# FINAL REPORT

# Columbia River Gorge Haze Gradient Study

Prepared by:

**Mark Green**
**Narendra Adhikari**
**Jin Xu**
**George Nikolich**

Division of Atmospheric Sciences
Desert Research Institute
755 E. Flamingo Road
Las Vegas, NV 89119

January 27, 2006

**Table of Contents**

**Executive Summary** ........ **3**
**1 Introduction** ........ **5**
**2 Monitoring sites, parameters measured, data recovery** ........ **7**
2.1 Monitoring Locations ........ 7
2.2 Instrumentation ........ 9
2.3 Data Recovery ........ 10
**3 Data analysis methodology** ........ **11**
3.1 Cluster analysis to group days with similar wind field characteristics ........ 11
3.2 Computation of pressure field patterns and their diurnal variation by cluster type 16
3.3 Relationship of clusters to particle light scattering coefficient (bsp) and aethalometer derived elemental carbon concentration ........ 18
**4 Results** ........ **19**
4.1 Meteorological Characteristics of each cluster ........ 19
4.1.1 Cluster 1 ........ 22
4.1.2 Cluster 2 ........ 24
4.1.3 Cluster 3 ........ 26
4.1.4 Cluster 4 ........ 28
4.1.5 Cluster 5 ........ 30
4.2 Light scattering patterns by cluster ........ 32
4.3 Aethalometer Elemental Carbon (EC) at Mt Zion and Wishram by Cluster ... 42
4.4 Summary of Cluster Wind patterns ........ 43
4.5 Summary of aerosol light scattering (bsp) patterns by Cluster ........ 44
**5 Summary** ........ **46**
**6 Appendix A – Monthly time series plots of daily average bsp** ........ **48**

# 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.

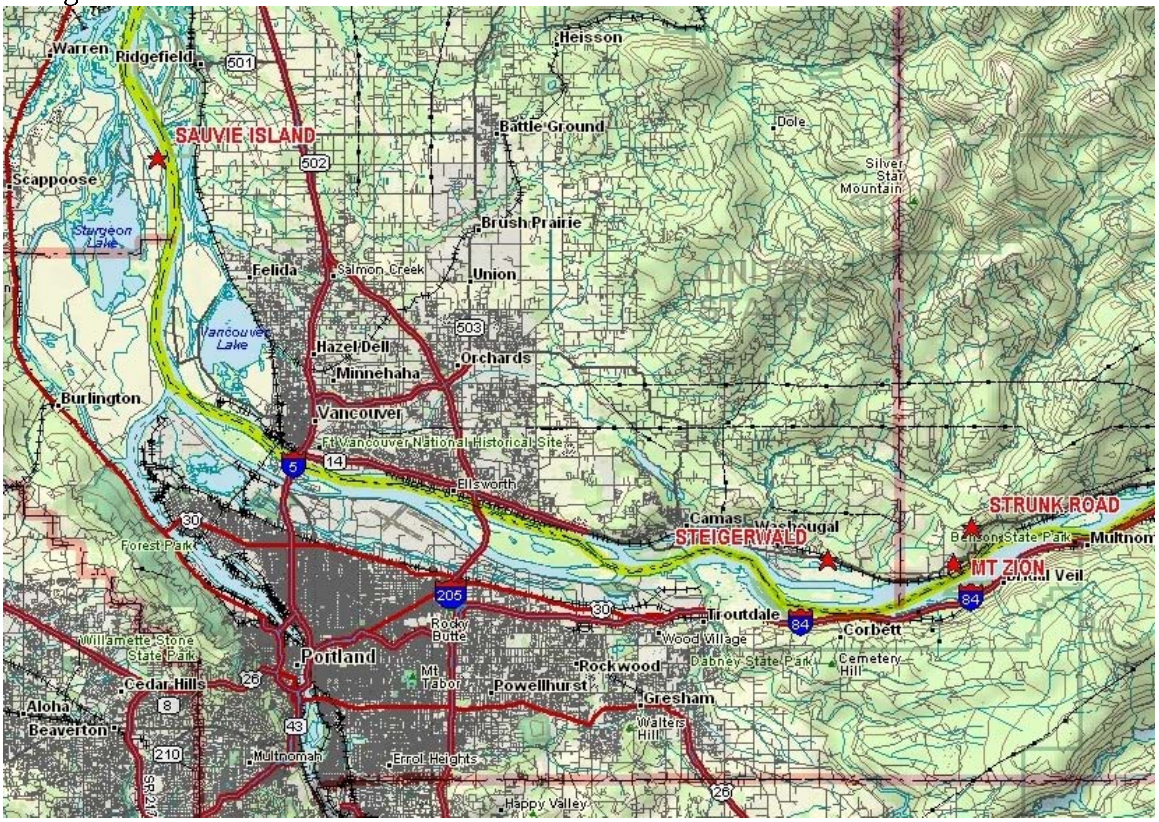



Figure 2-1. Map of western sites (Sauvie Island, Steigerwald, Mt. Zion, and Strunk Road).

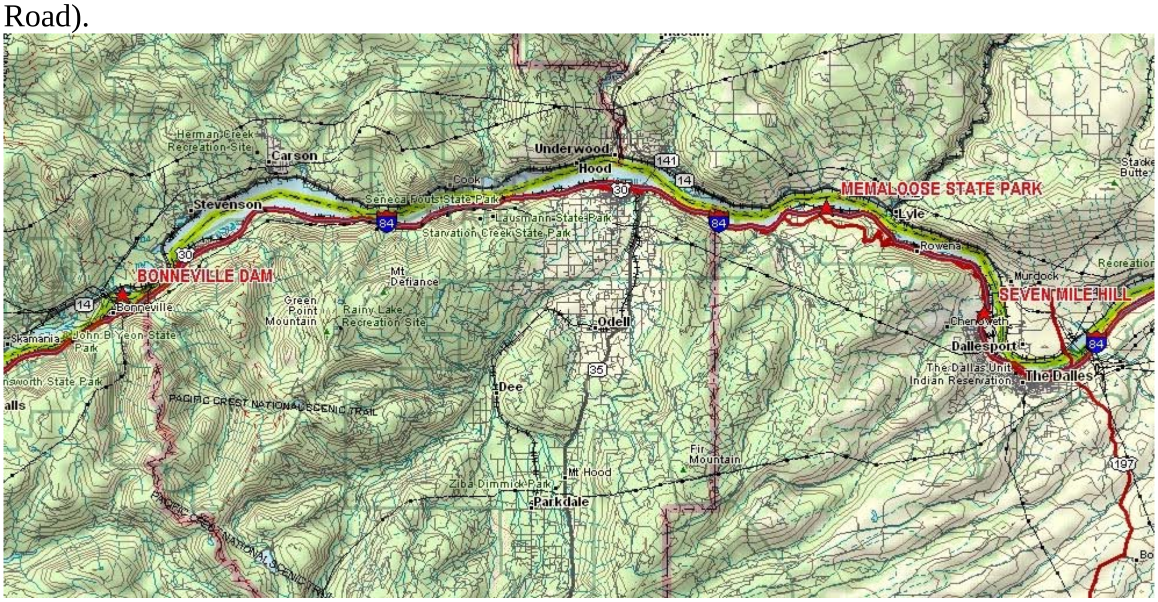



Figure 2-2. Map of Bonneville, Memaloose State Park, and Sevenmile Hill.

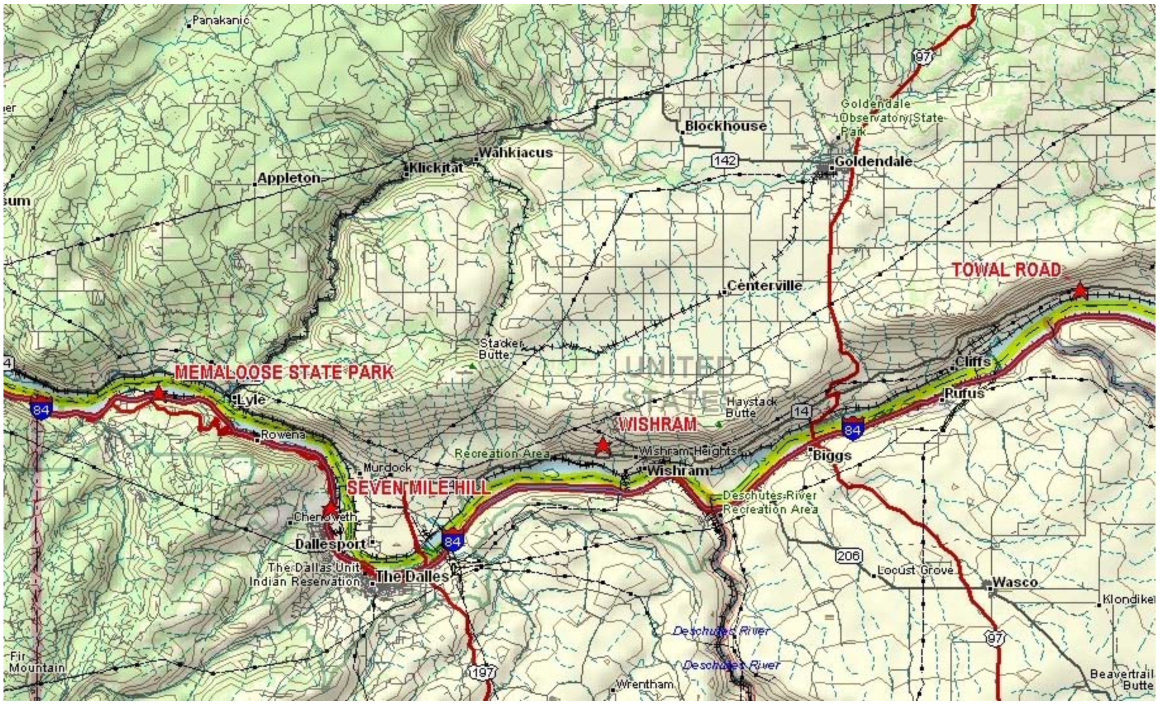



Figure 2-3. Map of eastern sites (Memaloose,Seven Mile Hill, Wishram, and Towal Road.

## 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.

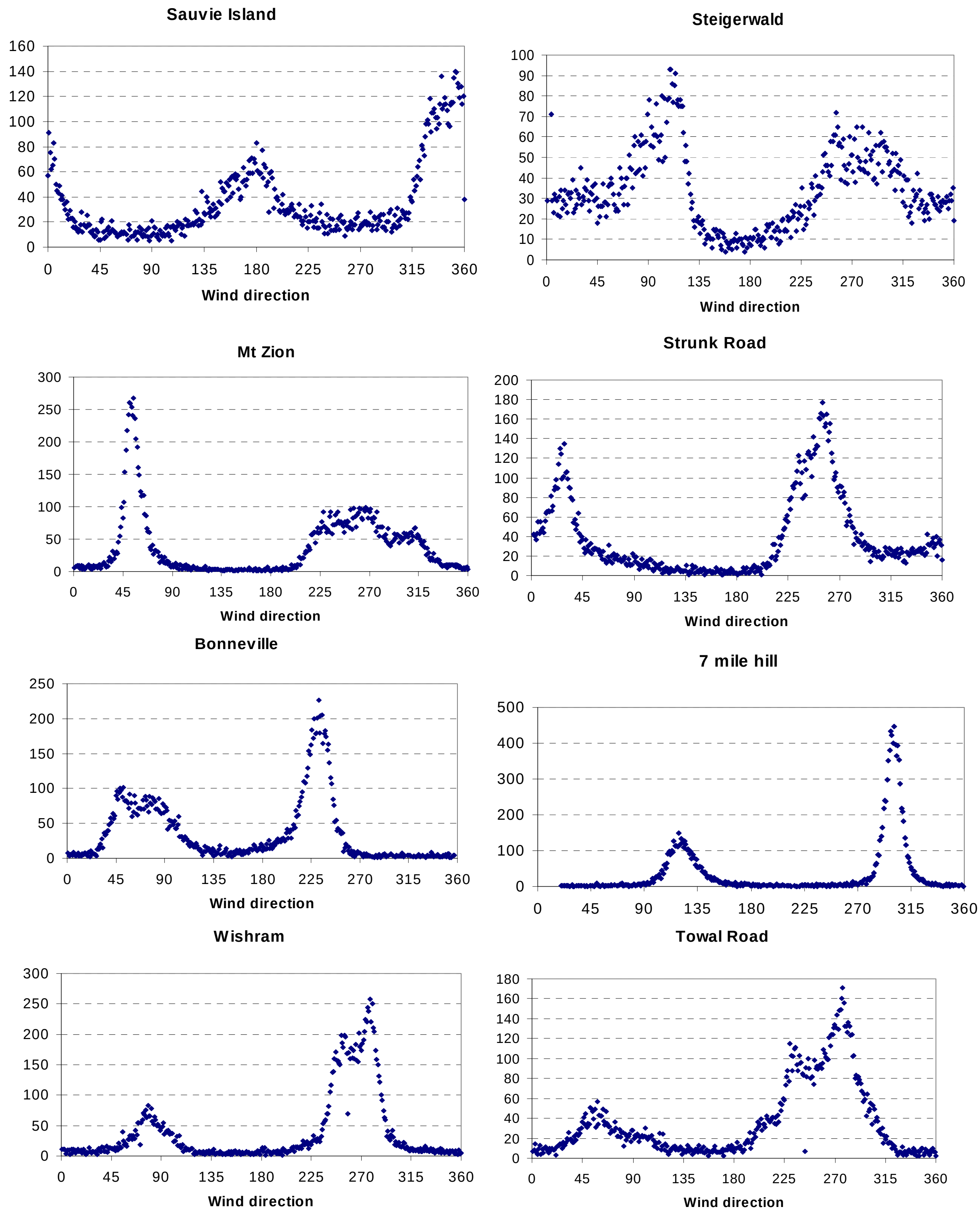
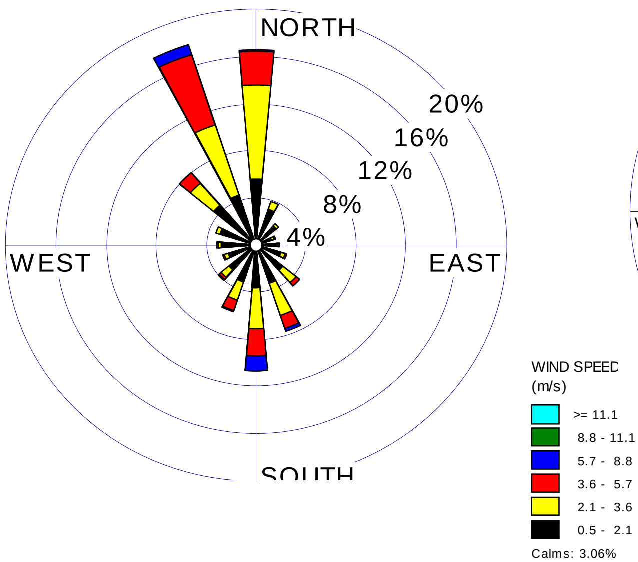
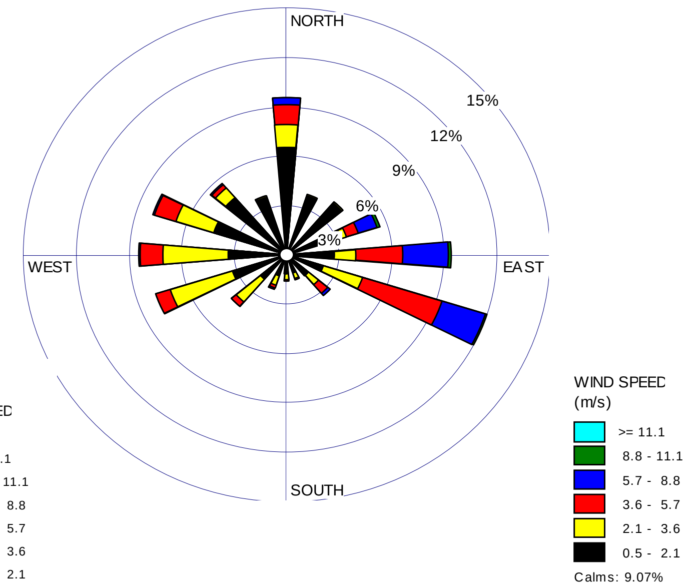



Figure 3-1. Frequency distribution of wind direction by site. X-axis is direction from which wind is blowing (meteorological convention); y-axis is number of hours with wind from each one-degree increment in direction. Period of record is July 1, 2003 to February 28, 2005.

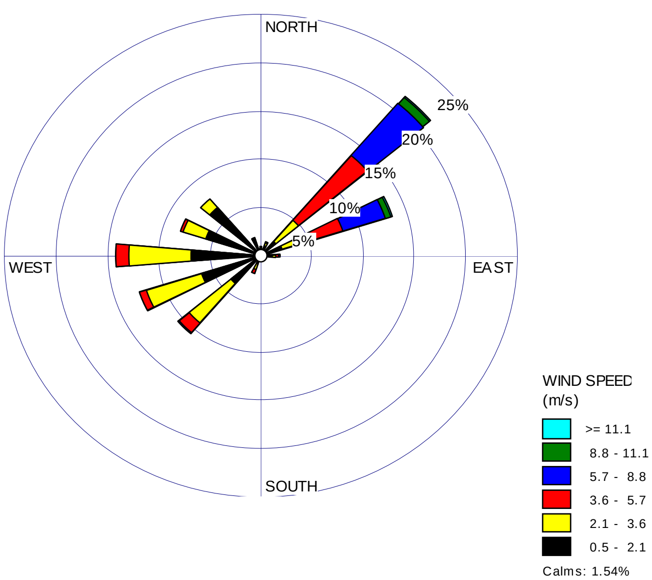
## Sauvie Island



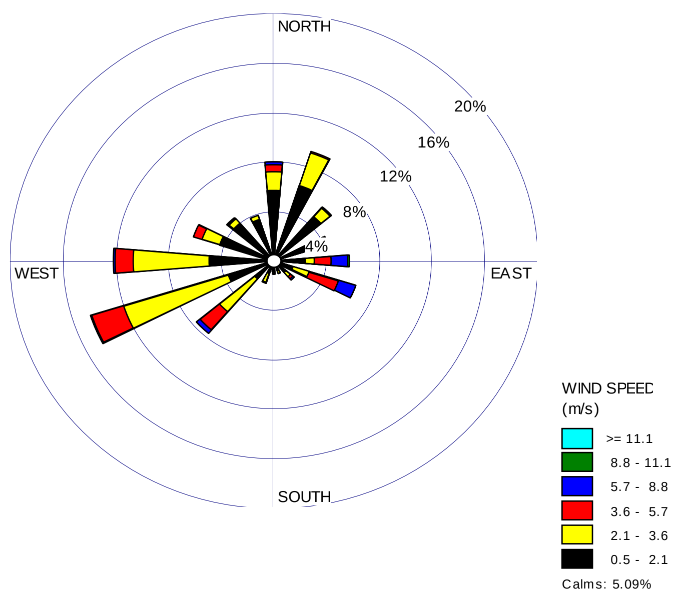

## Steigerwald




## Mt Zion




## Strunk Road



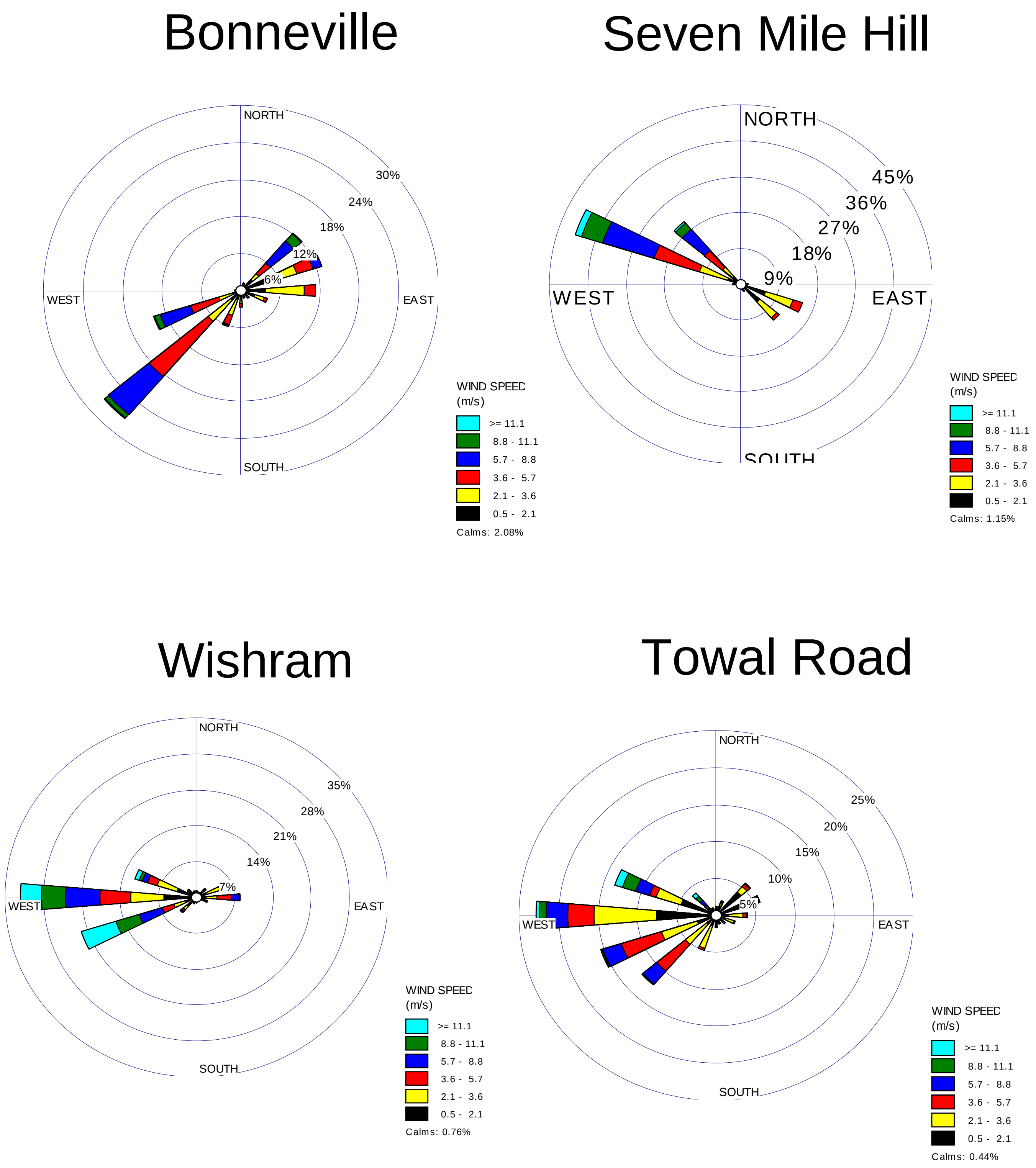



Figure 3-2. Wind roses for duration of the study period (July 2003- February 2005).

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.

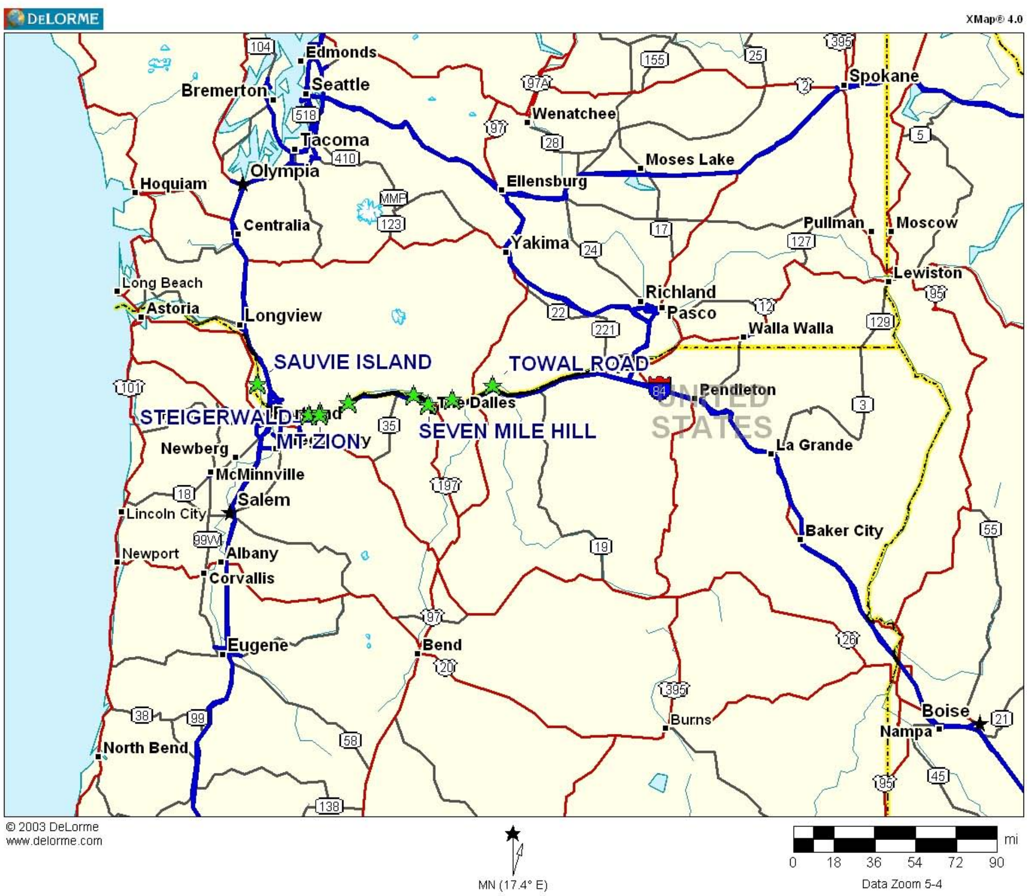



Figure 3-2. Location of monitoring sites for sea-level pressure.

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.