P1.13 SOURCE FOOTPRINT ANALYSIS FOR REGIONAL PARTICULATE AND VISIBILITY IMPACT

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1. INTRODUCTION

The impact of urban areas on regional aerosol concentrations and visibility is an important air quality issue in the western United States. To examine the relationship of urban emissions and regional air quality in the Pacific Northwest, an analysis of potential source regions, which may impact the Columbia River Gorge National Scenic Area was conducted. The assessment involved the application of an MM5/CALMET/CALPUFF footprint modeling system, previously described by O'Neill, 2002, and Jiang et al., 2003, to a selection of ten sampling days from 1997-98 in which high aerosol loadings were observed at the Wishram and Mt. Zion IMPROVE sites in Washington State. As a way of qualifying our results, CALPUFF was also run in the traditional forward mode and results were compared to those from the footprint system. In addition, the Community Multi-Scale Air Quality (CMAQ) model was used to examine aerosol concentration patterns within the region and at the two IMPROVE sites for a two-day period in July 1998.

2. FOOTPRINT MODELING SYSTEM

The components of the source footprint modeling system are: 1) Mesoscale modeling of the regional wind field using the MM5 modeling system (Dudhia et al., 1994), 2) Application of the CALMET meteorological model (Scire et al., 1995) and inversion of the resulting wind field, 3) Using the inverted CALMET winds to drive the CALPUFF dispersion model (Scire et al., 2002) in a backward trajectory mode, and 4) Overlaying the resulting CALPUFF backpuff with the emissions inventory for the area. The overlay of the backpuff distributions with the gridded emissions yields the weighted source contributions from each grid for each selected receptor. This process takes into account the average travel time and the diurnal pattern of emissions in the inventory.

2.1 METEOROLOGICAL MODELING

Archived MM5 data were obtained from the University of Washington's (UW) Pacific Northwest mesoscale forecast system (http://www.atmos.washington.edu/mm5rt/). The archived MM5 simulations were run using three nested domains with grid sizes of 36-km, 12-km, and 4-km centered around Seattle, WA.

2.2 CALMET PROCESSING

The CALMET meteorological processor was used to interpolate the 4-km domain MM5 winds to the CALPUFF domain. CALPUFF is designed to run in a strictly forward mode. Therefore, in order to run CALPUFF in reverse mode it is necessary to temporally and spatially invert the direction of the CALMET winds. For example, for a 24 hour period the direction of the uvw wind components are reversed for all hours. Hour 0 is then labeled as hour 23 and hour 23 is labeled as hour 0, and so on for all hours of the day. These inverted winds are then used to drive CALPUFF in a reverse mode.

2.3 CALPUFF APPLICATION

The CALPUFF dispersion model was applied in reverse mode to determine a 24-hr average of the source areas contributing to the selected receptor. Source contribution maps were developed for both the Wishram and Mt. Zion IMPROVE sites on each of the ten study days. Figure 1 depicts a backward puff representing the upwind source distribution of an inert pollutant for the Wishram site on July 8, 1998, where the inert pollutant is represented by CO. Figure 2 shows the corresponding backward puff for a pollutant undergoing first order transformation on July 8, 1998 for the Wishram site, where the pollutant is modeled as SO_2. Here, reverse chemistry was applied as the puff was advected along the backward trajectory to simulate production of the pollutant. By applying reverse chemistry we are allowing for the development of a more realistic source distribution that recognizes and takes into account the destruction of a pollutant as it is transported from source to receptor. It should be noted that the difference in magnitude of concentrations in Figures 1 and 2 is due to differing arbitrary emission rates, and does not affect study results because the backward puffs are normalized later in the modeling process.

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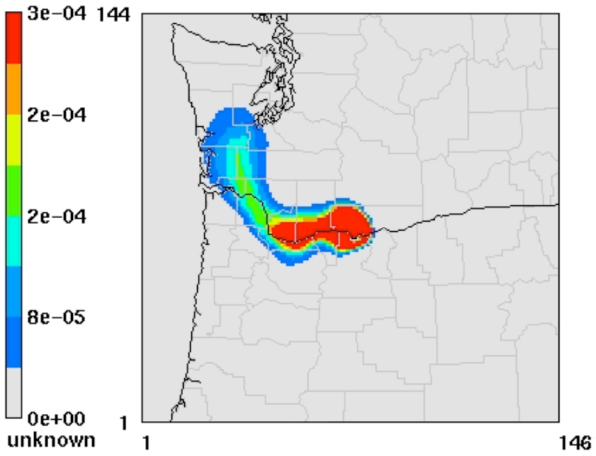

Figure 1. Backward puff depicting the upwind contributions of an inert pollutant (modeled as CO) for Wishram on PDT July 8, 1998.

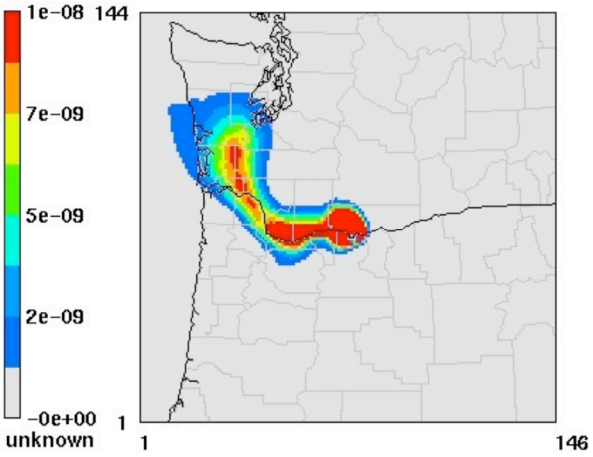

Figure 2. Backward puff depicting the upwind source contributions of a first order reactive pollutant (modeled as SO_2) for Wishram on PDT July 8, 1998.

2.4 OVERLAY WITH EMISSIONS

In order to develop a more meaningful source footprint, the CALPUFF source distribution is overlaid with gridded emission inventory data to create a source footprint which defines the 24-hr fractional source contribution area on pollutant concentrations for the two IMPROVE sites. To do this, a knowledge of travel time is necessary because the concentration at a receptor at time t is the result of a combination of upwind emission sources from earlier times. Since plumes from multiple emission sources at varying distances from the receptor may impact the receptor at the same time, a modified CALPUFF code was used. This code includes a procedure to compute the average travel time (t_{avg}) of a plume, weighted by its concentration contribution, to be transported from grid point (i,j) to the receptor for each grid cell in the domain at every time t (O'Neill, 2002),

$$t_{avg}(i,j,t) = \frac{\sum_{k=1}^{N} T(i,j,t,k) * C(i,j,t,k)}{C_T(i,j,t)} \qquad (1)$$

where,

N = Number of puffs emitted from the receptor from the beginning of the simulation to time t.

T(i,j,t,k) = Travel time of puff k from the receptor to the grid location (i,j), at time t.

C(i,j,t,k) = Concentration that puff k contributes to grid location (i,j), at time t.

C_T(i,j,t) = Total concentration from all puffs at grid location (i,j) at time t.

Once the average travel time from grid cell (i,j) to the receptor is known, the corresponding emission that contributed to the receptor is the emission rate at time t-t_{avg}. The final result is a 2-dimensional travel time weighted emission inventory, where each grid point contains an emission that contributed to some extent to the concentration at the receptor. The fractional contribution of emissions, at a particular grid point, to the concentration recorded at the receptor can then be calculated by (O'Neill, 2002),

$$f(i,j,t) = \frac{E(i,j,t - t_{avg}(i,j,t)) * C(i,j,t)}{\sum_{i=1}^{R}\sum_{j=1}^{C} E(i,j,t - t_{avg}(i,j,t)) * C(i,j,t)} \qquad (2)$$

where,

C,R = Number of columns and rows in the domain.

E(i,j,t-t_{avg}(i,j,t)) = Emission rate from the emission inventory contributing to the receptor concentration at time t.

C(i,j,t) = Concentration (as an indicator of probability) from the backward CALPUFF plume.

Figures 3 and 4 show the 24-hr fractional source contribution area on CO and SO_2 concentrations for the Wishram site on PDT July 8, 1998, respectively.

Emission inventory (EI) files for 1996 were provided by the Washington State Department of Ecology and the Oregon Department of Environmental Quality for use in this study. Emissions were not adjusted to reflect 1997 or 1998 values. All EI files were processed using the Sparse Matrix Operator Kernel Emissions (SMOKE) processor, and were allocated hourly by activity profiles. For example, weekday and weekend days use different allocation methods for different source categories so emissions will vary depending on the time of day and day of the week.

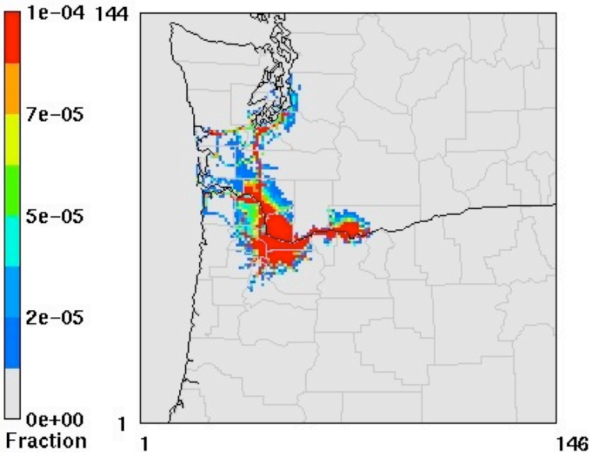

Figure 3. Fractional source contribution area of CO on the receptor concentrations at Wishram on PDT July 8, 1998.

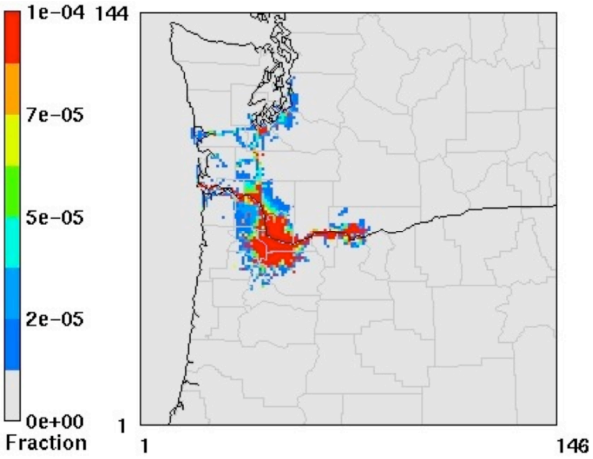

Figure 4. Fractional source contribution area of SO_2 on the receptor concentrations at Wishram on PDT July 8, 1998.

3. FOOTPRINT RESULTS

Two source footprints were generated for both the Wishram and Mt. Zion IMPROVE sites on each of the ten study days. The first footprint represents the fractional source contribution of CO to each site, where the CALPUFF backpuff was modeled as inert CO and overlayed with CO emissions to represent a surrogate for all anthropogenic emissions. The second footprint represents the fractional source contribution of SO_2 to each site. In this case, reverse SO_2 chemistry (conversion of SO_4^{2-} to SO_2) was applied to the CALPPUFF backpuff and the resulting source distribution was overlayed with SO_2 emissions.

Results for all days were summarized by summing the weighted emission footprint within each of several arbitrarily defined source areas: Puget Sound, Portland, Tri Cities, Yakima, and the Columbia Gorge (Figure 5). These results are shown in Figures 6 and 7. Model results showed a wide range of spatial variability in source footprints for both the Wishram and Mt. Zion sites. The majority of source areas were confined to the Portland and Columbia Gorge regions, and to the portion of the grid not included in the five source areas. In most cases, source areas were similar between the Wishram and Mt. Zion sites. However, in many cases the relative importance of each source area was significantly different between the two sites. Incorporating reverse chemistry into the footprint model had the effect of reducing the importance of emissions within the Columbia Gorge region, and placing more emphasis on those outside of the region. In all but one case, for both the Wishram and Mt. Zion sites, reverse chemistry increased the probability of a source outside the sampling areas contributing more heavily to the pollutant concentration at the two sites. In nearly half the cases, reverse chemistry also altered the importance of sources within the Portland area. Of these cases, approximately half resulted in an increased importance, with the remainder resulting in a decrease of importance.

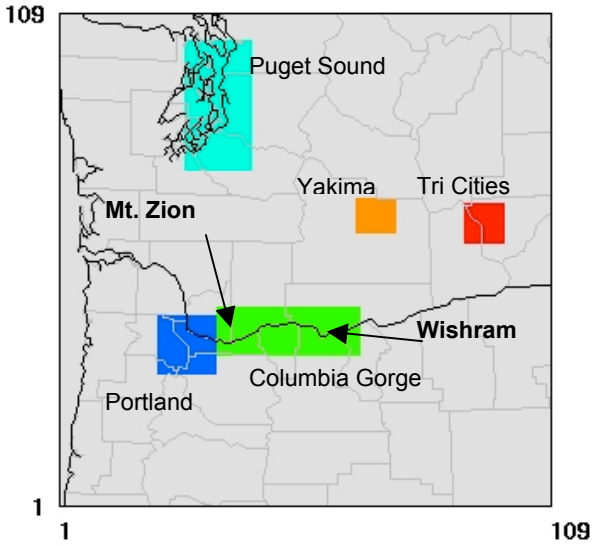

Figure 5. Source areas used to summarize weighted emission footprints.

As a way of analyzing the skill of our footprint modeling system, both CALPUFF and CMAQ were run in forward mode for a two day period (PDT July 21-22, 1998), and model results were compared. Both models were run using continuous emissions of inert tracer gases within each source region, and zero emissions every where else in the domain. The five tracer gasses were tracked to the Wishram and Mt. Zion sites, and a 24-hr fractional contribution of each source area was calculated for PDT July 22, 1998.

Table 1 shows the 24-hr fractional contribution, at the Wishram and Mt. Zion sites, from each of the five

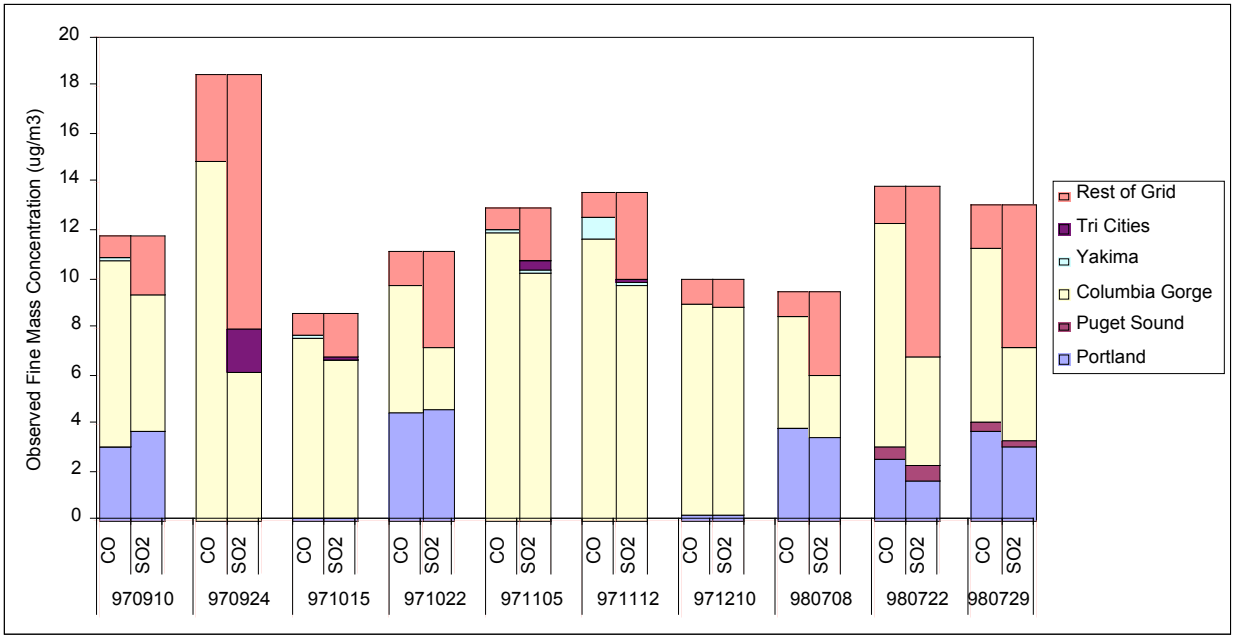

Figure 6. Probable source contribution areas as a fraction of the total observed fine mass for the Wishram IMPROVE site, where CO refers to an inert pollutant, and SO_2 refers to a first order reactive pollutant (note: fine mass data was not available for 971210 so a concentration of 10 □g m^{-3} was assumed).

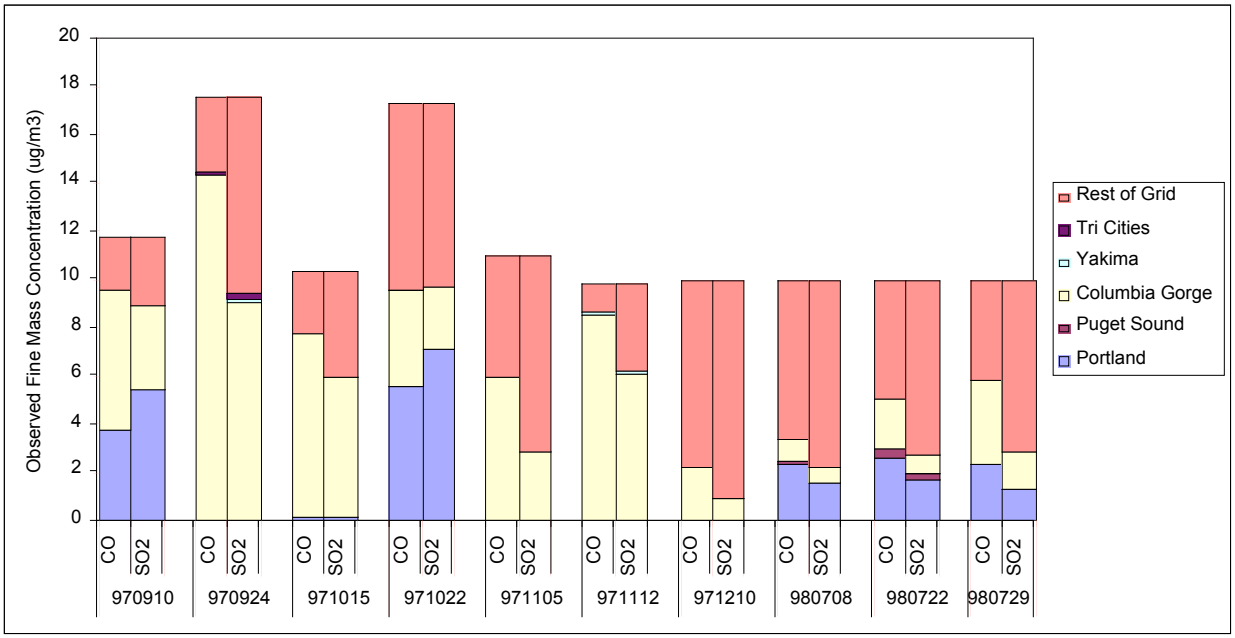

Figure 7. Probable source contribution areas as a fraction of the total observed fine mass for the Mt. Zion IMPROVE site, where CO refers to an inert pollutant, and SO_2 refers to a first order reactive pollutant (note: fine mass data was not available for 971210, 980722, and 980729 so a concentration of 10 □g m^{-3} was assumed).

source areas for the forward CALPUFF and CMAQ runs, as well as the fractional contribution of CO determined by the footprint modeling system. As can be seen, at the Wishram site all methods show the largest contribution coming from the Columbia Gorge region, followed by the Puget Sound and Portland source areas. No significant contribution was observed from the Yakima and Tri Cities regions. At the Mt. Zion site,

Table1. 24-hr fractional source area contributions from the footprint method, a forward CALPUFF calculation, and a CMAQ simulation using inert tracers for the Wishram and Mt. Zion IMPROVE sites on PDT July 22, 1998.

Source Area	Fractional Contribution					
	Footprint Method		CALPUFF		CMAQ	
	Wishram	Mt. Zion	Wishram	Mt. Zion	Wishram	Mt. Zion
Portland	0.202	0.533	0.012	0.328	0.067	0.416
Puget Sound	0.046	0.072	0.040	0.069	0.131	0.054
Columbia Gorge	0.752	0.395	0.947	0.603	0.802	0.530
Tri-Cities	0.000	0.000	0.000	0.000	0.000	0.000
Yakima	0.000	0.000	0.000	0.000	0.000	0.000

all methods show significant contributions from both the Portland and Columbia Gorge source regions, with a small contribution from the Puget Sound area and no significant contribution from the Yakima and Tri Cities regions. These trends are mostly consistent with what one would expect given the locations of the two sites and the predominant northwesterly flow over the region. However, it is surprising that the Portland source region contributes as little as it does to the Wishram site. One would expect much of the pollution from Portland to be funneled through the Columbia Gorge and impact the Wishram site, so that the Portland area would contribute a larger portion to the overall impact at Wishram than was modeled. The lower contribution from the Portland region may be due to the resolution of the 4-km gridded terrain data used, which will influence the MM5 and CALMET wind fields. The complex terrain of the Columbia Gorge is not completely resolved at 4-km and the Gorge itself is not continuous at its western end. This suggests that the wind flow patterns within and around the Gorge may not represent actual patterns.

It should be noted that the fractional contributions calculated from the footprint method take into account spatial and temporal variations in emissions (of CO from the emission inventory), as compared to the forward CALPUFF and CMAQ simulations, which use a constant emission rate over the entire source area.

4. SUMMARY

An assessment of potential source regions which may impact the Columbia River Gorge National Scenic Area was conducted on a set of ten study days between September 1997 and July 1998 for both the Wishram and Mt. Zion IMPROVE sites. The assessment involved the MM5/CALMET/CALPUFF modeling system applied in backward trajectory mode to develop an upwind probability source distribution. The probability source distribution was then overlaid with gridded emission inventory data to create a source footprint which defines the 24-hr fractional source contribution area on pollutant concentrations for the two IMPROVE sites. Two footprints were defined for each site on each modeling day, where one footprint is that of an inert pollutant and the other is for a pollutant undergoing first order transformation. Emission inventories of CO and SO_2 were used as surrogates for the inert and chemically reactive cases, respectively.

It was shown that chemistry effects play an important role in defining the footprint and results in increasing the importance of emissions further from the receptor. It was also shown that the Portland region can be a significant source of pollutants into the Columbia River Gorge, but that in most cases the Puget Sound, Yakima, and Tri Cities areas are either significantly far away or are too small of a source area to contribute to the pollutant concentrations at the Wishram and Mt. Zion IMPROVE sites. In addition, footprint results were shown to be consistent with output from CALPUFF run in forward mode, as well as consistent with CMAQ gridded simulations.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Dudhia, J., G. A. Grell, and D. R. Stauffer, 1994. A description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5). NCAR Technical Note NCAR/tN-398+STR.

Jiang, G., B. Lamb, H. Westberg, 2003. Using back trajectories and process analysis to investigate photochemical ozone production in the Puget Sound region. Atmospheric Environment 37, 1489-1502.

O'Neill, S. M., 2002. Modeling ozone and aerosol formation and transport in the pacific northwest and calculating fractional source contributions to downwind receptors. Doctorate Thesis, Department of Civil & Environmental Engineering, Washington State University, 160 pp.

Scire, J. S., E. M. Insley, R. J. Yamartino, and M. E. Fernau, 1995. A user's guide for the CALMET meteorological model. Earth Tech Inc., 193 pp.

Scire, J. S., D. G. Strimaitis, and R. J. Yamartino, 2000. A user's guide for the CALPUFF dispersion model (version 5.0). Earth Tech Inc., 517 p