FINAL REPORT

Columbia River Gorge Haze Gradient Study

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Executive Summary

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 from 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. More detailed data analysis will be done for the Causes of Haze in the Gorge (COHAGO) study. This will include additional analyses using the nephelometer and surface meteorology data from the Haze Gradient Study and aerosol composition data collected for COHAGO (e.g. filter samples, high time resolved sulfate, nitrate, EC/OC, etc).

Because of the large number of days (>600) monitored, a statistical method (cluster analysis) was used to group days with similar wind patterns. Summaries of wind, pressure, particle light scattering (bsp), and light absorption were computed for each group of similar days (each cluster). Wind data were classified as to their component upriver (basically west to east). Upriver was termed "upgorge", downriver termed "downgorge". Light scattering data were interpreted with respect to wind transport patterns to gain insight into likely source areas for each group of days.

Five clusters of similar days were identified:

1) light upgorge flow
2) moderate upgorge flow
3) strong upgorge flow
4) light downgorge flow (diurnal reversal at eastern sites)
5) winter downgorge flow (light at east end, strong at west end)

Strong upgorge (3) was the predominant pattern in mid-summer; Winter downgorge (5) was the most frequent winter pattern. Light upgorge (1) and light downgorge (4) were most frequent in fall and spring transition months; moderate upgorge (2) was most frequent in late summer to early fall.

Winter downgorge (5) had the highest average bsp at all sites except Sauvie Island. Highest bsp for winter downgorge was at the eastern sites, with a decrease with distance downgorge. Bsp increased again at Sauvie Island as the flow exited the Gorge and crossed the Portland/Vancouver area. This transport and bsp gradient pattern suggests that sources east of the Gorge cause much of the haze and that the Portland/Vancouver area contributes additional aerosol to the Sauvie Island site.

Light downgorge (4) had the highest bsp at Sauvie Island, suggesting impact from nearby sources such as the Portland/Vancouver area and/or downriver industry.

For days without precipitation, all the upgorge clusters (1-3) had highest bsp at Mt. Zion and a decreasing bsp with distance into the Gorge. Light upgorge (1) and moderate upgorge (2) showed diurnal patterns of increasing bsp progressing upgorge to the Bonneville site during the day. Bsp also increased across the Portland/Vancouver area for each cluster, suggesting the urban area as a significant contributor to aerosol in the Gorge for these clusters.

Light downgorge (4) and winter downgorge (5) showed an increase in bsp from Wishram to Sevenmile Hill and Memaloose, suggesting impact from The Dalles area. At Sevenmile Hill for light downgorge (4), the diurnal change in wind direction from upgorge to downgorge is accompanied by an increase in bsp (when the direction is from The Dalles).

At Mt. Zion and Wishram, light absorption was a minor contributor to haze.

1 Introduction

The Columbia River Gorge Commission was established pursuant to the federal legislation Columbia River Gorge National Scenic Area Act (1986). The National Scenic Area Act has two purposes:
1. To protect and provide for the enhancement of the scenic, cultural, recreational and natural resources of the Gorge; and
2. To protect and support the economy of the Gorge by encouraging growth to occur in existing urban areas and by allowing future economic development outside these areas if it is compatible with the first purpose.

The Columbia River Gorge Commission was created by an inter-state compact. Twelve voting members are appointed by the governors of Oregon and Washington and the six counties within the Columbia River Gorge National Scenic Area. One non-voting Forest Service member represents the U.S. Secretary of Agriculture. The Gorge Commission has several responsibilities under the National Scenic Area Act, including planning for the Scenic Area, implementing the Columbia River Gorge Scenic Area Management Plan and monitoring and hearing appeals of land-use decisions.

In May 2000 the Commission adopted an amendment to the Gorge Management Plan that calls for the protection and enhancement of Gorge air quality. The amendment directed the states of Oregon and Washington, working with the U.S. Forest Service and the Southwest Clean Air Agency and in consultation with affected stakeholders to develop a work plan. The purpose of the work plan, among other things, is to establish timelines for the gathering and analysis of necessary Gorge air quality data and, ultimately, for the development and implementation of an air quality protection strategy.

A peer-review workshop was held March 14-15, 2001 in Cascade Locks, Oregon to solicit comments from experts on a "strawman" study plan. After incorporating comments received at the workshop, a draft study plan was prepared by Desert Research Institute. In July of 2001, the Columbia River Gorge Technical Team and Interagency Coordination Team developed a phased, technical study plan for the Columbia River Gorge National Scenic Area. In 2003, WDOE, ODEQ and SWCAA asked the Technical Team to develop a "stand alone" study, leveraging other studies and within the available resources, that would:

a) provide an assessment of the causes of visibility impairment in the Columbia River Gorge National Scenic Area; b) identify emission source regions, emission source categories, and individual emission sources significantly contributing to visibility impairment in the Gorge; c) provide predictive modeling tools or methods that will allow the evaluation of emission reduction strategies; d) provide an initial assessment of air quality benefits to the Gorge from upcoming state and federal air quality programs; and e) refine or adapt predictive modeling tools already being developed for visibility or other air quality programs, including but not limited to Regional Haze.

Desert Research Institute (DRI) was contracted by the Washington Dept. of Ecology to perform a study of horizontal and vertical gradients of haze in the Columbia River Gorge. The study is titled the "Columbia River Gorge National Scenic Area Haze Gradient Study". Management of the study was subsequently transferred to the Southwest Clean Air Agency (SWCAA).

DRI's components of the study include:

1) Recommending locations for additional nephelometer and meteorological monitoring sites;
2) Obtaining data from local agencies (SWCAA and Oregon Dept. of Environmental Quality) ;
3) Performing quality assurance on the data and assembling a database;
4) Performing data analysis regarding temporal and spatial patterns of light absorption and light scattering under varying meteorological conditions (e.g. wind direction, synoptic scale pattern) by time-of-day and season.
5) Preparing draft and final reports for the study

It was the responsibility of SWCAA and ODEQ to collect the data and provide it to DRI. The study is closely associated with the Causes of Haze in the Gorge (COHAGO) study. COHAGO involves analysis and interpretation of data collected during portions of the haze gradient field study using additional instrumentation such as high time resolved gas and aerosol data at a much reduced number of sites.

The haze gradient study is intended to provide an overview of haze in the Gorge and to identify particular episodes of interest that will be analyzed in detail in COHAGO.

2 Monitoring sites, parameters measured, data recovery

2.1 Monitoring Locations

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) provide essentially a vertical profile at the west end of the Gorge.

Bonneville Dam – river level site (2m above) in the heart of the Gorge at Bonneville.

Memaloose State Park – river level site (8 m above) 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) site east of Wishram.

Maps showing site locations with respect to cities, highways, and topography are shown in Figures 2-1 to 2-3.

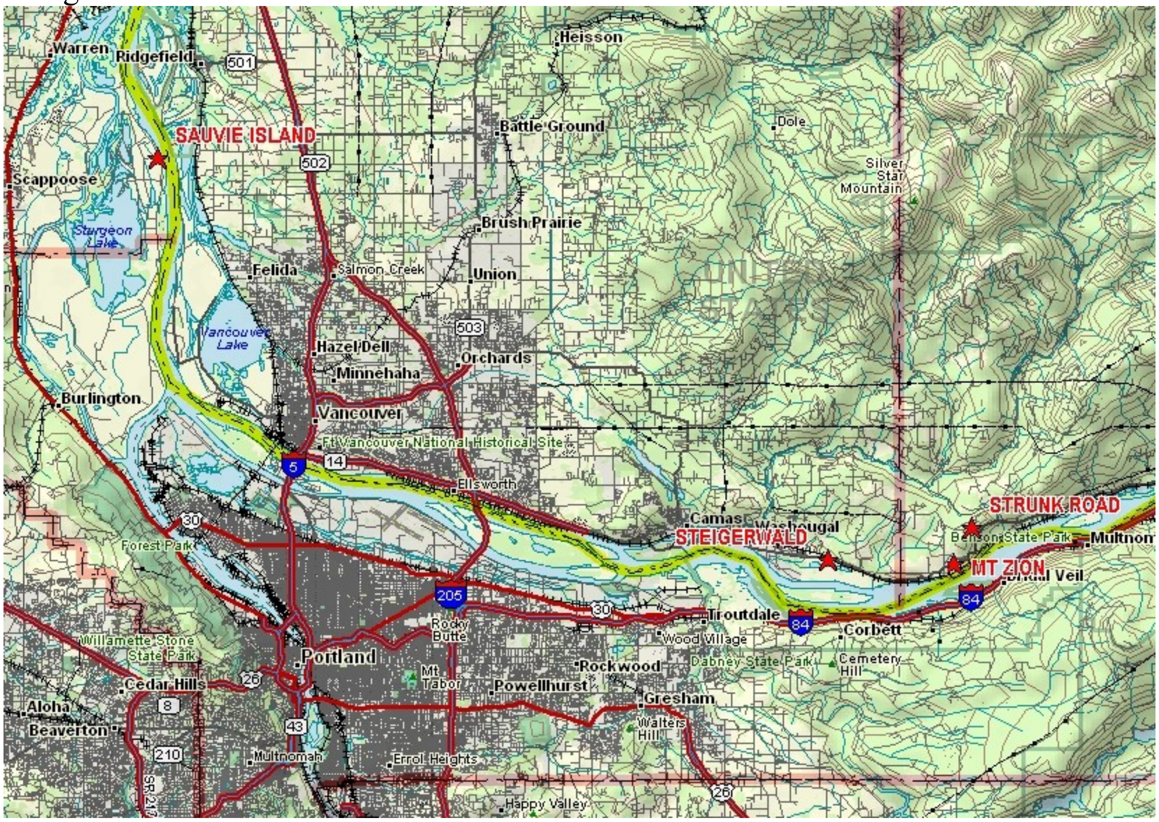


Figure 2-1. Map of western sites (Sauvie Island, Steigerwald, Mt. Zion, and Strunk Road).

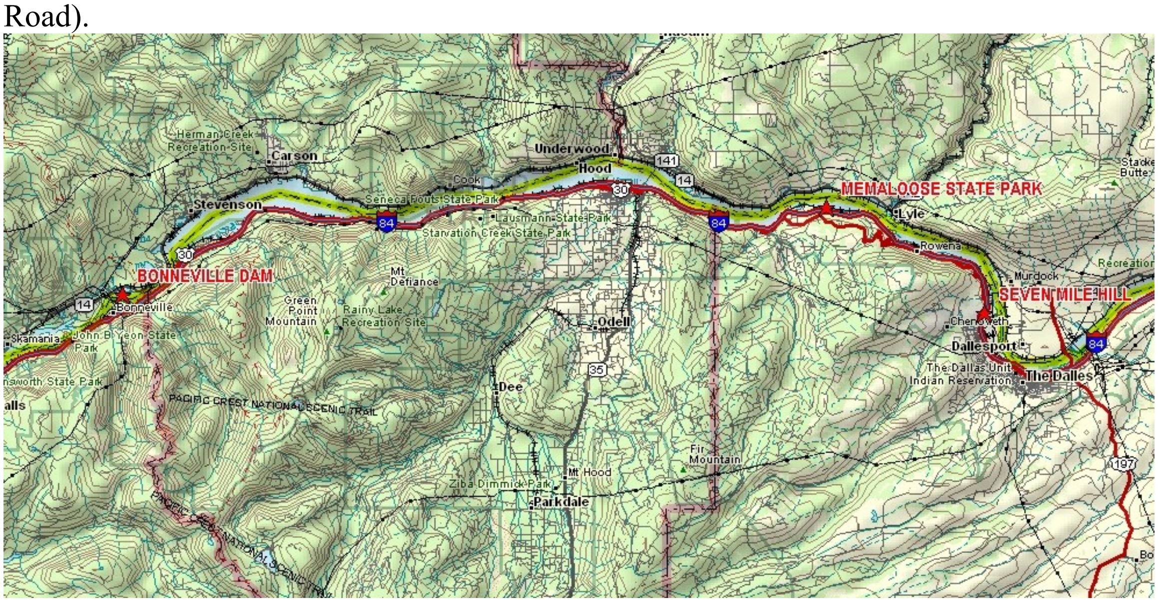


Figure 2-2. Map of Bonneville, Memaloose State Park, and Sevenmile Hill.

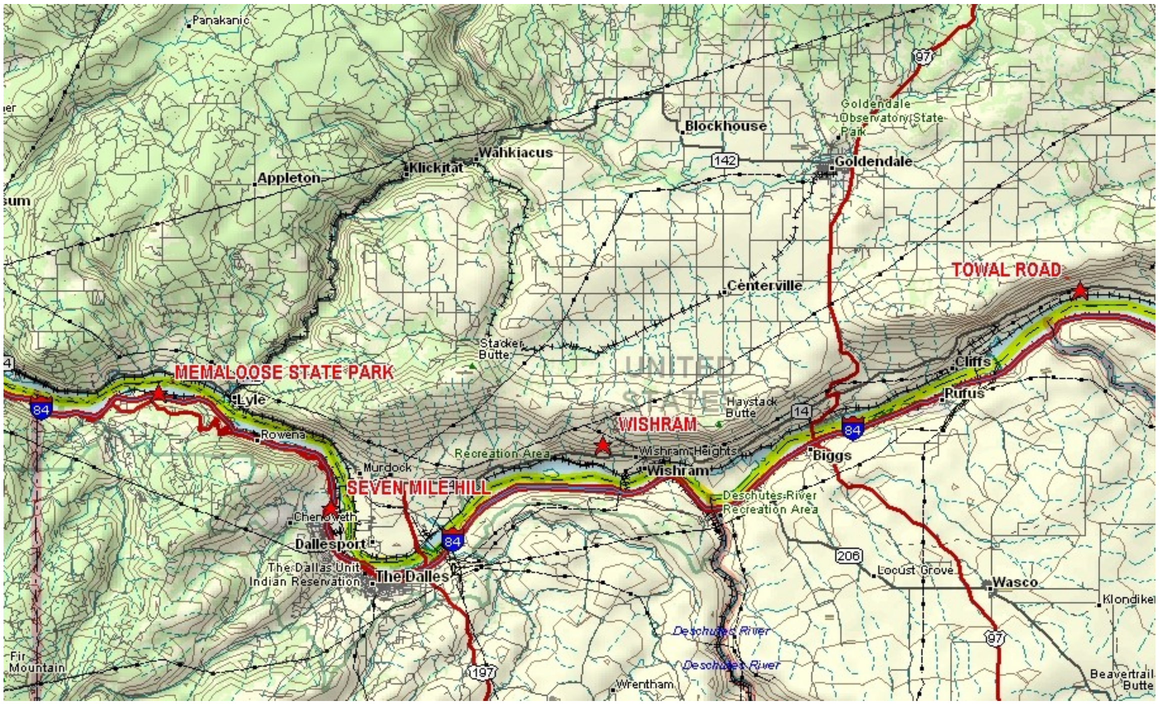


Figure 2-3. Map of eastern sites (Memaloose,Seven Mile Hill, Wishram, and Towal Road.

2.2 Instrumentation

All sites measured particle light scattering (bsp) using a Radiance Research nephelometer model M903. All sites except Memaloose had surface meteorological measurements of wind speed and direction, temperature, and relative humidity (RH). Wind speed and direction were measured using R.M. Young model 09305 systems. The temperature probes were R.M. Young model 41342VF. Relative humidity was measured with Rotronic MP100H/MP400H probes. Additionally, Mt. Zion and Wishram had Magee Scientific seven-wavelength aethalometers (AE-3 series) to obtain elemental carbon concentrations.

At high relative humidity (over about 70%) particles containing nitrate and sulfate grow rapidly with increased humidity due to uptake of water. The particles scatter much more light due to the water uptake. Particles stay in solution (the deliquescence effect) until humidity is reduced to less than 50%. To help minimize the effects of varying RH levels among sites, the nephelometers were set to heat the sample air stream as needed to maintain an RH of not more than 50%. Actual light scattering (haze) is thus higher under high RH conditions than measured by the nephelometers. This allows for a good comparison of scattering and determination of horizontal and vertical gradients within the Gorge, but does not allow for direct comparison to other measurements of light scattering using unheated nephelometers. Without knowledge of chemical composition, the nephelometer measurement cannot be directly compared to reconstructed extinction measurements such as is done for IMPROVE sites.

Nephelometers also fail to detect some coarse particle (>2.5 microns diameter) scattering, this leading to an underestimation of scattering. This effect is most significant in dusty environments where coarse particle scattering is substantial.

2.3 Data Recovery

The nominal monitoring period was July 1, 2003 to February 28, 2005. However, not all sites were operational until August 14, 2003. Nephelometer data recovery for each site is given in Table 2-2. Generally, the meteorological data recovery were the same as for nephelometer data.

Site	July 1, 2003-February 28, 2005	August 14, 2003-February 28, 2005
Bonneville	84.5	89.9
Strunk Road	91.6	90.9
Memaloose	86.3	91.7
Sevenmile Hill	83.2	89.6
Steigerwald	87.9	87.5
Sauvie Island	84.2	89.2
Towal Road	87.7	87.1
Wishram	92.7	92.2
Mt. Zion	92.0	92.6
All site average	87.8	90.1

The total data recovery for the period from August 14 through the end of the study (February 28, 2005) was 90%. For sites with wind data, greatest recovery was for Mt. Zion, followed by Wishram, and Strunk Road.

3 Data analysis methodology

3.1 Cluster analysis to group days with similar wind field characteristics

Cluster analysis is a tool that forms groups (clusters) based on similarities between members of each group. It calculates distances between each possible pair of members and forms clusters that minimize the within cluster variation and maximize the between cluster variation. For example, as applied in this study, we desire to form groups of days with similar spatial wind field patterns and a similar diurnal variation. We can then look at parameters of interest, such as light scattering and summarize these patterns for a number of groups that is considerably smaller than the total number of study days.

In order to organize the approximately 600 day study period for the haze gradient study (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. The nephelometer data were then summarized for spatial and diurnal patterns for each cluster. This provides a method for reducing the dimensionality of the analysis from 600 days to a far smaller number of "typical" days. Of course for understanding days of particular interest, e.g. very high light scattering days, case study analysis is necessary. Case study analysis will be done in the COHAGO study.

We hypothesized that days with similar winds at each monitoring site, including their diurnal variation, should be similarly affected by transport from sources. That is, days grouped based on similarity of winds should have similarities in diurnal patterns of light scattering (bsp). A potentially important factor not considered in the clustering was the occurrence of precipitation that could cause washout of particles from the atmosphere. Precipitation was considered when averaging light scattering for days with similar winds (i.e. by removing rainy days), as will be described later. Also not considered explicitly were the seasonal differences that may result due to greater reactivity rates, dust entrainment, etc. that can vary seasonally under the same wind patterns. As it turns out wind patterns, and thus the wind clusters, are strongly seasonally dependent, as will be demonstrated shortly.

Ideally, we would have used wind data from all eight nephelometer sites with meteorological data for the cluster analysis. However, the analysis requires all sites used to have complete data for a day for that day to be clustered. Using only the 3 sites with most complete data, (Mt. Zion, Wishram, and Strunk Road) we were able to cluster 563 out of 609 possible days. Using all 8 sites with meteorological and light scattering data, we would have been able to cluster only 332 days. A sensitivity analysis was done to compare clusters using all sites versus the 3 most complete sites. Qualitatively the results were similar, so results are presented for all sites with the clustering based on the 3 most complete sites. This allows us to include nearly all days for comparing typical diurnal patterns.

We also tested for the possibility of bias using 2 nearby western Gorge sites (Mt. Zion and Strunk Road) and only one eastern Gorge site (Wishram) by computing clusters using only Mt. Zion and Wishram wind data. The clusters were nearly identical with an average absolute value of hour-by hour differences of 0.20 meters/second for Wishram and 0.15 meters/second for Mt. Zion. This is 2.3% of the average absolute value of the along Gorge wind component at Wishram and 2.6% at Mt,. Zion. Only 17 of 563 days (3.0%) changed clusters between the two methods.

Winds at each of the monitoring sites showed 2 distinct wind directions, oriented either upgorge (upriver) or downgorge (Figure 3-1, site order west to east). Wind roses are shown in Figure 3-2. For each hour of the day the component of the wind in the up-gorge direction was computed and was assigned a positive sign for up-gorge flow and a negative sign for down-gorge flow. This simplifies the analysis by turning the vector wind into a scalar representation of it. Table 3-1 shows the frequency of upgorge (generally from the west) or downgorge (generally from the east) winds at each site averaged over the 20 month study period. All sites except Sauvie Island had a higher frequency of upgorge (westerly flow) than downgorge (easterly flow), with upgorge frequency ranging from 54% at Steigerwald to 76% at Wishram. At Sauvie Island winds were upriver (from the north) about 80 % of the time and from the south about 20% of the time.

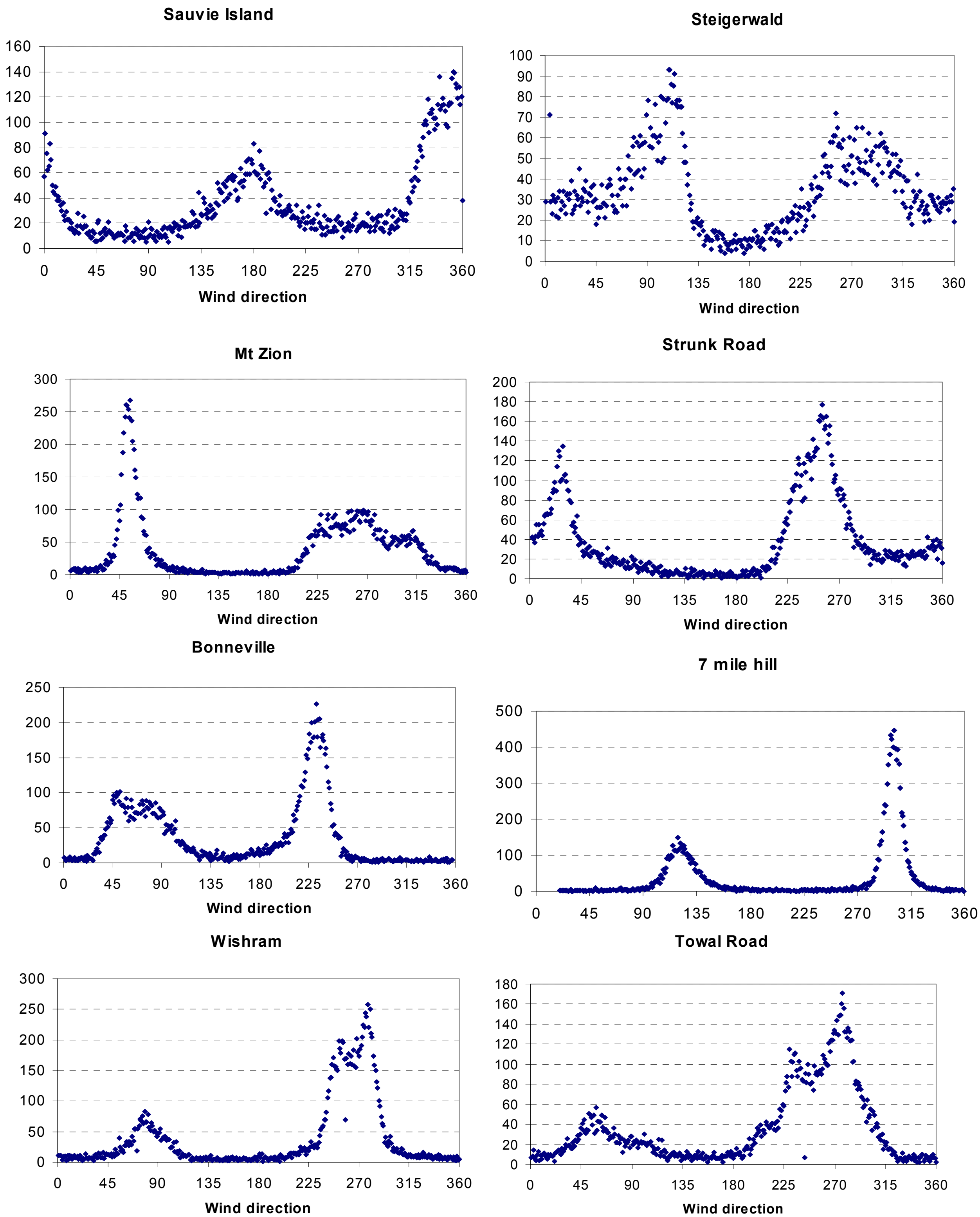
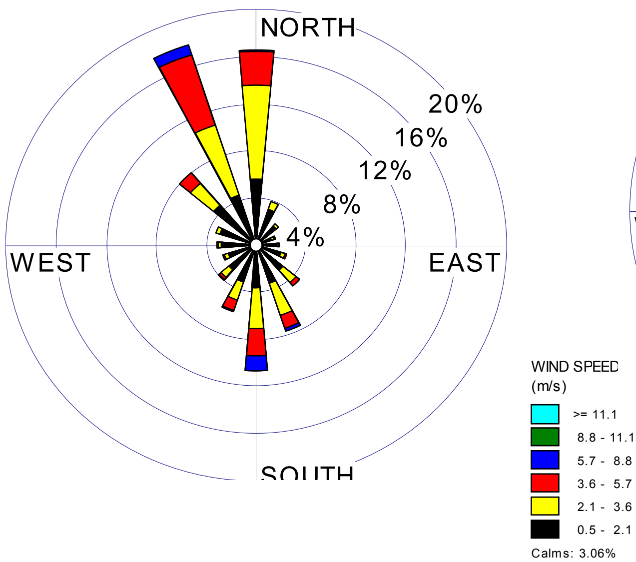
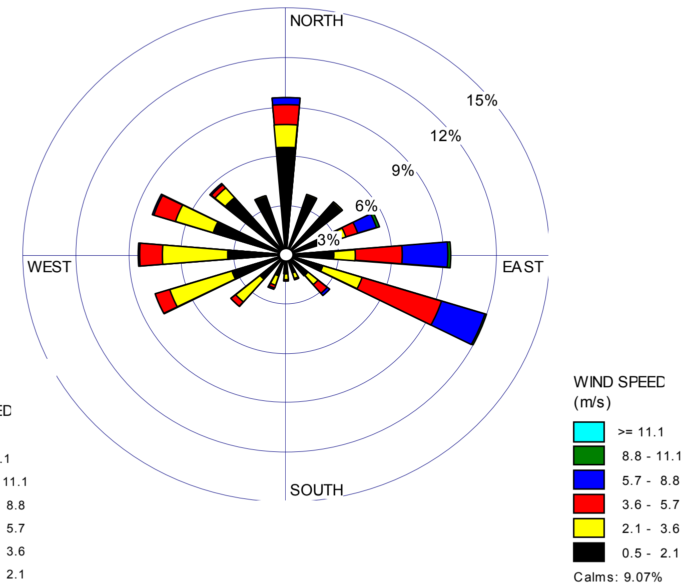


Figure 3-1. Frequency distribution of wind direction by site. X-axis is direction from which wind is blowing (meteorological convention); y-axis is number of hours with wind from each one-degree increment in direction. Period of record is July 1, 2003 to February 28, 2005.

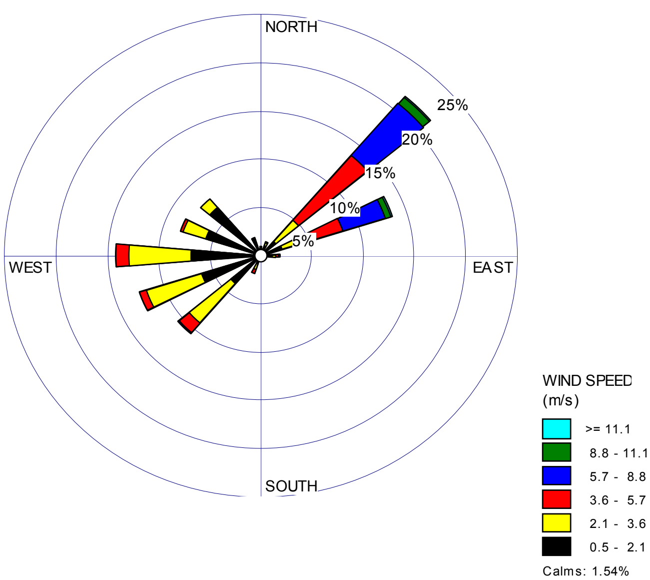
Sauvie Island



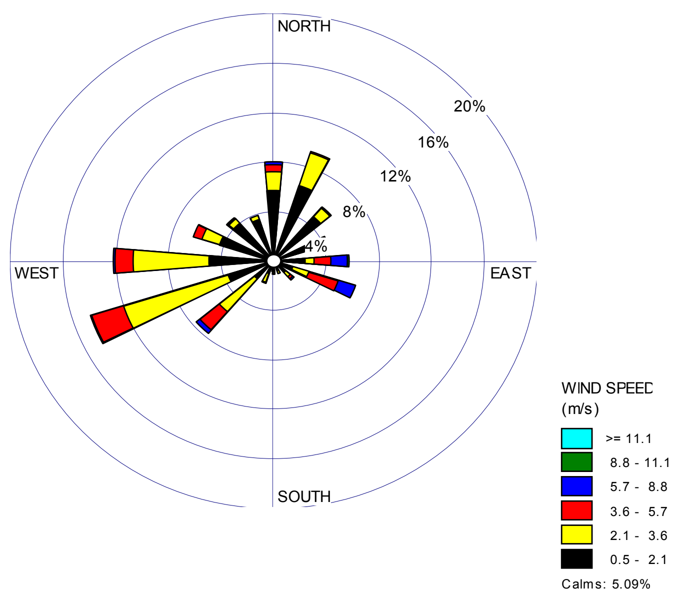
Steigerwald



Mt Zion



Strunk Road



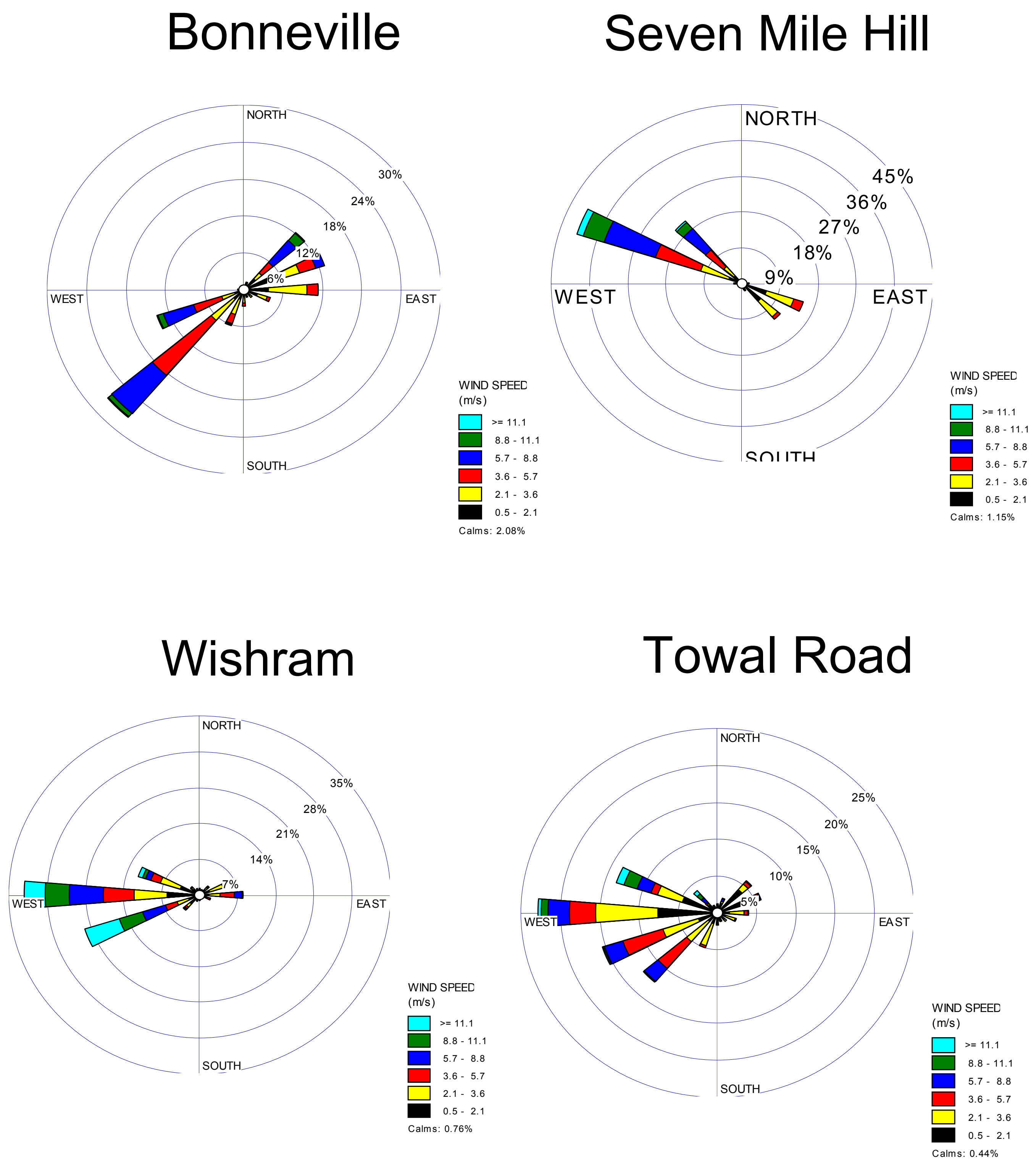


Figure 3-2. Wind roses for duration of the study period (July 2003- February 2005).

Table 3-1. Percentage of hours with wind direction upgorge and downgorge by site.

	% Upgorge	% Downgorge
Sauvie Island	79.1	20.9
Steigerwald	54.2	45.8
Mt Zion	58.1	41.9
Strunk Road	59.5	40.5
Bonneville	55.0	45.0
Sevenmile Hill	66.1	33.9
Wishram	76.3	23.7
Towal Road	75.7	24.3

The input data to the cluster analysis was the hourly upgorge wind component for each site used (Strunk Road, Mt. Zion, and Wishram) for each hour for each day between July 2003 and February 2005. Each column in the input array is for one day and thus has 72 rows (24 hours * 3 sites). For each possible pairs of days for each hour and each site, the absolute value of the difference between the two days is computed. These differences are summed over the 24 hours and 3 sites. The resultant number is a measure of the difference (distance) between the pair of days. For example, this is done for day 1 vs day 2, day 1 vs day 3,…, day 1vs day n, where n=number of days. Then, day 2 vs day 3, day 2 vs day 4, …, day 2 vs day n. This calculation of differences between each pair of days gives a distance matrix. It is this distance matrix that is used to form the clusters of "similar" days. The K-means cluster analysis used here requires the number of desired clusters to be specified. The more clusters that are specified, the less the variation within each cluster is. However, more clusters will also result in less difference between clusters and will be more effort to characterize.

We tried 5 and 7 clusters and interpreted the 5 cluster groups. While not used in the cluster analysis, typical winds for days in each cluster were generated for the five other nephelometer sites with meteorological data and will be presented and discussed. The cluster analysis software computes typical diurnal wind patterns for each cluster for each site. These were plotted and reviewed to understand the wind characteristics of each cluster. Example diurnal patterns are shown in the results section (section 4).

3.2 Computation of pressure field patterns and their diurnal variation by cluster type

To help understand the spatial and diurnal wind patterns associated with each cluster, pressure adjusted to sea-level was gathered and averaged by hour for each site and cluster combination. Hourly pressure data were obtained for the period of July 2003 – February 2005. Data were obtained for sites west and east of the Gorge, within the Gorge and to the north and south.

The following sites were used: Astoria, Portland Hillsboro, Portland International Airport, Troutdale, The Dalles, Pendleton, Pasco, Boise, Seattle, Salem, and Eugene. These sites are shown in Figure 3-2. A summary of the site locations is given below:

- Astoria- Pacific Coast site at mouth of Columbia
- Hillsboro, Portland Intl., Troutdale – River level sites spanning the Portland area (Troutdale near Gorge exit)
- The Dalles – in-Gorge location toward the eastern end of the Gorge
- Pasco and Pendleton – near east end of Gorge, Pasco along Columbia River, Pendleton some distance away.
- Boise, Seattle, Salem, and Eugene – sites north, south, and east of the Gorge.

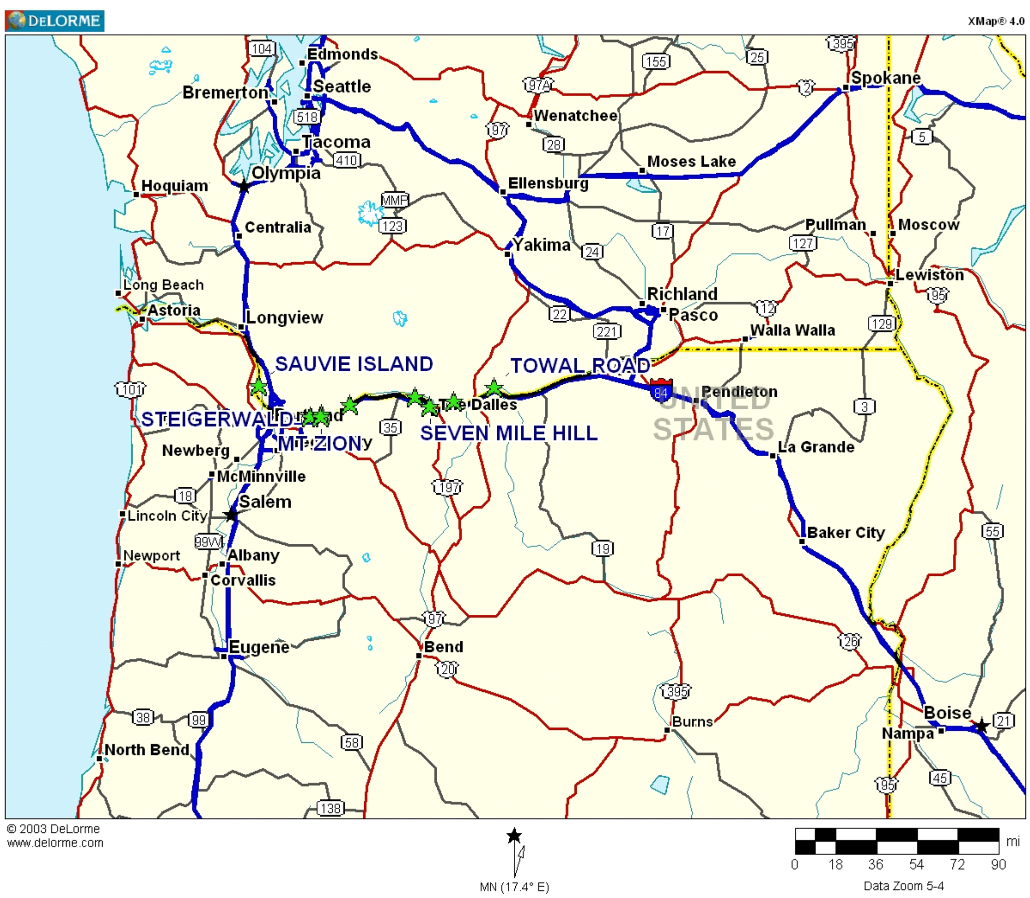


Figure 3-2. Location of monitoring sites for sea-level pressure.

Because of the tendency of flow from high to low pressure through the Gorge, we are mainly interested in along river pressure gradients. The pressure field patterns were used to help interpret the clusters based upon wind data.

3.3 Relationship of clusters to particle light scattering coefficient (bsp) and aethalometer derived elemental carbon concentration

For each cluster the nephelometer data were used to compute hourly average particle light scattering (bsp) coefficients for each nephelometer site. These diurnal patterns by site and cluster were then interpreted in light of the wind and pressure patterns for each cluster. This interpretation provided insight into the roles of source regions in affecting light scattering. We stratified the days in each cluster as to whether there was precipitation in the area or not, using data from the Portland International Airport (PDX) and The Dalles. Days with no precipitation were defined as those days with 0.01 inches of precipitation or less at both stations. We computed cluster average bsp at each nephelometer site for 1) all days; 2) days without precipitation; 3) days with >0.01" at PDX and 4) days with >0.01" at The Dalles. Note that some days would have precipitation at both PDX and the Dalles. Cluster average patterns for all days and each precipitation category are shown in Section 4 (Results) along with example diurnal patterns for some site/cluster combinations.

4 Results

4.1 Meteorological Characteristics of each cluster

The percentage frequency of occurrence of each cluster by month is shown graphically in Figure 4-1 and Tabularly in Table 4-1. A summary of cluster wind patterns and seasonality is given at the end of this section.

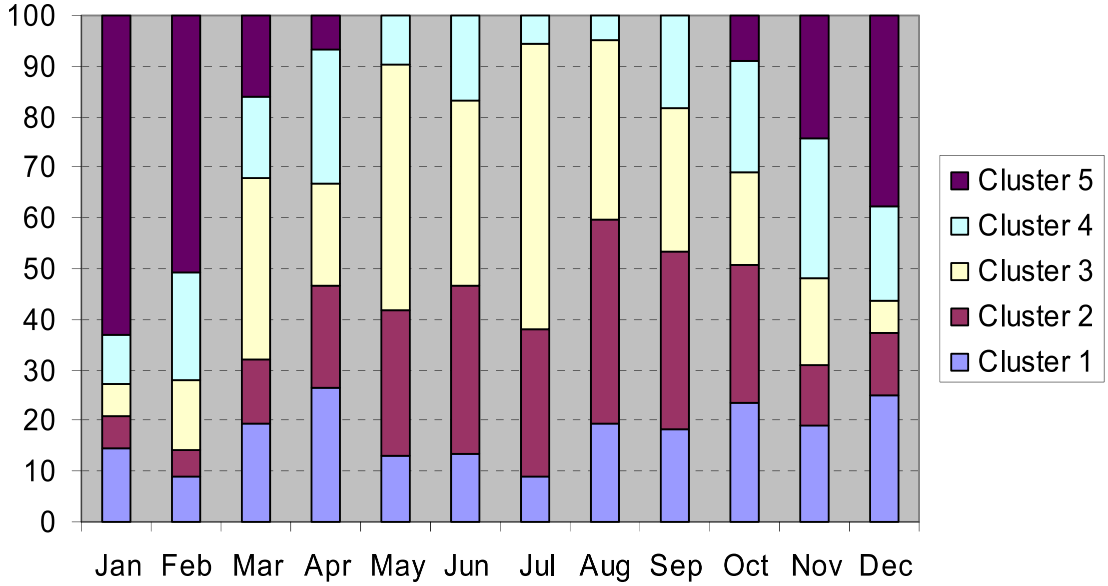


Figure 4-1. Percentage of days in each month assigned to each cluster type.

Table 4-1. Percentage of days in each month assigned to each cluster type.

Cluster	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	15	9	19	27	13	13	9	19	18	24	19	25
2	6	5	13	20	29	33	29	40	35	27	12	13
3	6	14	35	20	48	37	56	35	28	18	17	6
4	10	21	16	27	10	17	5	5	18	22	28	19
5	63	51	16	7	0	0	0	0	0	9	24	38

All months except March through June had data from two years. March-June had data from only one year (2004). Cluster 1 occurs throughout the year, with a peak in the transition months April and October. Cluster 2 peaks in the late summer to early fall (August-October). Cluster 3 occurs mainly in summer, peaking in frequency in July. Cluster 4 is another transition cluster, peaking in April and November. Cluster 5 is a winter-time cluster and never occurred from May – September.

For sites not used in the cluster analysis, we computed average winds for each hour for the days within each cluster. We used days assigned to each cluster that were close to the cluster center to calculate hourly mean upgorge (upriver) wind components. The daily average upgorge (upriver) wind component by site for each cluster is shown in Figure 4-2.

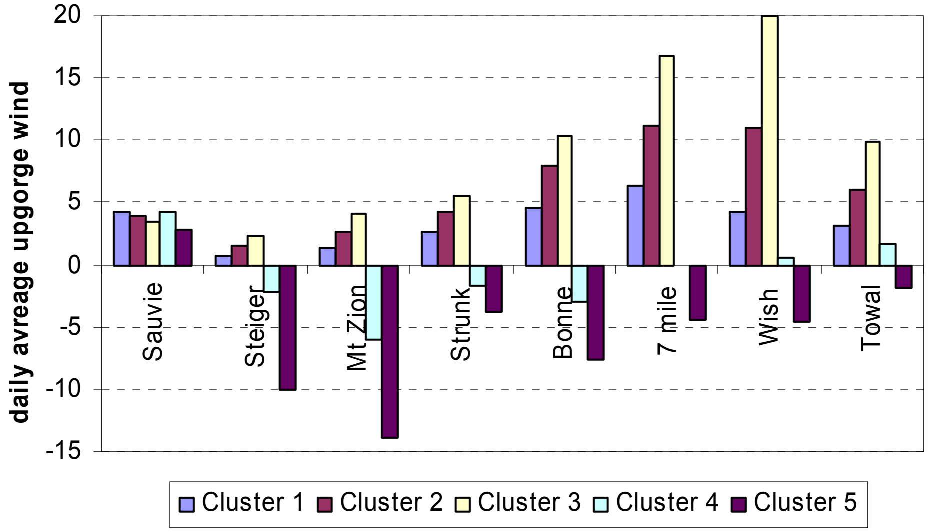
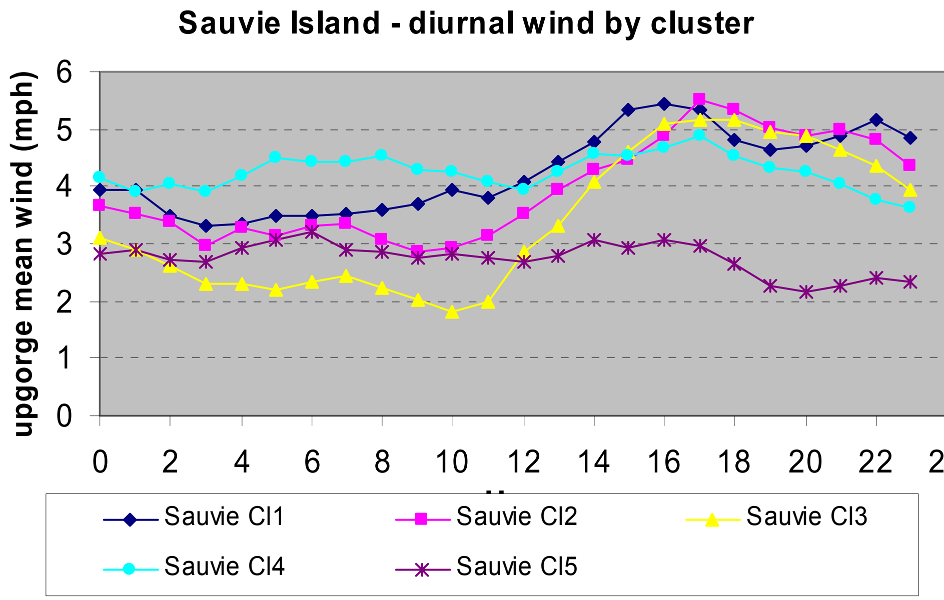
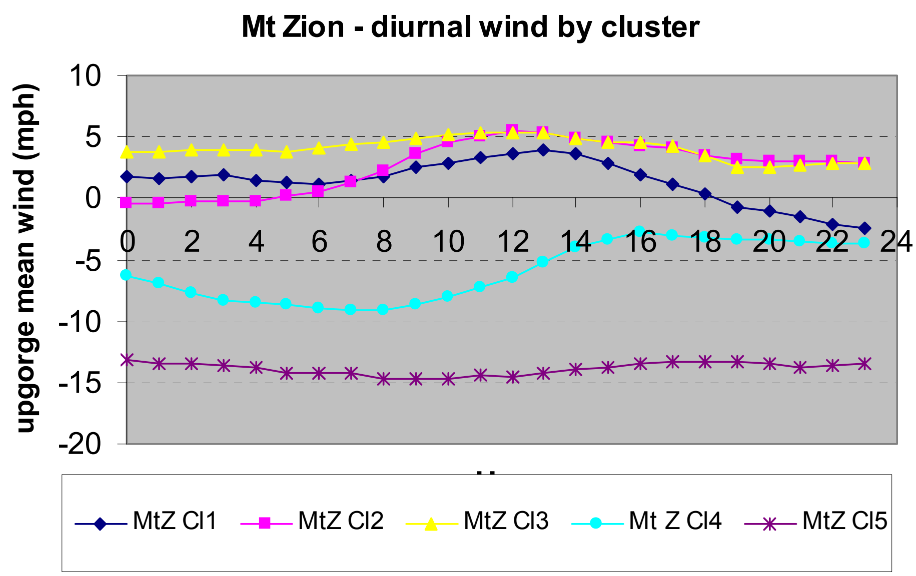


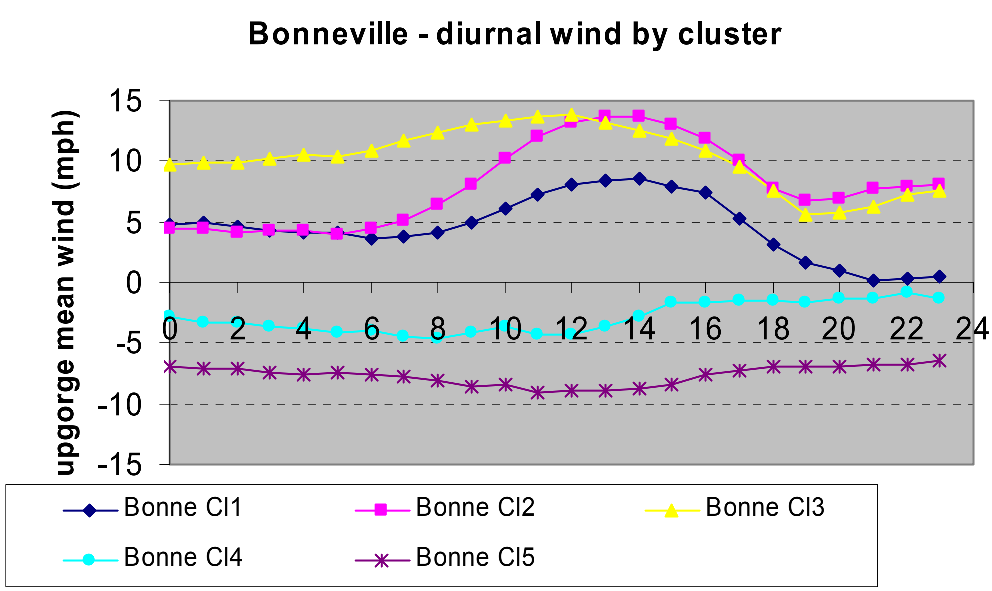
Figure 4-2. Daily average upgorge wind speed by cluster for each monitoring site.

Clusters 1-3 all have net (daily average) upgorge flow at all sites, increasing in strength by cluster number and with distance into the Gorge. Cluster 4 has either downgorge or weak upgorge net flow at all sites. Cluster 5 has downgorge flow at all sites, increasing in speed from east to west, except at Sauvie Island, which is outside of the Gorge and has light northerly flow.

The basic wind patterns, including their relative diurnal variations were similar for the following groups of sites: west- Strunk Road, Mt. Zion, and Steigerwald; east- Wishram, Towal Road, Sevenmile Hill. Sauvie Island and Bonneville were unique in their patterns. Figure 4-3 shows the diurnal wind variation for one representative site for the west end (Mt. Zion), one for the east end (Wishram), and for Sauvie Island and Bonneville Dam. Sauvie Island can be affected by Willamette Valley flows as well as flows channeled along the Columbia River; thus the concept of upgorge or downgorge is less meaningful for Sauvie Island as for other sites.


Sauvie Island - diurnal wind by cluster
upgorge mean wind (mph)
0
1
2
3
4
5
6
0 2 4 6 8 10 12 14 16 18 20 22 24
Sauvie Cl1
Sauvie Cl2
Sauvie Cl3
Sauvie Cl4
Sauvie Cl5


Mt Zion - diurnal wind by cluster
upgorge mean wind (mph)
10
5
0
-5
-10
-15
-20
0 2 4 6 8 10 12 14 16 18 20 22 24
MtZ Cl1
MtZ Cl2
MtZ Cl3
Mt Z Cl4
MtZ Cl5


Bonneville - diurnal wind by cluster
upgorge mean wind (mph)
15
10
5
0
-5
-10
-15
0 2 4 6 8 10 12 14 16 18 20 22 24
Bonne Cl1
Bonne Cl2
Bonne Cl3
Bonne Cl4
Bonne Cl5

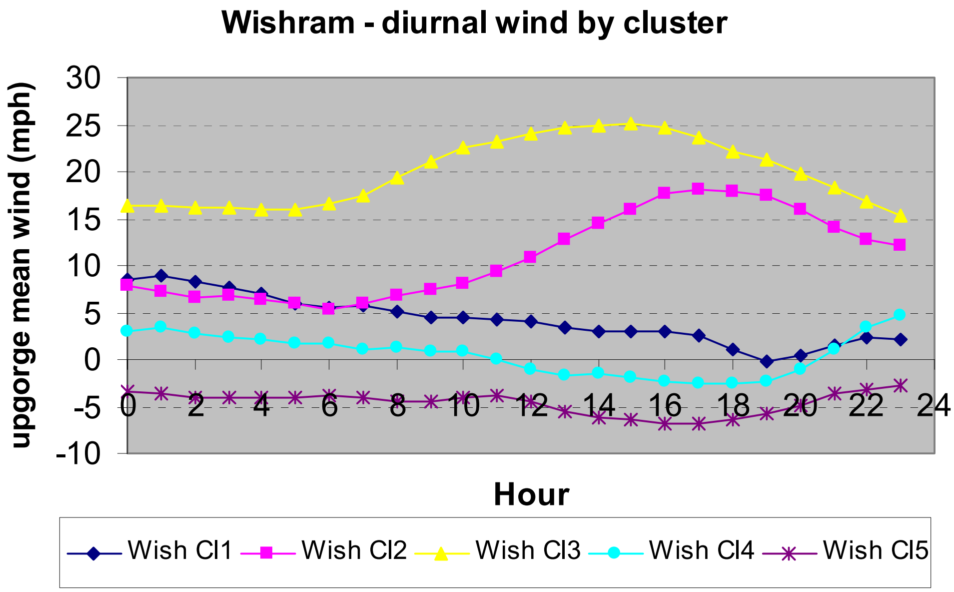


Figure 4-3. Diurnal variation in mean upgorge wind component by cluster at selected sites: a) Sauvie Island; b) Mt. Zion; c) Bonneville; d) Wishram.

A summary of the precipitation associated with each cluster is shown in Table 4-2.

Table 4-2. Fraction of days with no precipitation, precipitation at PDX and The Dalles, PDX only, and The Dalles only by Cluster number. If a day has greater than 0.01 inches of precipition, it is classified as having precipitation.

Cluster	Fraction no precip	Fraction with precip	Fraction both precip	Fraction PDX only precip	Fraction Dalles only precip
1	0.56	0.44	0.20	0.21	0.03
2	0.66	0.34	0.18	0.16	0.00
3	0.62	0.38	0.12	0.25	0.01
4	0.71	0.29	0.12	0.12	0.04
5	0.63	0.37	0.25	0.07	0.05
All days	0.61	0.39	0.18	0.18	0.03

Overall 61% of the days had 0.01" of precipitation or less at Both Portland International Airport and The Dalles. Of the 39% of days with precipitation >0.01" at one or both sites, about one-half had precipitation at both sites, about one-half has precipitation at Portland only, and a small number of days had precipitation at The Dalles only. Cluster 2 had no days with precipitation at The Dalles but not at PDX. Cluster 5 was about equally likely to have precipitation only at The Dalles as only at PDX.

4.1.1 Cluster 1

Figure 4-4 shows the daily average upgorge wind speed by site. Cluster 1 showed weak up-gorge flow that decreased in evening at most sites to near zero on average (At Sevenmile Hill and Sauvie Island upgorge flow increased in the evening. Sauvie Island is outside of the Gorge, so upgorge should be interpreted as upriver, downgorge - downriver). This pattern occurred most frequently in April and then again in late Autumn to early winter. The cluster 1 pressure pattern is shown in Figure 4-5.

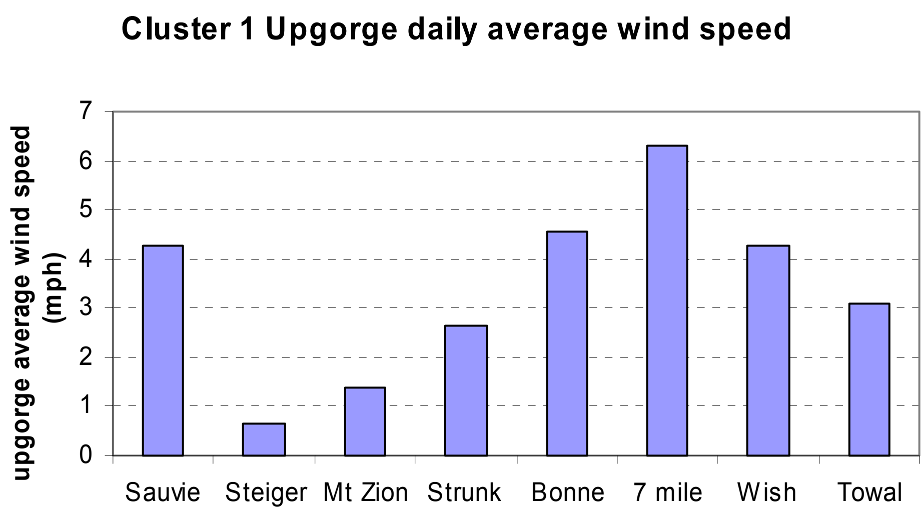


Figure 4-4. Cluster 1 average upgorge wind speed by site.

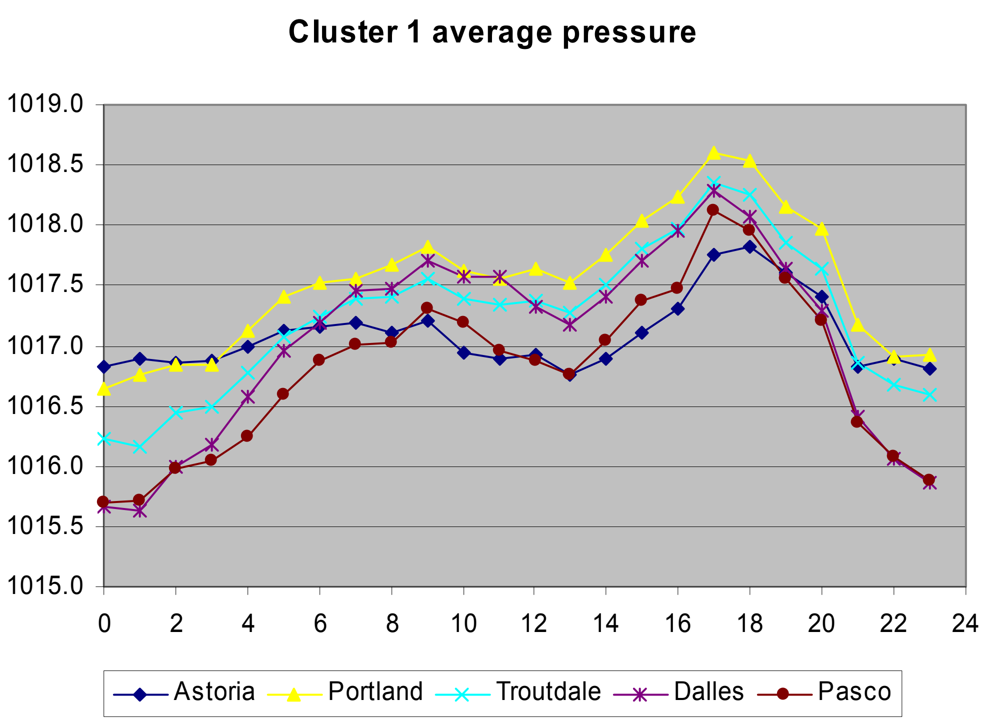


Figure 4-5. Average pressure (mb) by time of day at selected sites for Cluster 1.

The pressure gradient across the Gorge (from Troutdale to The Dalles is small and changes direction during the day. Upgorge winds at Sevenmile Hill are compared to the Troutdale – The Dalles pressure gradient in Figure 4-6. Upgorge wind and pressure gradient decreases during morning and then increases in the second half of the day.

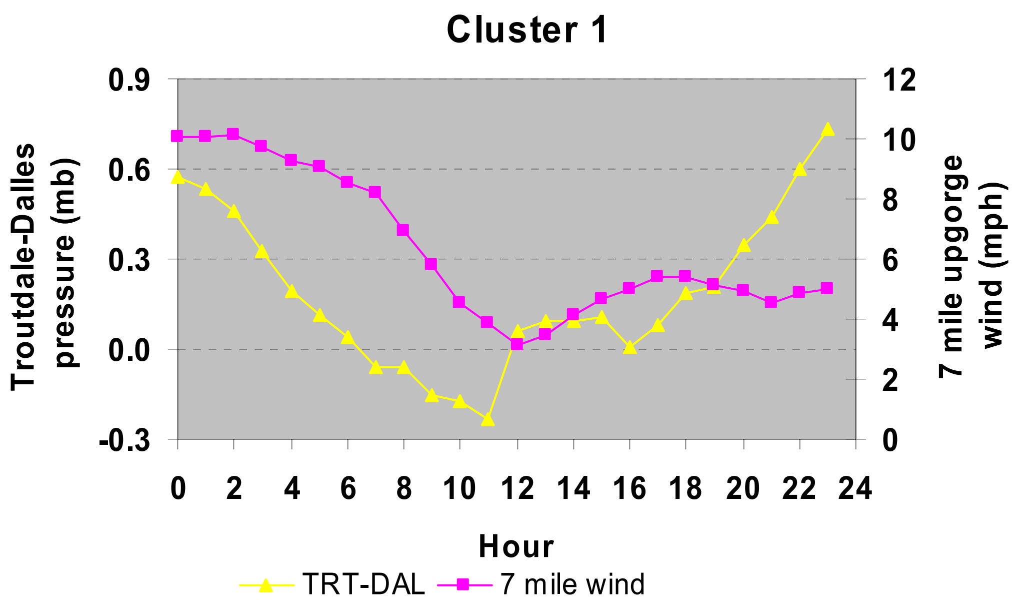


Figure 4-6. Relationship between Sevenmile Hill winds and Astoria – Pasco and Troutdale- The Dalles pressure gradients for cluster 1.

4.1.2 Cluster 2

Cluster 2 is the most frequent cluster for the months August-October and has a peak frequency (40%) in August. Figure 4-7 shows the average upgorge wind speed by site. Like Clusters 1 and 3, it is consistently up-gorge, but has a more pronounced diurnal cycle in speed than do Clusters 1 and 3. Cluster 2 diurnal variations in winds are shown in Figures 4-8 and 4-9. Cluster 2 speed increases from about 6 am to noon at the western sites and a steady increase from about 6 am to 4-5 pm at Wishram. At Mt. Zion from about midnight to 6 am the up-gorge wind component is near zero. This pattern is something of a modification of the Cluster 3 summer pattern and with lighter wind speeds implies weaker pressure gradients and a substantial diurnal variation of these gradients. The pressure patterns associated with cluster 2 is shown in Figure 4-10. The along river pressure gradient is greatest in the morning and evening and a minimum about 5 pm. Winds accelerating in response to this pressure gradient peak early in the western Gorge The wind peak in the eastern Gorge occurs later and with greater magnitude as the acceleration in response to the imposed gradient takes longer to be fully realized.

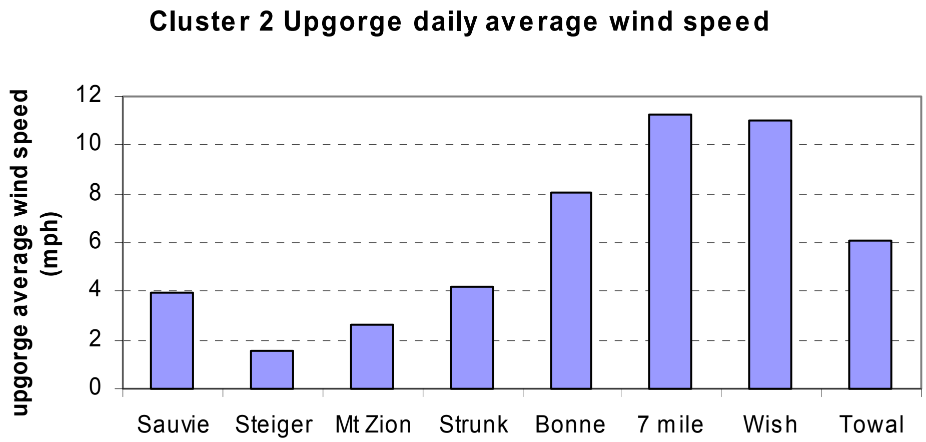


Figure 4-7. Cluster 2 average upgorge wind speed by site.

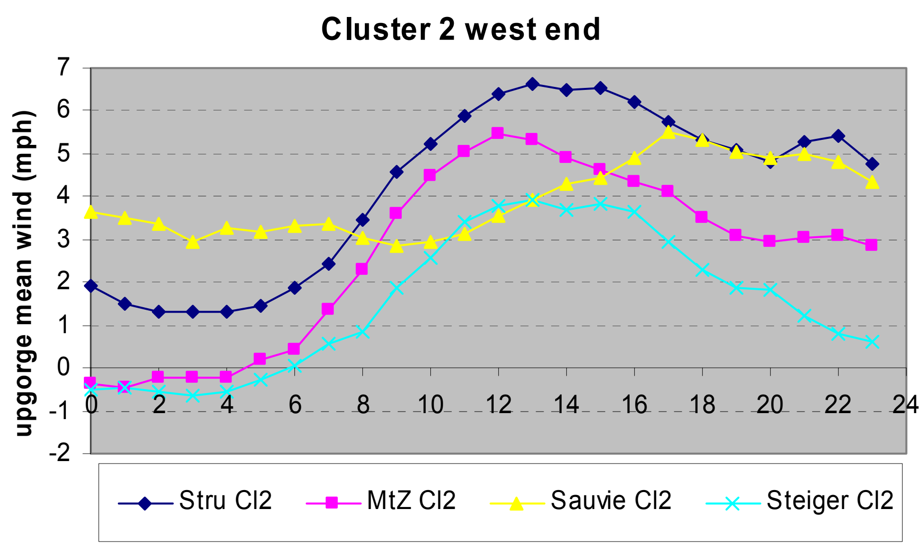


Figure 4-8. Cluster 2 diurnal patterns in upgorge wind for western sites.

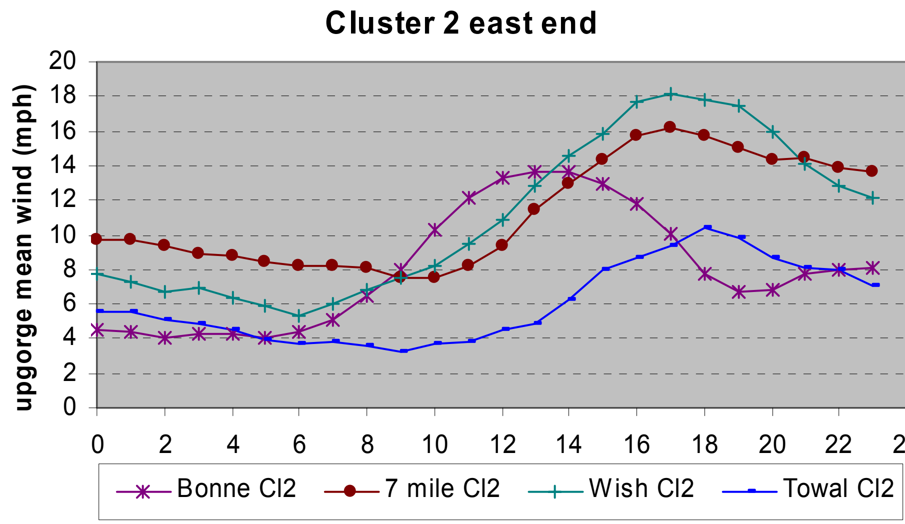


Figure 4-9. Cluster 2 diurnal patterns in upgorge wind for eastern sites.

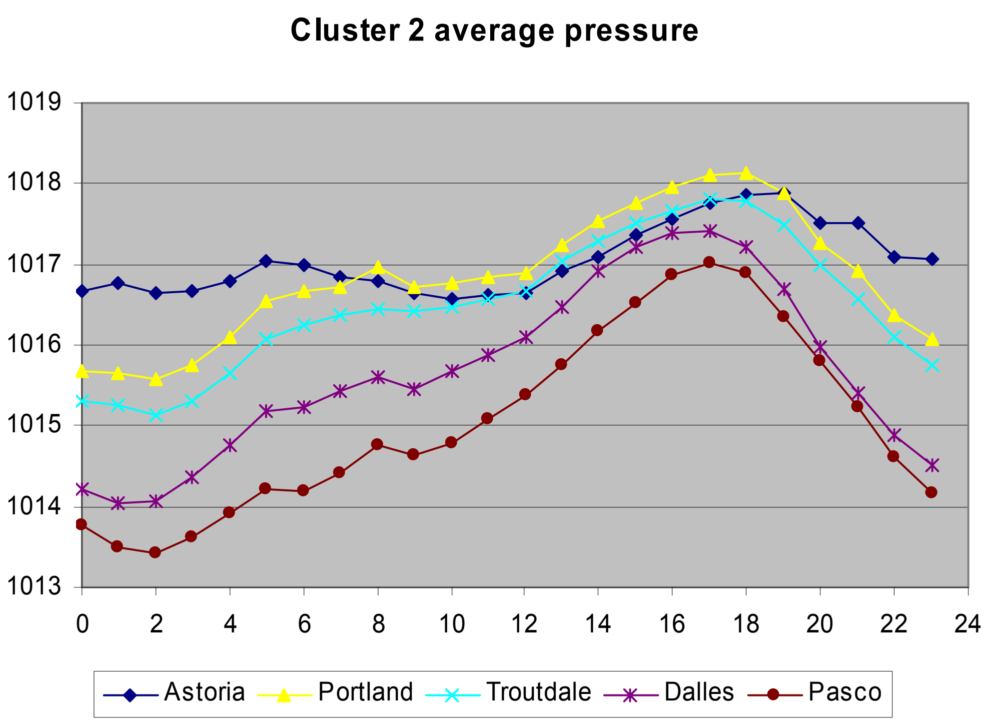


Figure 4-10. Cluster 2 diurnal patterns in average sea-level pressure for selected sites.

4.1.3 Cluster 3

Figure 4-11 shows the cluster 3 average upgorge wind speed by site. Cluster 3 was associated with persistent upgorge flow, increasing in speed toward the east end of the gorge and peaks in frequency in July. Clusters 3 and 5 appear to represent classical Gorge summer and winter patterns. Cluster 3 shows persistent up-gorge flow, increasing in speed toward the east end of the Gorge (strongest at Sevenmile Hill and Wishram), as the consistent pressure gradient continues to accelerate air moving through the Gorge. Cluster 5 shows persistent down-gorge flow, increasing in speed from Wishram to Mt. Zion. Both of these flows are expected to result from an acceleration along the Gorge due to a pressure gradient across the Gorge, as described in Sharp and Mass (2005) and elsewhere. In summer, pressure is higher to the west of the Gorge due to the northward migration of the Pacific High and lower to the east of the Gorge due to a thermal low resulting from intense heating. Hourly averaged pressure for Cluster 3 days for selected stations is shown in Figure 4-12.

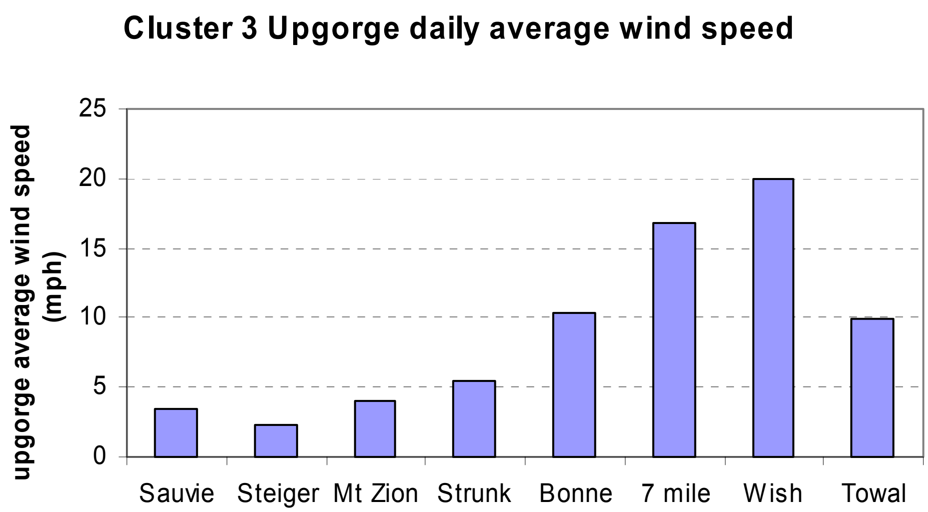


Figure 4-11. Cluster 3 average upgorge wind speed by site.

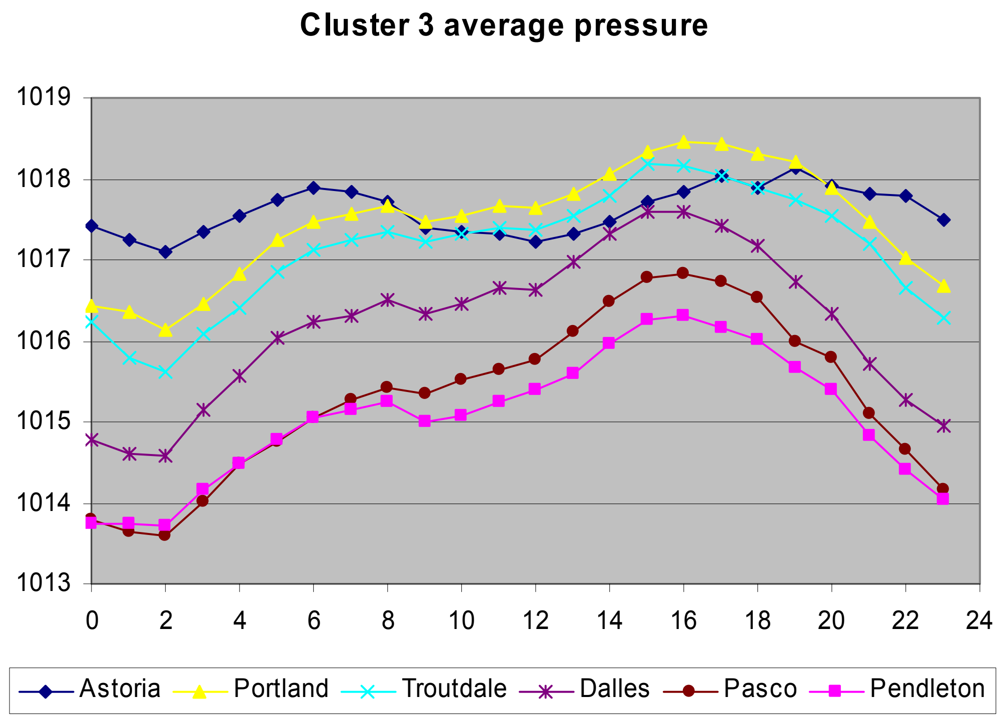


Figure 4-12. Cluster 3 diurnal patterns in average sea-level pressure for selected sites.

4.1.4 Cluster 4

Figure 4-13 shows the average upgorge wind speed by site. Cluster 4 occurred most frequently during transition periods February to April and again from October to November. Cluster 4 had downgorge flow at Mt. Zion and Bonneville, weak downgorge flow at Strunk Road and Steigerwald, and diurnally fluctuating (down in afternoon, up all other hours) flow at the 3 easternmost sites, Sevenmile Hill, Wishram, and Towal Road. Sauvie Island had upriver flow (from the north) all day. Averaged pressure data for Cluster 4 days is shown in Figure 4-14. The pressure gradient though the Gorge (From Troutdale to The Dalles decreases and changes sign during Cluster 4 days. Figure 4-15 compares the diurnal variation in Cluster 4 Sevenmile Hill winds and the Troutdale-The Dalles pressure difference.

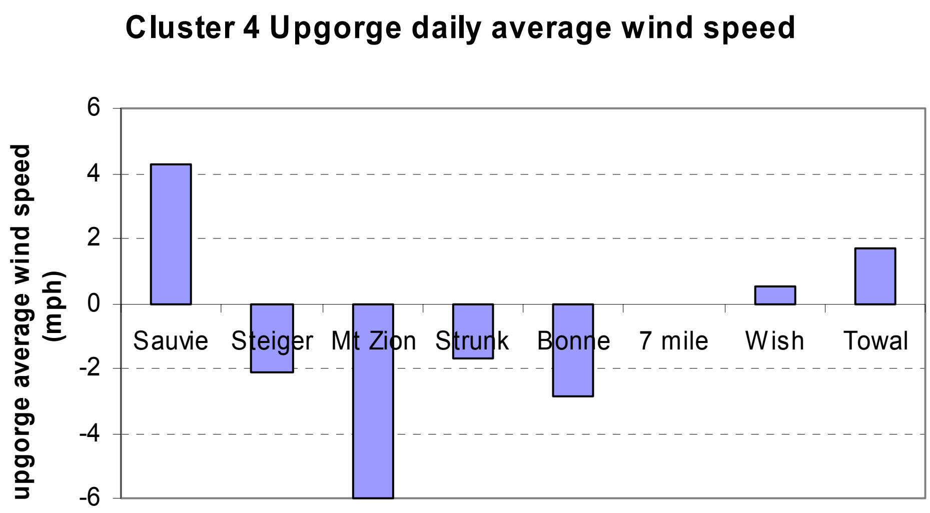


Figure 4-13. Cluster 4 average upgorge wind speed by site.

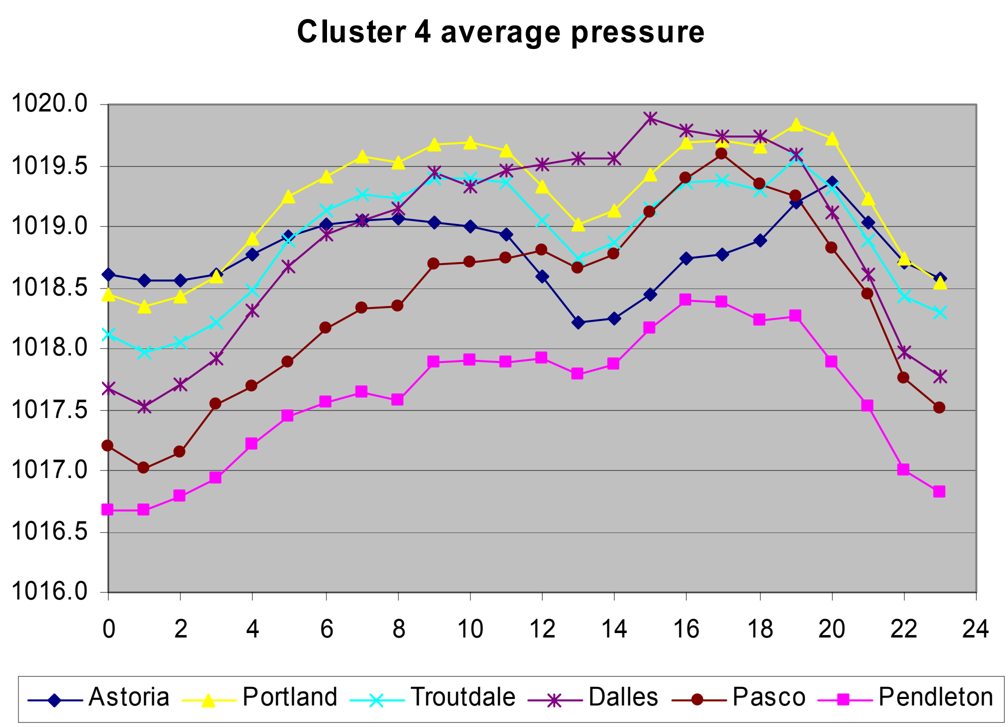


Figure 4-14. Cluster 4 diurnal patterns in average sea-level pressure for selected sites.

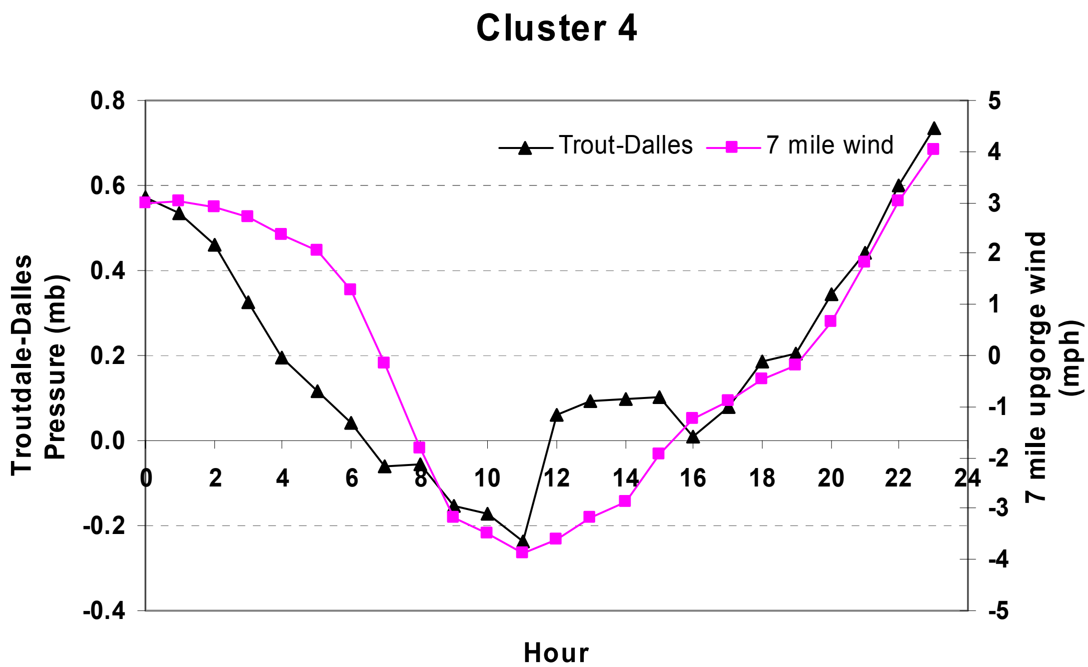


Figure 4-15. Relationship between Sevenmile Hill winds and Troutdale – The Dalles pressure gradients for cluster 4.

4.1.5 Cluster 5

Figure 4-16 shows the average upgorge wind speed by site. Hourly averaged pressure for Cluster 5 days for selected stations is shown in Figure 4-17. For cluster 5, there is:

1) essentially equal pressure all day at Pasco and The Dalles
2) a lower, but nearly equal pressure at Hilsboro, Portland Intl., and Troutdale
3) lower pressure at Astoria

Thus, the main pressure gradient through the Gorge is entirely between the Dalles and Troutdale. These 3 noted items above can explain:

1) light winds at Towal Road
2) strong down gorge winds at Bonneville, Mt. Zion, and Steigerwald
3) light winds at Sauvie Island

In winter the gradient is often reversed from summer with higher pressure east of the Gorge due to a cold, synoptic scale high pressure area and lower to the west of the Gorge, often due to Pacific lows. The less strong down-gorge winds for cluster 5 at Strunk Road compared to the nearby Mt. Zion probably are due to the Strunk Road site being farther from the center of the Gorge and thus out of the zone of the strongest winds.

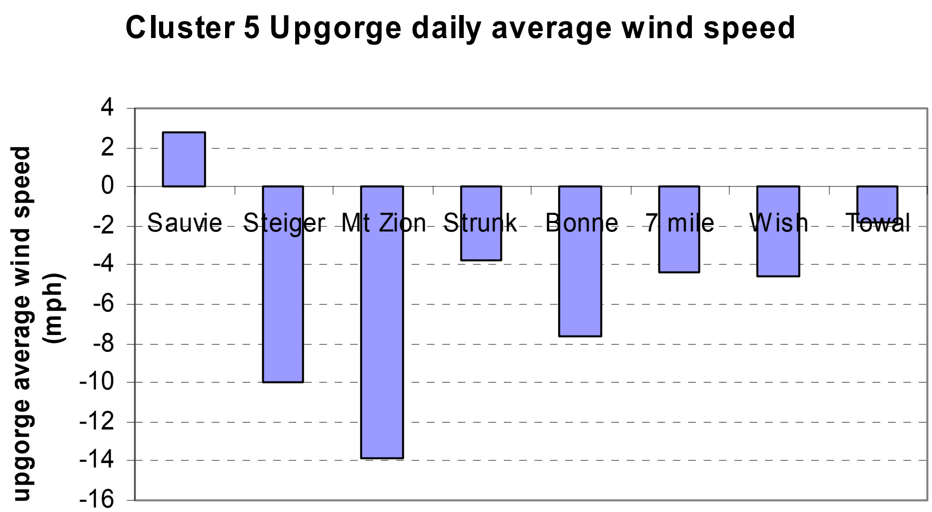


Figure 4-16. Cluster 5 average upgorge wind speed by site.

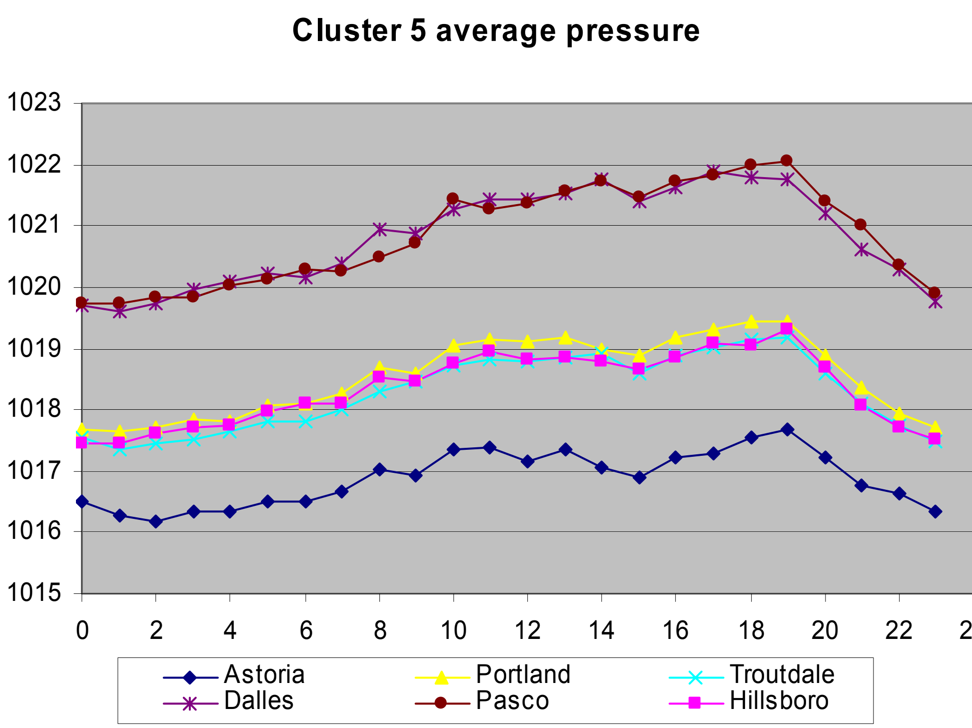


Figure 4-17. Cluster 5 diurnal patterns in average sea-level pressure for selected sites.

Before considering light scattering by cluster in the next section, it is helpful to the reader to summarize the wind patterns and seasonality by cluster; these are given below. Also, added to the cluster number are short descriptors of the cluster that will be used in the next section to refer to the clusters in a way that will be easier for the reader to relate to than the cluster number.

Cluster	Wind Pattern	Seasonality
Light upgorge transition (1)	Light upgorge, increasing with distance into Gorge	Peak in transition months April and October, more common in winter than summer
Moderate upgorge late-summer (2)	Moderate upgorge, increasing with distance into Gorge, large diurnal variation in speed	Late summer- early fall Peak in August, most common cluster August to October
Strong upgorge (3)	Strong upgorge, increasing with distance into Gorge	Peak in July, most common cluster May-July
Light downgorge transition (4)	Light downgorge, except diurnally changing direction at eastern sites, upgorge Sauvie Island	Mainly Autumn and Spring (most common cluster November), uncommon summer
Winter downgorge (5)	Downgorge, light in eastern end, increasing through Gorge, except light northerly at Sauvie Island	Predominantly winter – most common cluster December-February, no occurrences May-September

4.2 Light scattering patterns by cluster

A summary of average light scattering by site and cluster is shown in Figure 4-18 and Table 4-3.

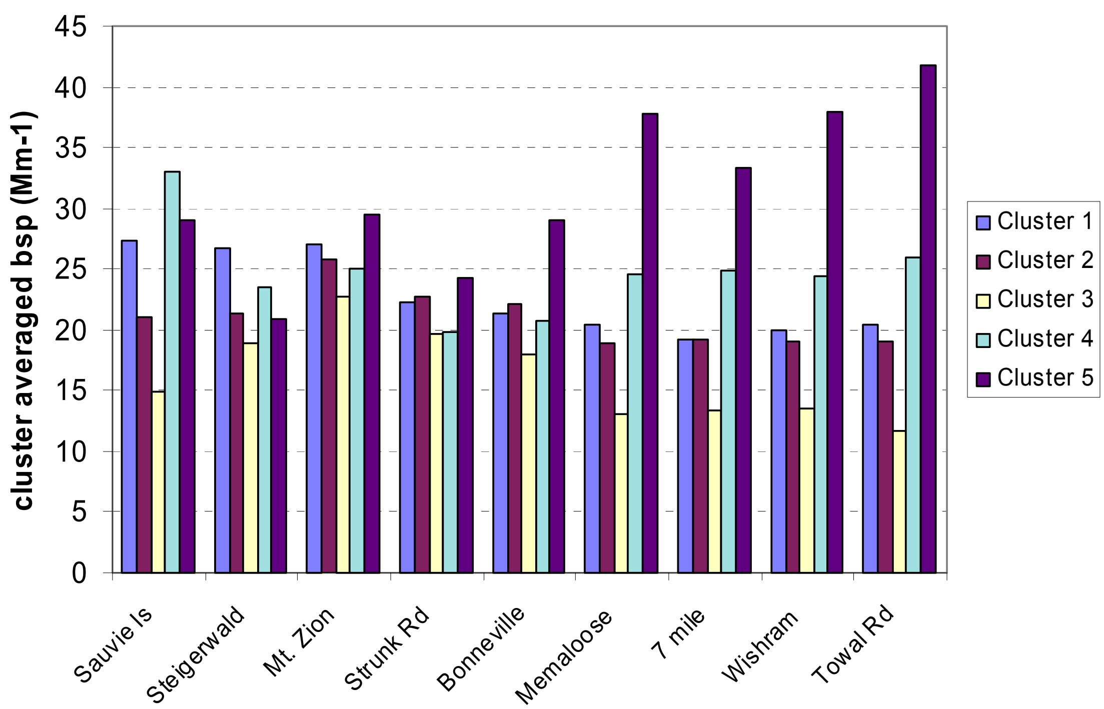


Figure 4-18. Average bsp (Mm^{-1}) at each nephelometer site for each cluster. Average is over all hours for all days within each cluster.

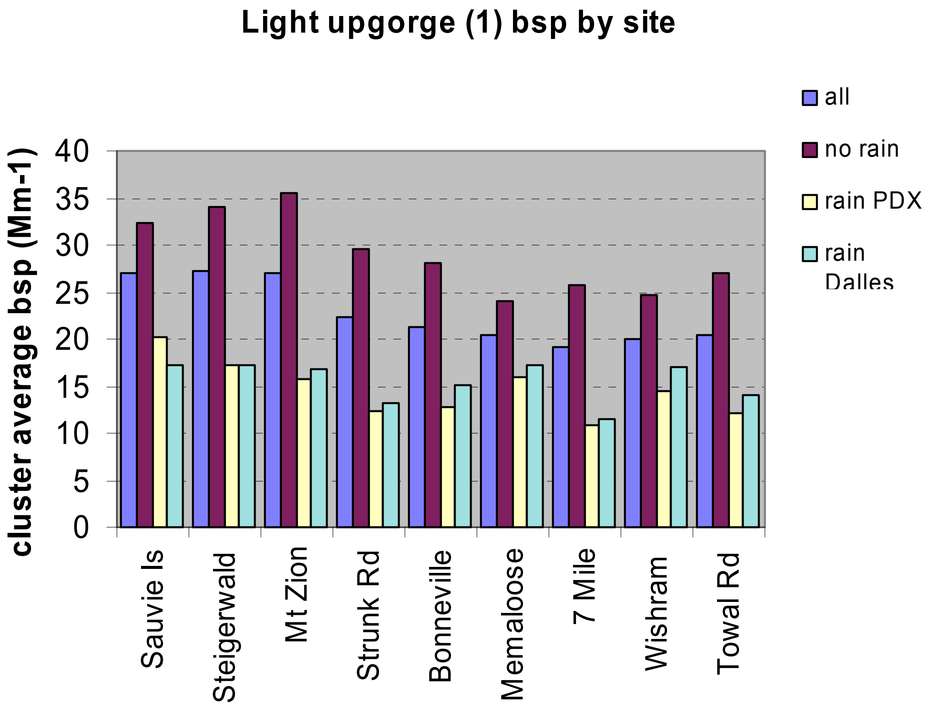
Table 4-3. Average bsp (Mm-1) by cluster by site.

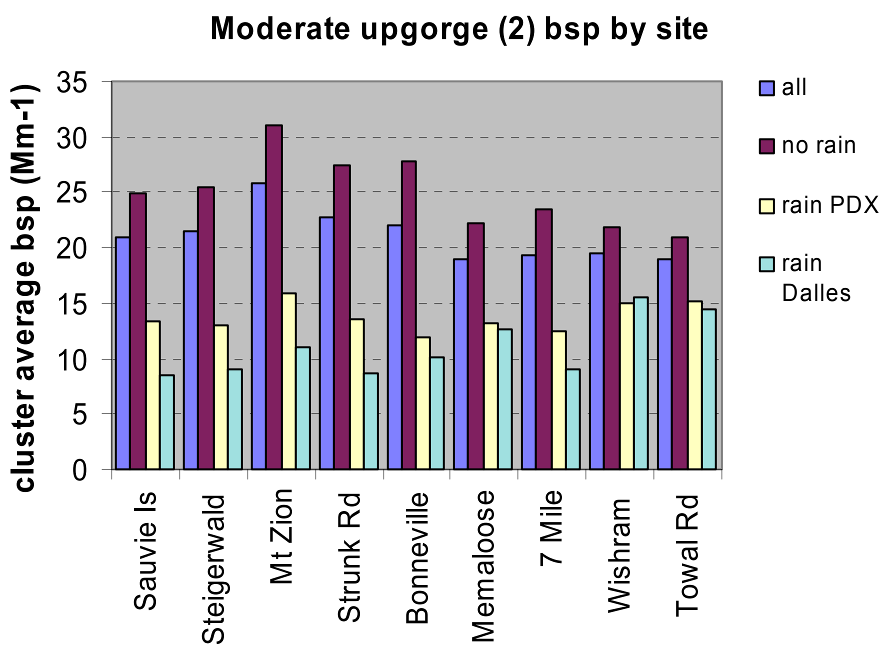
	Light upgorge (1)	Moderate upgorge (2)	Strong upgorge (3)	Light downgorge (4)	Winter downgorge (5)
Sauvie Is	27.4	21.1	14.8	33.0	29.1
Steigerwald	26.8	21.4	18.9	23.4	21.0
Mt Zion	27.0	25.9	22.7	25.1	29.6
Strunk Rd	22.3	22.7	19.7	19.8	24.3
Bonneville	21.3	22.2	18.0	20.7	29.0
Memaloose	20.4	19.0	13.1	24.6	37.7
7 Mile	19.3	19.3	13.3	24.9	33.4
Wishram	20.0	19.1	13.6	24.4	37.9
Towal Rd	20.5	19.0	11.7	26.0	41.7

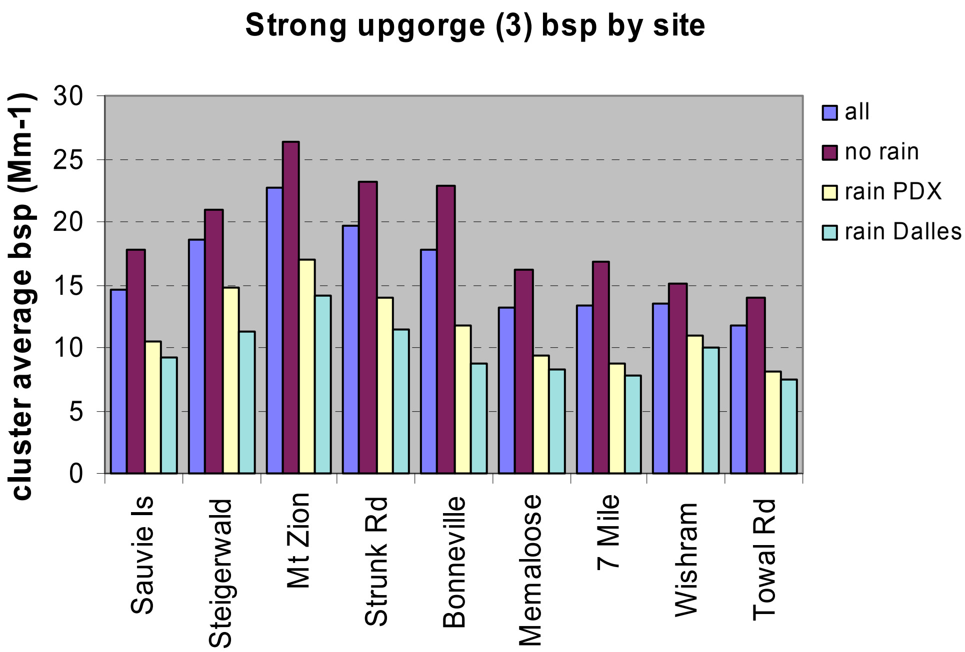
While there is a lot of information to process from Figure 4-18 (or Table 4-3), the following facts may be easily noted:

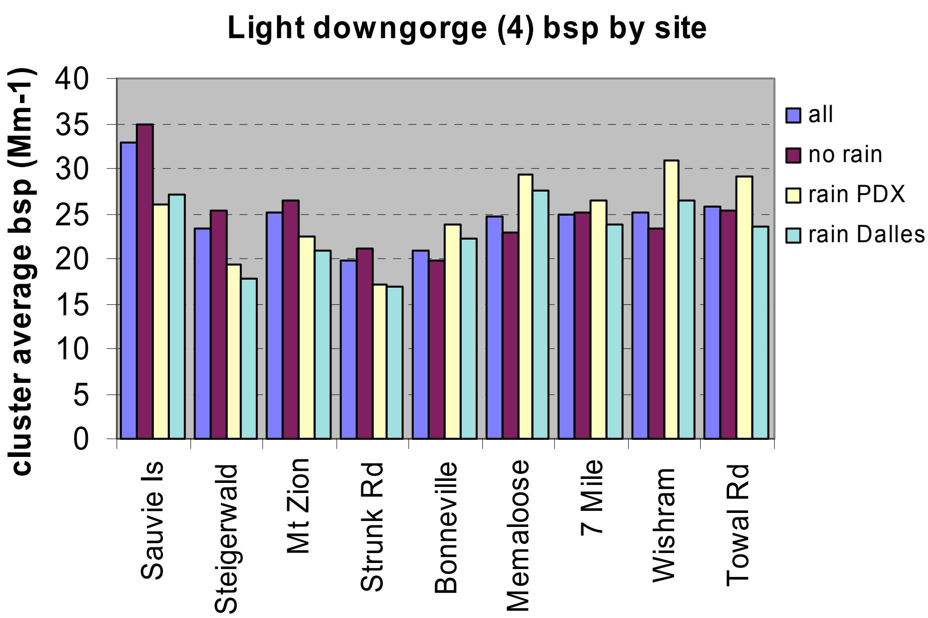
1) For all sites except Sauvie Island and Steigerwald, winter downgorge (cluster 5) has the highest average bsp of all clusters. For all sites, strong upgorge (cluster 3) has the lowest average bsp. Thus, the most typical summer pattern and most typical winter pattern have the lowest and highest bsp, respectfully for nearly all sites
2) The westernmost site (Sauvie Island, west of the Gorge), and the eastern sites (from Memaloose east) have much larger variations in average bsp between clusters than do the other sites (Steigerwald, Mt Zion, Strunk, and Bonneville).

To more easily discern the spatial patterns corresponding to each cluster and to understand effect of precipitation on bsp, we present in Figure 4-19 bar charts of cluster averaged bsp by site (ordered west to east) individually by cluster. For each cluster bsp is averaged over all days, days without precipitation, days with precipitation at Portland International Airport (PDX) , and days with precipitation at The Dalles. (Some clusters also show interesting diurnal patterns for some sites. Diurnal patterns for selected sites for some clusters will be shown later to illustrate these patterns).


Light upgorge (1) bsp by site
cluster average bsp (Mm-1)
40
35
30
25
20
15
10
5
0
Sauvie Is
Steigerwald
Mt Zion
Strunk Rd
Bonneville
Memaloose
7 Mile
Wishram
Towal Rd
all
no rain
rain PDX
rain Dalles


Moderate upgorge (2) bsp by site
cluster average bsp (Mm-1)
35
30
25
20
15
10
5
0
Sauvie Is
Steigerwald
Mt Zion
Strunk Rd
Bonneville
Memaloose
7 Mile
Wishram
Towal Rd
all
no rain
rain PDX
rain Dalles


Strong upgorge (3) bsp by site
cluster average bsp (Mm-1)
30
25
20
15
10
5
0
all
no rain
rain PDX
rain Dalles
Sauvie Is
Steigerwald
Mt Zion
Strunk Rd
Bonneville
Memaloose
7 Mile
Wishram
Towal Rd


Light downgorge (4) bsp by site
cluster average bsp (Mm-1)
40
35
30
25
20
15
10
5
0
all
no rain
rain PDX
rain Dalles
Sauvie Is
Steigerwald
Mt Zion
Strunk Rd
Bonneville
Memaloose
7 Mile
Wishram
Towal Rd

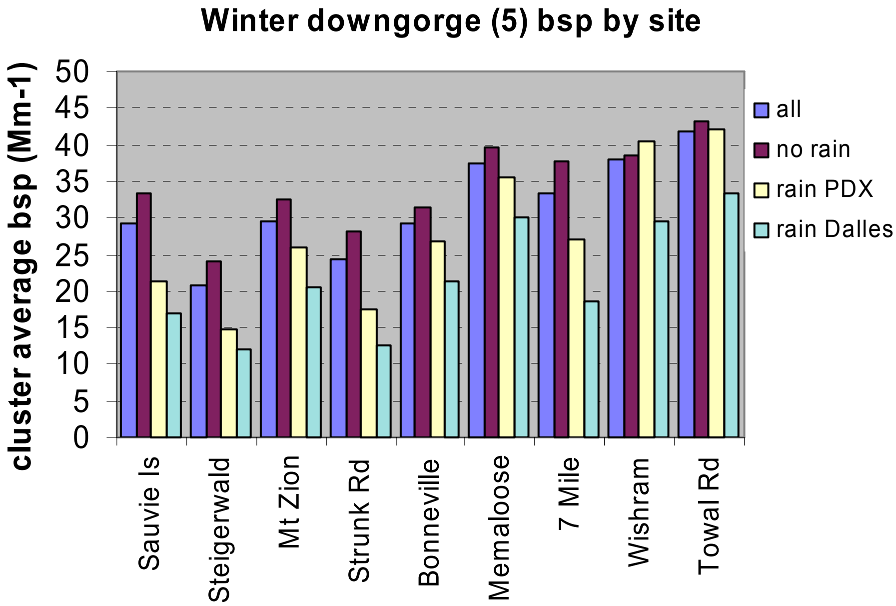


Figure 4-19. Cluster average bsp (Mm-1) for each nephelometer monitoring site. Site order is from west to east.

With some exceptions, days without precipitation have considerably higher bsp than days with precipitation at one or both sites. For light downgorge (4) days with precipitation at PDX had higher average bsp at sites from Bonneville on east than did days with no precipitation. In most cases, days with precipitation at The Dalles have the lowest bsp. As Table 4-2 showed, most days that had precipitation at The Dalles also had precipitation at PDX; this implies widespread precipitation resulting in scavenging of aerosol by precipitation throughout the Gorge.

The remaining discussion refers to all days in each cluster (not stratified by precipitation category). For strong upgorge (3), while it was the cleanest at all sites, there is a large gradient in bsp with the sites from Memaloose east being much lower than sites west of Memaloose. Average bsp at Towal Road was half that at Mt. Zion. Low bsp at the eastern sites is likely a result of two effects: 1) deeper mixing layers due to greater heating; and 2) dispersion due to stronger winds from acceleration caused by the along-gorge pressure gradient. Note that the highest bsp is at Mt. Zion and for the western sites, lowest bsp is at Sauvie Island. Flow is consistently upriver for strong upgorge (3) and Sauvie Island would therefore be upwind of the Portland/Vancouver urban area, possibly accounting for its lower values relative to other western sites. For all clusters except weak upgorge (1), Mt. Zion average bsp is higher than that of neighboring sites Strunk Road and Steigerwald. Furthur investigation is needed to determine if there is a physically explainable reason for this, such as localized mixing conditions or measurement bias in the nephelometer data. In any case, for strong upgorge (3), it is reasonable to expect that the Portland/Vancouver urban area may be the reason for the higher bsp levels in the western Gorge compared to the eastern Gorge and Sauvie Island sites.

For winter downgorge (5), highest bsp is at the eastern sites, with lower values in the western Gorge and an increase at Sauvie Island, downwind of the urban area. High bsp levels at the eastern sites are associated with consistent light down gorge flow, except at Towal Road which alternates between light upgorge and light downgorge flow. This common winter pattern allows for buildup of aerosols in the eastern Gorge area that then gets transported down through the Gorge. There is a decrease in bsp from Wishram to Sevenmile Hill, then an increase from Sevenmile Hill to Memaloose. Memaloose bsp is much higher than Sevenmile Hill in mid-morning (Figure 4-20) when the 7 mile site is likely above the mixed layer depth. However, Memaloose, essentially at River level is within the layer carrying high concentrations of aerosols downgorge. From about 1 pm on, Memaloose and Sevenmile Hill bsp is very similar in magnitude as aerosols are mixed upward.

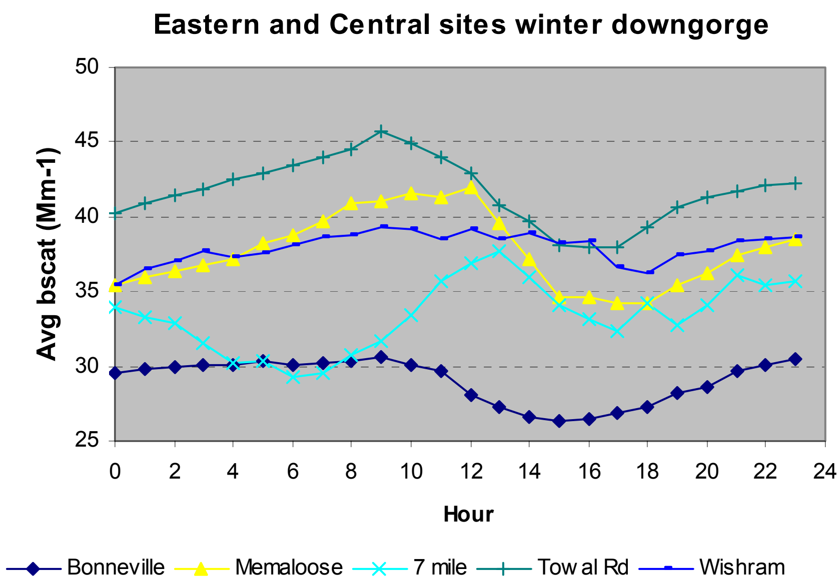


Figure 4-20. Diurnal patterns of bsp for Cluster 5 eastern and central sites.

Again Mt Zion had higher average bsp than Strunk Road; a possible explanation is that the Strunk Road site, being further from the Columbia River is not within the strong downgorge flow and may thus be less affected by transport of haze causing particles down the Gorge. The winds are much lighter at Strunk Road compared to Mt. Zion for winter downgorge (5). (Figure 4-16). Bsp for river level sites is shown in Figure 4-21.

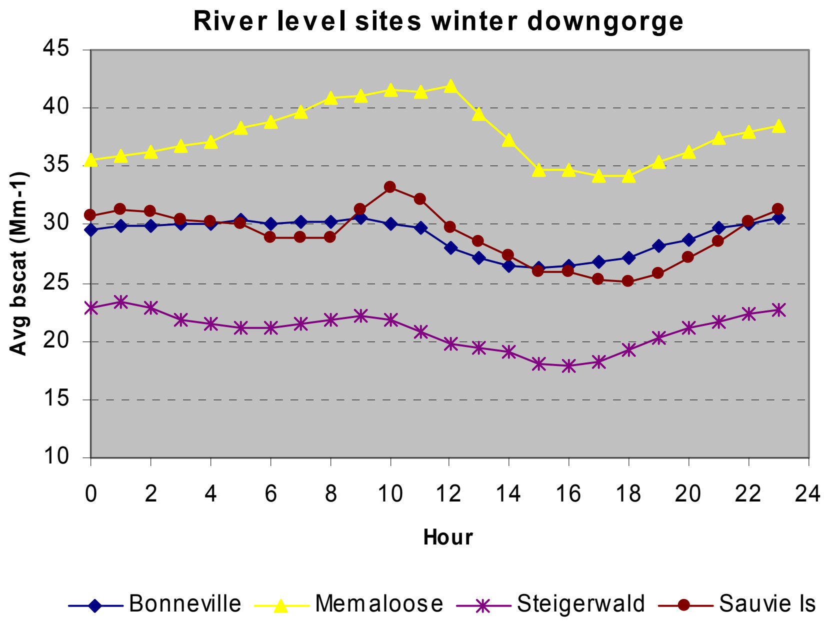


Figure 4-21. Diurnal patterns of bsp for winter downgorge (5), river level sites.

Diurnal bsp patterns for the western sites for moderate upgorge (2) are shown in Figure 4-22. Moderate upgorge is a typically late summer to autumn flow pattern with strong diurnal variation in wind speed.

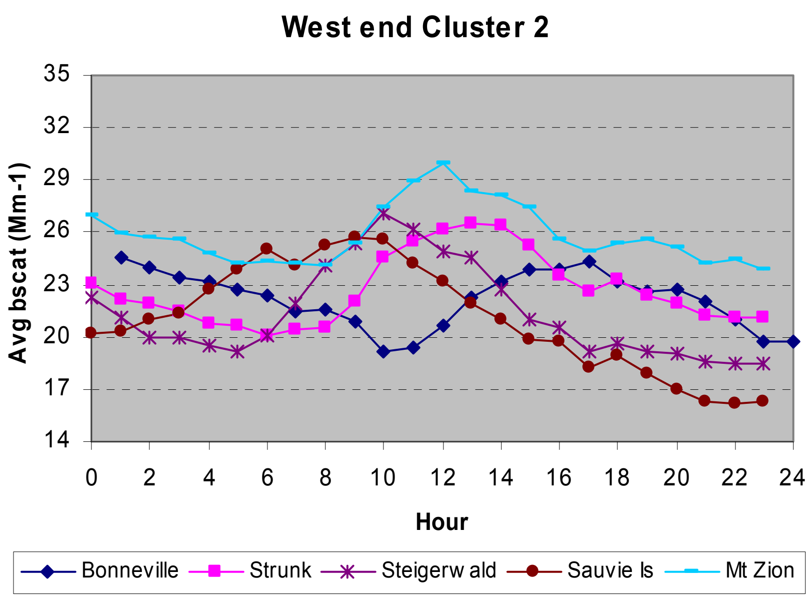


Figure 4-22. Diurnal patterns of bsp for moderate upgorge (2), western sites.

There are significant diurnal variations in bsp at the western sites. Steigerwald and Sauvie Island have peaks at 10 am, though the increase starts later at Steigerwald. At Mt.

Zion bsp peaks at noon, Strunk Road 1 pm, and a peak at 5 pm at Bonneville. This pattern shows an increase first at the westernmost site, then later increases in bsp progressively with eastward distance in the Gorge to Bonneville.

This apparent west to east transport of higher levels of bsp can also be noted in a plot of the diurnal variation of light scattering for all July-August days (Figure 4-23).

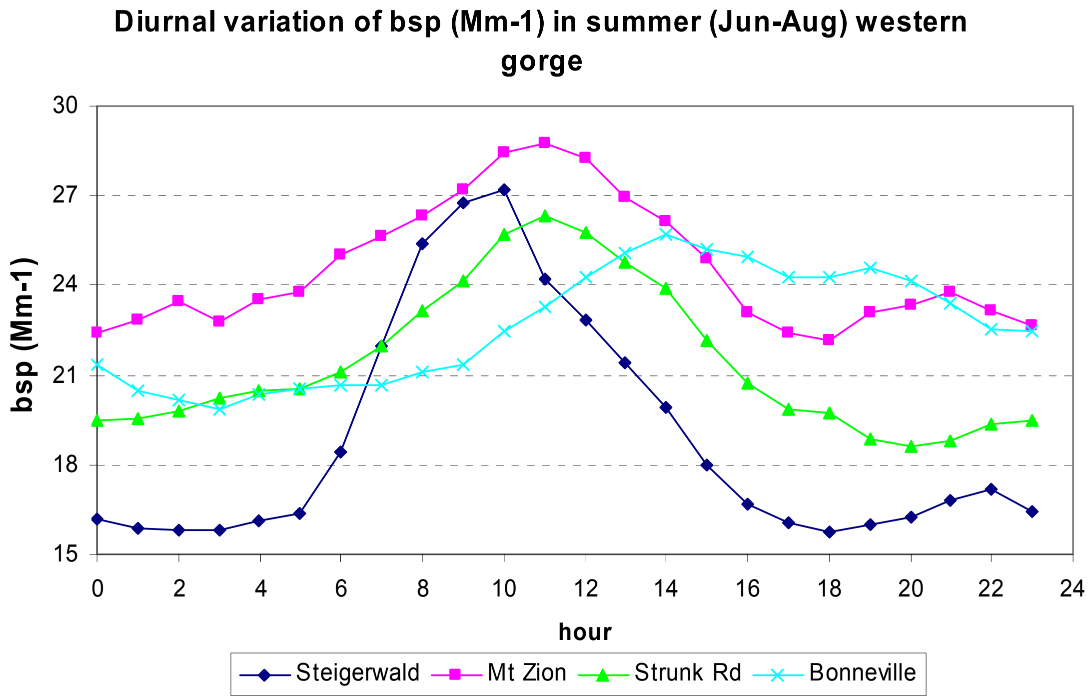


Figure 4-23. June- August average diurnal patterns of bsp at western Gorge sites and Bonneville Dam.

At Bonneville Dam, wind speed increased substantially during the mid-late morning hours for moderate upgorge (2). As shown in Figure 4-24, this increase was closely followed by an increase in bsp, further suggestion of a transport of aerosols from the Portland/Vancouver area.

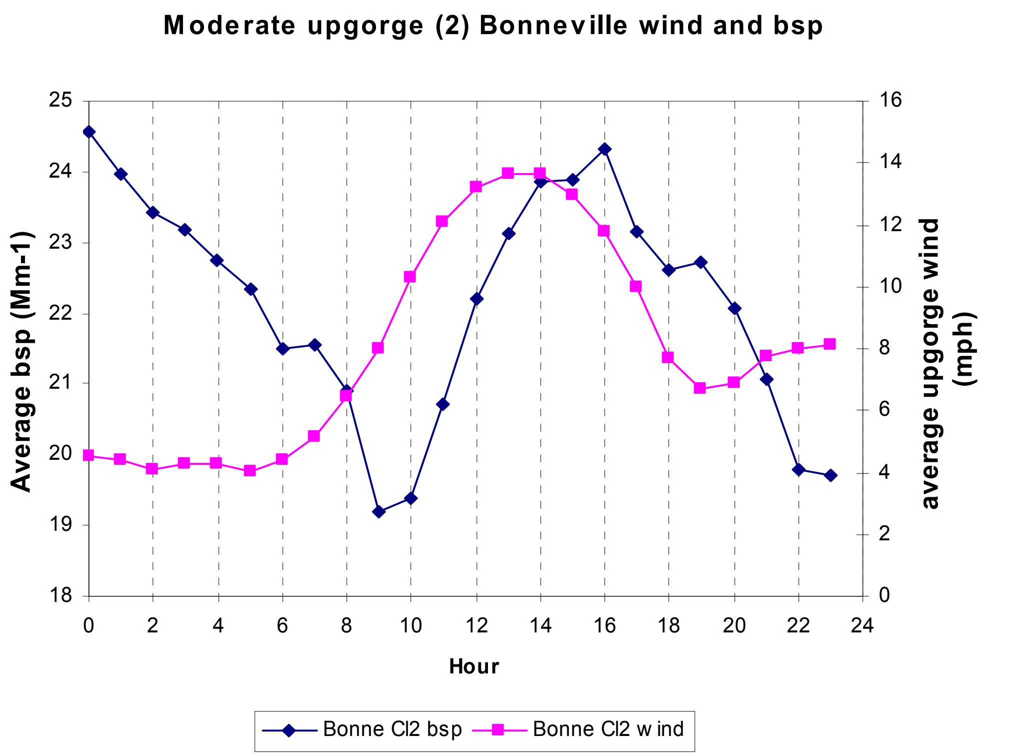


Figure 4-24. Bonneville upgorge wind component and bsp, moderate upgorge (2).

A similar pattern occurs for Light upgorge (1), as shown in Figure 4-25.

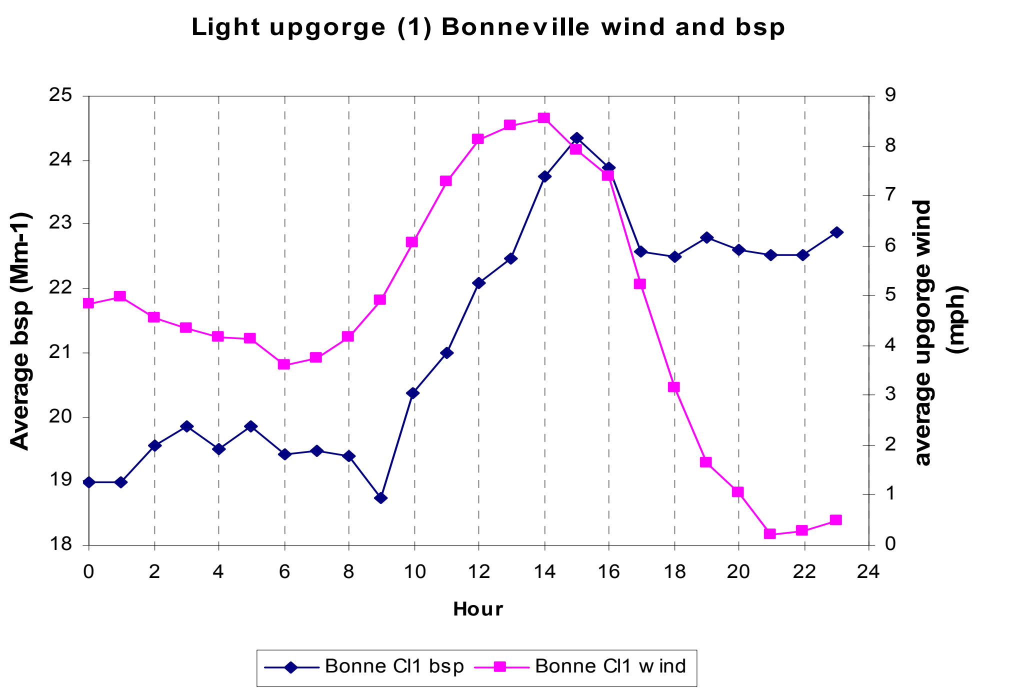


Figure 4-25. Bonneville upgorge wind component and bsp, light upgorge (1).

Light upgorge (1) has bsp highest at Sauvie Island and then decreasing with distance into the Gorge.

Light downgorge (4) has highest average bsp at Sauvie Island. While Sauvie Island has light average winds upriver all hours for light downgorge (4), nearby sites have downriver (downgorge) winds. The high average bsp at Sauvie Island for light downgorge (4) compared to other sites needs to be further investigated. High bsp at Sauvie Island may be a result of sloshing back and forth of Portland/Vancouver area emissions or sources somewhat downstream of Portland that do not impact the other sites because flow is coming down gorge at the exit. As there is light flow coming out of the Gorge, sources affecting Sauvie Island for light downgorge (4) days would not affect the in-gorge sites.

Further east in the Gorge, the Sevenmile Hill and Memaloose sites have higher average bsp than do the other sites. All sites from Memaloose east have their 2nd highest average bsp for light downgorge (4) (highest is winter downgorge (5)). Bonneville shows diurnally consistent down gorge flow for light downgorge, while Sevenmile Hill, Wishram, and Towal Road showed diurnal variation in flow direction (upgorge and downgorge both) during light downgorge(4) days. Figure 4-26 shows the diurnal variation in upgorge wind component and bsp at Sevenmile Hill for light downgorge (4) days. At 7 am the wind direction changed from upgorge to downgorge and average bsp increased 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, bsp increases. This increase suggests contributions from local sources in the area of The Dalles.

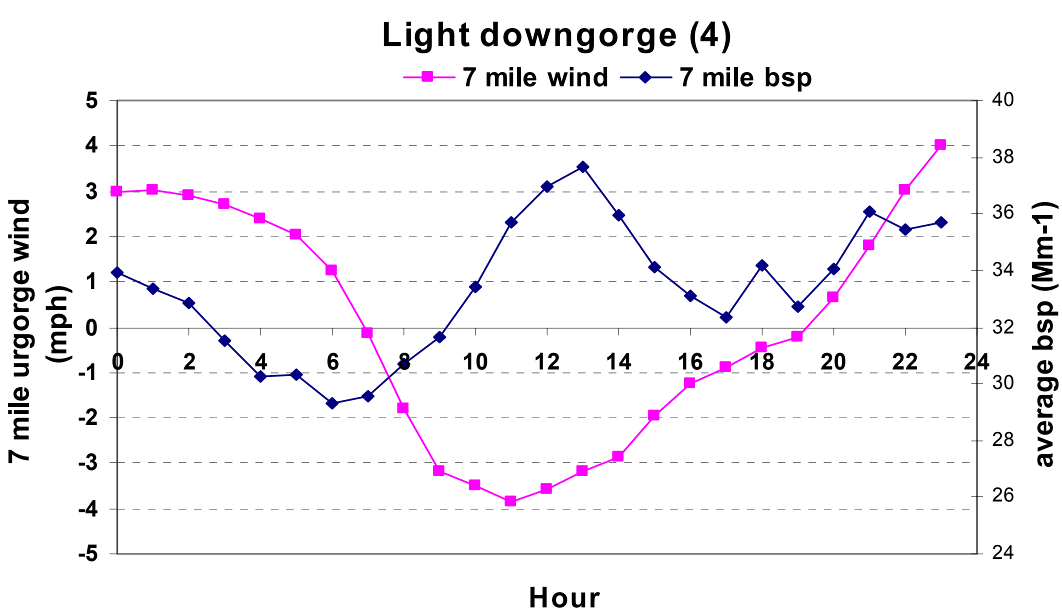


Figure 4-26. Relationship between average Sevenmile Hill upgorge wind and average bsp by time of day for light downgorge (4).

4.3 Aethalometer Elemental Carbon (EC) at Mt Zion and Wishram by Cluster

Aethalometers were operated at Mt. Zion and Wishram for the duration of the study. Aethalometers give a calculated elemental or black carbon concentration based upon light transmittance through a filter tape over which ambient air is drawn. While there are some limitations with aethalometers (e.g. Arnott, et al., 2005), the data are of sufficient quality to identify diurnal and seasonal patterns in elemental carbon (EC). EC affects visibility by absorbing light. The extinction efficiency of EC is on the order of 10 m^2g^{-1}. So EC concentrations in ng/m^3 divided by 100 will give a good approximation to the light absorption in Mm-1 by EC.

Average aethalometer derived EC concentrations by cluster and hour at Mt Zion and Wishram are shown in Figures 4-27 and 4-28. EC concentrations by cluster, averaged over all hours are shown in Table 4-4. EC concentrations are quite low and contribute very little to light extinction. Assuming an extinction efficiency of 10 m^2g^{-1}, the average light extinction at Mt. Zion due to EC would be 0.73 Mm^{-1}, compared to an average of 25.8 Mm-1 due to light scattering by particles (bsp). At Wishram, EC would contribute on average 0.65 Mm^{-1}, compared to 22.6 Mm^{-1} by particle scattering.

At Mt. Zion light upgorge (1) has highest EC and winter downgorge (5) the lowest. For clusters 1-3, Mt. Zion shows a similar shape in the diurnal curve for EC as for bsp, again suggesting transport from the Portland/Vancouver area. At Wishram, strong upgorge (3) has much lower EC than the others, with light downgorge (4) the greatestWishram shows a pronounced morning peak in EC for light downgorge (4) at 8-9 am, suggesting local source contributions at this time.

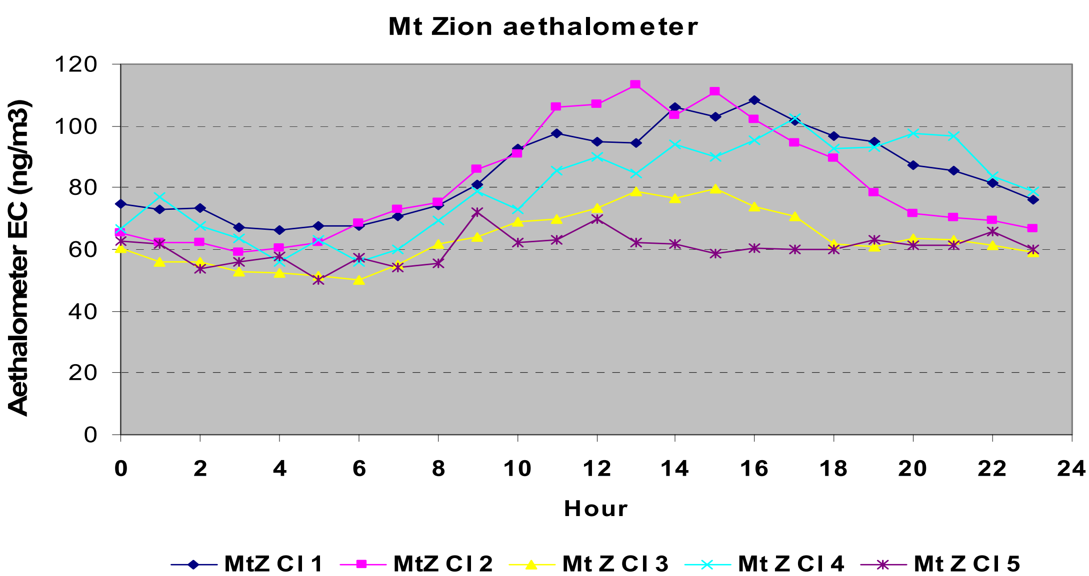


Figure 4-27. Hourly average Aethalometer derived elemental carbon at Mt. Zion by cluster.

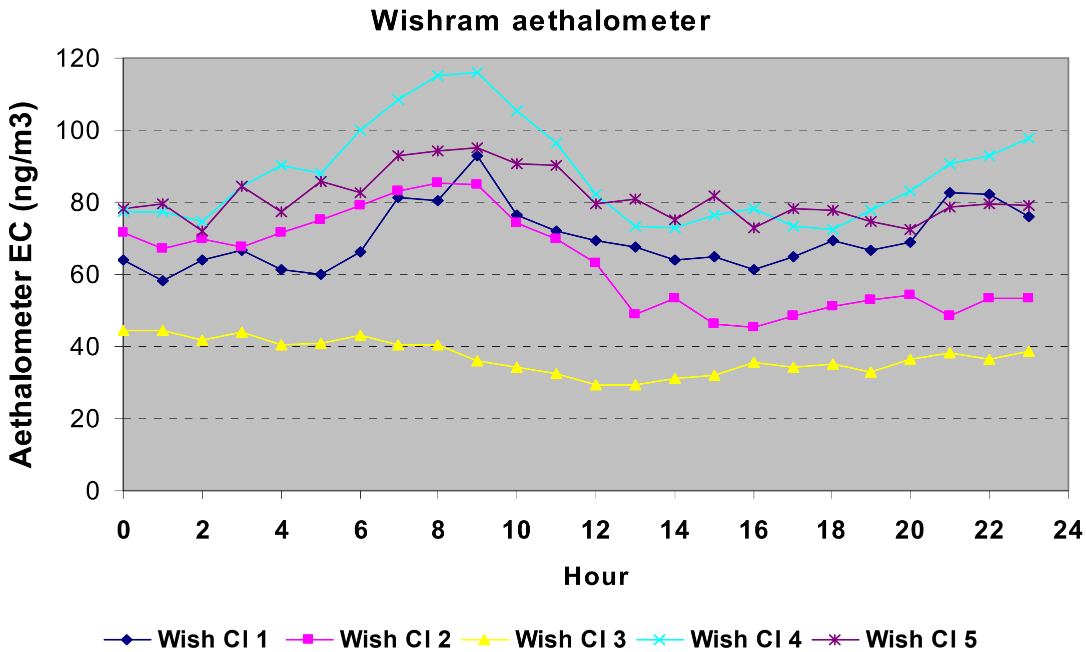


Figure 4-28. Hourly average Aethalometer derived elemental carbon at Wishram by cluster.

Table 4-4. Cluster average aethalometer derived elemental carbon (ng/m3) at Mt. Zion and Wishram.

	Mt Zion	Wishram
Light upgorge (1)	85	70
Moderate upgorge (2)	81	63
Strong upgorge (3)	63	37
Light downgorge (4)	80	87
Winter downgorge (5)	60	81
All Clusters	73	65

4.4 Summary of Cluster Wind patterns.

Table 4-5 is a summary of wind patterns and seasonal frequency for each cluster.

Table 4-5. Wind patterns and seasonal frequency by cluster.

Cluster	Wind Pattern	Seasonality
Light upgorge (1)	Light upgorge, increasing with distance into Gorge	Peak in transition months April and October, more common in winter than summer
Moderate upgorge (2)	Moderate upgorge, increasing with distance into Gorge, large diurnal variation in speed	Late summer- early fall Peak in August, most common cluster August to October
Strong upgorge (3)	Strong upgorge, increasing with distance into Gorge	Peak in July, most common cluster May-July
Light downgorge (4)	Light downgorge, except diurnally changing direction at eastern sites, upgorge Sauvie Island	Mainly Autumn and Spring (most common cluster November), uncommon summer
Winter downgorge (5)	Downgorge, light in eastern end, increasing through Gorge, light down at Sauvie Island	Predominantly winter – most common cluster December-February, no occurrences May-September

4.5 Summary of aerosol light scattering (bsp) patterns by Cluster

Light upgorge (1) Bsp is highest at Sauvie Island for all days, then decreases with distance into the Gorge. Bsp for days without precipitation was highest at Mt. Zion. Diurnal transport of aerosol was noted with peaks later in day with distance into the Gorge. Light upgorge(1) was the 2nd highest bsp cluster for western sites.

Moderate upgorge (2) Bsp was highest at Mt. Zion, gradual decreasing with distance into the Gorge. Diurnal transport of aerosol noted with peaks later in day with distance into Gorge.

Strong upgorge (3) Cleanest cluster at all sites, with a large gradient in bsp, highest bsp at Mt. Zion, lowest at eastern sites. Increase of bsp across Portland/Vancouver metropolitan area.

Light downgorge (4) Highest bsp at Sauvie Island (much higher than nearby sites), suggesting impact from Portland/Vancouver and/or downriver industry. Higher bsp at Sevenmile Hill and Memaloose than other sites, suggesting impact from The Dalles area.

Winter downgorge (5) Highest bsp among clusters for all sites except Sauvie Island. Highest at eastern sites, then decreasing westward through the Gorge until increasing at Sauvie Island (suggesting impact from Portland/Vancouver). Higher at Memaloose than Wishram and Sevenmile Hill sites, suggesting impact from the Dalles. High bsp at eastern sites suggests impacts from areas east of the gorge. Lower bsp at Sevenmile Hill than other eastern sites perhaps due to being above mixed layer at night and morning. Increase in bsp at Sevenmile Hill in afternoon, with mixing of aerosols up to the monitoring site.

5 Summary

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 from 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. More detailed data analysis will be done for the Causes of Haze in the Gorge (COHAGO) study. This will include additional analyses using the nephelometer and surface meteorology data from the Haze Gradient Study and aerosol composition data collected for COHAGO (e.g. filter samples, high time resolved sulfate, nitrate, EC/OC, etc).

Because of the large number of days (>600) monitored, a statistical method (cluster analysis) was used to group days with similar wind patterns. Summaries of wind, pressure, particle light scattering (bsp), and light absorption were computed for each group of similar days (each cluster). Wind data were classified as to their component upriver (basically west to east). Upriver was termed "upgorge", downriver termed "downgorge". Light scattering data were interpreted with respect to wind transport patterns to gain insight into likely source areas for each group of days.

Five clusters of similar days were identified:

6) light upgorge flow
7) moderate upgorge flow
8) strong upgorge flow
9) light downgorge flow (diurnal reversal at eastern sites)
10) winter downgorge flow (light at east end, strong at west end)

Strong upgorge (3) was the predominant pattern in mid-summer; Winter downgorge (5) was the most frequent winter pattern. Light upgorge (1) and light downgorge (4) were most frequent in fall and spring transition months; moderate upgorge (2) was most frequent in late summer to early fall.

Winter downgorge (5) had the highest average bsp at all sites except Sauvie Island. Highest bsp for winter downgorge was at the eastern sites, with a decrease with distance downgorge. Bsp increased again at Sauvie Island as the flow exited the Gorge and crossed the Portland/Vancouver area. This transport and bsp gradient pattern suggests that sources east of the Gorge cause much of the haze and that the Portland/Vancouver area contributes additional aerosol to the Sauvie Island site.

Light downgorge (4) had the highest bsp at Sauvie Island, suggesting impact from nearby sources such as the Portland/Vancouver area and/or downriver industry.

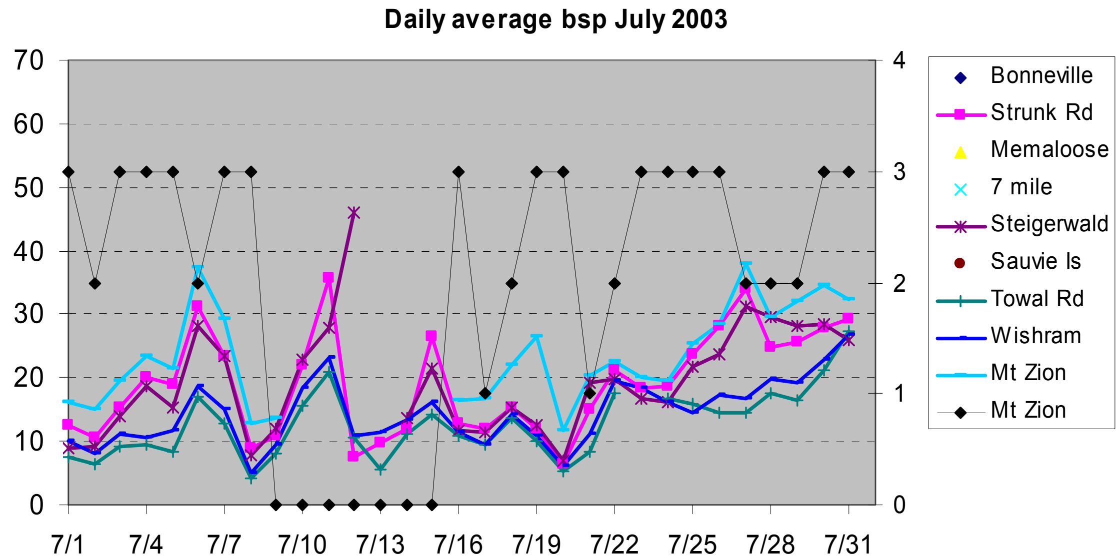
For days without precipitation, all the upgorge clusters (1-3) had highest bsp at Mt. Zion and a decreasing bsp with distance into the Gorge. Light upgorge (1) and moderate upgorge (2) showed diurnal patterns of increasing bsp progressing upgorge to the Bonneville site during the day. Bsp also increased across the Portland/Vancouver area for each cluster, suggesting the urban area as a significant contributor to aerosol in the Gorge for these clusters.

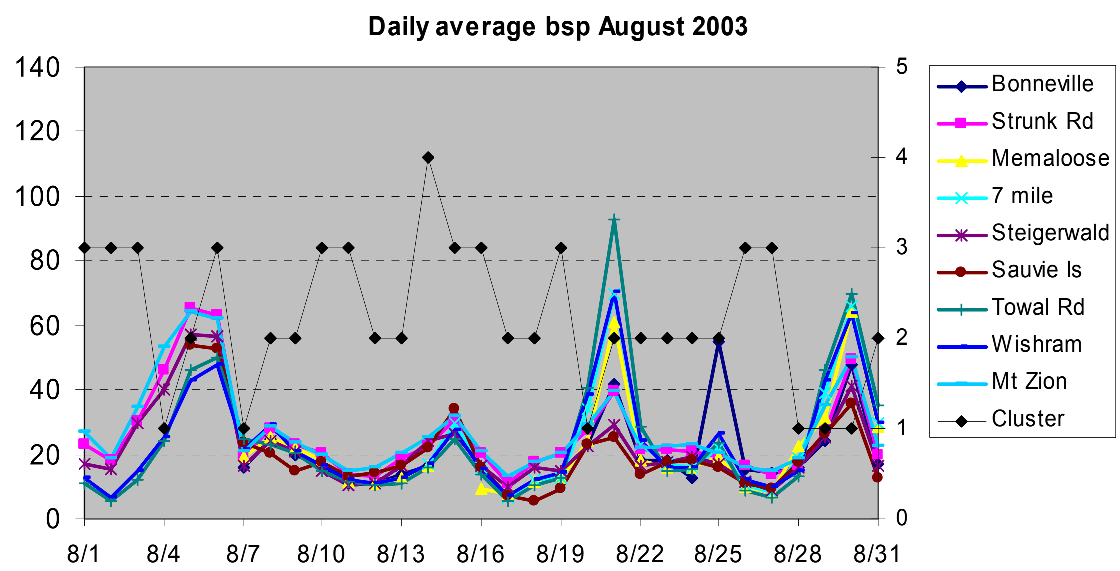
Light downgorge (4) and winter downgorge (5) showed an increase in bsp from Wishram to Sevenmile Hill and Memaloose, suggesting impact from The Dalles area. At Sevenmile Hill for light downgorge (4), the diurnal change in wind direction from upgorge to downgorge is accompanied by an increase in bsp (when the direction is from The Dalles).

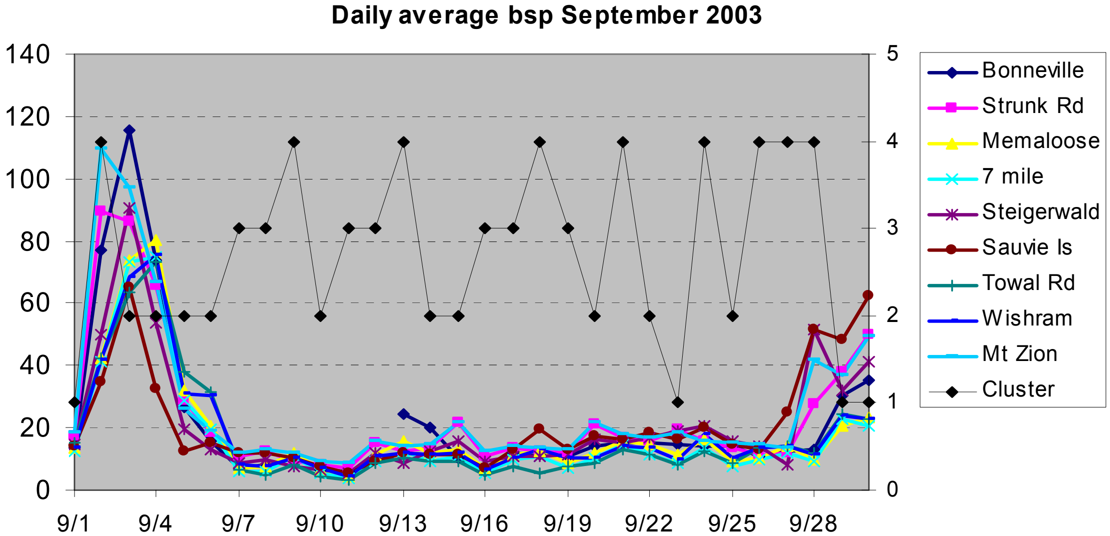
At Mt. Zion and Wishram, light absorption was a minor contributor to haze.

6 Appendix A – Monthly time series plots of daily average bsp

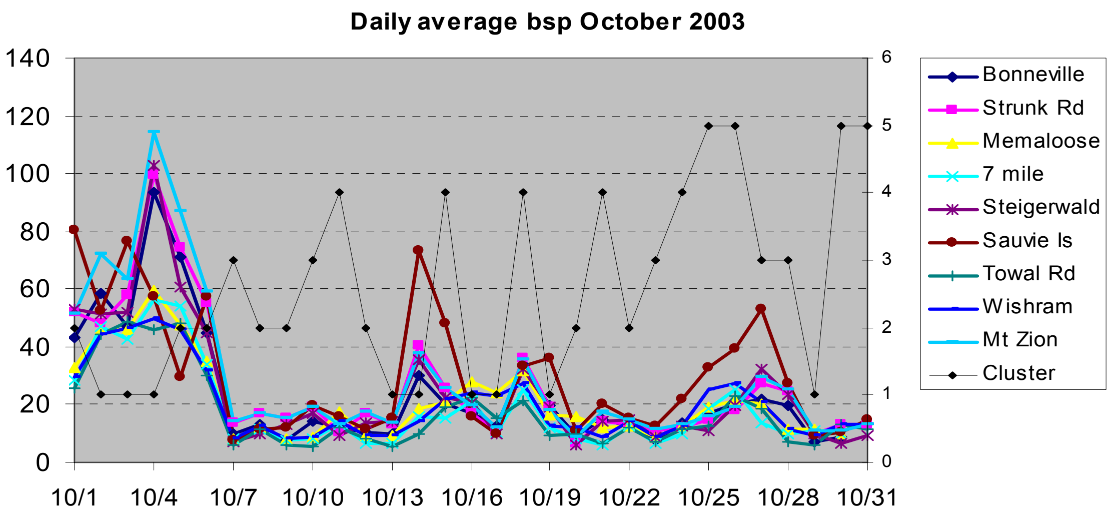
Left Y-axis in all plots is nephelometer light scattering (bsp) in inverse megameters (Mm-1). Right Y-axis is daily cluster number.



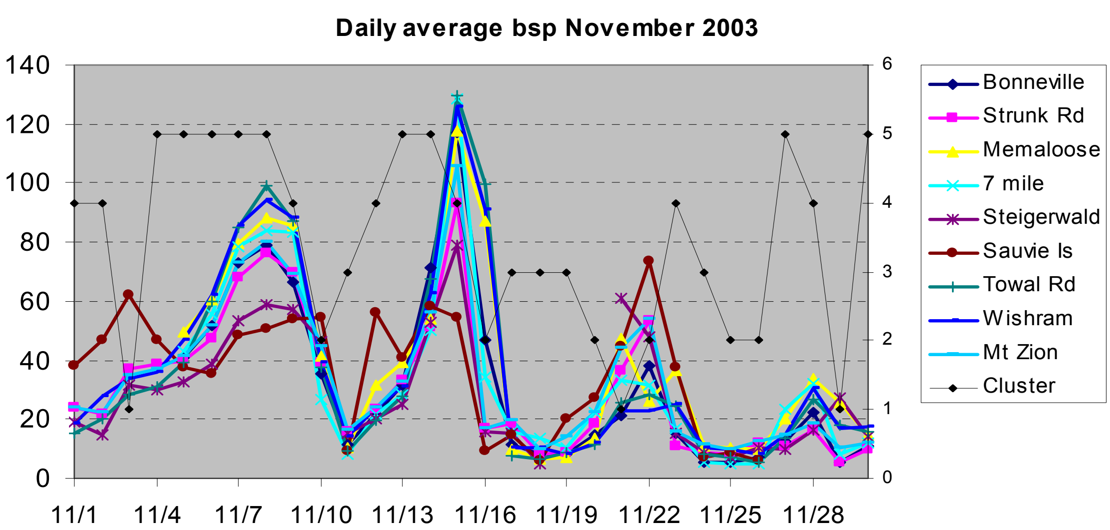




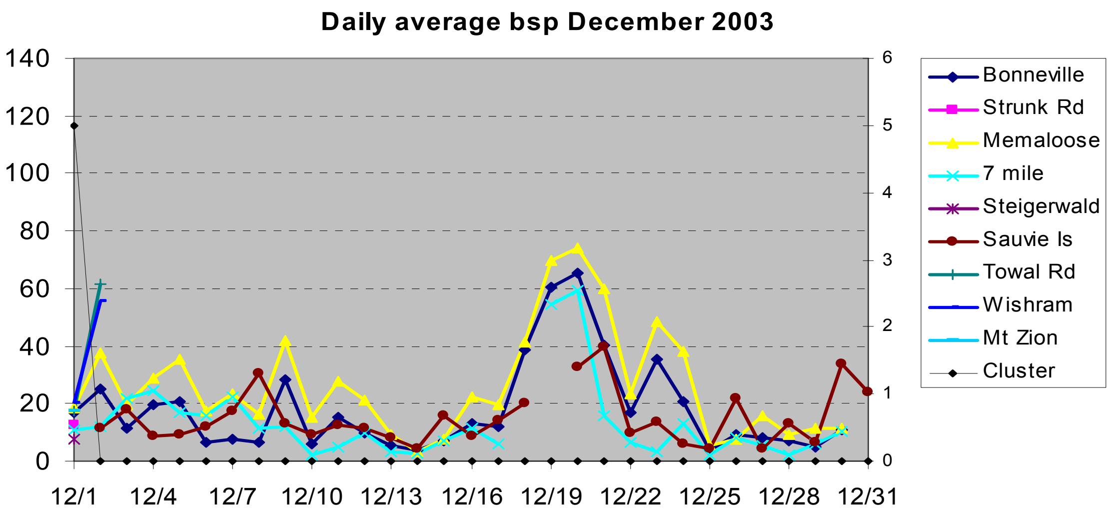
Daily average bsp September 2003
140
120
100
80
60
40
20
0
5
4
3
2
1
0
9/1
9/4
9/7
9/10
9/13
9/16
9/19
9/22
9/25
9/28
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster

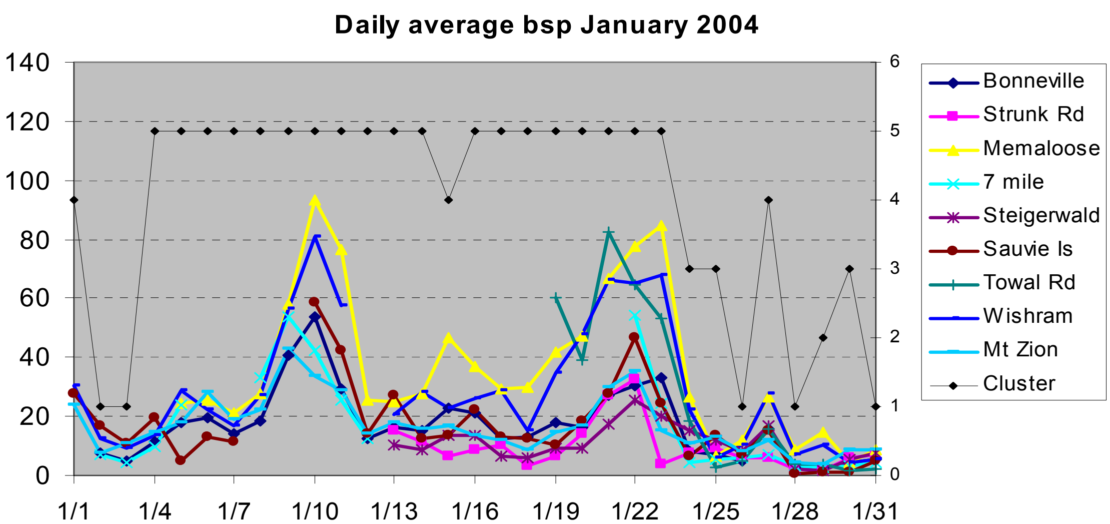


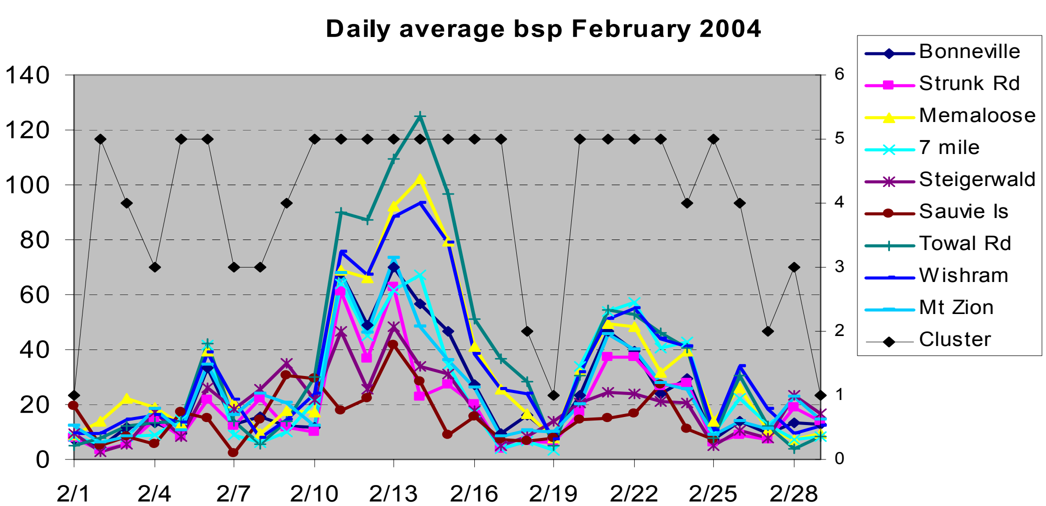
Daily average bsp October 2003
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
10/1
10/4
10/7
10/10
10/13
10/16
10/19
10/22
10/25
10/28
10/31
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster



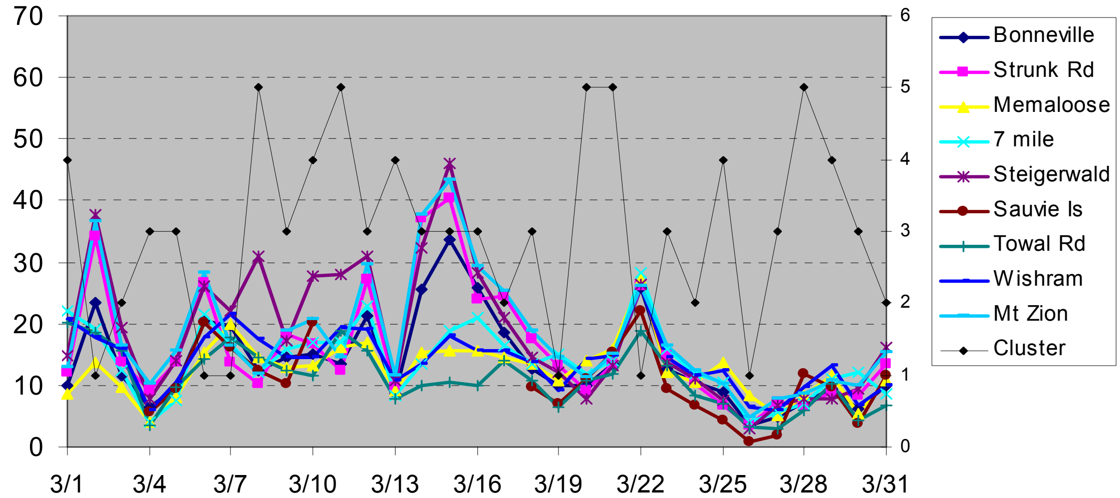
Daily average bsp November 2003
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
11/1
11/4
11/7
11/10
11/13
11/16
11/19
11/22
11/25
11/28
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster


Daily average bsp December 2003
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
12/1
12/4
12/7
12/10
12/13
12/16
12/19
12/22
12/25
12/28
12/31
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster

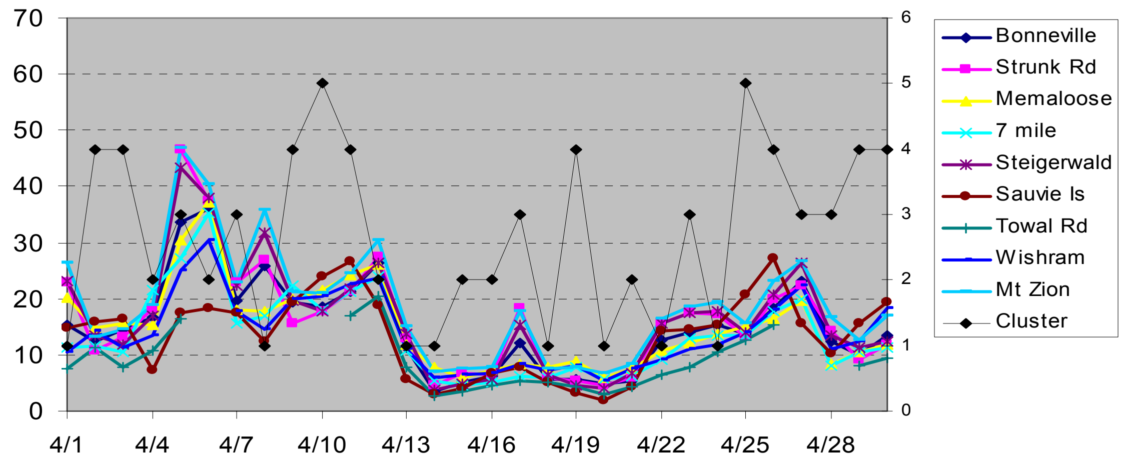

Daily average bsp January 2004
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
1/1
1/4
1/7
1/10
1/13
1/16
1/19
1/22
1/25
1/28
1/31
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster


Daily average bsp February 2004
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
2/1
2/4
2/7
2/10
2/13
2/16
2/19
2/22
2/25
2/28
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster

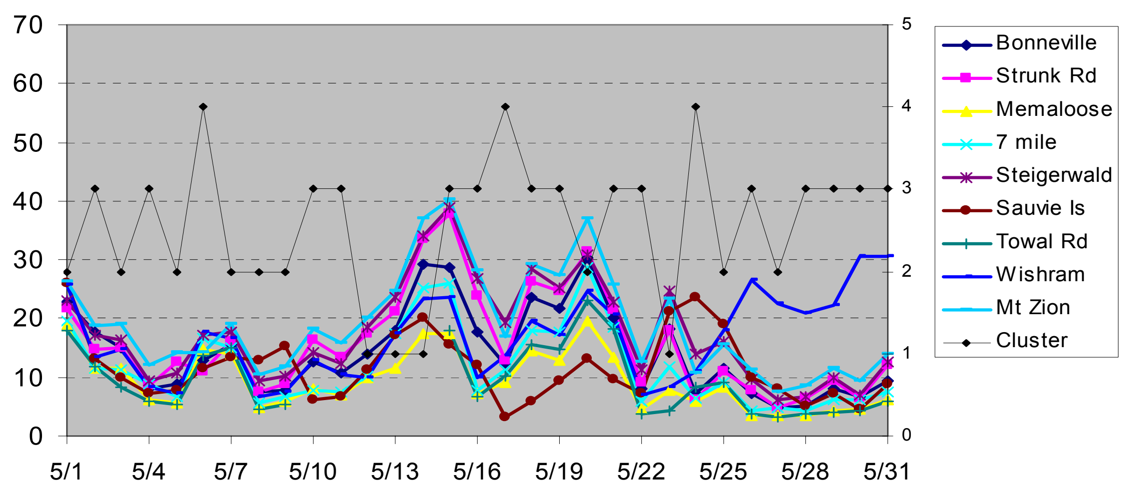
Daily average bsp March 2004



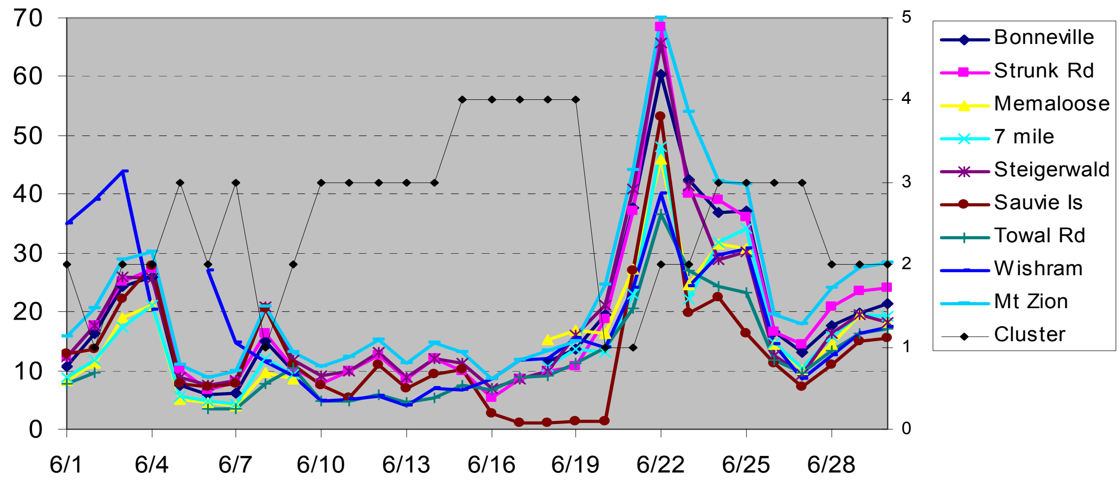
Daily average bsp April 2004



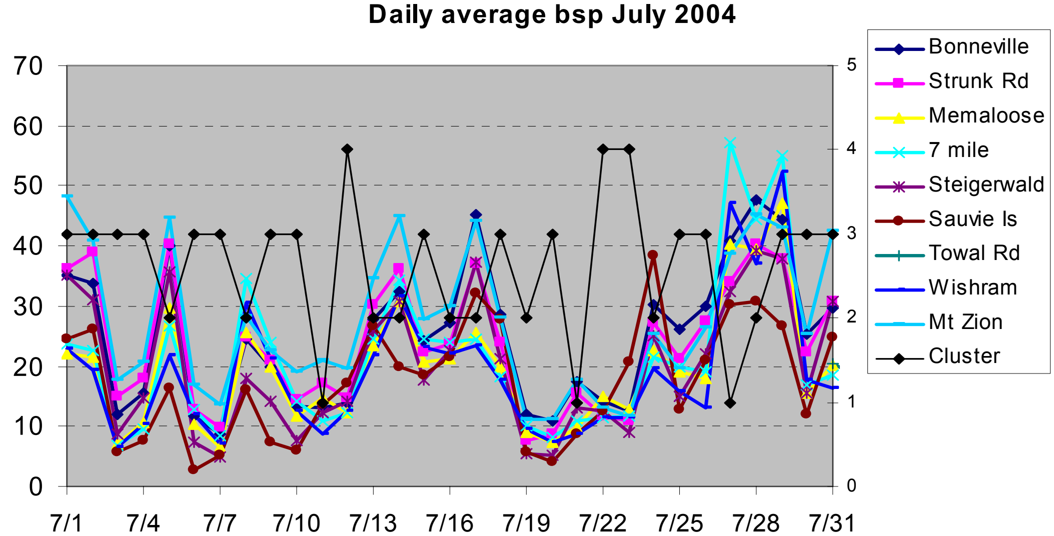
Daily average bsp May 2004



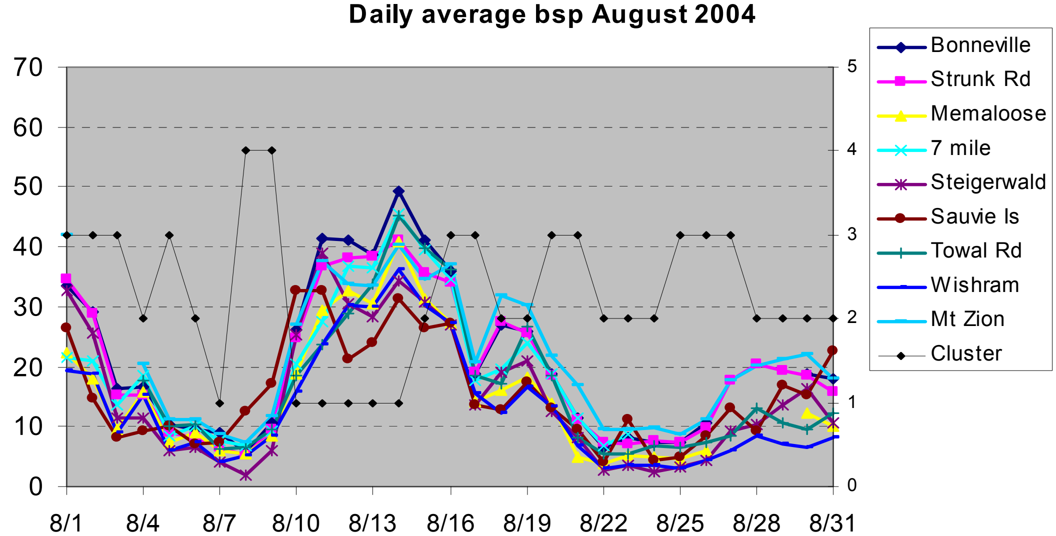
Daily average bsp June 2004

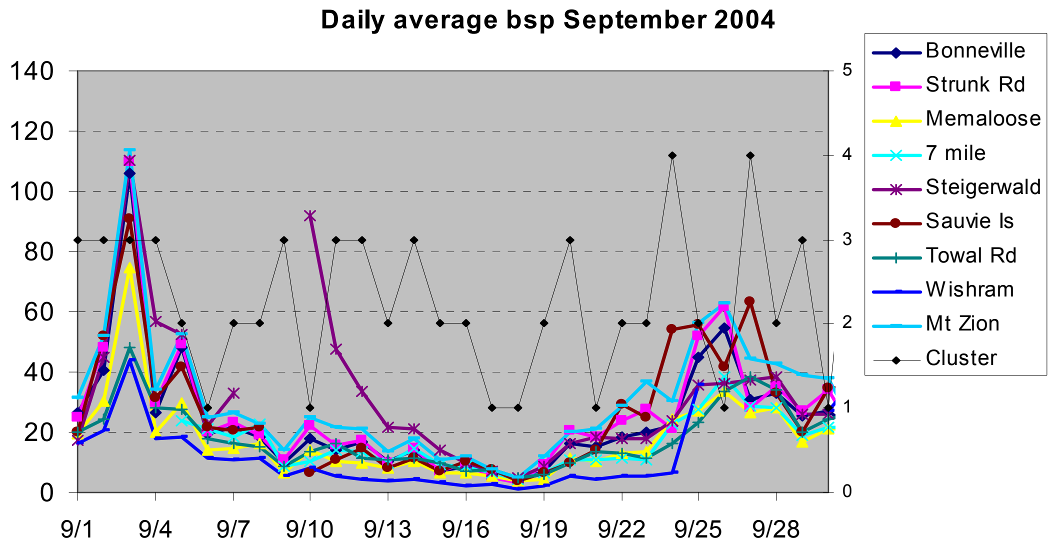


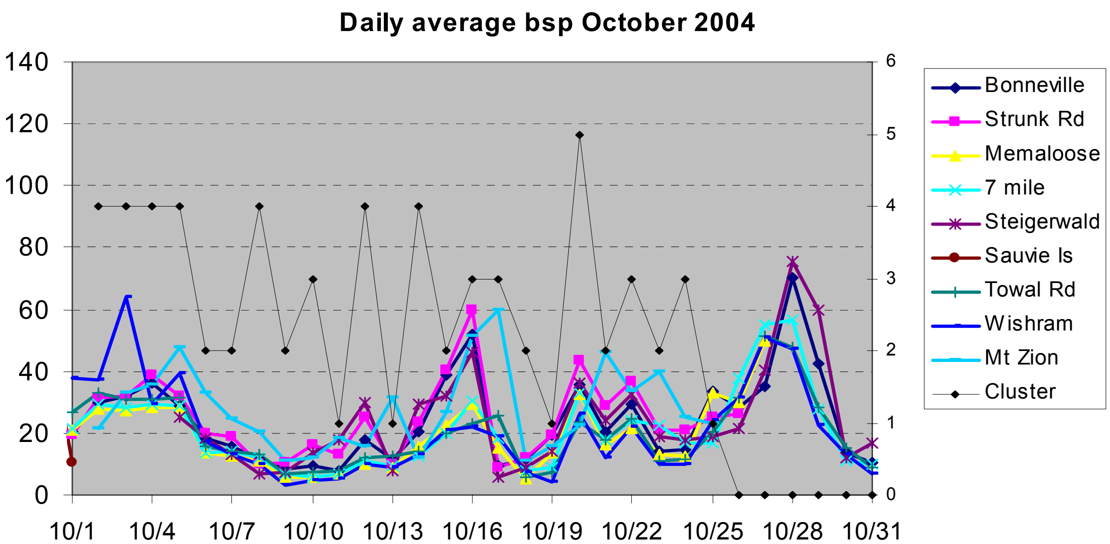
Daily average bsp July 2004



Daily average bsp August 2004




Daily average bsp September 2004
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster
0
20
40
60
80
100
120
140
0
1
2
3
4
5
9/1
9/4
9/7
9/10
9/13
9/16
9/19
9/22
9/25
9/28


Daily average bsp October 2004
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster
0
20
40
60
80
100
120
140
0
1
2
3
4
5
6
10/1
10/4
10/7
10/10
10/13
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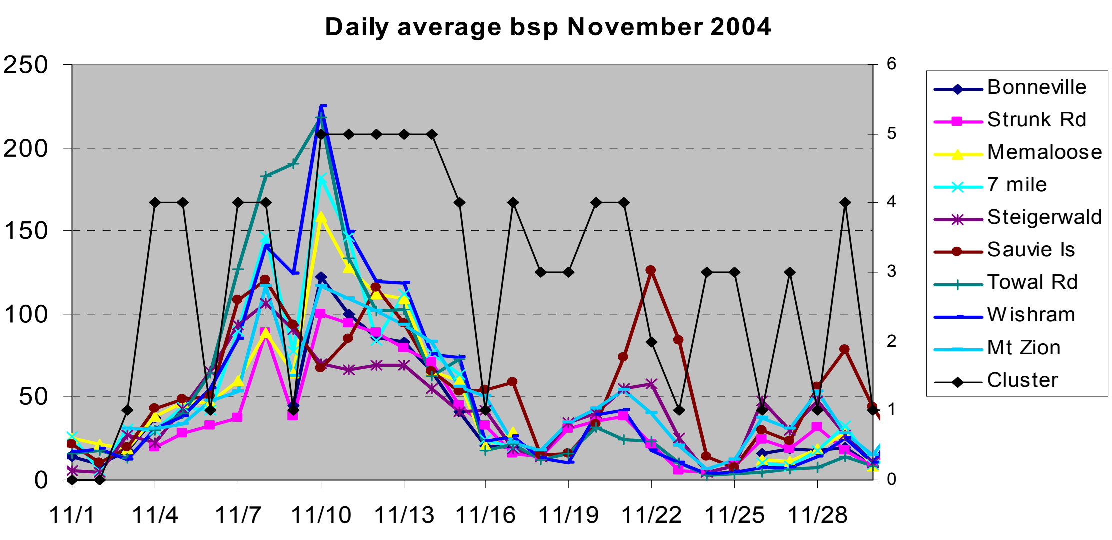
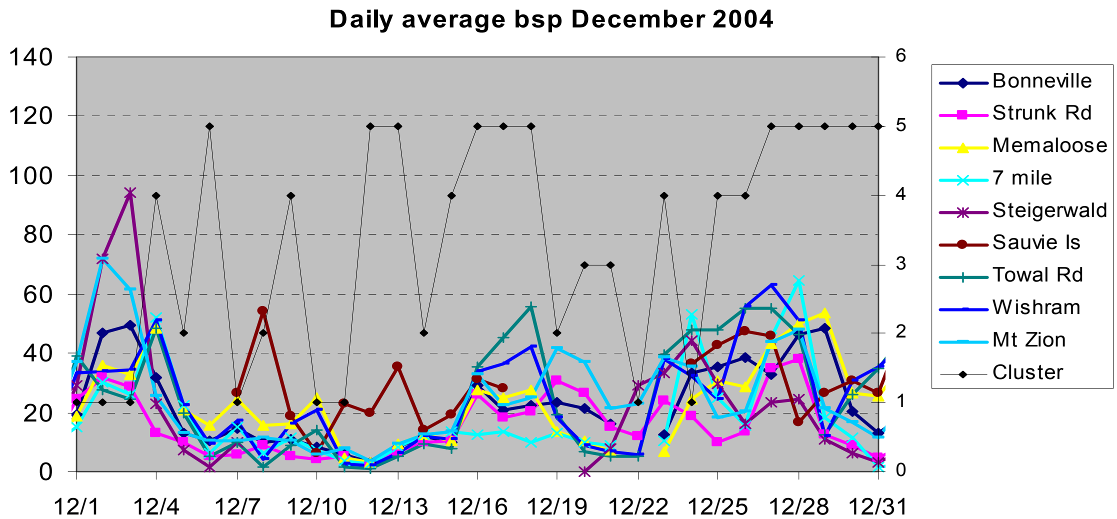
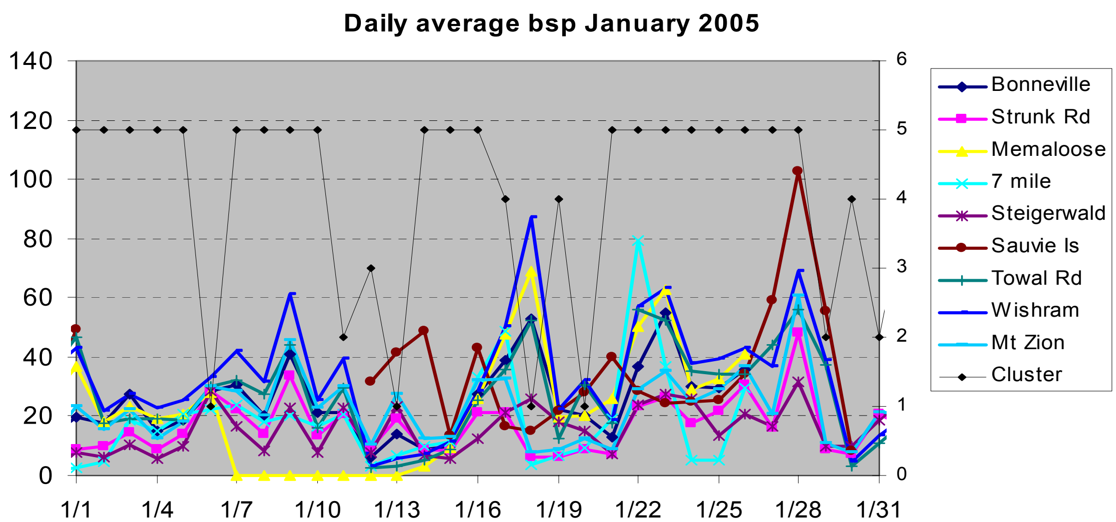
10/19
10/22
10/25
10/28
10/31


Daily average bsp November 2004
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster
0
50
100
150
200
250
0
1
2
3
4
5
6
11/1
11/4
11/7
11/10
11/13
11/16
11/19
11/22
11/25
11/28


Daily average bsp December 2004
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
12/1
12/4
12/7
12/10
12/13
12/16
12/19
12/22
12/25
12/28
12/31
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster


Daily average bsp January 2005
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
1/1
1/4
1/7
1/10
1/13
1/16
1/19
1/22
1/25
1/28
1/31
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster

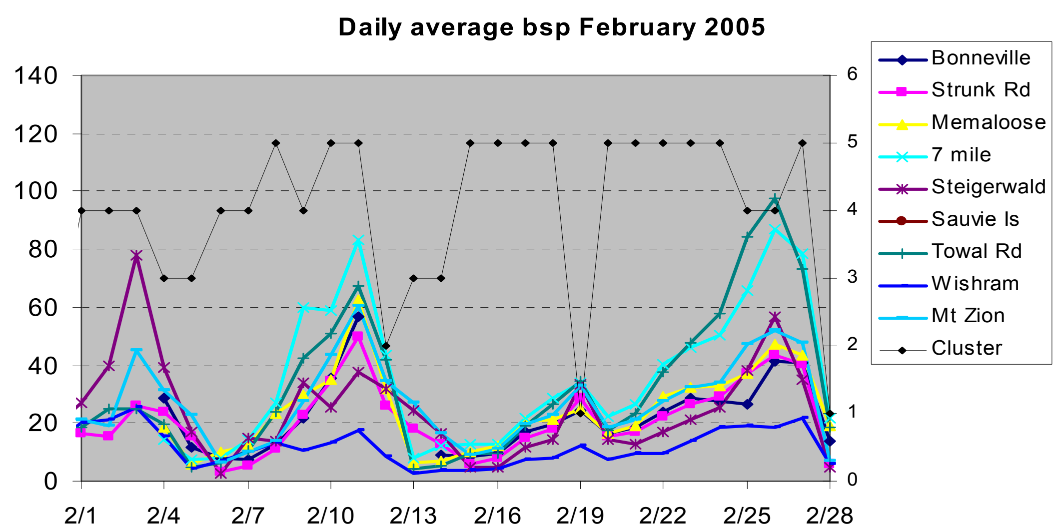

Daily average bsp February 2005
140
120
100
80
60
40
20
0
6
5
4
3
2
1
0
2/1
2/4
2/7
2/10
2/13
2/16
2/19
2/22
2/25
2/28
Bonneville
Strunk Rd
Memaloose
7 mile
Steigerwald
Sauvie Is
Towal Rd
Wishram
Mt Zion
Cluster

Table A-1. Cluster number by date. Cluster 0 is for days that had missing wind data and were not clustered.

Date	Cluster	Date	Cluster	Date	Cluster	Date	Cluster
7/1/2003	3	8/21/2003	2	10/11/2003	4	12/1/2003	5
7/2/2003	2	8/22/2003	2	10/12/2003	2	12/2/2003	0
7/3/2003	3	8/23/2003	2	10/13/2003	1	12/3/2003	0
7/4/2003	3	8/24/2003	2	10/14/2003	1	12/4/2003	0
7/5/2003	3	8/25/2003	2	10/15/2003	4	12/5/2003	0
7/6/2003	2	8/26/2003	3	10/16/2003	1	12/6/2003	0
7/7/2003	3	8/27/2003	3	10/17/2003	1	12/7/2003	0
7/8/2003	3	8/28/2003	1	10/18/2003	4	12/8/2003	0
7/9/2003	0	8/29/2003	1	10/19/2003	1	12/9/2003	0
7/10/2003	0	8/30/2003	1	10/20/2003	2	12/10/2003	0
7/11/2003	0	8/31/2003	2	10/21/2003	4	12/11/2003	0
7/12/2003	0	9/1/2003	1	10/22/2003	2	12/12/2003	0
7/13/2003	0	9/2/2003	4	10/23/2003	3	12/13/2003	0
7/14/2003	0	9/3/2003	2	10/24/2003	4	12/14/2003	0
7/15/2003	0	9/4/2003	2	10/25/2003	5	12/15/2003	0
7/16/2003	3	9/5/2003	2	10/26/2003	5	12/16/2003	0
7/17/2003	1	9/6/2003	2	10/27/2003	3	12/17/2003	0
7/18/2003	2	9/7/2003	3	10/28/2003	3	12/18/2003	0
7/19/2003	3	9/8/2003	3	10/29/2003	1	12/19/2003	0
7/20/2003	3	9/9/2003	4	10/30/2003	5	12/20/2003	0
7/21/2003	1	9/10/2003	2	10/31/2003	5	12/21/2003	0
7/22/2003	2	9/11/2003	3	11/1/2003	4	12/22/2003	0
7/23/2003	3	9/12/2003	3	11/2/2003	4	12/23/2003	0
7/24/2003	3	9/13/2003	4	11/3/2003	1	12/24/2003	0
7/25/2003	3	9/14/2003	2	11/4/2003	5	12/25/2003	0
7/26/2003	3	9/15/2003	2	11/5/2003	5	12/26/2003	0
7/27/2003	2	9/16/2003	3	11/6/2003	5	12/27/2003	0
7/28/2003	2	9/17/2003	3	11/7/2003	5	12/28/2003	0
7/29/2003	2	9/18/2003	4	11/8/2003	5	12/29/2003	0
7/30/2003	3	9/19/2003	3	11/9/2003	4	12/30/2003	0
7/31/2003	3	9/20/2003	2	11/10/2003	2	12/31/2003	0
8/1/2003	3	9/21/2003	4	11/11/2003	3	1/1/2004	4
8/2/2003	3	9/22/2003	2	11/12/2003	4	1/2/2004	1
8/3/2003	3	9/23/2003	1	11/13/2003	5	1/3/2004	1
8/4/2003	1	9/24/2003	4	11/14/2003	5	1/4/2004	5
8/5/2003	2	9/25/2003	2	11/15/2003	4	1/5/2004	5
8/6/2003	3	9/26/2003	4	11/16/2003	2	1/6/2004	5
8/7/2003	1	9/27/2003	4	11/17/2003	3	1/7/2004	5
8/8/2003	2	9/28/2003	4	11/18/2003	3	1/8/2004	5
8/9/2003	2	9/29/2003	1	11/19/2003	3	1/9/2004	5
8/10/2003	3	9/30/2003	1	11/20/2003	2	1/10/2004	5
8/11/2003	3	10/1/2003	2	11/21/2003	1	1/11/2004	5
8/12/2003	2	10/2/2003	1	11/22/2003	2	1/12/2004	5
8/13/2003	2	10/3/2003	1	11/23/2003	4	1/13/2004	5
8/14/2003	4	10/4/2003	1	11/24/2003	3	1/14/2004	5
8/15/2003	3	10/5/2003	2	11/25/2003	2	1/15/2004	4
8/16/2003	3	10/6/2003	2	11/26/2003	2	1/16/2004	5
8/17/2003	2	10/7/2003	3	11/27/2003	5	1/17/2004	5
8/18/2003	2	10/8/2003	2	11/28/2003	4	1/18/2004	5
8/19/2003	3	10/9/2003	2	11/29/2003	1	1/19/2004	5
8/20/2003	1	10/10/2003	3	11/30/2003	5	1/20/2004	5

Date	Cluster	Date	Cluster	Date	Cluster	Date	Cluster
1/21/2004	5	3/12/2004	3	5/2/2004	3	6/22/2004	2
1/22/2004	5	3/13/2004	4	5/3/2004	2	6/23/2004	2
1/23/2004	5	3/14/2004	3	5/4/2004	3	6/24/2004	3
1/24/2004	3	3/15/2004	3	5/5/2004	2	6/25/2004	3
1/25/2004	3	3/16/2004	3	5/6/2004	4	6/26/2004	3
1/26/2004	1	3/17/2004	2	5/7/2004	2	6/27/2004	3
1/27/2004	4	3/18/2004	3	5/8/2004	2	6/28/2004	2
1/28/2004	1	3/19/2004	1	5/9/2004	2	6/29/2004	2
1/29/2004	2	3/20/2004	5	5/10/2004	3	6/30/2004	2
1/30/2004	3	3/21/2004	5	5/11/2004	3	7/1/2004	3
1/31/2004	1	3/22/2004	1	5/12/2004	1	7/2/2004	3
2/1/2004	1	3/23/2004	3	5/13/2004	1	7/3/2004	3
2/2/2004	5	3/24/2004	2	5/14/2004	1	7/4/2004	3
2/3/2004	4	3/25/2004	4	5/15/2004	3	7/5/2004	2
2/4/2004	3	3/26/2004	1	5/16/2004	3	7/6/2004	3
2/5/2004	5	3/27/2004	3	5/17/2004	4	7/7/2004	3
2/6/2004	5	3/28/2004	5	5/18/2004	3	7/8/2004	2
2/7/2004	3	3/29/2004	4	5/19/2004	3	7/9/2004	3
2/8/2004	3	3/30/2004	3	5/20/2004	2	7/10/2004	3
2/9/2004	4	3/31/2004	2	5/21/2004	3	7/11/2004	1
2/10/2004	5	4/1/2004	1	5/22/2004	3	7/12/2004	4
2/11/2004	5	4/2/2004	4	5/23/2004	1	7/13/2004	2
2/12/2004	5	4/3/2004	4	5/24/2004	4	7/14/2004	2
2/13/2004	5	4/4/2004	2	5/25/2004	2	7/15/2004	3
2/14/2004	5	4/5/2004	3	5/26/2004	3	7/16/2004	2
2/15/2004	5	4/6/2004	2	5/27/2004	2	7/17/2004	2
2/16/2004	5	4/7/2004	3	5/28/2004	3	7/18/2004	3
2/17/2004	5	4/8/2004	1	5/29/2004	3	7/19/2004	2
2/18/2004	2	4/9/2004	4	5/30/2004	3	7/20/2004	3
2/19/2004	1	4/10/2004	5	5/31/2004	3	7/21/2004	1
2/20/2004	5	4/11/2004	4	6/1/2004	2	7/22/2004	4
2/21/2004	5	4/12/2004	2	6/2/2004	1	7/23/2004	4
2/22/2004	5	4/13/2004	1	6/3/2004	2	7/24/2004	2
2/23/2004	5	4/14/2004	1	6/4/2004	2	7/25/2004	3
2/24/2004	4	4/15/2004	2	6/5/2004	3	7/26/2004	3
2/25/2004	5	4/16/2004	2	6/6/2004	2	7/27/2004	1
2/26/2004	4	4/17/2004	3	6/7/2004	3	7/28/2004	2
2/27/2004	2	4/18/2004	1	6/8/2004	1	7/29/2004	3
2/28/2004	3	4/19/2004	4	6/9/2004	2	7/30/2004	3
2/29/2004	1	4/20/2004	1	6/10/2004	3	7/31/2004	3
3/1/2004	4	4/21/2004	2	6/11/2004	3	8/1/2004	3
3/2/2004	1	4/22/2004	1	6/12/2004	3	8/2/2004	3
3/3/2004	2	4/23/2004	3	6/13/2004	3	8/3/2004	3
3/4/2004	3	4/24/2004	1	6/14/2004	3	8/4/2004	2
3/5/2004	3	4/25/2004	5	6/15/2004	4	8/5/2004	3
3/6/2004	1	4/26/2004	4	6/16/2004	4	8/6/2004	2
3/7/2004	1	4/27/2004	3	6/17/2004	4	8/7/2004	1
3/8/2004	5	4/28/2004	3	6/18/2004	4	8/8/2004	4
3/9/2004	3	4/29/2004	4	6/19/2004	4	8/9/2004	4
3/10/2004	4	4/30/2004	4	6/20/2004	1	8/10/2004	1
3/11/2004	5	5/1/2004	2	6/21/2004	1	8/11/2004	1

Date	Cluster	Date	Cluster	Date	Cluster	Date	Cluster
8/12/2004	1	10/2/2004	4	11/22/2004	2	1/12/2005	3
8/13/2004	1	10/3/2004	4	11/23/2004	1	1/13/2005	1
8/14/2004	1	10/4/2004	4	11/24/2004	3	1/14/2005	5
8/15/2004	2	10/5/2004	2	11/25/2004	3	1/15/2005	5
8/16/2004	3	10/6/2004	2	11/26/2004	1	1/16/2005	5
8/17/2004	3	10/7/2004	4	11/27/2004	3	1/17/2005	4
8/18/2004	2	10/8/2004	2	11/28/2004	1	1/18/2005	1
8/19/2004	2	10/9/2004	3	11/29/2004	4	1/19/2005	4
8/20/2004	3	10/10/2004	1	11/30/2004	1	1/20/2005	1
8/21/2004	3	10/11/2004	4	12/1/2004	1	1/21/2005	5
8/22/2004	2	10/12/2004	1	12/2/2004	1	1/22/2005	5
8/23/2004	2	10/13/2004	4	12/3/2004	1	1/23/2005	5
8/24/2004	2	10/14/2004	2	12/4/2004	4	1/24/2005	5
8/25/2004	3	10/15/2004	3	12/5/2004	2	1/25/2005	5
8/26/2004	3	10/16/2004	3	12/6/2004	5	1/26/2005	5
8/27/2004	3	10/17/2004	2	12/7/2004	1	1/27/2005	5
8/28/2004	2	10/18/2004	1	12/8/2004	2	1/28/2005	5
8/29/2004	2	10/19/2004	5	12/9/2004	4	1/29/2005	2
8/30/2004	2	10/20/2004	2	12/10/2004	1	1/30/2005	4
8/31/2004	2	10/21/2004	3	12/11/2004	1	1/31/2005	2
9/1/2004	3	10/22/2004	2	12/12/2004	5	2/1/2005	4
9/2/2004	3	10/23/2004	3	12/13/2004	5	2/2/2005	4
9/3/2004	3	10/24/2004	1	12/14/2004	2	2/3/2005	4
9/4/2004	3	10/25/2004	0	12/15/2004	4	2/4/2005	3
9/5/2004	2	10/26/2004	0	12/16/2004	5	2/5/2005	3
9/6/2004	1	10/27/2004	0	12/17/2004	5	2/6/2005	4
9/7/2004	2	10/28/2004	0	12/18/2004	5	2/7/2005	4
9/8/2004	2	10/29/2004	0	12/19/2004	2	2/8/2005	5
9/9/2004	3	10/30/2004	0	12/20/2004	3	2/9/2005	4
9/10/2004	1	10/31/2004	0	12/21/2004	3	2/10/2005	5
9/11/2004	3	11/1/2004	0	12/22/2004	1	2/11/2005	5
9/12/2004	3	11/2/2004	0	12/23/2004	4	2/12/2005	2
9/13/2004	2	11/3/2004	1	12/24/2004	1	2/13/2005	3
9/14/2004	3	11/4/2004	4	12/25/2004	4	2/14/2005	3
9/15/2004	2	11/5/2004	4	12/26/2004	4	2/15/2005	5
9/16/2004	2	11/6/2004	1	12/27/2004	5	2/16/2005	5
9/17/2004	1	11/7/2004	4	12/28/2004	5	2/17/2005	5
9/18/2004	1	11/8/2004	4	12/29/2004	5	2/18/2005	5
9/19/2004	2	11/9/2004	1	12/30/2004	5	2/19/2005	1
9/20/2004	3	11/10/2004	5	12/31/2004	5	2/20/2005	5
9/21/2004	1	11/11/2004	5	1/1/2005	5	2/21/2005	5
9/22/2004	2	11/12/2004	5	1/2/2005	5	2/22/2005	5
9/23/2004	2	11/13/2004	5	1/3/2005	5	2/23/2005	5
9/24/2004	4	11/14/2004	5	1/4/2005	5	2/24/2005	5
9/25/2004	2	11/15/2004	4	1/5/2005	5	2/25/2005	4
9/26/2004	1	11/16/2004	1	1/6/2005	1	2/26/2005	4
9/27/2004	4	11/17/2004	4	1/7/2005	5	2/27/2005	5
9/28/2004	2	11/18/2004	3	1/8/2005	5	2/28/2005	1
9/29/2004	3	11/19/2004	3	1/9/2005	5		
9/30/2004	1	11/20/2004	4	1/10/2005	5		
10/1/2004	4	11/21/2004	4	1/11/2005	2		