local areas from mobile and area sources (particularly non-road), suggesting diesel activity. Other carbon sources include fires. Dust (coarse and fine) is nearly entirely from local on-road sources (road dust) and local area sources.

Table 7-3 ranks the contributions to visibility impairment at Mt. Zion under the 2018 emissions scenario by species, source region and source category at Mt. Zion for the August 2004 episode. Table 7-4 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze included:

1. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (10%);**
2. **Primary organic carbon from Portland area sources (4%);**
3. **Elemental carbon from Portland non-road sources (3%);**
4. **Sulfate from pulp mills northwest of Portland (3%); and**
5. **Primary organic carbon from eastern OR/WA wildfires (3%).**

Table 7-3. Top-ranked list of source region/categories contributing to visibility-impairing haze over the August 2018 episode at Mt. Zion. Source regions/categories shown account for roughly 60% of the total episode-average light extinction.

Species	Region	Source	ug/m^3	Mm^{-1}	Contribution
Sulfate	BC		0.30	3.48	10%
POA	Portland	Other area	0.33	1.33	4%
EC	Portland	Non-road	0.11	1.11	3%
Sulfate	NW of Gorge	Pulp mills	0.08	0.94	3%
POA	East of Gorge	Wildfires	0.22	0.87	3%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.07	0.85	3%
EC	NW of Gorge	Non-road	0.07	0.72	2%
Nitrate	Portland	Non-road	0.06	0.60	2%
Nitrate	BC		0.05	0.56	2%
EC	Gorge	Non-road	0.05	0.55	2%
Sulfate	NW of Gorge	Other points	0.04	0.52	2%
Sulfate	NW of Gorge	Non-road	0.04	0.49	1%
EC	East of Gorge	Wildfires	0.05	0.47	1%
Nitrate	Portland	On-road mobile	0.04	0.45	1%
Nitrate	NW of Gorge	Non-road	0.04	0.39	1%
POA	Gorge	Other area	0.10	0.39	1%
Sulfate	Portland	Other area	0.03	0.39	1%
Sulfate	Portland	Other points	0.03	0.35	1%
Sulfate	Portland	Non-road	0.03	0.33	1%
EC	Portland	Other area	0.03	0.33	1%
Sulfate	West of Gorge	EGUs	0.03	0.31	1%
EC	Portland	On-road mobile	0.03	0.31	1%
Fine Other	Portland	Other area	0.30	0.30	1%
POA	Portland	On-road mobile	0.07	0.29	1%
POA	West of Gorge	Other area	0.07	0.28	1%
POA	Portland	Non-road	0.07	0.26	1%
Nitrate	NW of Gorge	Other points	0.02	0.25	1%
Sulfate	East of Gorge	Wildfires	0.02	0.25	1%
Sulfate	Gorge	Non-road	0.02	0.25	1%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.02	0.21	1%
Nitrate	Portland	Other area	0.02	0.21	1%
Sulfate	West of Gorge	Other area	0.02	0.20	1%
POA	BC		0.05	0.20	1%
Nitrate	NW of Gorge	Pulp mills	0.02	0.18	1%
POA	NW of Gorge	Other area	0.04	0.17	1%
Nitrate	West of Gorge	On-road mobile	0.02	0.17	1%
Nitrate	West of Gorge	EGUs	0.01	0.15	0%
POA	Gorge	Non-road	0.04	0.14	0%
EC	West of Gorge	Non-road	0.01	0.13	0%
POA	Outside 4 km domain	Outside 4 km domain	0.03	0.13	0%

Table 7-4. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the August 2018 episode at Mt. Zion. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm^{-1}	Contribution
Portland	6.69	20%
BC/Outside 4 km Domain	5.84	17%
NW of Gorge	4.03	12%
Gorge	1.88	6%
West of Gorge	1.65	5%
East of Gorge	1.61	5%
Biogenic SOA	12.00	35%

As seen for the Mt. Zion site, areas outside the 4-km domain contribute to the bulk of sulfate during this episode at Wishram. However, there is a stronger influence from local Gorge area sources and wildfires in the eastern portion of the 4-km grid, and a smaller influence from Portland and the western areas. Nitrate is primarily attributed to local and upwind regions to the west, from on-road and non-road sources. Ammonium has a strong source locally in the Gorge and in the eastern area from ammonia-specific sources, which are dominated by agricultural activities. Primary elemental and organic carbon components indicate a rather strong contribution from wildfires occurring in north-eastern Washington during this episode; elemental carbon further shows a large contribution from in-gorge non-road sources, which implicate diesel emissions from railroads, barges, and off-road equipment. Primary organics show a relatively large attribution to local Gorge area sources and regional fires. Coarse and fine dust are nearly entirely from in-gorge on-road and area sources, while other fine/coarse fractions of primary PM are mostly from area sources (again, mostly agricultural activities) and fires.

Table 7-5 summarizes the contributions to visibility impairment at Wishram for the August 2018 emissions scenario. Table 7-6 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze included:

1. **Primary organic carbon from eastern OR/WA wildfires (11%);**
2. **Sulfate from local Gorge area sources (10%);**
3. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (8%);**
4. **Elemental carbon from eastern OR/WA wildfires (6%); and**
5. **Primary organic carbon from local Gorge area sources (4%).**

Table 7-5. Top-ranked list of source region/categories contributing to visibility-impairing haze over the August 2018 episode at Wishram. Source regions/categories shown account for roughly 60% of the total episode-average light extinction.

Species	Region	Source	ug/m^3	Mm^{-1}	Contribution
POA	East of Gorge	Wildfires	0.80	3.20	11%
Sulfate	Gorge	Other area	0.26	2.97	10%
Sulfate	BC		0.20	2.24	8%
EC	East of Gorge	Wildfires	0.17	1.75	6%
POA	Gorge	Other area	0.28	1.10	4%
EC	Gorge	Non-road	0.09	0.93	3%
Fine Other	Gorge	Other area	0.91	0.91	3%
Sulfate	East of Gorge	Wildfires	0.06	0.70	2%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.06	0.62	2%
Nitrate	BC		0.03	0.31	1%
POA	West of Gorge	Other area	0.06	0.26	1%
Nitrate	West of Gorge	EGUs	0.02	0.25	1%
Sulfate	Gorge	Non-road	0.02	0.22	1%
Coarse Dust	Gorge	Other area	0.35	0.21	1%
Sulfate	West of Gorge	Other area	0.02	0.20	1%
Sulfate	West of Gorge	EGUs	0.02	0.19	1%
POA	Outside 4 km domain	Outside 4 km domain	0.04	0.17	1%
EC	West of Gorge	Non-road	0.02	0.17	1%
Nitrate	Gorge	Non-road	0.02	0.16	1%
Nitrate	West of Gorge	On-road mobile	0.01	0.16	1%
EC	BC		0.01	0.15	1%
Nitrate	Portland	On-road mobile	0.01	0.14	0%
Nitrate	Portland	Non-road	0.01	0.13	0%
EC	Outside 4 km domain	Outside 4 km domain	0.01	0.13	0%
Sulfate	Portland	Other points	0.01	0.13	0%
POA	BC		0.03	0.13	0%
Nitrate	West of Gorge	Non-road	0.01	0.12	0%
Sulfate	NW of Gorge	Pulp mills	0.01	0.12	0%
EC	NW of Gorge	Non-road	0.01	0.11	0%
Sulfate	NW of Gorge	Other points	0.01	0.10	0%

Table 7-6. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the August 2018 episode at Wishram. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm^{-1}	Contribution
Gorge	7.00	24%
East of Gorge	5.86	20%
BC/Outside 4 km Domain	4.07	14%
West of Gorge	1.93	6%
Portland	0.64	2%
NW of Gorge	0.50	2%
Biogenic SOA	9.43	32%

ii) 2018 PSAT results for the November episode

At Mt. Zion, secondary sulfate/nitrate/ammonium salts continue to dominate the mass budgets during the November episode in 2018 as seen in the 2004 modeling. Several $\mu g/m^3$ are predicted for episode-average sulfate, but the largest contributor is no longer EGU emissions since SO_2 controls are reflected in the future year inventory (e.g., the Boardman BART controls). However, a wide array of source types and areas contribute to the Mt. Zion sulfate, including local area sources and areas outside the 4-km domain, indicating the regional nature of this secondary pollutant. Nitrate also remains rather high (nearly 2 $\mu g/m^3$), with large contributions from on-road, non-road, and area NOx sources mainly from Portland and areas to the west and along the Gorge. Ammonium is attributed to specific ammonium sources (mostly agricultural activities such as feed lots and fertilizer applications). Again, a vast area of emissions contributes to ammonium, but most comes from the eastern Gorge area where there are some large agricultural sources. Both elemental and organic carbon show some contributions from on-road and non-road sources within the Gorge and from Portland, but now the POA is apportioned in large measure to area sources. Elemental carbon in particular has a large non-road component, likely due to heavy duty diesel engines on off-road equipment, barges, and railroads. The area source contribution to POA is dominated by residential wood smoke, both locally and from the Portland area. Coarse/fine dust are mostly locally generated, and given the wetter nature of the November episode, are likely overstated since the modeling emissions inventory does not account for local day-specific rainfall patterns. Most sources of primary fine/coarse PM are very local in origin and are likely from fugitive and wind-blown dust sources as well as road dust.

Table 7-7 ranks the contributions to visibility impairment at Mt. Zion for the November 2018 emissions scenario. Table 7-8 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze included:

1. **Sulfate from super-regional sources (i.e., Boundary Conditions) outside the 12-km Pacific Northwest grid (11%);**
2. **Sulfate from local Gorge area sources (9%);**
3. **Sulfate from Portland area sources (5%);**
4. **Nitrate from Portland on-road sources (4%); and**
5. **Nitrate from Portland non-road sources (4%).**

Table 7-7. Top-ranked list of source region/categories contributing to visibility-impairing haze over the November 2018 episode at Mt. Zion. Source regions/categories shown account for roughly 80% of the total episode-average light extinction.

Species	Region	Source	ug/m³	Mm⁻¹	Contribution
Sulfate	BC		0.58	11.31	11%
Sulfate	Gorge	Other area	0.48	9.43	9%
Sulfate	Portland	Other area	0.29	5.73	5%
Nitrate	Portland	On-road mobile	0.24	4.43	4%
Nitrate	Portland	Non-road	0.23	4.22	4%
Nitrate	BC		0.23	4.17	4%
POA	Gorge	Other area	1.02	4.07	4%
POA	Portland	Other area	0.85	3.39	3%
Sulfate	East of Gorge	EGUs	0.16	3.19	3%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.16	3.02	3%
Nitrate	Portland	Other area	0.15	2.82	3%
Fine Other	Gorge	Other area	2.32	2.32	2%
Nitrate	West of Gorge	On-road mobile	0.12	2.28	2%
Nitrate	West of Gorge	Non-road	0.12	2.17	2%
Sulfate	Portland	Other points	0.11	2.17	2%
Nitrate	Gorge	Non-road	0.12	2.12	2%
Sulfate	Gorge	Non-road	0.10	1.94	2%
Sulfate	West of Gorge	Other area	0.09	1.71	2%
Sulfate	East of Gorge	Pulp mills	0.08	1.48	1%
EC	Portland	Other area	0.14	1.43	1%
Nitrate	East of Gorge	Non-road	0.07	1.34	1%
EC	Gorge	Non-road	0.12	1.25	1%
Nitrate	West of Gorge	Other area	0.06	1.17	1%
Sulfate	Portland	Non-road	0.06	1.17	1%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.06	1.14	1%
Sulfate	NW of Gorge	Other points	0.06	1.14	1%
Sulfate	East of Gorge	Other points	0.06	1.13	1%
EC	Gorge	Other area	0.11	1.10	1%
Nitrate	NW of Gorge	Non-road	0.05	0.90	1%
EC	Portland	Non-road	0.08	0.80	1%

Table 7-8. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the November 2018 episode at Mt. Zion. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm⁻¹	Contribution
Portland	28.07	26%
Gorge	24.70	23%
BC/Outside 4 km Domain	21.54	21%
East of Gorge	8.98	8%
West of Gorge	8.78	8%
NW of Gorge	2.05	2%
Biogenic SOA	13.35	12%

Wishram continues to experience more episode-average sulfate than Mt. Zion in 2018, with nearly a 4 μg/m^3 episode average. However, local EGU emissions contribute much less; sources in the eastern portion of the domain dominate, and are fairly evenly spread across several industrial source types, as well as non-road and area source categories. Nitrate is also higher at Wishram for this episode (about 4 μg/m^3), with contributions primarily from on-road, non-road, area, and EGU NOx sources in the eastern area. NOx sources outside the 4-km grid (mostly well to the east) also contribute to nitrate. Ammonium continues to be nearly entirely attributed to local sources in the eastern area of the domain. Carbonaceous PM is much lower than the secondary salts, and also lower than the 2004 Base Case PSAT results. Most EC stems from local non-road sources in the Gorge and in the eastern area, which suggests a large contribution from diesel exhaust. POA at Wishram has local origins from area sources (residential wood combustion) and fires. Like Mt. Zion, coarse/fine dust is mostly locally generated in Gorge and in the eastern area, with mostly area and on-road sources contributing.

Table 7-9 ranks the November 2018 contributions to visibility impairment. Table 7-10 presents the same information, but aggregated over all species and source categories to show the relative contribution from each of the six source regions.

The top five ranked non-biogenic sources contributing to haze included:

1. **Nitrate from eastern OR/WA non-road sources (12%);**
2. **Sulfate from super-regional sources outside the 12-km Pacific Northwest grid (8%);**
3. **Sulfate from eastern OR/WA EGU sources (7%);**
4. **Nitrate from super-regional sources outside the 12-km Pacific Northwest grid (7%); and**
5. **Sulfate from local Gorge area sources (6%).**

Table 7-9. Top-ranked list of source region/categories contributing to visibility-impairing haze over the November 2018 episode at Wishram. Source regions/categories shown account for roughly 85% of the total episode-average light extinction.

Species	Region	Source	ug/m³	Mm⁻¹	Contribution
Nitrate	East of Gorge	Non-road	1.05	19.30	12%
Sulfate	BC		0.70	13.70	8%
Sulfate	East of Gorge	EGUs	0.58	11.42	7%
Nitrate	BC		0.61	11.21	7%
Sulfate	Gorge	Other area	0.51	9.97	6%
Nitrate	East of Gorge	Other area	0.53	9.77	6%
Sulfate	East of Gorge	Other area	0.48	9.30	6%
Nitrate	Outside 4 km domain	Outside 4 km domain	0.49	9.00	5%
Sulfate	East of Gorge	Other points	0.36	6.98	4%
Sulfate	East of Gorge	Pulp mills	0.35	6.86	4%
Nitrate	East of Gorge	EGUs	0.37	6.86	4%
Nitrate	East of Gorge	On-road mobile	0.30	5.43	3%
Sulfate	Outside 4 km domain	Outside 4 km domain	0.26	5.10	3%
Sulfate	Gorge	Non-road	0.18	3.47	2%
Nitrate	Gorge	Non-road	0.19	3.41	2%
Sulfate	East of Gorge	Non-road	0.15	2.89	2%
EC	Gorge	Non-road	0.26	2.58	2%
POA	Gorge	Other area	0.52	2.10	1%
Fine Other	Gorge	Other area	2.09	2.09	1%

Table 7-10. Ranked list of source regions (aggregated over all species and source categories) contributing to visibility-impairing haze over the November 2018 episode at Wishram. Natural biogenic sources of haze (SOA) are shown at the bottom.

Region	Mm⁻¹	Contribution
East of Gorge	86.10	51%
BC/Outside 4 km domain	41.31	25%
Gorge	26.73	16%
Portland	3.04	2%
West of Gorge	0.25	0%
NW of Gorge	0.00	0%
Biogenic SOA	9.58	6%

8) Working Conclusions and Observations

There are many conclusions and observations that can be made from a study as comprehensive as this. This section will generally not repeat detailed conclusions from the report about who is causing haze, how much haze exists, or from which region haze comes from. Rather, it will provide observations that could help focus the policy discussion surrounding further haze reduction efforts in the Gorge. Some are more obvious than others, but they bear highlighting here.

1) The purpose of this study was two-fold. The first was to monitor and assess conditions in the Gorge for calendar year 2004. This was done and the resulting findings are presented in Sections 1 through 5 of this report. The second purpose was to develop a tool that could be used to forecast conditions for the out-year of 2018 to determine if there was a visibility trend that could be identified based on current and planned emission reduction strategies. That tool has been developed and a projection for visibility conditions in 2018 has been provided in Section 7 of this report. This tool will also help the future testing of proposed reductions strategies. As a result, the objectives of the study have been achieved.

2) Visibility impairment is worst in the winter, and especially so at the east end of the Gorge. During winter, the manmade contribution to the haze is highest. Likely, any strategy developed for winter will have varying corresponding improvements in the summer as it is expected that any emission reductions would be made on an annual basis. Manmade emissions from throughout the region impact visibility at both the east and west ends of the Gorge in both winter and summer to varying degrees given the season and location.

3) The manmade pollutants most contributing to haze in both summer and winter episodes are sulfates and nitrates. These are secondary aerosol pollutants and their precursor gases (sulfur dioxide, nitrogen oxide and ammonia) come from a wide range of human activities and human-controlled sources.

4) Visibility improvement can only come as a result of emission reductions. The only emission reductions that can be made are those that are the result of manmade activities. Therefore, opportunities for improvement should be focused on those times and locations that have the worst impairment and have the most manmade emissions impact recognizing that some of these pollutants come from outside the region.

5) The 2018 results presented in Section 7 conclude that no single solution exists to remedy haze. Rather, a multifaceted approach may be necessary if further reductions are desired. Because there is not a dominant manmade source of emissions that is responsible for haze in the Gorge, numerous smaller emission reduction opportunities would be required to make any meaningful improvements.

6) The data presented in this report is as accurate as can be provided at the time of publication given the project's budget and schedule limitations. It is essential to continue to monitor Gorge haze levels to track trends and provide data that will be needed for future evaluation and refinement of modeling tools which should be applied to an entire annual

cycle not just short episodes. Several improvements and updates could be applied to the air quality model, emissions inventory, and model re-runs prior to any specific source attribution exercise or detailed cost benefit analyses. Whether, when and how to accomplish this additional work are policy questions beyond the scope of this scientific report.

Appendix 1
Planning and Execution of the Gorge Study

History of the National Scenic Area Act
The 292,500 acre Columbia River Gorge National Scenic Area (NSA) was created by act of Congress in 1986 (PL92-663, 1986). The purposes of the Act are –
> (1) to establish a national scenic area to protect and provide for the enhancement of the scenic, cultural, recreational, and natural resources of the Columbia River Gorge; and
> (2) to protect and support the economy of the Columbia River Gorge area by encouraging growth to occur in existing urban areas and by allowing future economic development in a manner that is consistent with paragraph (1).

The special beauty and value of the Columbia River Gorge has been recognized for centuries. Efforts to provide some special protection for this area began as early as 1937 and continued throughout the following decades. In 1986, President Ronald Reagan signed the Columbia River Gorge National Scenic Area Act, establishing this nation's only National Scenic Area at that time.

Other national legislation such as the Clean Air Act complement the Columbia River Gorge National Scenic Area Act in that emission reduction strategies adopted to protect public health can have the secondary benefit of improving other valued resources in and near the Gorge NSA. However, the Columbia River Gorge National Scenic Area Act calls for an independent effort to protect and enhance key resources in the Gorge NSA while supporting local economies.

To achieve its purposes, the National Scenic Area Act called for a new partnership between the USDA Forest Service, a bi-state regional planning agency (the Columbia River Gorge Commission), the states of Oregon and Washington, the Southwest Clean Air Agency (SWCAA), and the six counties with land in the Scenic Area. The Act also calls for interagency and tribal cooperation and coordination. The results of the regional air quality study completed for the National Scenic Area as documented in this report is designed to meet the purposes of the Columbia River Gorge National Scenic Area Act.

Columbia River Gorge Commission
The Columbia River Gorge Commission was authorized by the 1986 Columbia River Gorge National Scenic Area Act (Act) and created through a bi-state compact between Oregon and Washington in 1987. The Commission was established to develop and enforce policies and programs that carry out the purposes of the Act. The Commission works in partnership with a number of entities to develop and implement a regional Management Plan. Partners include the states of Oregon and Washington, the Southwest Clean Air Agency, the USDA Forest Service, four treaty Indian Tribes -- the Nez Perce, Umatilla, Warm Springs, and Yakama Indian Nations, Clark, Klickitat, and Skamania counties in Washington, and Hood River, Multnomah, and Wasco counties in Oregon.

Regional Air Quality Strategy
In May 2000, the Gorge Commission approved an air quality amendment to the Gorge
National Scenic Area Management Plan. The amendment language states that: Air quality
shall be protected and enhanced, consistent with the purposes of the Scenic Area Act. The
States of Oregon and Washington shall: (1) continue to monitor air pollution and visibility
levels in the Gorge; (2) conduct an analysis of monitoring and emissions data to identify all
sources, both inside and outside the Scenic Area that significantly contribute to air pollution.
Based on this analysis, the States shall develop and implement a regional air quality strategy
to carry out the purposes of the Scenic Area Act, with the U.S. Forest Service, the Southwest
Air Pollution Control Authority [now the Southwest Clean Air Agency] and in consultation
with affected stakeholders.

Work Plan Development and Funding Process
An initial work plan was developed over many months in 2000 and 2001 through the
collaborative efforts of the states of Oregon and Washington; the Southwest Clean Air
Agency; Klickitat, Wasco, Skamania, Hood River, Multnomah, and Clark Counties; the U.S
Forest Service; local and national experts in the fields of air science; interested stakeholder
groups and the public. This early planning process was guided by two groups. These groups
were the inter-agency project coordination team and the project technical team. Early work
plan efforts relied heavily on stakeholder and public input in developing the original work
plan. The work plan reflected, to the greatest extent possible, the values, priorities, and
preferences of these groups for a fair and equitable process leading to a regional air quality
strategy that satisfies the dual purposes of the Gorge Scenic Area Act. A draft work plan was
prepared and presented at a public workshop on June 28, 2001. Public comments were
incorporated into the Work Plan and the Work Plan was submitted to the Columbia River
Gorge Commission and was approved on August 14, 2001.

Initial funding to develop the first work plan was provided by the states of Oregon and
Washington. The U.S. Environmental Protection Agency also generously provided initial
grant funding to begin the scientific study of Gorge air quality. The U.S. Forest Service
provided $150,000 to $200,000 per year to support on-going air monitoring activities at
IMPROVE monitoring locations in the Gorge NSA.

The Work Plan called for a three phased approach for conducting studies. This approach was
chosen to make best use of limited funding for the project. The initial study was referred to
as the Foundation Study. The purpose of the Foundation Study was to lay important
groundwork for future phases of the technical study program. The next phase of the Work
Plan was a program of technical study that included ambient monitoring, emission inventory
development and computerized modeling. The final phase of the Work Plan consisted of
long-term monitoring to track the progress of any implemented visibility improvement
strategies.

A peer-review workshop was held March 14-15, 2001 in Cascade Locks, Oregon to solicit
comments and input on development of a strategy for assessing air quality within the Gorge.
A study plan was developed and issued on June 7, 2001 that provided a comprehensive
program for assessing air quality in the Gorge. Due to the cost magnitude of the study plan

and the lack of available funding, a scaled down study plan was requested by the Air Quality Managers of Oregon and Washington. A scaled down Study Plan was developed that projected costs at approximately $1.2 million. Funding was sought through the Oregon/Washington Congressional Delegation.

In 2001 and 2002 efforts were underway to install a network of nephelometers and meteorological monitoring instruments throughout the length of the Gorge Scenic Area that would characterize visibility impairment through the Gorge. Initial funding in the amount of approximately $223,000 was provided by the States to purchase equipment, select sites, install the equipment and operate the sites. The goal was to operate the network in such a manner as to collect at least one year's worth of concurrent data from all sites. This initial study was referred to as the Haze Gradient Study. The field portion of the Columbia River Gorge Haze Gradient Study was conducted from July 2003 through February 2005. Measurements included particle light scattering (bsp) at nine locations downriver from the Gorge (Sauvie Island) to upriver from the Gorge (Towal Road), including several sites in the Gorge. Meteorological measurements were taken at all sites except Memaloose. The objectives of the study were to characterize horizontal, vertical, and temporal patterns in haze and to gain insight into possible source regions contributing to haze in the Gorge. Data from this monitoring activity was analyzed by the Desert Research Institute and the final Haze Gradient Report was issued on January 27, 2006.

Congressional funding in the amount of $670,600 was provided in early to mid 2003. The Work Plan was revised to accommodate a total budget of $670, 600 not including the Haze Gradient Study. An air quality project Technical Team was formed with staff from the Washington State Department of Ecology (WDOE), the Oregon State Department of Environmental Quality (ODEQ) the USDA Forest Service (USFS), the Southwest Clean Air Agency (SWCAA), the US Environmental Protection Agency (EPA), the National Park Service (NPS), ENVIRON International, the National Oceanic and Atmospheric Administration (NOAA) and Klickitat County. The Technical Team prepared a revision to the Work Plan as sufficient funding was not available to complete the Foundation Study as originally envisioned. That technical study plan was referred to as the "Redesigned Technical Study Plan" and was issued July 25, 2003. The Redesigned Technical Study Plan prioritized the measurement and modeling elements that would best meet the new charge with the available funding.

Due to budget shortfalls in Washington State in 2003, the Department of Ecology disinvested in visibility programs statewide effective July 1, 2003. At that point the Southwest Clean Air Agency was selected as the lead agency for Gorge air quality monitoring activities and served as the Lead Agency for the Technical Studies and Grant /Program Management.

The Redesigned Technical Study Plan outlined two major elements to be funded under the plan along with funding for project management. The two major elements consist of a Measurements Program and a Modeling Program. A third component not funded under the Redesigned Technical Study Plan but integral to project activities was the Technical Advisory Committee process. No funding was initially made available to support this process however, this process was still envisioned to be performed after the Measurement

and Modeling Programs were completed. The Measurements Program and Modeling Program would provide the data and serve as the basis and starting point for the Technical Advisory Committee.

The Redesigned Technical Study Plan called for intensive monitoring for two distinct seasons (three months each) within the Gorge that are driven by unique seasonal meteorology. Generally this was described as a wintertime monitoring regime at the east end of the Gorge and a summertime monitoring regime at the west end of the Gorge. Grant documents were prepared and funding was provided to initiate the first seasonal intensive monitoring regime for the east end of the Gorge. Ambient monitoring equipment was ordered in August 2003 and two mobile trailers were outfitted with identical monitoring equipment. Initial ambient monitoring was started in December 2003 for a three month wintertime monitoring regime at the east end of the Gorge.

In February 2004 SWCAA was notified that supplemental funding in the amount of $422,500 was appropriated by Congress for additional Gorge Studies. The original Redesigned Study Plan provided for "Potential Add-ons" that could be completed if additional funding was made available. After receiving notice of this supplemental funding in February 2004, the Technical Team met to review the "Potential Add-ons" and determine how the Redesigned Study Plan should be revised. The recommended approach by the Technical Team was a basic continuation of the existing studies with additional new equipment to gather additional upper air meteorological data within the Gorge. The original Redesigned Study Plan was constrained due to lack of funding to two short time periods for intensive monitoring activities. The additional funding provided an opportunity to collect a more complete record for about one year and provided additional meteorological data to help validate the meteorological model performance in areas within the Gorge. The Redesigned Study Plan was updated (Revision 1) in June of 2004 to reflect the recommendation of the Technical Team.

The first intensive monitoring period concluded at the end of February 2004 and the second intensive monitoring period commenced in July 2004. The second intensive monitoring regime was focused on a summertime regime and ran from July 2004 through November 2004. As the summertime intensive monitoring regime was extended to 5 months, a second wintertime intensive monitoring regime was conducted from December 2004 through February 2005 to provide about 6 months of monitoring data for the wintertime regime. The ambient monitoring program concluded in February 2005. The ambient data and analysis are summarized in the Causes of Haze in the Gorge (CoHaGo) report. This report was prepared by the Desert Research Institute and was issued final on July 31, 2006.

The Redesigned Technical Study Plan called for numerical computer visibility modeling within the Columbia River Gorge to achieve two purposes. The first purpose was to more succinctly identify source regions and source categories contributing to visibility impairment in the Gorge for calendar year 2004. The second purpose was to project visibility conditions for an outyear identified to be 2018. This outyear was selected to be consistent with the Federal Regional Haze Program projections being made for the Class I areas in the Pacific

Northwest and across the nation. This second purpose would determine if visibility was worsening, staying the same or getting better in the future year.

Three major tasks were identified in the numerical computer modeling exercise. The first task was the development of an emission inventory for calendar years 2004 and 2018. The second task was development and application of a meteorological model to simulate meteorological conditions across the modeling domain. The third task was the selection and implementation of the computer model that would integrate the meteorology and emissions data with the appropriate chemistry and dispersion algorithms.

Under task one of the modeling exercise, the Southwest Clean Air Agency and the Oregon Department of Environmental Quality coordinated with the modeling contractor, ENVIRON International, to develop emission inventories that would be used as model inputs. The 2004 calendar year emission inventory was developed by using the 2002 National Emission Inventory (NEI) data submitted by the States to EPA and updating point and selected area source inventory data to be as current as possible. Because emission inventory development is extremely complex and time intensive that this project's timeline did not allow, the Technical Team decided to use the inventory developed by the Western Regional Air Partnership (WRAP) for regional haze purposes for the outyear 2018.

The second task involved running the meteorological model (MM5) under various configurations to best characterize meteorological conditions within the Gorge. Under the monitoring task it was clearly identified that two unique conditions existed in the Gorge that represent summer and winter conditions. Because of the uniqueness of these meteorological conditions it was necessary to develop two data sets, one for each summer and winter conditions. This modeling was also performed by ENVIRON International.

The third task was to integrate the emissions inventory data with the meteorological data in a model that could make visibility projections. Under the original study plan, the project envisioned being able to run two slightly different models. Due to meteorology and emissions inventory complications, budget and schedule constraints limited the modeling activity to execution of only one model. The selected model was identified as Comprehensive Air Quality Model with extensions (CAMx) and ENVIRON International was selected to perform this modeling.

In addition to running the model for calendar year 2004 for summer and winter and the outyear of 2018 for summer and winter, the project also ran five selected sensitivity cases to better understand unique source region and source category contributions to Gorge visibility. The results of the emission inventory activities are presented in Section 3 (Emission Inventory) and the results of the modeling activities are presented in Section 5 (Current Year 2004), and Section 7 (Future Year Projections) of this report. The visibility modeling results are summarized in the Final Report - Modeling Analyses Conducted for the Columbia River Gorge National Scenic Area. This report was prepared by ENVIRON International and Alpine Geophysics and was issued final on August 28, 2007.

Glossary of Terms

absorption: a class of processes by which one material is taken up by another.

absorption coefficient: a measure of the ability of particles or gases to absorb photons; a number that is proportional to the number of photons removed from the sight path by absorption per unit length.

absorption cross section: the amount of light absorbed by a particle divided by its physical cross section.

adsorption: a process by which two or more materials adhere or stick to each other.

acidic precipitation or acid rain: is rain, snow, sleet and so forth that is more acidic than normal, generally due to human produced air pollutants. Usually characterized as precipitation with a pH < 5.0, to reflect human induced pollution.

aerosol: a dispersion of microscopic solid or liquid particles in a gaseous medium, such as smoke and fog or a suspension of colloidal particles in a gas.

air parcel: a volume of air that tends to be transported as a single entity.

ammonium nitrate: a colorless, crystalline salt (NH_4NO_3) generally used as a fertilizer.

anion: an ionic species having a negative charge.

anthropogenic: produced by human activities.

apportionment: to distribute or divide and assign proportionately.

attenuation: the diminuation (lessening) of quantity. In the case of visibility, attenuation or extinction refers to the loss of image-forming light as it passes from an object to the observer.

back trajectory: a trace backwards in time showing where an air mass has been.

bifurcated: defined as having two branches or peaks; forked.

bimodal distribution: a plot of the frequency of occurrence of a variable versus the variable. A bimodal distribution exists if there are two maxima of the frequency of occurrence separated by a minimum. See mode.

biogenics or biogenic emissions: are defined as all pollutants emitted from non-anthropogenic (man made) sources. Example sources include trees and vegetation, oil and gas seeps, and microbial activity. While fermentation produces biogenic emissions, gases from this process are included under either point or area sources.

boundary condition: when used in discussions of air quality modeling refers to air quality conditions or properties (i.e., pollutant concentrations) that exist at the boundary or domain edge for a given area. These conditions exist as a result of processes beyond the purview of the model but need to be considered because they may ultimately change the results of the model as a result of transport or chemical interaction.

budget: See light extinction budget.

carbonaceous aerosol: an aerosol that has a carbon based component.

cation: an ionic species with a positive charge. The most common cations for this report include ammonium, sodium, calcium, and potassium.

coagulation: the process by which small particles collide with and adhere to one another to form larger particles.

condensation: the process by which molecules in the atmosphere collide and adhere to small particles.

condensation nuclei: the small nuclei or particles with which gaseous constituents in the atmosphere (e.g., water vapor) collide and adhere.

deciview: a unit of visibility proportional to the logarithm of the atmospheric extinction. Under many circumstances a change in one deciview will be perceived to be the same on clear and hazy days.

diffraction: modification of the behavior of a light wave resulting from limitations of its lateral extent by an obstacle. For example, the bending of light into the "shadow area" behind a particle.

diffusion: a process by which substances, heat, or other properties of a medium are transferred from regions of higher concentration to regions of lower concentration.

EGU: means electric generating unit or power plant. This is a general term that includes various fuel types including coal-fired, gas fired and oil fired units. This can include turbines, engines and boilers.

elemental carbon: forms include charcoal, soot, graphite, and coal. The primary source is incomplete combustion products of organic matter (i.e., charcoal, graphite, and soot), from geologic sources (i.e., graphite and coal), or dispersion of these carbon forms during mining, processing, or combustion of these materials.

Eulerian air quality models: considers changes as they occur at a fixed point in the fluid. Examples include CMAQ and CAMx.

extinction: the attenuation of light due to scattering and absorption as it passes through a medium.

extinction coefficient: a measure of the ability of particles or gases to absorb and scatter photons from a beam of light; a number that is proportional to the number of photons removed from the sight path per unit length. See absorption.

extinction cross section: the amount of light scattered and absorbed by a particle divided by its physical cross section.

haze: an atmospheric aerosol of sufficient concentration to be visible. The particles are so small that they cannot be seen individually, but are still effective in visual range restriction. See visual range.

homogenous nucleation: process by which gases interact and combine with droplets made up of their own kind. For instance, the collision and subsequent adherence of water vapor to a water droplet is homogenous nucleation. See nucleation.

hydrocarbons: compounds containing only hydrogen and carbon. Examples: methane, benzene, decane, etc.

hygroscopic: readily absorbing moisture, as from the atmosphere.

IMPROVE: Interagency Monitoring of PROtected Visual Environments – refer to the following websites http://vista.cira.colostate.edu/improve/ and http://vista.cira.colostate.edu/views/.

integrating nephelometer: an instrument that measures the amount of light scattered (scattering coefficient).

inversion: See temperature inversion.

isopleth: a line drawn on a map through all points having the same numerical value.

isotropic: a situation where a quantity (or its spatial derivatives) are independent of position or direction.

isotropic scattering: the process of scattering light equally in all directions.

Lagrangian air quality model: considers changes which occur as you follow a fluid particle (i.e. along a trajectory)**.**

LAC: See Light-Absorbing Carbon.

light-absorbing carbon: carbon particles in the atmosphere that absorb light. Black carbon.

light extinction budget: the percent of total atmospheric extinction attributed to each aerosol and gaseous component of the atmosphere.

long path measurement: an atmospheric measurement process that is made over distances in excess of a few hundred meters.

micron: a unit of length equal to one millionth of a meter; the unit of measure for wavelength.

mode: the maximum point in a plot of the frequency of occurrence of a variable versus the variable.

natural source emissions: sources that are not biogenic sources; these include lightning and oil and gas seeps.

nitrates: those aerosols which have origins in the gas-to-aerosol conversion of nitrogen dioxide; of primary interest are nitric acid (HNO_3) and ammonium nitrate (NH_4NO_3). Also, a salt of nitric acid containing the monovalent, negative radical NO_3.

nitrate aerosols: see nitrates; are formed from the neutralization of nitric acid gas (which is produced by the atmospheric oxidation of NOx emissions) by cations such as ammonium, sodium, calcium, and potassium. Ammonium is by far the most abundant cation available away from oceans, so ammonium nitrate is the most abundant form of nitrate particles.

nitric oxide (NO): a gas formed by combustion under high temperature and high pressure in an internal combustion engine; it is converted by sunlight and photochemical processes in ambient air to nitrogen oxide. NO is a precursor of ground-level ozone pollution, or smog.

nitrogen dioxide: a gas (NO_2) consisting of one nitrogen and two oxygen atoms. It absorbs blue light and therefore has a reddish-brown color associated with it. It is one of the major byproducts of wood and fossil fuel combustion.

nitrogen oxides: is any combination of an oxide of nitrogen including NO, NO_2, N_2O, NO_3. It is the result of photochemical reactions of nitric oxide in ambient air; a major component of photochemical smog. Is a byproduct of combustion from transportation and stationary sources and are a major contributor to the formation of ozone in the troposphere and to acid deposition.

NO_2: See nitrogen dioxide.

NOx: See nitrogen oxides.

non-road mobile emission: pollutants emitted by combustion engines on farm and construction equipment, gasoline-powered lawn and garden equipment, and power boats,off road motorcycles, outboard motors, trains and ships.

nucleation: process by which a gas interacts and combines with droplets. See homogenous nucleation.

on-road mobile emissions: pollutants emitted by combustion engines on trucks, automobiles, motorcycles, buses; generally vehicles licensed to travel the roadways.

organics: (1) Referring to or derived from living organisms. (2) In chemistry, any compound containing carbon.

organic carbon: a naturally occuring (animal or plant-produced or synthetic) substance containing mainly carbon, hydrogen, nitrogen, and oxygen; forms are derived from the decomposition of plants and animals. A wide variety of organic carbon

forms exist and range from freshly deposited litter (e.g., leaves, twigs, branches)
to highly decomposed forms such as humus.

Perceived Visual Air Quality (PVAQ): an index that relates directly to how human
observers perceive changes in visual air quality.

phase shift: a change in the periodicity of a waveform such as light.

photometry: instrumental methods, including analytical methods, employing measurement
of light intensity. See telephotometer.

photon: a bundle of electromagnetic energy that exhibits both wave-like and particle-like
characteristics.

plume blight: visual impairment of air quality or a scene that manifests itself as a coherent
plume.

point source: a source of pollution that is point-like in nature. An example is the smoke
stack of a coal fired power plant or smelter. See source.

polar nephelometer: an instrument that measures the amount of light scattered in a specific
direction. See integrating nephelometer.

precipitation: a depositing of rain, snow, sleet, etc.

precursor emissions: emissions from point or regional sources that transform into pollutants
with varied chemical properties.

psychophysical: the branch of psychology that deals with the relationships between physical
stimuli and resulting sensations and mental states.

PVAQ: See Perceived Visual Air Quality.

Rayleigh scattering: the scattering of light by particles much smaller than the wavelength of
the light. In the ideal case, the process is one of a pure dipole interaction with the
electric field of the light wave.

refraction: the change of direction of a ray of light in passing obliquely from one medium
into another in which the speed of propagation differs.

relative humidity: the ratio of the partial pressure of water to the saturation vapor pressure,
also called saturation ratio; often expressed as a percentage.

scattering (light): an interaction of a light wave with an object that causes the light to be
redirected in its path. In elastic scattering, no energy is lost to the object.

scattering angle: the angle between the direction of propagation of the scattered and incident
light (or transmitted light).

scattering coefficient: a measure of the ability of particles or gases to scatter photons out of
a beam of light; a number that is proportional to the amount of photons scattered per
unit length.

scattering cross section: the amount of light scattered by a particle divided by its physical
cross section.

secondary aerosols: aerosol formed by the interaction of two or more gas molecules and/or
primary aerosols.

SOA: means secondary organic aerosols. Is not emitted directly as a pollutant but is formed
as part of atmospheric chemical interactions and includes organic compounds. Most
common pollutants formed for purpose of this study are ammonium sulfate and
ammonium nitrates.

SO2: See sulfur dioxide.

source: in atmospheric chemistry, the place, places, group of sites, or areas where a
substance is injected into the atmosphere. Can include point sources, elevated

sources, area sources, regional sources, multiple sources, individual stack or collection of stacks, etc.

spectral: an adjective implying a separation of wavelengths of light or other waves into a spectrum or separated series of wavelengths.

stable air mass: an air mass which has little vertical mixing. See temperature inversion.

stagnant: referring to meteorological conditions that are not conducive to atmospheric mixing.

stagnation episodes: See stagnation periods.

stagnation periods: lengths of time during which little atmospheric mixing occurs over a geographical area, making the presence of layered hazes more likely. See temperature inversion.

sulfates: those aerosols which have origins in the gas-to-aerosol conversion of sulfur dioxide; of primary interest are sulfuric acid (H_2SO_4)and ammonium sulfates ((NH_4)$_2SO_4$).

sulfate aerosols: see sulfates; are produced by the atmospheric oxidation of SO_2 emissions; exists as an aerosol regardless of its state of neutralization by the same cations as nitrate aerosols. Thus, there is a "competition" between sulfate and nitrate to react with available cations; the process is complex and dependent on atmospheric conditions and the mix of chemicals. In simple terms, ammonia preferentially reacts with sulfuric acid aerosols, and any excess is then available to form nitrate aerosols.

sulfur dioxide: a gas (SO2) consisting of one sulfur and two oxygen atoms. Of interest because sulfur dioxide converts to an aerosol that is a very efficient light scatterer. Also, it can convert into acid droplets consisting primarily of sulfuric acid.

sun angle: refers to the angle of the sun above the horizon of the earth.

telephotometer: an instrument that measures the brightness of a specific point in either the sky or vista.

temperature inversion: in meteorology, a departure from the normal decrease of temperature with increasing altitude such that the temperature is higher at a given height in the inversion layer than would be expected from the temperature below the layer. This warmer layer leads to increased stability and limited vertical mixing of air.

transmissometer: an instrument that measures the amount of light attenuation over a specified path length.

unstable air mass: an air mass that is vertically well mixed. See also stable air mass, temperature inversion.

visual range: the distance at which a large black object just disappears from view.

VOC: Volatile Organic Compound - gaseous hydrocarbon. Means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions. Certain listed items have been identified as having negligible photochemical reactions. Defined by EPA in 40 CFR 51.100(s).

wavelength: the distance, measured in the direction of propagation of a wave, between two successive points in the wave that are characterized by the same phase of oscillation.