Who is polluting the Columbia River Gorge?

Final report to the Yakima Nation
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December 31, 2006

Executive Summary

We have analyzed the 12 year record of IMPROVE aerosol data from the Wishram, Washington site in the Columbia River Gorge. The aerosol fine mass and chemical data were combined with Hysplit backward trajectories, which indicate the atmospheric transport for each sample day. Our analysis focused on the 50 worst air quality days over the past 12 years, or, in other words, the days with the highest fine aerosol mass concentration.

The primary conclusions from this study are:

1) Sources on the eastern end of the CRG clearly contribute to high PM concentrations on the worst air quality days in the Gorge. Our analysis indicates that on the 50 worst air quality days over the past 12 years (as measured by the IMPROVE samples at Wishram), sources on the eastern end of the CRG were largely responsible for at least 15 of these days, and probably at least 19 days. While the west end of the CRG is probably responsible for elevated PM on some days, sources in the eastern end of the Gorge clearly dominate the worst air quality days.
2) Fall has the greatest occurrence of poor air quality days. Days in October and November accounted for 24 out of the 50 worst air quality days in the past 12 years.
3) On days with flow from the eastern end of the Gorge, nitrogen concentrations in the fine mode aerosol are significantly elevated compared to all other days. This is consistent with the large NOx and NH_3 sources at the east end of the Gorge.
4) The 12 years of aerosol fine mass concentrations show some improvement in the overall annual means. This likely reflects a decrease in regional PM sources. However the frequency of days with poor air quality and the fine aerosol mass concentrations during

fall shows no improvement over the 12 years of data. This indicates that air quality problems in the CRG remain significant.

Background

Because of concerns about air quality in the Columbia River Gorge National Scenic Area (CRGNSA) the Yakima Nation contracted with Dr. Dan Jaffe to conduct analyses that would help identify major sources of pollutants in the gorge. This project should complement other work being done by state and federal agencies. An overview of the work to be conducted is described below. The project began in August 2006 and was completed in December 2006. This report describes the primary findings and conclusions.

Approach

1) Using the Wishram IMPROVE network fine aerosol mass data (particles smaller than 2.5 microns), I have identified the 50 worst air quality days going back to 1993.
2) For each of these 50 days, I have calculated multiple HYSPLIT back trajectories which will give us an indication of the air mass transport for that day. For each sample day (24 hours), back-trajectories were calculated every 2 hours, at 3 different starting heights, resulting in a total of 39 trajectories for each sample (13 starting times x 3 starting heights);
3) Using the trajectories for each sample, I have classified each of the 50 days according to the most likely pollutant source region.
4) Based on the trajectories, I have examined the aerosol chemistry to see if there is a significant difference in the two types of air masses (Portland vs. east Gorge). Our hypothesis is that the aerosol chemistry will reflect the different source types.
5) Finally, we have evaluated the 12 years of IMPROVE data to examine whether there is evidence for significantly improving or deteriorating air quality in the Columbia River Gorge (CRG).

Our working hypothesis is that sources in the Portland metropolitan area and the east Gorge/Boardman region, are primarily responsible for the pollutants in the CRG on the worst air quality days.

IMPROVE Sampling at Wishram

IMPROVE aerosol samples have been taken at the Wishram site since 1993 and analyzed using the standard IMPROVE protocols (see http://vista.cira.colostate.edu/IMPROVE/). Each sample consists of a set of filters collected over a 24 hour period. Samples are collected approximately 2 times per week. Because of this sampling protocol (2 days per week) it is important to recognize that not all days are sampled and significant pollution episodes will be missed. Nonetheless, the large number of samples (1139) and the long time period (12 years) provides confidence that these samples are an accurate characterization of the air quality at this location.

For each sampling date, the IMPROVE analysis consists of fine and coarse mode aerosol mass, with a cut point at 2.5 um diameter. In this report, we will use the terms "fine aerosol mass" and "PM2.5 mass" interchangeably. The fine aerosol samples undergo extensive chemical analysis for nitrate, sulfate, organic carbon, elemental carbon and numerous trace metals. Chemical analysis is not routinely conducted on the coarse mode aerosols. Data were obtained from the IMPROVE website as ASCII files (http://vista.cira.colostate.edu/IMPROVE).

The site is located approximately 1 km west of the town of Wishram. Tables 1 provides details on the site and an overview of the fine particle data. Figure 1 shows a "Google Earth" locator map. Figures 2 shows a photo of the sampling shed and Figure 3 is a photo looking SW from the site towards the Columbia River.

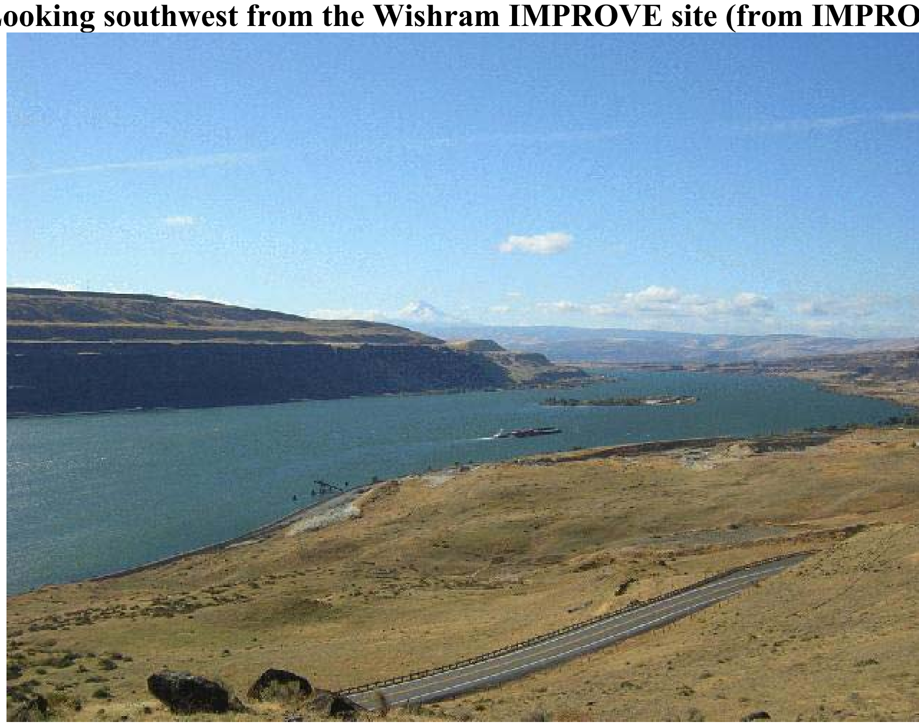
Table 1. Overview of the Wisharam IMPROVE site and data.

Database/site	IMPROVE/COR1
Location	45.66^{o}N, 121.00^o W, 178 meters asl
Dates	June 1993-Dec 2004
Number of days with valid PM2.5 data	1139
Average PM2.5-all days	5.9 ug/m^3
Average PM2.5 for the 50 highest days	18.3 ug/m^3
Highest PM2.5	34.7 ug/m^3 (Nov 7, 2002)

Figure 1. Location of Wishram IMPROVE monitoring site (Google Earth)

Figure 2. Picture of the Wishram IMPROVE monitoring site (from IMPROVE website http://vista.cira.colostate.edu/IMPROVE/Web/Sitebrowser/Sitebrowser.aspx?SiteID=113)

Figure 3. Looking southwest from the Wishram IMPROVE site (from IMPROVE website)



Trajectory Analysis

While trajectories do not give absolute identification of sources, they may indicate the most likely source. Trajectories are good at discriminating between two possible sources that are in different directions. Trajectory analysis does not provide a quantitative measure of one sources contributions when multiple sources are adjacent. Trajectory uncertainty, of which there are many possible causes, can also complicate interpretation. In general, trajectories have a horizontal uncertainty of approximately 1/3-1/2 of the distance traveled. In addition, on certain days, the trajectories will give a confusing or ambiguous result, due to errors in the meteorological data or model assumptions. Trajectories can not provide a quantitative answer as to how much different sources contribute to the overall pollution loading in the Columbia River Gorge. However despite these limitations, trajectories can add important information to chemical observations.

Trajectories were calculated using the NOAA-HYSPLIT model, with arrival heights of 0, 100 and 500 meters above model ground level. For each 24 sample period, trajectories were calculated at 2 hour intervals, leading to a total of 13 trajectories for each sample and each arrival height. In other words, a total of 39 trajectories were calculated for each date. Trajectories were calculated using the highest resolution meteorological data available. For 2004 we used the EDAS database with a 40 km grid resolution. For 1997-2003, we used the EDAS database, with an 80 km grid resolution. For 1993-1996, we used the NCEP reanalysis data, which has a much coarser 2.5^{o} x 2.5^{o} grid resolution. Some exceptions to this were made when higher resolution data was not available for a particular date.

Appendix 1 shows a listing of the 50 days with the highest fine mass (PM2.5) concentrations from the Wishram IMPROVE data going back to June 1993. Table 2 shows the monthly distribution of these 50 days.

Table 2. Monthly distribution of 50 highest PM2.5 days.

Jan	3
Feb	3
March	0
April	1
May	0
June	1
July	8
Aug	4
Sept	3
Oct	6
Nov	18
Dec	3

For each sample date, the airmass was classified as to the most likely source region based on the 39 trajectories at the 3 heights. If the trajectories arriving at multiple times and at all three heights showed consistent transport, then we have the greatest confidence in our assignment of a source region. Trajectories were classified into one of five categories: 1=West Gorge; 2= West gorge-possible, but not certain; 3= unassigned or other; 4= East gorge possible, but not certain; 5 = East Gorge.

As examples, Figures 4 and 5 show backward trajectories for the IMPROVE samples taken on November 8th and 11th, 2004. These dates had PM2.5 concentrations of 26.0 and 24.6 ug/m^3, respectively, making them the 4th and 6th highest PM2.5 days in the 12 years of IMPROVE samples. The 13 trajectories shown (for an arrival height of 0 meters AGL) suggest that pollution sources in the western end of the Gorge (e.g. Portland) were not responsible and that sources to the east were most likely responsible for the high PM 2.5. In the report "Causes of Haze in the Gorge (CoHaGo)" (Green et al., 2006), high levels of particulate matter were found between November 7-12, 2004 and were attributed to sources to the east of the Columbia Gorge. To quote from this report "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." (Green et al., 2006). Thus our trajectory analysis is consistent with the results from the CoHaGo study. Based on the monthly analysis shown in Table 2, November is the most common month to see high PM2.5 at Wishram. These two dates, November 8th and 11th, 2004, were classified as category 5 (East Gorge) based on these trajectories.

Figure 4. Hysplit one day backward trajectories arriving at Wishram on Nov 8th, 2004 at two hour intervals. At the bottom of the figure, the stars show the arrival time for each back-trajectory in Greenwich Mean Time. The trajectories indicate air flow from the east.

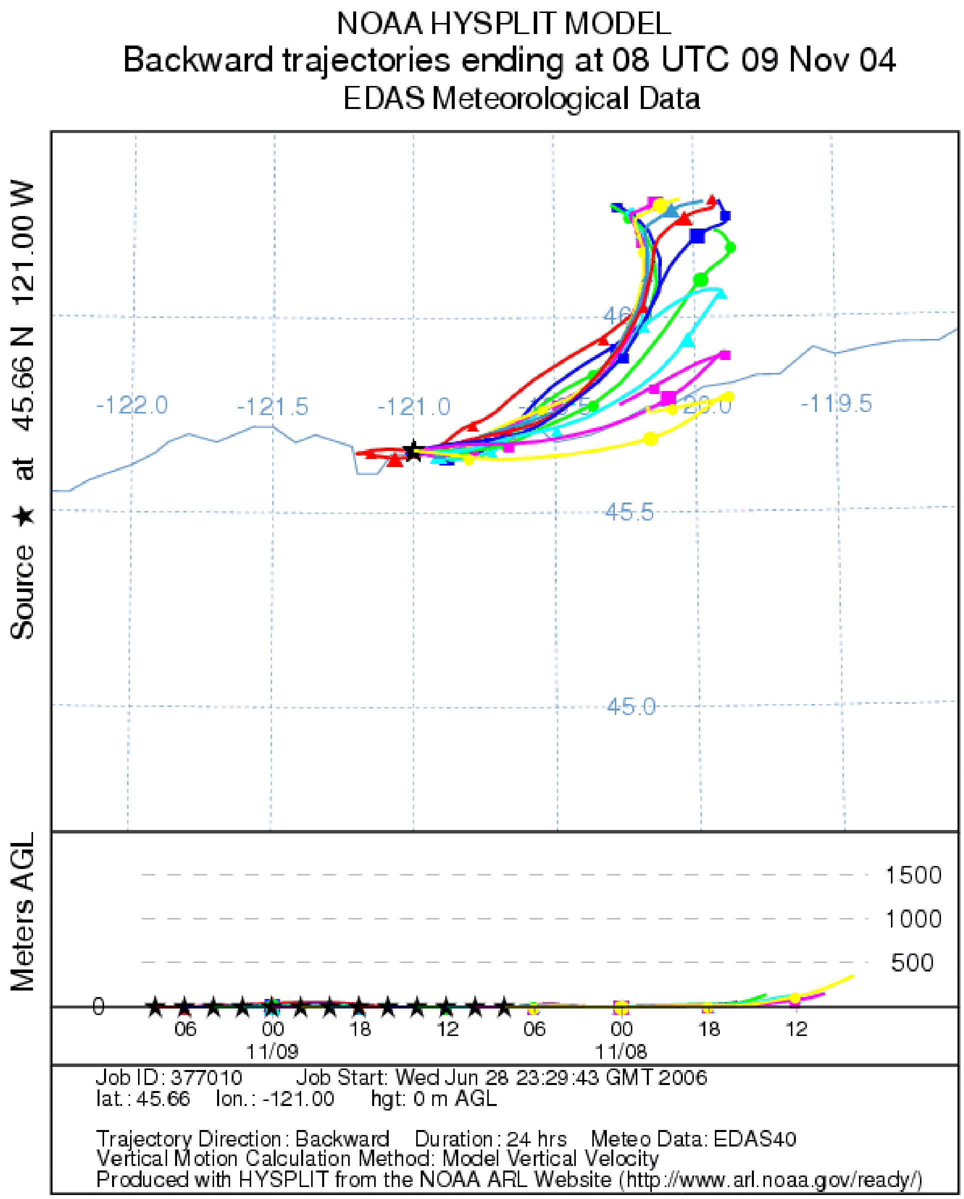


Figure 5. Hysplit one day backward trajectories arriving at Wishram on Nov 11th, 2004 at two hour intervals. At the bottom of figure, the stars show the arrival time for each back-trajectory in Greenwich Mean Time. The trajectories indicate air flow from the east.

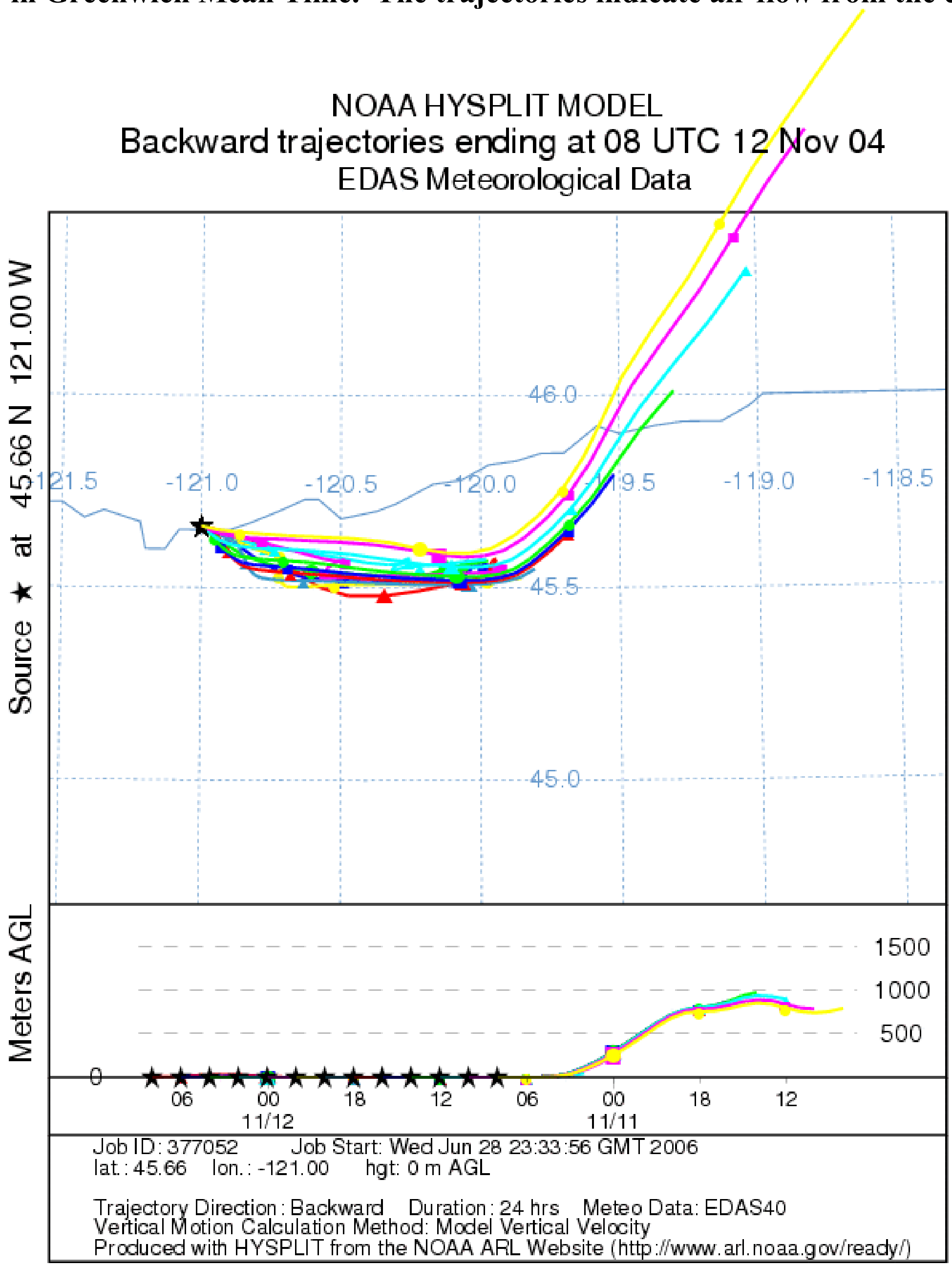
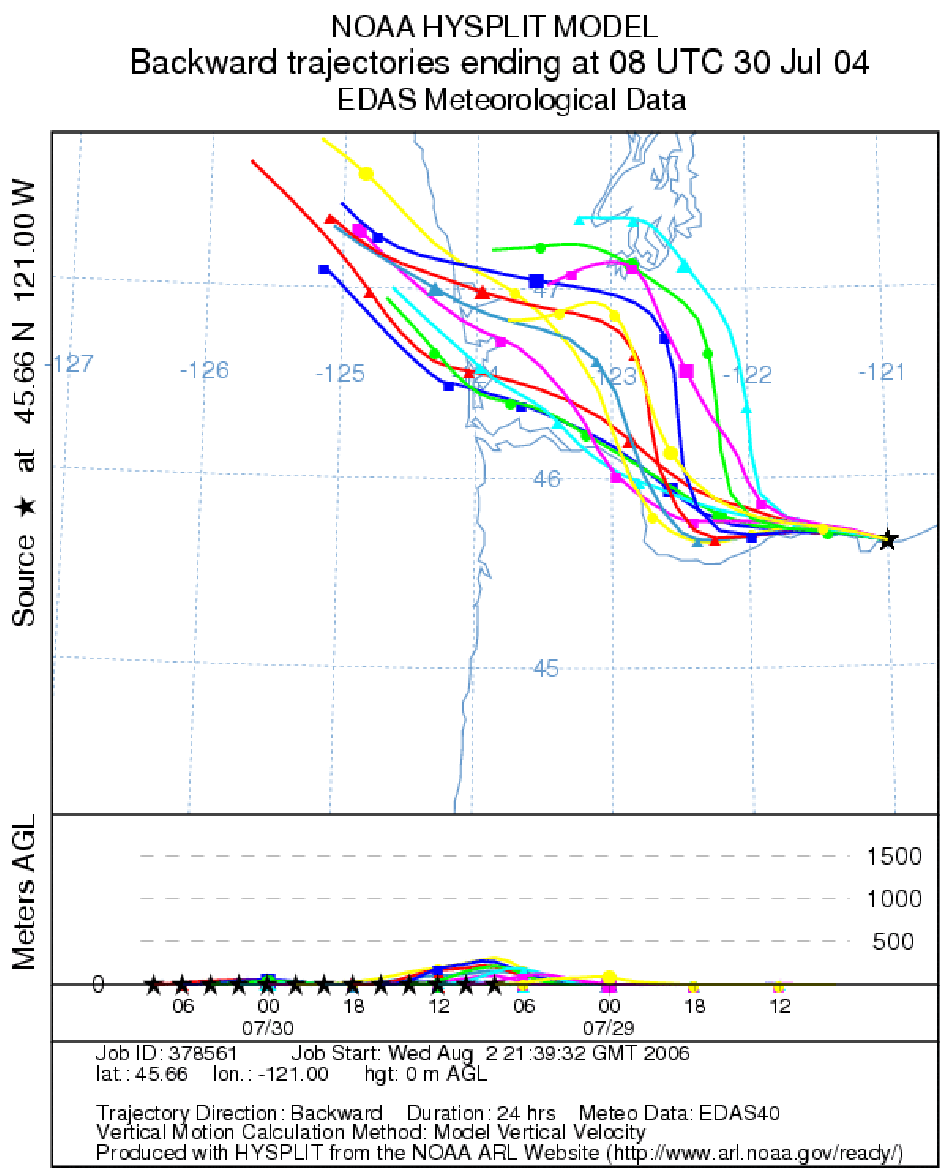


Figure 6 shows the trajectories for July 29th, 2004. For this date, the measured fine mass concentration at Wishram was 14.2 ug/m3, making this the 47th highest day in the 12 years of IMPROVE observations (still in the top 50 out of 1139 samples). This date was classified as category 1 (West gorge) based on these trajectories.

Figure 6. Hysplit one day backward trajectories arriving at Wishram on July 29th, 2004 at two hour intervals. At the bottom of figure, the stars give the arrival time for each back-trajectory in Greenwich Mean Time. The trajectories indicate air flow from the west.



Each of the 50 days with the highest fine particle mass were classified in this way. The results are shown in Table 3, along with the average PM2.5 mass concentration for the trajectory type.

Table 3. Distribution by category for the 50 highest PM2.5 days.

Category	Number	Average PM2.5 (ug/m^3)
1- West Gorge	5	14.8
2-West Gorge possible	4	17.7
3-Unassigned or other	22	17.5
4-East Gorge possible	4	20.1
5-East Gorge	15	20.5
All others	1089	5.3

Based on this analysis, transport from the East end of the GRG is responsible for at least 30% of the worst air quality days. Adding in category 4, indicates that about 40% of the days with high PM2.5 concentration, are most likely due to sources on the east end of the Gorge. These days also have the highest average fine mass concentration.

Chemical Analysis

Because the IMPROVE samples undergo a fairly complete chemical characterization, we can use this information to examine the chemical characteristics by transport type. Table 4 shows a breakdown of the chemical composition (% of total mass) by transport classification and Figures 7 and 8 show a pie chart of this information for category 1 (West Gorge) and 5 (East Gorge) samples. From this analysis, two features stand out, one is the very high NO_3^- concentrations in the East Gorge samples and the other is the very high soil component in the West Gorge samples.

Table 4. Percent composition of Wishram PM2.5 aerosol by trajectory classification. Classes 1-5 refer to the trajectory classifications for the 50 days with the highest PM2.5 concentrations.

Trajectory type =	1 n=5	2 n=4	3 n=22	4 n=4	5 n=15	All others n=1089
NO3	2.2	6.1	16.8	16.9	32.2	11.0
SO4	9.8	8.0	15.8	9.8	8.8	17.2
Organic	34.8	55.6	37.6	46.0	36.4	38.5
Soil	39.0	9.7	9.2	9.0	8.0	13.2
Other	14.2	20.6	20.6	18.3	14.6	20.1

Figure 7. Average composition of Wishram PM2.5 aerosol for 15 days in the highest PM2.5 grouping, with trajectories from the East gorge (category 5)

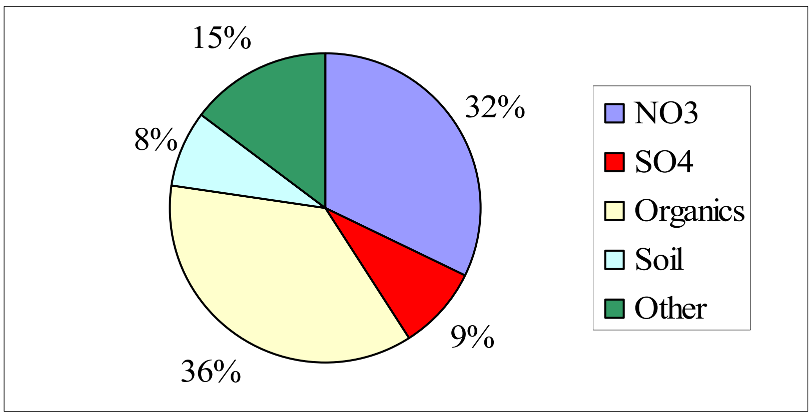
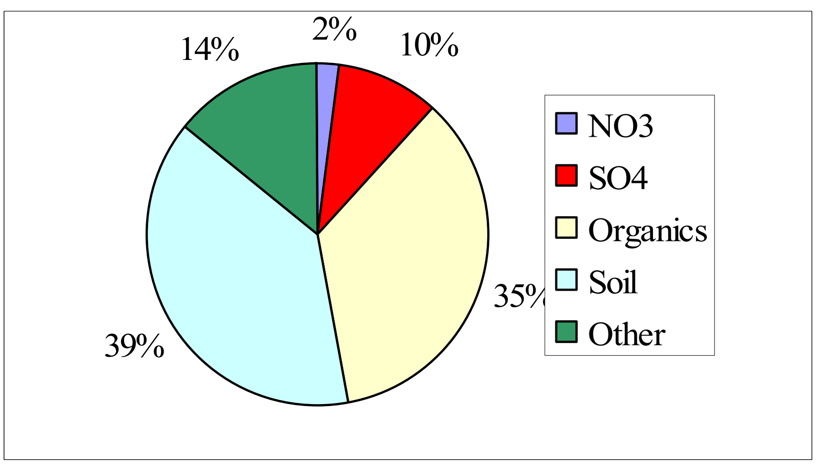


Figure 8. Average composition of Wishram PM2.5 aerosol for 5 days in the highest PM2.5 grouping, with trajectories from the West gorge (category 1)



Atmospheric nitrate can come from two sources: (1) emissions of NOx, followed by oxidation to HNO_3 or aerosol NO_3^-, and (2) emissions of NH_3 (ammonia), followed by oxidation to NOx and subsequently NO_3^-, as above. Most likely, the NOx source is dominant in our region, but a significant contribution from NH_3 can not be ruled out. Thus, the high nitrate component from the east gorge sources is consistent with our understanding of sources in the region. The PGE plant at Boardman in Morrow County emits approximately 15,000 short tons/year of NOx, which is about 6-7% of all Oregon NOx emissions. Also, the Oregon counties on the east end of the Columbia Gorge (Morrow, Umatilla, Union, Grant and Baker) emit nearly 10,000 short tons/year of ammonia (2001 data), which is approximately 20% of the Oregon total. Umatilla county is one of the most concentrated regions for ammonia emissions, accounting for nearly 10% of the statewide total. These numbers may in fact be low due to significant recent growth in the dairy industry in this region. While the IMPROVE data do not provide reliable ammonia air concentrations, it is likely that significant concentrations of gaseous ammonia and ammonium compounds also occur under easterly wind conditions in the CRG.

The high soil component for the west gorge episodes (category 1) is somewhat surprising. We examined these cases in more detail to understand the cause. First, this category contains only 5 episodes, so a small number of data points can significantly influence the mean. For this category, we found that two cases (7/17/2004 and 7/16/2002) had unusually high soil concentrations. The high soil component was responsible for the elevated PM2.5 concentration on these dates. According to the IMPROVE chemical analysis, soil dust made up 75% and 77% of the total fine aerosol mass on these two dates, 7/17/2004 and 7/16/2002, respectively. One possible explanation is that these samples were significantly influenced by forest fire emissions, which can contain substantial soil dust. Using the Navy's NAAPS aerosol model and MODIS satellite detected fire data (see http://www.nrlmry.navy.mil/aerosol/index_shortcuts.html), it appears that the CRG was likely influence by forest fire smoke during these two periods. Associated with the fires a significant amount of soil dust can get lofted with the smoke and this was probably responsible for the high soil dust on these two dates.

It is somewhat surprising that there are not more days with high PM concentrations coming from the Portland metropolitan area, since westerly winds are common in the CRG. Although we have not conducted a detailed analysis to explain this result, it seems likely that the relatively lower concentrations seen at Wishram during westerly transport is probably a result of strong dilution of the Portland airmasses, associated with strong westerly winds.

Is air quality in the CRG improving or deteriorating?

The continuous record of IMPROVE data from Wishram should allow us to evaluate how air quality has changed over the ~12 years of observations. However some caution is in order since there were likely analytical problems with the IMPROVE nitrate analysis during 1997-1999 (see reports on the IMPROVE website at http://vista.cira.colostate.edu/IMPROVE/). However these concerns should not impact the fine mass concentrations, as these are measured independent of the chemical measurements. There are several ways to evaluate trends in the IMPROVE data. First, we will examine the frequency of the 50 highest fine aerosol mass days. Then we have conducted a trend analysis on the fine mass data aggregated by year and by season.

Figure 9 below shows the fine mass for each of the 50 worst air quality days of the past 12 years and Table 5 shows the number of days each year.

Figure 9. Plot of fine mass concentration (ug/m3) vs year for the 50 highest days. The number of days in each year is shown in Table 5.

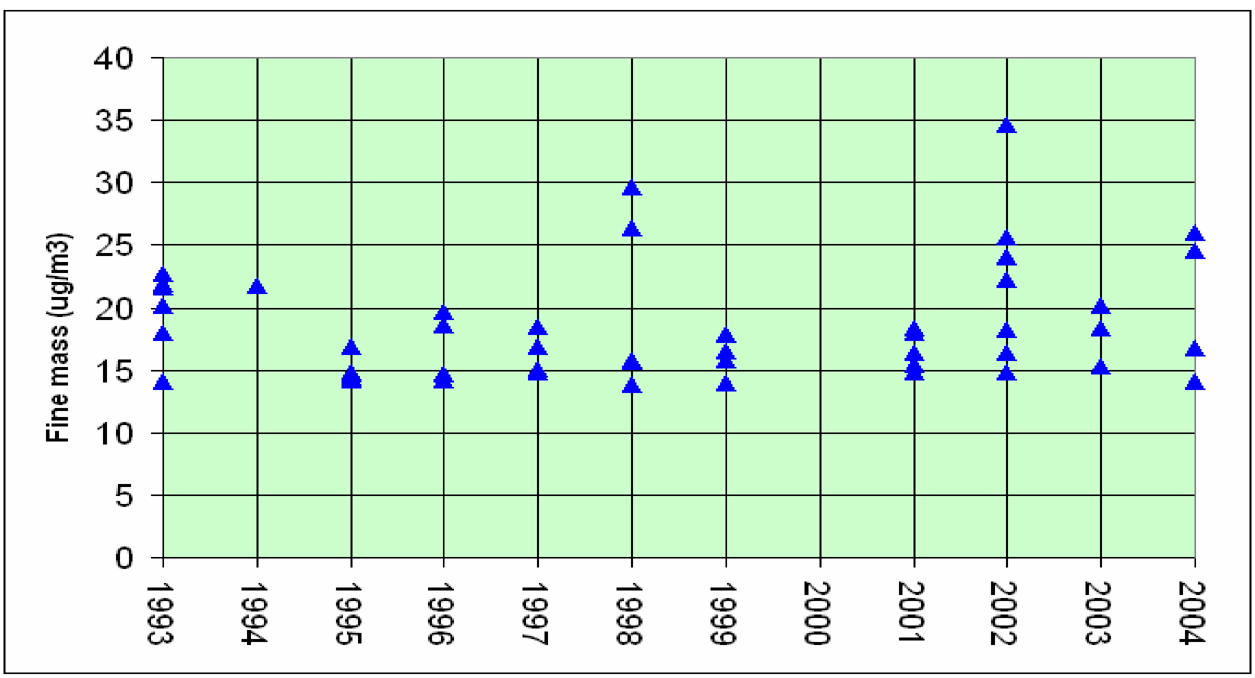


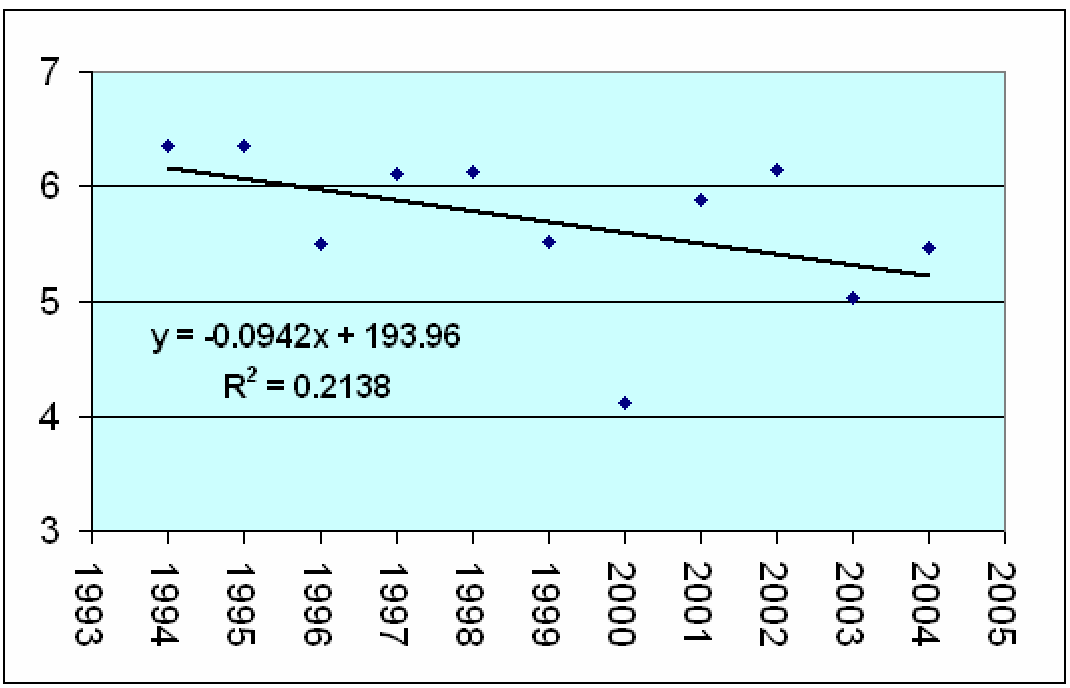
Table 5. Number of days each year that are in the 50 worst air quality days for 1993-2004.

1993	1994	1995	1996	1997	1998	1999	2001	2002	2003	2004
6	1	6	4	4	5	4	6	7	3	4

These data do not suggest a significant change in the occurrence of the worst air quality days. For example 14 of these days occurred in 2002-2004, whereas 13 of these days occurred in 1993-1995. In other words, the frequency of occurrence of a day with high PM2.5 does not seem to have changed significantly over the past 12 years.

Analysis of the annual mean fine mass concentration gives a somewhat different result. Figure 10, below, shows the annual mean fine mass concentration for each year starting with the data in 1993 (only 6 months of data are available for 1992).

Figure 10. Annual mean fine mass concentration at Wishram with a linear regression fit. Using all data points, the trend is not significant, but if the year 2000 data is omitted the trend becomes statistically significant at a 95% confidence level.



The annual means appear to be declining, with a slope of ~ 0.1 ug/m3 per year. However the R^2 for this regression is only 0.21 and therefore with this relatively short data record, the trend is not statistically significant. If the very low data point in the year 2000 is omitted, then the trend becomes statistically significant at a confidence level of 95%. So this suggests that annual mean fine mass concentrations at Wishram are improving. This is likely due to the overall reductions in regional PM emissions and/or precursor emissions.

Next we will evaluate possible trends by season. These results are shown in Table 6 below.

Table 6. Concentration and trend in Wishram fine mass by season. Winter is defined as December-February and other seasons are defined accordingly.

	Winter	Spring	Summer	Fall
Mean fine mass (ug/m^3)	5.5	4.7	6.1	7.3
Trend (ug/m^3 per year)	-0.22	-0.23	-0.02	0.00
Correlation coefficient (R^2)	0.24	0.58	0.06	0.00
Statistically significant trend at 95% confidence?	No	Yes	No	No

What these results indicate is that changes in CRG air quality are not uniform by season. The only season showing a statistically significant improvement in PM2.5 concentrations is spring. The season with the greatest frequency of poor air quality days and the highest overall mean concentration, fall, shows no improvement whatsoever. Our conclusion from this analysis is that while there is a suggestion that the annual mean fine mass concentrations at Wishram are declining, it would be incorrect to imply that CRG air quality is currently improving. This conclusion stems from the fact that the frequency of poor air quality days has not changed since 1993 and the average fall fine mass concentrations are not declining. In summary, we conclude that air quality in the CRG is not showing significant improvement at this time.

Summary

We have analyzed the 12 year record of IMPROVE aerosol data from the Wishram, Washington site in the Columbia River Gorge. Our focus was on the 50 days with the highest PM2.5 concentrations over the past 12 years. On these days, sources on the east end of the CRG appear to make a significant contribution. On approximately 40% of these days, atmospheric transport to the CRG is from the east and these airmasses contain not only high fine aerosol mass, but also elevated aerosol NO_3^- concentrations. We have also examined possible trends in air quality using the 12 year data record. At this time, there is no evidence for improving air quality on the worst days or in the fall, when most air quality problems occur in the CRG.

Appendix 1. The 50 IMPROVE sample dates with the highest fine aerosol mass concentration at Wishram for June 1993 – December 2004. Transport category determined by Hysplit trajectories (see text). Category 1= transport from the West Gorge; 2= transport from the West gorge-possible, but not certain; 3= unassigned or other; 4= transport from the East gorge possible, but not certain; 5 = transport from the East Gorge.

Number	Year	Month	Day	Transport Category	Fine aerosol mass concentration (ug/m^3)
1	2002	11	7	5	34.7
2	1998	10	24	4	29.7
3	1998	4	29	3	26.4
4	2004	11	8	5	26.0
5	2002	11	28	5	25.7
6	2004	11	11	5	24.6
7	2002	11	4	5	24.1
8	1993	11	20	3	22.7
9	2002	11	16	2	22.3
10	1993	11	27	3	21.9
11	1994	1	22	3	21.7
12	1993	12	29	3	21.6
13	2003	11	8	5	20.2
14	1993	11	10	5	20.2
15	1996	2	3	3	19.7
16	1996	2	17	3	18.6
17	1997	9	24	5	18.5
18	2001	11	12	5	18.4
19	2003	9	3	4	18.4
20	2002	11	22	3	18.2
21	1993	10	23	2	18.0
22	2001	1	10	4	17.9
23	1999	11	10	3	17.9
24	1995	6	28	5	16.9
25	1997	1	29	3	16.9
26	2004	7	17	1	16.7
27	1999	7	10	3	16.5
28	2001	11	9	5	16.4

29	2002	12	1	3	16.4
30	1998	11	4	3	15.8
31	1999	10	23	2	15.8
32	1998	10	21	5	15.7
33	2001	2	21	5	15.4
34	2003	11	14	5	15.3
35	1997	8	6	3	15.1
36	2001	12	30	5	14.9
37	2002	7	16	1	14.9
38	1995	9	16	3	14.9
39	1997	11	15	3	14.8
40	2001	8	14	3	14.8
41	1995	11	22	3	14.8
42	1996	8	24	3	14.7
43	1995	7	1	2	14.5
44	1995	10	14	4	14.3
45	1995	7	19	1	14.3
46	1996	7	27	3	14.3
47	2004	7	29	1	14.2
48	1993	10	30	3	14.1
49	1999	8	28	1	13.9
50	1998	7	22	3	13.9