

Appendix B

Analysis of Historical Aerosol Data

This chapter reviews the present state of knowledge regarding aerosols in and around the Lake Tahoe Air Basin (LTAB) to present a “first look” assessment of the kind of aerosols present over the lake, preliminary assign aerosol contributions to various sources, and to provide context for the current field program. This baseline information supports the LTADS science program in three ways: facilitating interpretation of individual field measurements, aiding recognition of unusual events in the field data, and providing the basis for extrapolating from the LTADS measurement period to the long term patterns of meteorology, pollutant emission, and deposition.

1 Aerosol Records

1.1 *Relevance to Tahoe Air Quality and Deposition*

The contemporary aerosol data available for this analysis were collected for traditional air quality purposes – protection of human health and regulation of visibility degradation. As a result, the timing, location, and technical approaches for these measurements reflect the evolving programs and policies of air regulatory agencies, and are generally “sub-optimal” for the characterization of aquatic deposition. The lack of aquatic impact specificity in the data imposes some restrictions on their use and interpretation, but it does not prevent their application here.

Fortunately, the mismatch between routine air quality monitoring methods and deposition-specific needs is more than offset by these data sets’ utility for source interpretation and regional air transport analyses. In fact, the spatial and temporal extent of the routine air quality monitoring far exceeds what could ever have been established for a dedicated network focused on Lake Tahoe.

The historical record in California includes simple total aerosol mass measurements, mass below specified size cuts, and, occasionally, mass in multiple size bins. Routine aerosol chemistry, when measured, tends to focus on particular species (*e.g.* sulfate or lead) or a provide a spectrum of results from a single analytical method (*e.g.* X-ray fluorescence - XRF, or ion chromatography - IC).

Records from the Tahoe Basin include 24-hour samples collected one day in six (TSP, PM10, PM2.5) (CARB, 2003; NDEP, 2003), Wednesday and Saturday, or one day in three (IMPROVE). Recent changes include more frequent sampling - some sites operate every 3 days – and there is a growing network of sites reporting hourly aerosol mass concentration using continuous instruments.

Conventional filter-based aerosol sampling is discontinuous is not ideal for calculating deposition, because, at any point in time, it is a function of the instantaneous

concentrations and deposition velocities of individual pollutant types. Calculating annual deposition thus requires knowing pollutant concentration throughout the year. Discontinuous monitoring allows estimation of long-term average concentrations, but has only a limited probability of measuring absolute maximum and minimum concentrations, and thus leaves some uncertainty in calculating total annual deposition.

Sustained monitoring for many years produces statistics that converge with the “real” range of pollutant concentrations at a site. However, since a limited term program like LTADS cannot wait for this convergence, the decision was made to capture as many hours of pollutant concentration as possible in the roughly one year of LTADS data collection.

The LTADS program design achieves high temporal completeness and broad spectrum chemical characterization by sacrificing temporal resolution. The basic LTADS aerosol sampling method uses two-week integrated filter sampling for multiple chemical analyses (the “Two Week Sampler” – TWS). Four TWS sites are spread around the Tahoe Basin, and there is one “upwind” site on the western slope of the Sierra Nevada between the Lake Tahoe Basin and the San Francisco Bay - Sacramento Valley population mass. TWS sampling is supported by hourly and daily aerosol mass concentration monitoring to assist interpretation of sample results.

1.2 Size, Chemistry, and Aerosol Dynamics

Ambient aerosols are a mixture of particles of different sizes and chemical compositions. At a minimum, particle measurements should categorize them by size and describe the chemical composition of each size category. Greater size specificity, more complete chemical characterization, and more frequent measurement all enhance the value of the data. The “Holy Grail” of aerosol measurement is single particle analysis reporting the size and chemistry of a representative sample of individual particles captured from the air in real time. Such data would permit summarizing particle size distributions and chemical profiles at whatever level of specificity may be required for analysis.

Unfortunately, no measurement method exists that can meet all of these goals; there are research methods that can do some of this, but full aerosol characterization remains unworkable for routine monitoring. Cost, technological limitations, and historical factors (especially the need for temporal continuity within data sets) conspire to present an historical aerosol record that is far from this ideal.

Particle size is the single most important factor in aerosol dynamics – size reflects a particle’s origins and history and governs its atmospheric lifetime. A particle’s size determines how far it can be transported, and how efficiently it can be deposited to land or water. Particle chemistry also varies according to particle size, and thus deposition of particular chemical species, too, is modulated, at least in part, by particle size. Fortunately, health effects, visibility, atmospheric transport and aquatic deposition evaluation all require particle size data. Although the data needs for such analyses are

not entirely parallel, the gradual shift in the size focus of routine aerosol monitoring over recent decades has produced a rich, if poorly coordinated, set of size resolved data both for distinguishing among potential aerosol sources and for characterizing ambient air in the Tahoe basin.

Particle size distributions change during transport as larger, heavier particles settle to the ground (“deposition”) and very fine particles collide and merge into larger particles (“aggregation”). These tendencies cause aged aerosol clouds to have large populations of particles in the size range of 0.1 to 2 μm , often termed the “accumulation mode.” Particles can also grow due to condensation of water onto them, and by heterogeneous chemical processes by which gaseous pollutants react with aerosols and are converted into new aerosol mass. Under conditions of high humidity, particle growth can proceed to the point that aerosol deposition is enhanced as enlarged particles settle more rapidly, and, of course, aerosols incorporated into raindrops are rapidly removed from the atmosphere.

The chemical compositions of aerosols are important not only as they contribute to the chemistry of Lake Tahoe, but also as indices of their origins. Various sources produce aerosols with characteristic chemical compositions. Analysis of aerosol chemistry thus can provide information on what is deposited to the lake, and also permit associating that input with air pollution sources.

In order to properly assess the role of aerosols in atmospheric deposition to Lake Tahoe, sampling must resolve both aerosol size and chemical composition. The discussion below summarizes current data about aerosols in California, the Sierra-Cascade mountain range, and the Tahoe basin in particular, with particular attention to the chemical composition of the “accumulation mode” aerosol as represented by PM_{2.5} (particles less than 2.5 μm diameter).

2 Regional Overview

Understanding Lake Tahoe air quality requires appreciating the regional setting and distinguishing between the regional and local factors that determine pollutant concentrations over the lake. Situated just east of the crest of the Sierra-Cascade mountain chain, in the middle of California’s eastern boundary, Lake Tahoe is often downwind of much of northern and central California, and occasionally downwind of other parts of the state or portions of Nevada. Pollutants such as gases and small particles released almost anywhere in California have at least some potential to reach the lake. The following discussion compares Lake Tahoe data to that from surrounding areas. It begins with a review of statewide PM₁₀ data, then moves to discussion of PM₁₀ and PM_{2.5} data within the Sierra-Cascade mountains, and concludes with detailed evaluation of data collected within the Tahoe basin.

2.1 PM10 in California – A Regional Perspective

California is divided into 15 Air Basins comprised of areas of relatively homogeneous meteorology and free mixing of air, and bounded, where possible, along county lines. Unlike hydrologic basins, air basins are not strict physical entities, but administrative units for tracking air quality and regionalizing control programs. **Figure B-1** maps the state's air basins. **Table B-1** summarizes PM10 "basin maximum"¹ statistics (size selective inlet) by air basin from the 1980s to 2000. Frequency distributions of basin maxima are plotted in **Figure B-2**. The seasonal distributions of basin maxima are shown by month in **Figure B-3**.

2.2 PM10 by Air Basin

The data in **Table B-1** and perusal of **Figure B-2** and **Figure B-3** permit insights into the differences among the air basins. Sorted in order of increasing mean concentration, the air basins fall into four general groups.

Group 1 contains only Lake County (LC). LC is an anomaly in this data set: the absence of any strong PM10 sources near the basin's single monitor and the county's low population density work together to produce a record with no reported high PM10 days (unusual events such as large wildfires are excluded from these data). The Lake County data are anomaly of many rural areas in the state unaffected by urban, industrial, or large-scale agricultural activities.

Group 2 includes much of eastern California: Great Basin Valleys (GBV), Northeast Plateau (NEP), and Lake Tahoe (LT) air basins. These basins are generally rural, with limited agriculture and low population density. These basins are generally "clean" areas, recording many days with very low PM10 (below 10 $\mu\text{g}/\text{m}^3$), but there are pockets of high PM10 associated with winter chimney-smoke accumulation and one large dust source in the GBV (i.e., Owens Lake). It is interesting to note that the median concentrations in these basins show no relation to their extreme values.

Group 3 includes most of the rest of the state: North Coast (NC), San Francisco Bay (SFB), Central Coast (North (NCC) and South (SCC)), Mountain Counties (MC), Sacramento Valley (SV), Mojave Desert (MD), and San Diego (SD). These basins show low to moderate PM10 loadings most of the time, while the maxima are driven mostly by high winter PM10 concentrations in population centers – the exception being Mojave, which experiences infrequent strong springtime dust events in some areas.

Group 4 includes the heavily farmed and urbanizing San Joaquin Valley (SJV), the irrigated Salton Sea (SS) region (Coachella and Imperial Valleys), and the Los-Angeles megalopolis in the South Coast (SC). PM10 maxima exceed 100 $\mu\text{g}/\text{m}^3$ in all seasons; values below 10 $\mu\text{g}/\text{m}^3$ are rare. Both dust and combustion are strong contributors in these areas.

¹ "Basin Maximum" is the highest value recorded anywhere in the basin during each monitoring period.

From a statewide perspective, the Lake Tahoe Air Basin is a low pollution area. PM10 air quality in the Lake Tahoe basin is somewhat cleaner than the foothill and mountain areas of the Mountain Counties Air Basin, and more like that in areas more isolated from the pollution sources in western California (the Northeast Plateau Air Basin and the northern portions of the Great Basin Valleys Air Basin). The basin maxima records support the general impression of the Lake Tahoe basin's air as being relatively "clean," but the data also show that the basin is far from "pristine." This is an expected consequence of the basin's moderate population density and intensive recreational use, although these data give no indication of the sources of PM in the basin.

Figure B-1. California Air Basins.



Table B-1. California PM10 Statistics for Daily Maxima by Air Basin 1986-2000 ($\mu\text{g}/\text{m}^3$)

AIR BASIN	MINIMUM	MAXIMUM	ARITHMETIC MEAN	MEDIAN	STANDARD DEVIATION	BASIN DAYS
Lake County	2	67	12	11	6.3	826
Great Basin Valleys	1	3059	48	21	130.6	1812
Northeast Plateau	0	249	26	22	19.5	937
Lake Tahoe	1	177	27	23	16.4	830
North Coast	3	266	31	27	18.9	1326
North Central Coast	5	152	32	29	15.4	1019
San Francisco Bay	5	173	36	29	23.2	1601
Mountain Counties	3	350	40	33	29.5	1127
South Central Coast	3	321	40	36	24.1	1509
Sacramento Valley	2	179	42	36	25.4	1562
Mojave Desert	3	780	44	37	42.4	1247
San Diego	10	159	42	38	19.6	1201
San Joaquin Valley	6	439	64	54	41.1	1805
Salton Sea	3	1613	87	66	98.9	1280
South Coast	1	649	76	69	46.1	1375

Figure B-2. Frequency distributions (percent) of basin maximum PM10 concentrations (log scale - $\mu\text{g}/\text{m}^3$).

(Vertical lines are medians (values after names). Plots arrayed as a quasi-map of the state.)

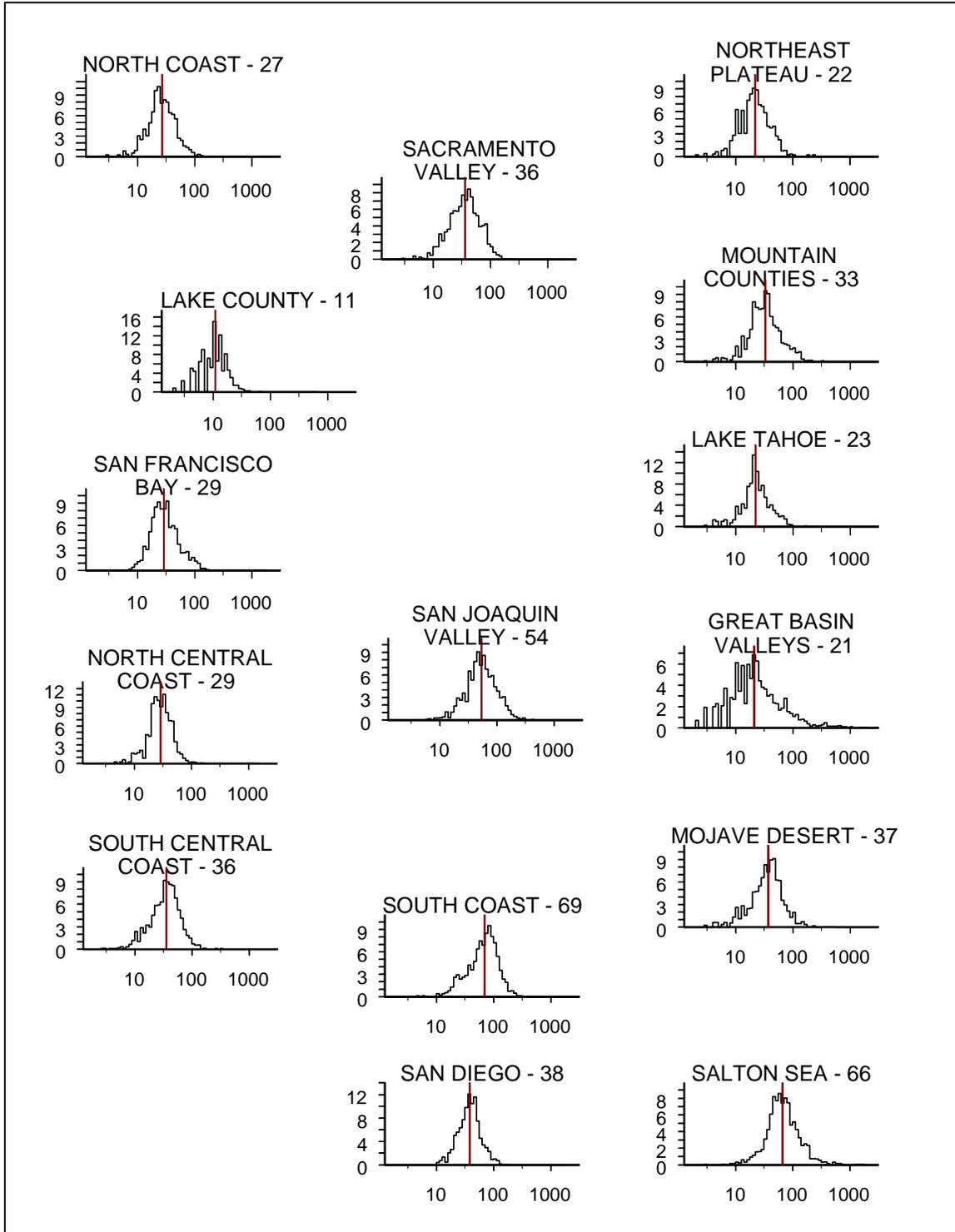
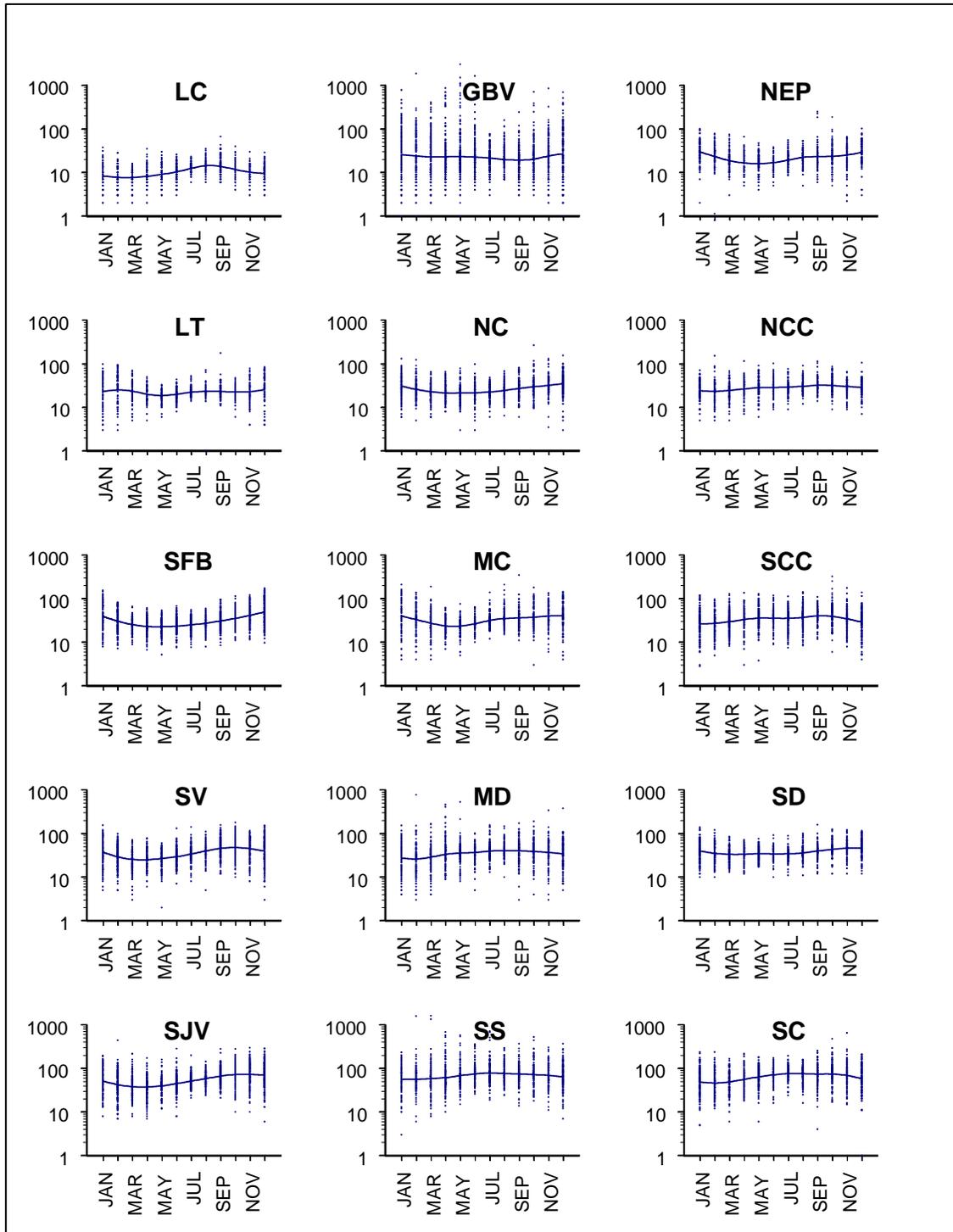


Figure B-3. Monthly distributions of PM10 basin maxima ($\mu\text{g}/\text{m}^3$) 1980s to 2000. Curves connect monthly means.



3 Sierra PM Patterns – The Lake Tahoe Basin in a Montane Perspective

3.1 General

The Sierra-Cascade mountain chain lies cross-wise to the prevailing westerly winds, downwind of most of the populated regions along the Pacific coast and the major agricultural inland valleys. This geographic orientation suggests that air pollution generated in the coastal zone or California's Central Valley has the potential to reach into the mountain (Elford, 1974). This simple image, however, does not take into account the complicated interactions of wind and terrain in California that cause air pollutant concentrations in the mountains to vary strongly with altitude, exposure, and season.

The basic mechanism of air movement and pollutant dispersal in spring and summer in California is thermal advection. Cool, marine air is driven onshore by local pressure differences created by rising warm air inland. The sea breeze in coastal regions moves pollutants inland; "delta breezes" move air up the major valleys between the mountain ranges – up the Salinas valley from Monterey Bay, into the Napa Valley from San Pablo Bay, and through the Sacramento-San Joaquin delta into the lower reaches of the Sacramento and San Joaquin Valleys. Higher temperatures ("thermal lows") farther up these valleys draw air north toward Redding and south toward Bakersfield. The heated western slopes of the mountains create a "chimney effect" drawing valley air eastward up major canyons. Under the right conditions, pollutants from upwind areas can reach far into the mountains, occasionally overtopping the crest of the range (Austin and Gouze, 2001).

In fall and winter, solar heating weakens; cool inland areas develop persistent stable air masses, pollutant transport diminishes, and air quality in most areas is determined by "stagnation." Transport into the mountains is negligible in winter, but during this "clean" season many mountain communities experience very high pollutant concentrations due to trapping of locally generated pollutants, especially wood smoke from domestic heating.

There is also a vertical dimension to airflow in California. The "meso-scale" processes noted in the preceding paragraphs adequately describe meteorological controls on air quality at low altitudes where the ocean and land interact strongly with the atmosphere. At high elevations, "macro-scale" meteorological factors operating at continental and hemispheric scales govern air movements, and local air quality in unpopulated montane locations is a product of these global dynamics modulated on a "micro-scale" by local terrain. The vertical boundary between these two regimes varies day-to-day and seasonally. On the coast it is typically less than 500 meters almost year-round; inland it ranges from 500 to 1000 meters in fall and winter to almost twice that in spring and early summer.

The following discussion compares air quality across a suite of sites in the Sierra-Cascade range to demonstrate how micro-, meso-, and macro-scale dynamics interact to modulate air quality in mountain environments.

3.2 A Transect from Sequoia to Crater Lake

The Federal Interagency Monitoring of Protected Visual Environments (IMPROVE) program operates a network of aerosol sampling sites in National Parks and Wilderness Areas throughout the U.S. (Cahill and Wakabayashi, 1993; Malm *et al.*, 1994). This includes four long-standing sites that bookend the Californian portion of the Sierra-Cascade range: Sequoia National Park and Yosemite National Park in the southern Sierra, and Lassen Volcanic National Park and Crater Lake National Park straddling the California-Oregon border in the southern Cascade range. The Tahoe Regional Planning Agency (TRPA) has supplemented these sites with two “IMPROVE Protocol” sites located in the Tahoe Basin: an urban site at lake level at South Lake Tahoe, and an elevated rural site at D. L. Bliss State Park, near Emerald Bay. Although not part of the IMPROVE network, these sites duplicate the IMPROVE measurements.

The IMPROVE data reviewed here consist of more than 10 years of 24-hour integrated PM₁₀ and PM_{2.5} samples taken every Wednesday and Saturday. IMPROVE analyzes PM₁₀ samples for mass, PM_{2.5} for mass, 24 elements in the range from Na (atomic Number 19) to Pb (atomic number 82), organic and elemental carbon, and chloride, sulfate and nitrate ions². These sites are mapped in **Figure B-1**.

3.3 Sierra-Cascade Site Characteristics

The Sierra-Cascade IMPROVE sites run the gamut of montane air quality conditions from near pristine to strong, frequent pollutant impact.

The **Crater Lake National Park** IMPROVE site (CRLA or Crater Lake) sits at 1981 m (6500 ft.) elevation on the crest of the Cascade Range in southern Oregon. This site is higher than the average crest of the coastal ranges to the west, and thus open to air flowing off the Pacific Ocean. This site it is remote from any major North American urban or industrial pollutant sources.

² IMPROVE analysis includes 24 elements (Al, As, Br, Ca, Cl, Cr, Cu, Fe, K, Mn, Mo, Na, Ni, P, Pb, Rb, S, Se, Si, Sr, Ti, V, Zn, Zr) measured by proton-induced x-ray emission (PIXE) and x-ray fluorescence (XRF), selected ions (Cl⁻, NO₃⁻, SO₄⁼) by ion chromatography (IC), organic and elemental carbon (OC/EC) by staged thermal desorption and combustion, and total hydrogen by proton elastic scattering (PESA). IMPROVE reports PM_{2.5} mass down to about 300 ng/m³ with uncertainty of ± 200 ng/m³.

Figure B-1. Six IMPROVE sites in the Sierra Nevada and southern Cascade mountain chain.

(CRLA: Crater Lake; LAVO: Lassen Volcanic National Park; BLIS: D. L. Bliss State Park; SOLA: South Lake Tahoe; YOSE: Yosemite National Park; SEQU: Sequoia National Park.)



The **Lassen Volcanic National Park** IMPROVE site (LAVO or Lassen or Mt. Lassen), altitude 1790 m (5900 ft), is at Manzanita Lake, about 8 km (5 mi.) NNW of Lassen Peak. This site is weakly separated from the Pacific Ocean by coast ranges somewhat higher than those in Oregon (Yolla Bolly-Trinity-Siskiyou- Marble Mts.), and exposed to occasional upslope transport from the head of the Sacramento Valley. Nonetheless, air quality at Lassen is generally comparable to that at Crater Lake (Sisler *et al.*, 1996).

Although separated by 265 km, Crater Lake and Mt. Lassen experience very similar air quality; they are presented here to represent regional montane air quality in the absence of major upwind urban or industrial emissions.

The **D. L. Bliss State Park** IMPROVE site (BLIS or Bliss) is located at 2042 m (6700ft), above and west of Highway 89, about 150 m (550 ft.) above and 1.5 km (1 mi.) west of the mouth of Emerald Bay. This site was initially established by TRPA as an elevated site to represent regional air quality for the Tahoe basin; in 2001 it was taken over by IMPROVE to represent the air quality for the region's Sierra crest Wilderness areas (Desolation and Mokelumne). BLIS represents the Tahoe basin above the near-lake surface inversion (or in its absence, the whole basin), and is included in this comparison to represent a montane site exposed to transport from the Sacramento Valley. Transport from the west (Sacramento Valley) may reach BLIS but be prevented from mixing to the lake surface when the lake inversion is present. It is extremely unlikely that material regularly transported into the basin from the west could reach the lake surface without being sampled at BLIS.

The **South Lake Tahoe** IMPROVE Protocol site (SOLA or South Lake Tahoe) is near lake level (1905 m, 6250 ft) in the city of South Lake Tahoe. It sits on the north side of Lake Tahoe Blvd., approximately 250 m (800 ft) west of Trout Creek and about 100 m (300 ft) from the lake shore. This site is operated by TRPA as part of their air quality and visibility program. SOLA represents air quality in the most heavily developed, high traffic areas around the lake.

The **Yosemite National Park** IMPROVE site (YOSE or Yosemite), at 1615 m (5300 ft) on Turtleback Dome, is about 500 m (1500 ft) above the Merced River and about 20 km (12 mi.) west of Yosemite Village. YOSE is exposed to regional upper air flow, transport up-canyon from the San Joaquin Valley, and, occasionally, to local pollutants generated in the Yosemite Village area. This site is typical of montane sites exposed to occasional transport impacts from the heavily polluted San Joaquin Valley.

The **Sequoia National Park** IMPROVE site (SEQU or Sequoia) is the lowest of this group at 549 m (1800 ft.), situated at Ash Mountain in the canyon of the Kaweah River. This site is typical of low elevation canyon and foothill locations that are frequently below the Valley inversion and thus regularly exposed to Central Valley pollutants.

3.4 PM Mass

Figure B-2 and **Figure B-3** show total and monthly mass concentration frequency distributions for coarse particles (2.5 – 10 µm diameter) and **Figure B-4** and **Figure B-5** show total and monthly mass concentration frequency distributions for fine particles (<2.5 µm diameter) for the six Sierra-Cascade sites. The distributions reflect the effects of location and altitude. Crater Lake data are used as a benchmark for site comparisons.

Crater Lake and Lassen show nearly identical distributions for both coarse and fine mass, reflecting the similarity of the sampler environments (remote, lightly populated montane forest) and the common, persistent influence of hemispheric-scale circulation patterns.

Bliss generally shares the same dominant modes as Crater Lake and Mt. Lassen. The coarse mass distributions are essentially the same, and the fine mass is only modestly elevated at Bliss, showing that the regional patterns dominate all three sites.

Bliss' coarse particle data show a compressed distribution relative to Crater Lake and Lassen, with somewhat fewer very low mass days (below 0.5 µg/m³) and fewer elevated mass days (over 10 µg/m³). Since locally generated dust is a significant source of coarse mass, the difference is probably due to differences in local traffic. The very low coarse mass events at Crater Lake and Mt. Lassen reflect the very limited winter activity at these two northern sites, especially compared to winter visitation to the Tahoe basin. At Bliss, Hwy 89 remains open much of the winter, reducing the number of very clean days. The reduced number of high coarse mass days at Bliss probably reflects the reverse situation in summer, when visitation at Crater Lake and Lassen peak, while there is little development and less intense summer visitor activity in the immediate vicinity of the Bliss sampler.

Bliss' fine mass shows a modest increase compared to Mt. Lassen, which is, in turn, a little higher than Crater Lake. The increase at Mt. Lassen appears to be due to somewhat higher springtime values, while the increase between Mt. Lassen and Bliss appears to be driven by increased winter concentrations and fewer low-mass days throughout the year. This pattern suggests a north-south gradient of increasing summer upslope transport, consistent with the increased upwind populations, coupled with a modest but consistent fine particle impact at Bliss, perhaps from within the Tahoe basin.

Yosemite is somewhat "dirtier" overall than Bliss, but still follows the pattern for the other open montane sites (CRLA, LAVO, and BLIS). Yosemite coarse mass data show a reduction in very low days similar to that of Bliss, again probably due to higher winter activity, but with a corresponding increase in high-mass events, as well. The fine mass data for Yosemite show a general tendency toward higher mass numbers except in mid-winter (Dec.-Jan.). This is consistent with the lower altitude and western slope location of the site compared to Crater Lake, Lassen, or Bliss, as well as the greater upwind particle source in the San Joaquin Valley (compare the SJV and SV PM10 data in **Figure B-2** and **Figure B-3**). Moreover, the canyon location increases exposure to

upslope air movement, probably increasing the frequency with which Central Valley air reaches this site.

Sequoia mass frequency data (**Figure B-2** and **Figure B-4**) clearly show that it does not experience the same regional air masses as do the higher open montane sites (CRLA, LAVO, BLIS, and YOSE). Located at low elevation and connected to the floor of the San Joaquin Valley by the canyon of the Kaweah River, Sequoia receives transported PM from the valley on a regular basis. The Sequoia IMPROVE site's modest elevation puts it above the Valley inversion only infrequently, primarily in winter. The monthly data in **Figure B-5** reflect this with high diversity in mass concentrations in winter (Dec.-Jan.-Feb.) as the site is alternately in and out of contact with the Valley floor air mass. As spring progresses, the Valley inversion rises above the altitude of the Sequoia IMPROVE site; the low mass concentration days cease, and transport from the San Joaquin Valley occurs almost every day. The Sequoia data have the classic temporal structure of a transport-dominated site – concentrations peak in summer when moderate mixing levels, stable regional air masses, high source-area emissions, and thermally-driven surface winds combine to easily move pollutants horizontally.

South Lake Tahoe is unique in this set. The seasonal cycles at all other sites show winter minima and summer maxima, consistent with transport from distant sources as the dominant aerosol source. South Lake Tahoe, on the other hand, peaks in winter, when transport dynamics are weakest. Under stable, calm conditions aerosols tend to accumulate near their sources. In winter, air is frequently trapped on the floor of the Tahoe basin by a local temperature inversion. Under these conditions, locally produced pollutants accumulate, including both coarse and fine aerosols; the data indicate that South Lake Tahoe is its own pollutant source in winter. Moreover, comparison with nearby Bliss suggests a significant local input in summer, as well.

Figure B-2. Coarse mass (2.5 – 10 μm diameter) concentration frequency distributions.
(The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

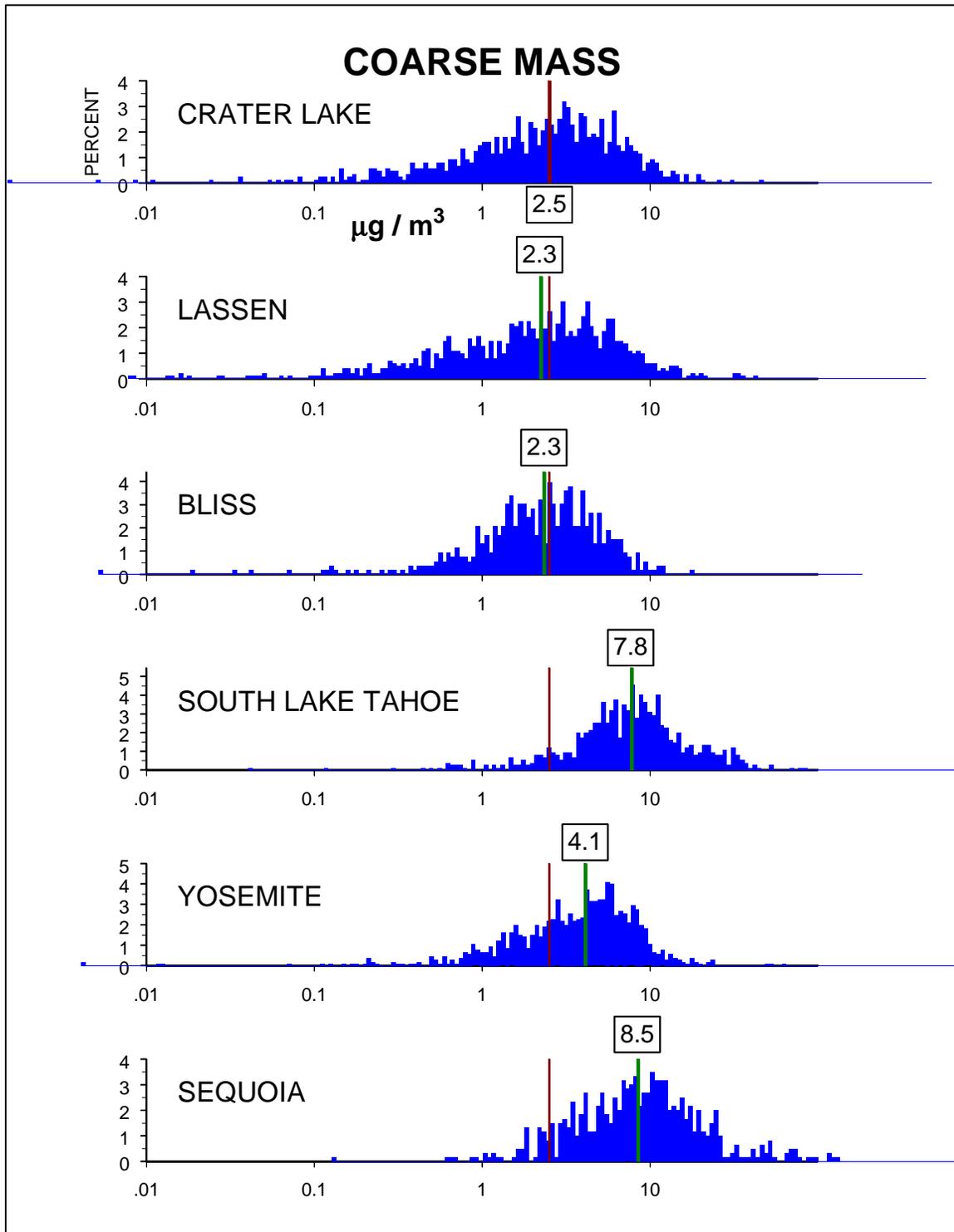


Figure B-3. Coarse mass monthly distributions ($\mu\text{g}/\text{m}^3$).

(The center line at each month is the median; the notch is the standard deviation; the bottom line spans the first quartile, the lower box section the second, the upper box section the third, and the upper line spans the fourth. Reference lines at Crater Lake 10th and 90th percentiles.)

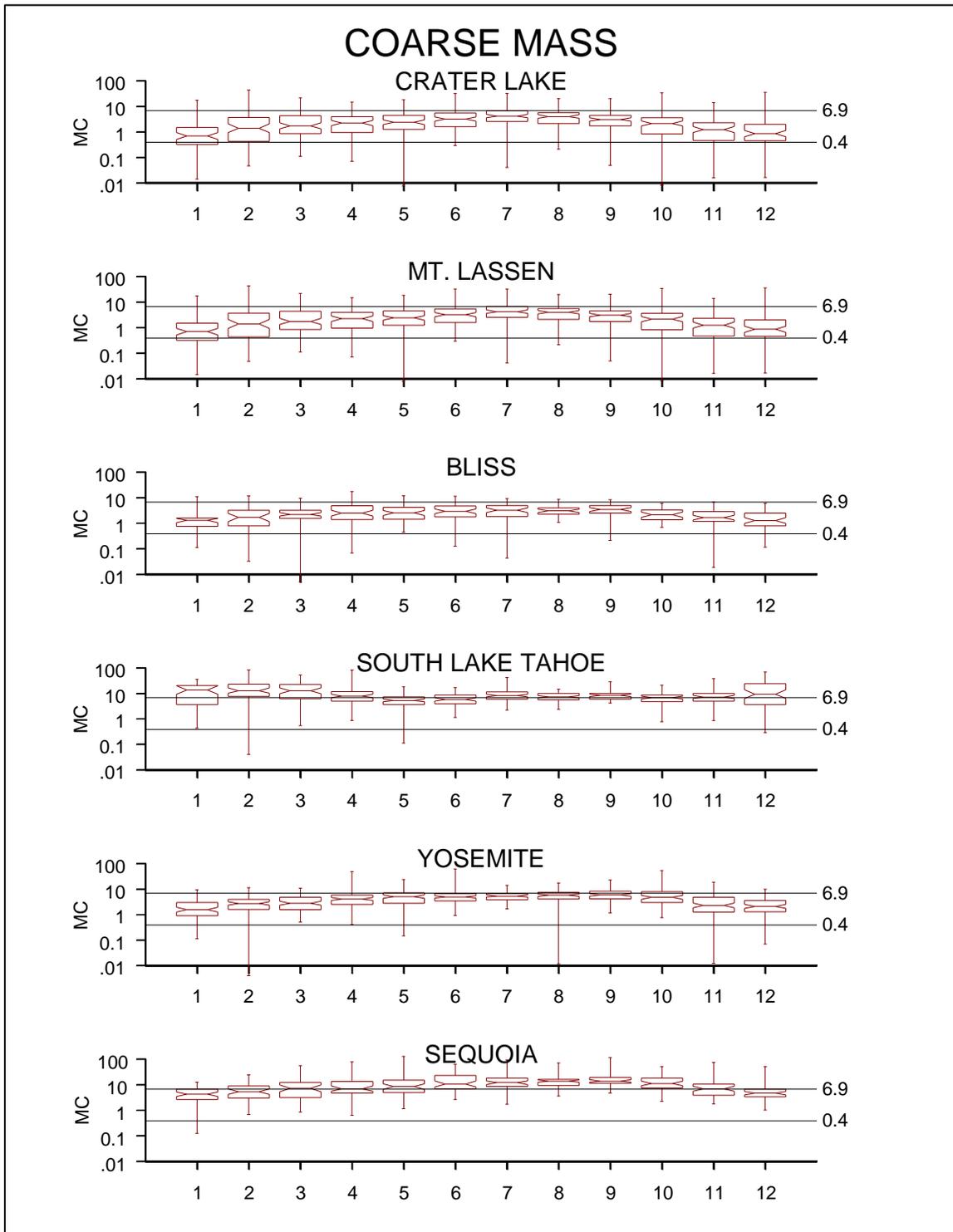


Figure B-4. Fine mass (< 2.5 μm diameter) concentration frequency distributions. (The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

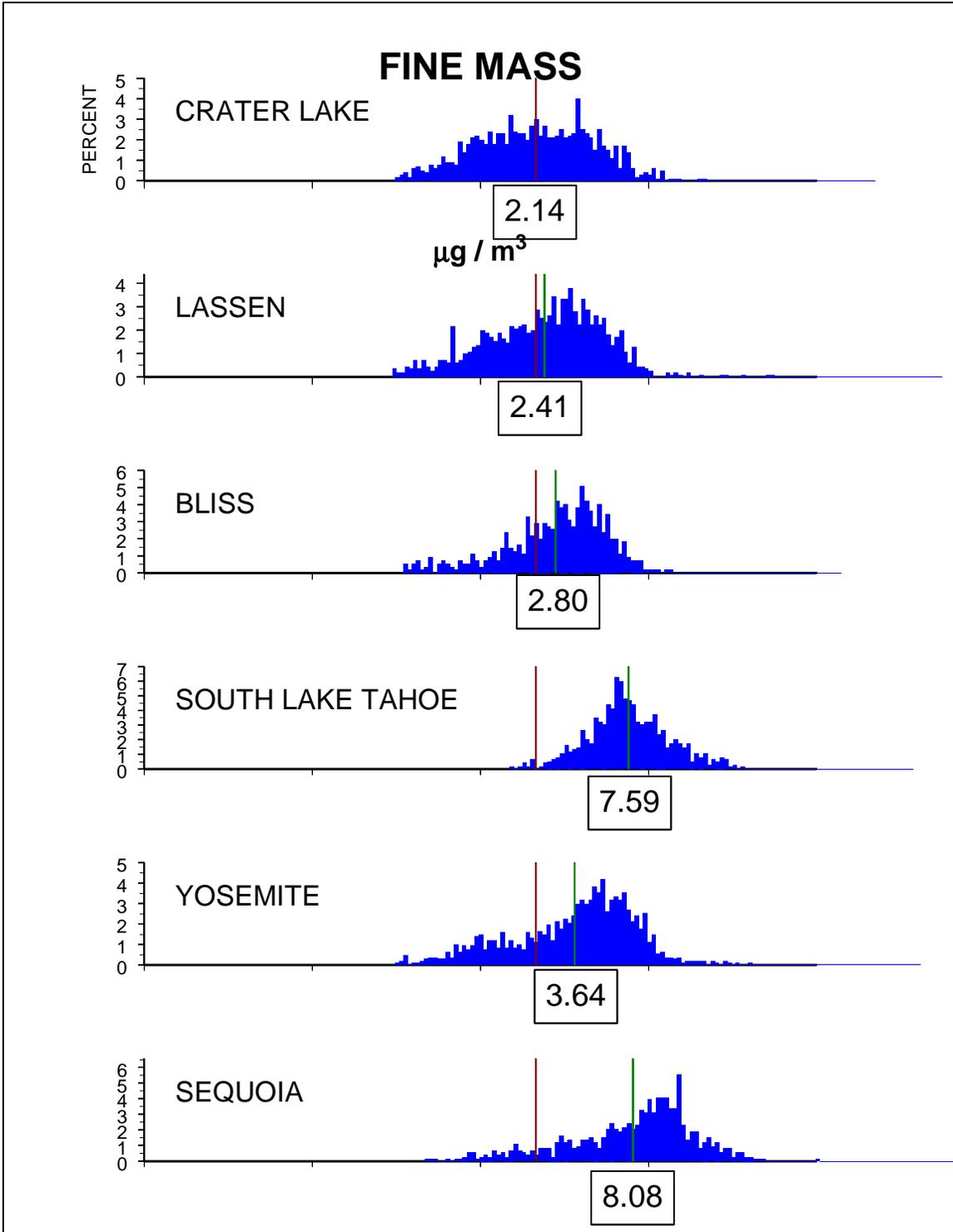
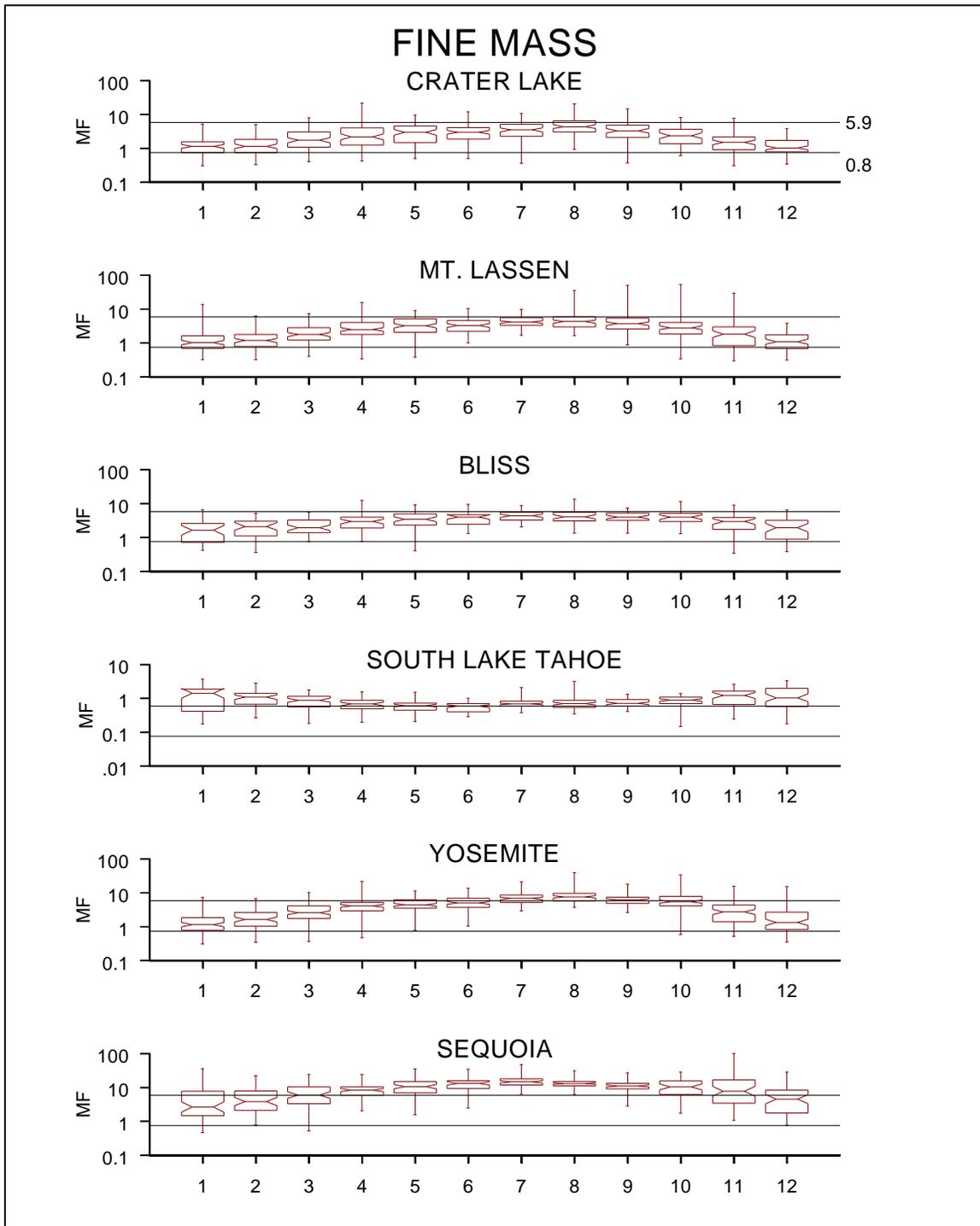


Figure B-5. Fine mass monthly distributions ($\mu\text{g}/\text{m}^3$).

(The centerline at each month is the median; the notch is the standard deviation; the bottom line spans the first quartile, the lower box section the second, the upper box section the third, and the upper line spans the fourth. Reference lines at Crater Lake 10th and 90th percentiles.)



3.5 *PM Composition*

The composition of the aerosols reaching montane sites in the Sierra-Cascade range is broadly similar, but individual site chemical data provides useful clues to the sources of pollution.

3.5.1 “Soil”

Figure B-6 shows frequency distributions for fine soil for the six Sierra-Cascade sites. Crater Lake, Mt. Lassen, Bliss, and Yosemite have nearly identical distributions, while South Lake Tahoe and Sequoia are sharply different. The pattern clearly shows the effect of human activity at South Lake Tahoe and Sequoia.

Sequoia fine soil runs the gamut from very small loadings, similar to the cleanest days at the high mountain sites, to very high soil loading due to exposure to material transported from the San Joaquin Valley.

South Lake Tahoe fine soil loadings span a much narrower range of concentrations; the lack of very low values reflects the nearly continuous emission of road dust due to urban traffic, while the lack of very high values shows that this site does not experience local “dust storms” or the strong transport from upwind agricultural areas seen at Sequoia.

The seasonality of fine soil (**Figure B-7**) follows the pattern of the overall frequency data: Crater Lake, Lassen, and Bliss are similar, while the South Lake Tahoe and Sequoia data are idiosyncratic.

Sequoia fine soil follows an annual cycle similar to that at the high altitude montane sites. Fine soil is very low in mid winter, but the enhanced transport from the San Joaquin Valley in the warm seasons causes the concentrations to be two to ten times higher in midsummer.

The seasonal cycle at South Lake Tahoe clarifies why the annual distribution is so narrow. Summer soil concentrations are not a great deal higher than at the other montane sites, but the winter values at South Lake Tahoe do not drop (in January, South Lake Tahoe soil is about ten times that at Mt. Lassen, Crater Lake, or Bliss). This is due to the continuing road dust emissions in the urban area, especially when roads are sanded for winter traction; a sharp contrast to the unpopulated montane sites where traffic is light and snow cover strongly suppresses local dust.

Figure B-6. Fine soil (<2.5 µm diameter) concentration frequency distributions.
 (The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

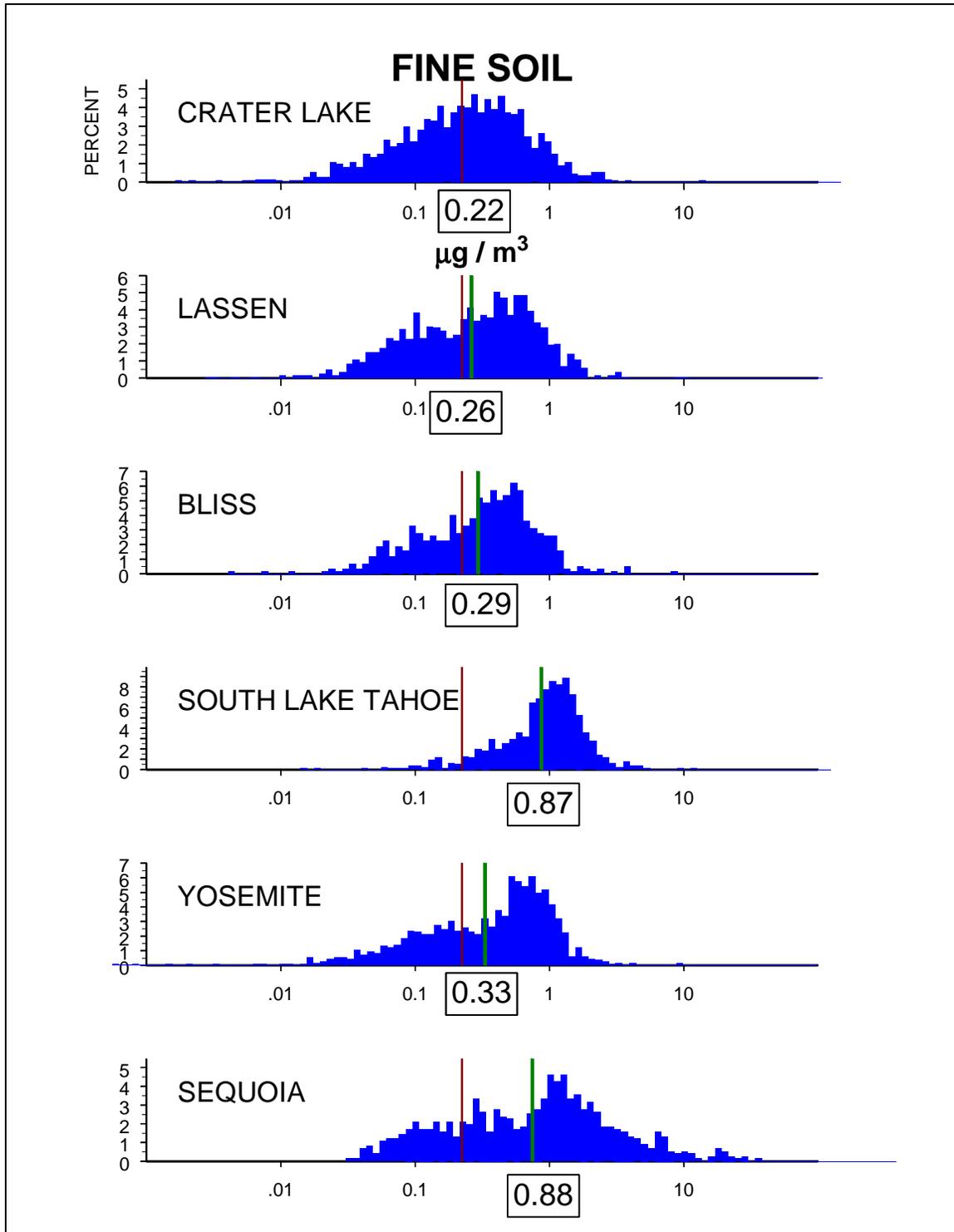
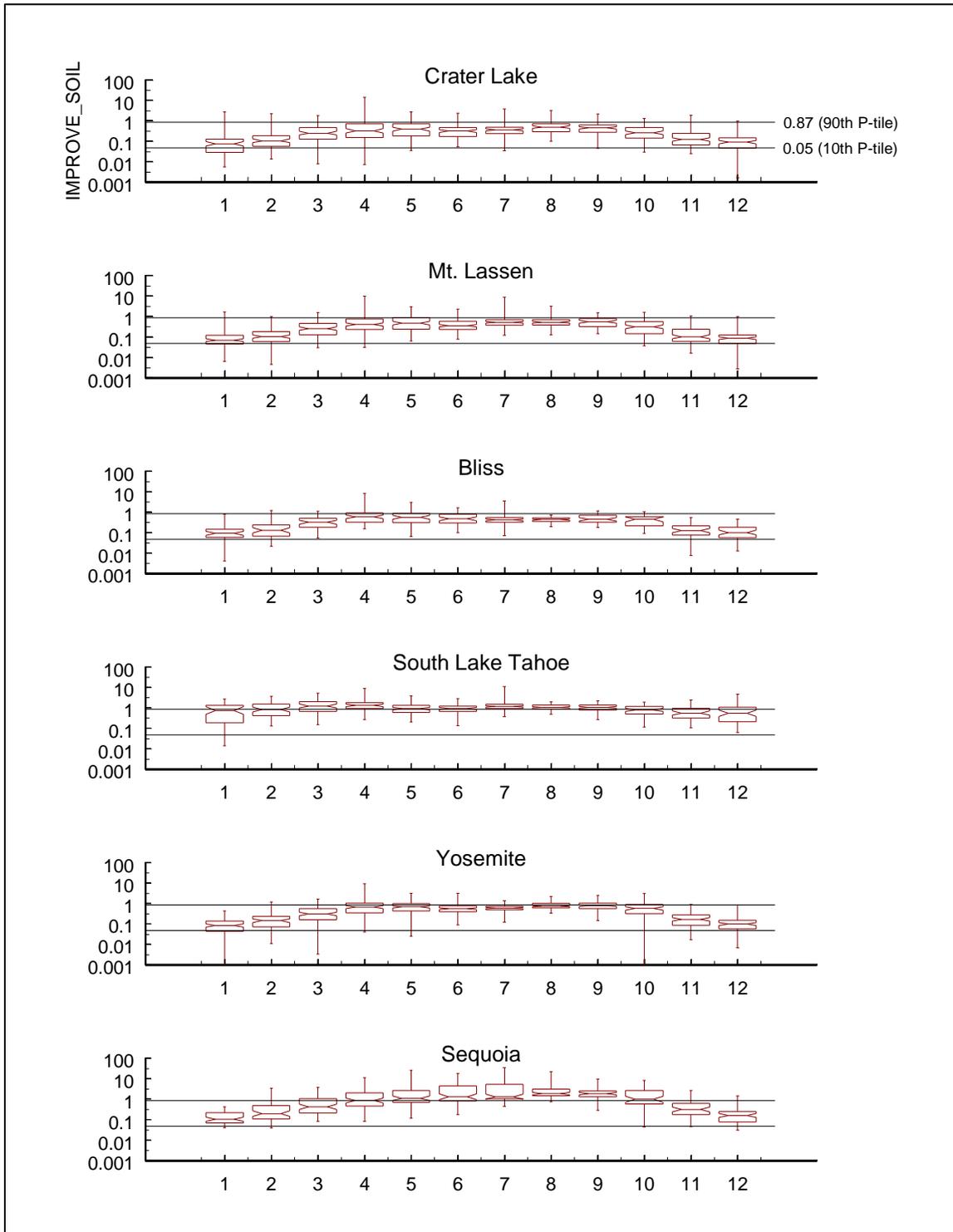


Figure B-7. Seasonal distributions of fine soil ($\mu\text{g}/\text{m}^3$).
(Reference lines at Crater Lake 10th and 90th percentiles.)



3.5.2 Carbon

Carbonaceous aerosols originate from multiple sources, including biomass burning, motor vehicle emissions, industrial and utility fossil fuel use, and atmospheric conversion of organic vapors to aerosols. In the Sierra-Cascade region carbon from biomass burning (wild fires, prescribed fires, domestic heating, campfires, etc.) is a substantial source, while motor vehicles and distant urban and industrial sources contribute smaller fractions. **Figure B-8** and **Figure B-9** show the mass distributions and seasonal cycles for carbon at the six Sierra-Cascade sites.

The annual ranges for Crater Lake, Mt. Lassen, Bliss, and Yosemite are substantially similar, but the frequency distributions for Yosemite and Bliss are skewed toward higher values. Sequoia skews even more toward higher values, but still has some very low carbon loadings. South Lake Tahoe differs completely from the other sites, with uniformly high carbon loadings and a compact distribution of carbon concentrations.

The seasonal cycles (**Figure B-9**) help to explain the frequency distributions. Crater Lake, Mt. Lassen and Yosemite show substantially similar carbon loadings throughout the year; their seasonal cycle is compatible with the annual cycles of hemispheric aerosol loading and of wild and prescribed fires in Northern and Central California and Southern Oregon. These data show a relatively uniform regional carbon burden. Sequoia has the seasonal pattern of the regional carbon signature, but concentrations are enhanced, probably due to emissions from the San Joaquin Valley in summer, possibly greater fire frequency due to the greater shrub cover at low altitude, and probably some local smoke from the Kaweah River communities near the monitoring site in the cool months.

Bliss tracks the elevated National Park sites from April to October, responding to the regional conditions, but shows anomalously high carbon loadings in fall and winter, most likely due to smoke from residential wood combustion in the Tahoe Basin. The strong Tahoe wood smoke source is evident in the extreme carbon values at South Lake Tahoe during winter, when concentrations are enhanced by frequent trapping of smoke in a shallow inversion in the basin. Since the Bliss site is about 200m above the lake, very tight inversions isolate it from air on the basin floor. This is illustrated by the fact that the highest winter TC concentrations at South Lake Tahoe are associated with TC ratios between the two sites in the range of 0.02 to 0.2, indicating limited mixing, while more moderate TC concentrations at South Lake Tahoe, a sign of enhanced mixing, have inter-site ratios ranging as high 0.6.

Figure B-8. Total fine carbon (<2.5 μm diameter) concentration frequency distributions.
 (The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

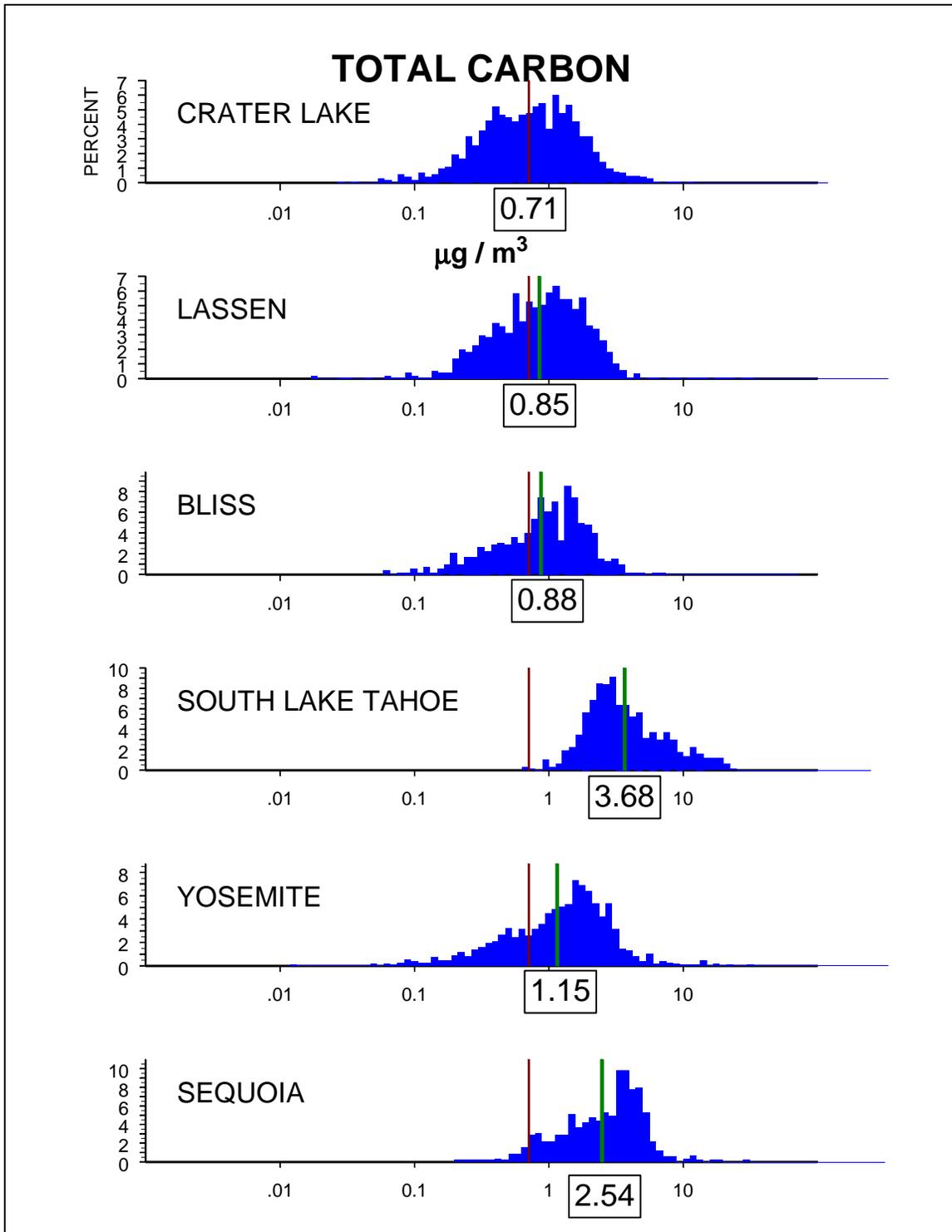
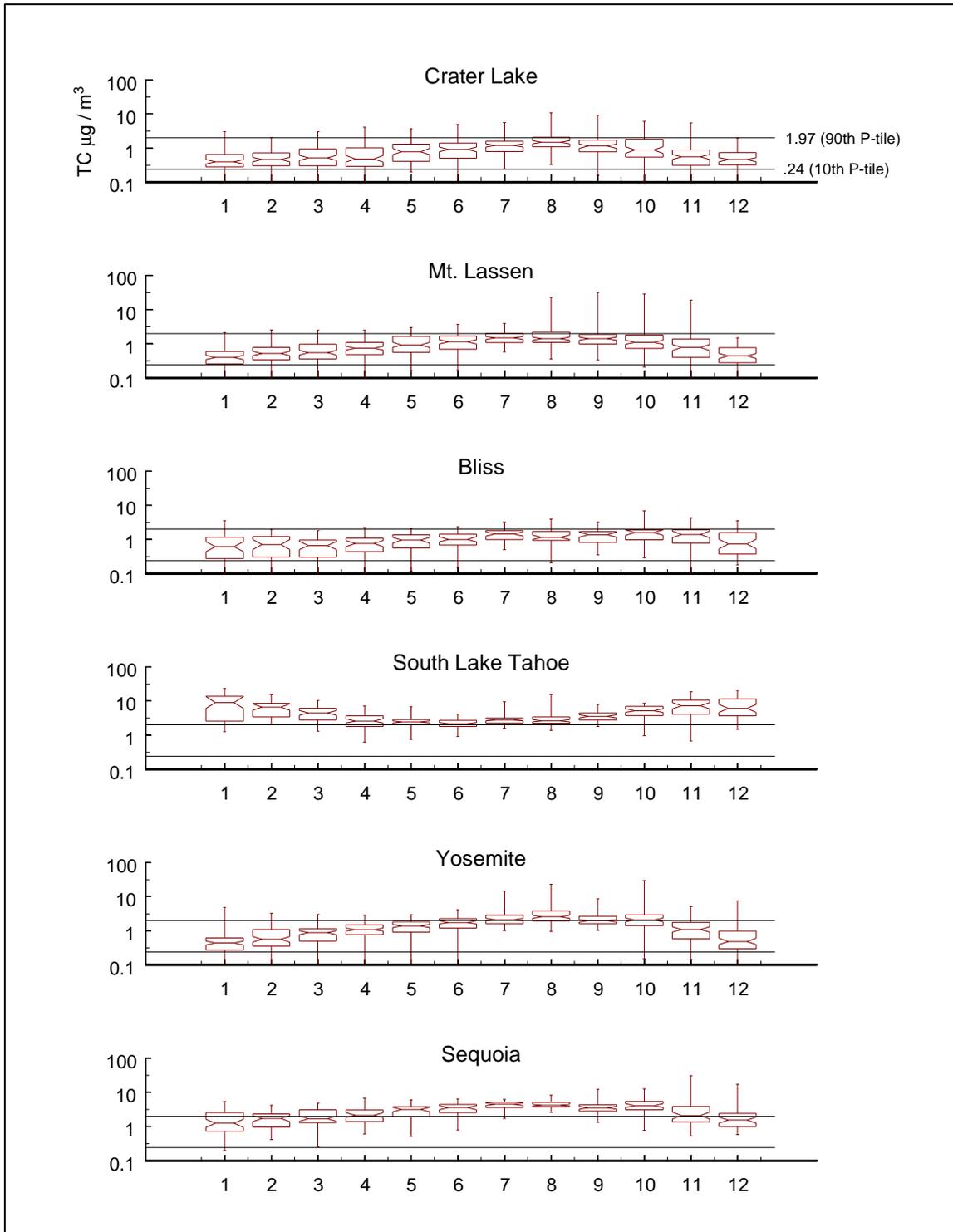


Figure B-9. Seasonal distributions of total fine carbon ($\mu\text{g}/\text{m}^3$)
 (Reference lines at Crater Lake 10th and 90th percentiles.)



3.5.3 Sulfate

Sulfate in the atmosphere over the Sierra-Cascade ranges is predominantly from combustion of fossil fuels, with a small but not insignificant fraction from biomass burning. **Figure B-10** and **Figure B-11** show the frequency distributions and seasonality of sulfate for the six Sierra-Cascade sites.

Overall, the frequency distributions for sulfate (**Figure B-10**) are much less variable across these sites than other major aerosol constituents. Sulfate concentrations at high altitudes are largely due to hemispheric-scale dispersion. Local and regional sulfur sources in California and Oregon are relatively weak due to stringent fuel sulfur content regulations in the United States, especially in California (VanCuren, 2003). Moreover, local emissions of fossil fuel sulfur oxides within the mountains are slow to convert to aerosol sulfate, thus further suppressing the local sulfate fraction.

There is a general trend of slightly increased sulfate going south along the range, reflecting the increased emissions in upwind areas going from the low population regions of southern Oregon and extreme Northern California toward the urban, industrial, and agricultural regions of Sacramento, San Francisco Bay, and the San Joaquin Valley. Only Sequoia stands out as having a distinctive distribution, due to its low altitude and thus much greater exposure to sulfates concentrated below inversions in the southern San Joaquin Valley.

The seasonal cycles shown in **Figure B-11** show that all sites peak in summer, consistent with long range transport as the sulfate source. Only Yosemite and Sequoia experience significantly more sulfate than the regional pattern seen at Crater Lake and Lassen. Bliss and South Lake Tahoe show slight elevations in summer (June-August), possibly due to emissions in the Sacramento Valley and San Francisco Bay areas. South Lake Tahoe has a minor local sulfate increment in winter (December – February), suggesting a small effect due to in-basin fuel sulfur.

Figure B-10. Fine sulfate (<2.5 μm diameter) Concentration Frequency Distributions.
 (The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

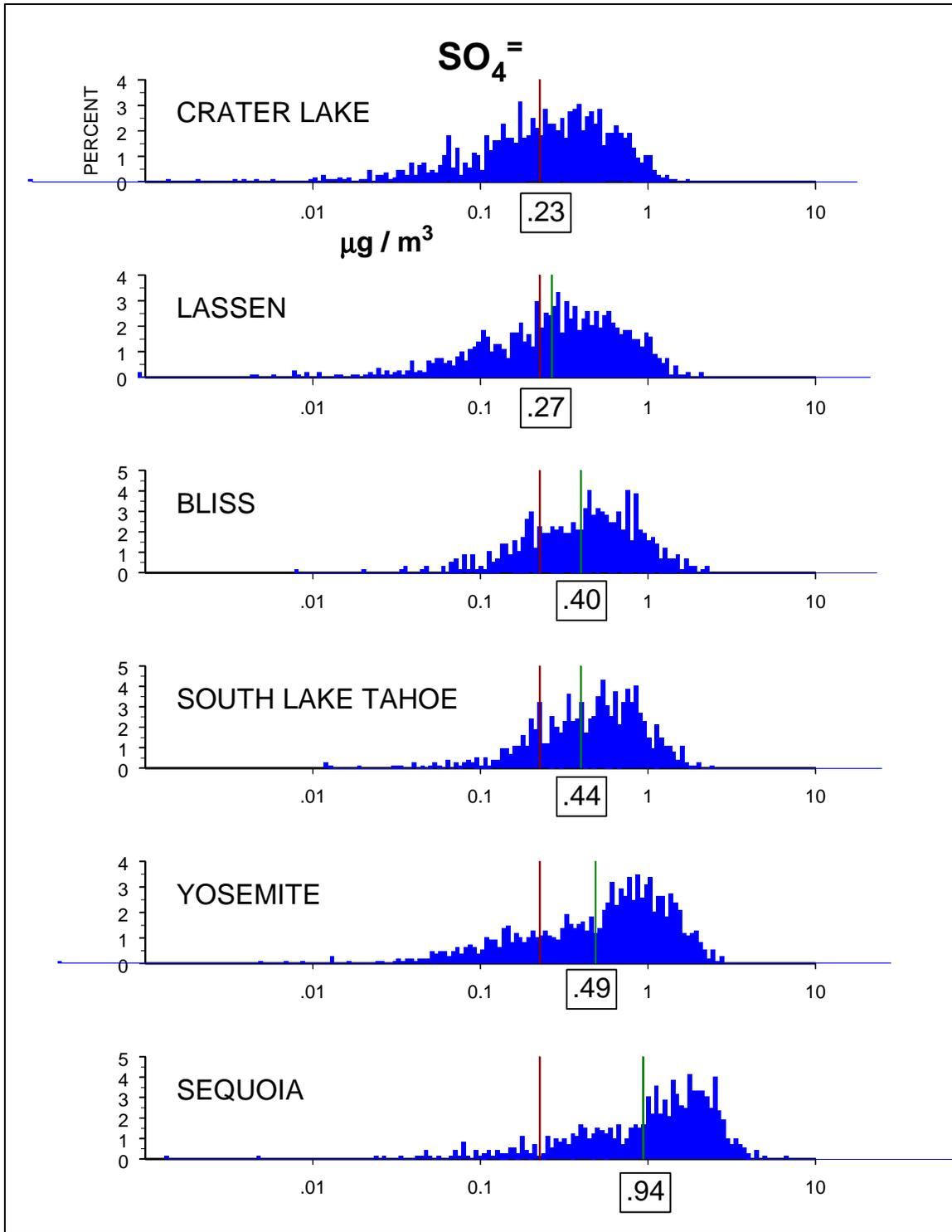
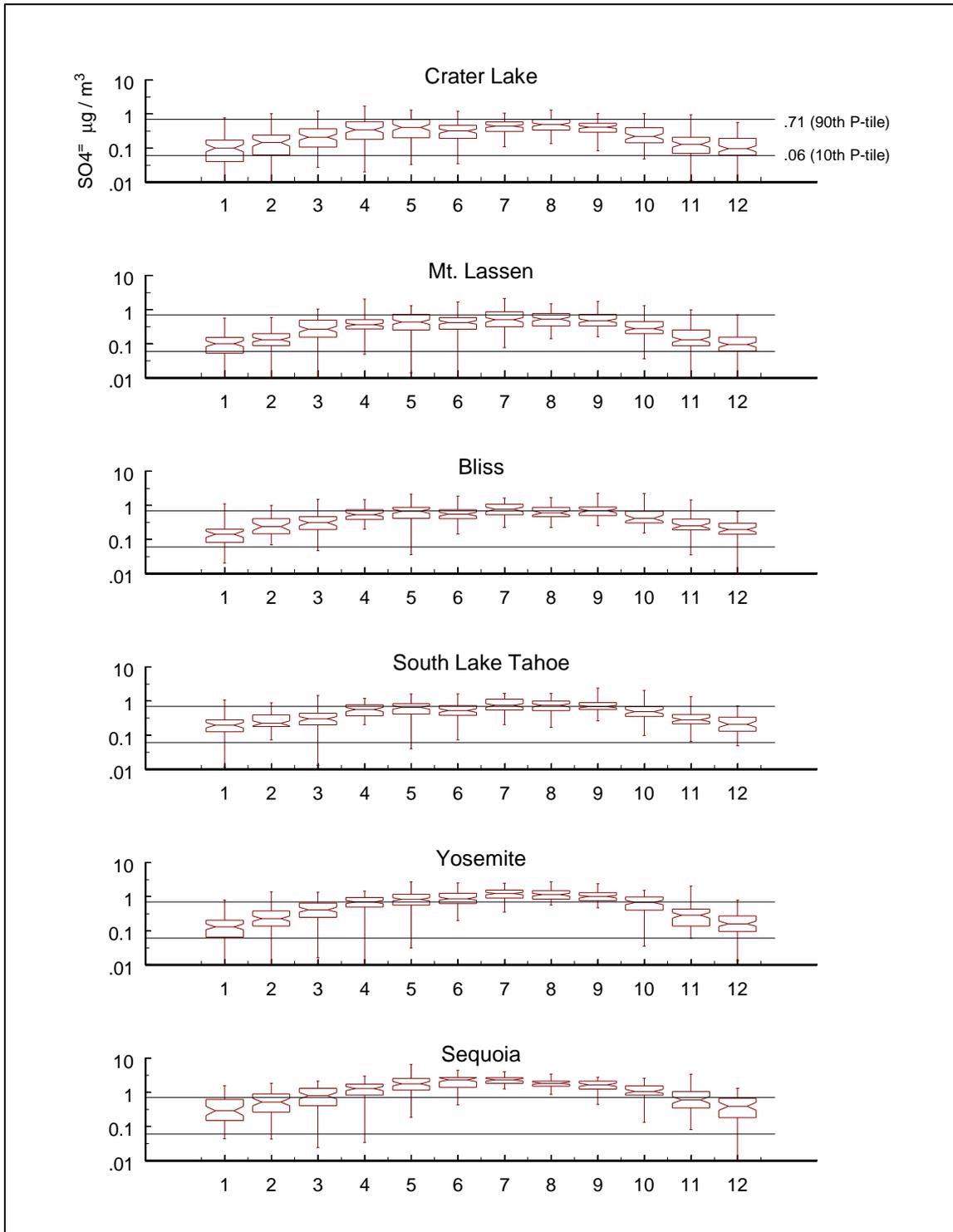


Figure B-11. Seasonal distributions of fine sulfate ($\mu\text{g}/\text{m}^3$).
(Reference lines at Crater Lake 10th and 90th percentiles.)



3.5.4 Nitrate

Nitrate is a tertiary product formed as nitric acid, a secondary product formed from NO_x emissions, reacts with gaseous ammonia, sea salt, or mineral material. Nitrate formation is most efficient under cool, humid conditions. Unlike most other aerosol components, nitrate (especially ammonium nitrate) can decompose back to its gaseous precursors, thus it is sensitive to both emissions and atmospheric conditions, and ammonium nitrate is not efficiently transported long distances.

Figure B-12 shows frequency distributions for nitrate aerosol at the six Sierra-Cascade sites. Nitrate distributions at Crater Lake and Mt. Lassen share a distribution that is clearly lower than the other sites. Bliss appears to be somewhat influenced by local or upwind NO_x sources, reducing the frequency of very low nitrate concentrations, but maximum values are not significantly greater than those at Crater Lake and Mt. Lassen. South Lake Tahoe and Yosemite share a common elevated distribution, but Yosemite has a small number of very low nitrate concentration days not seen in the South Lake Tahoe data. This suggests that, as with fine dust, South Lake Tahoe has a persistent local source (motor vehicles) that prevents very low nitrate values from occurring. Sequoia experiences strongly elevated nitrate concentrations, not unexpected due to its frequent exposure to the San Joaquin Valley floor, a region known for very high nitrate concentrations.

The monthly distributions shown in **Figure B-13** help to explain the nitrate dynamics in the Sierra-Cascade region. The patterns at Crater Lake and Mt. Lassen track with the summer-maxima expected of pure long-range transport; Bliss replicates the cycle, but with much narrower range of variation and substantially elevated winter concentrations. Bliss has the expected pattern of a mixture of a weak local source added to the regional transport signature – and South Lake Tahoe, with its high winter nitrate values, is the apparent source.

The strength of the Lake Tahoe basin nitrate influence at both Bliss and South Lake Tahoe does not come from overwhelming NO_x emissions, but from in-basin concentration due to strong inversions. This is demonstrated by the fact that in mid summer, when atmospheric mixing is strong, South Lake Tahoe nitrate concentrations roughly equal those at Bliss, and remain near the upper range of the regional nitrate concentrations seen at Crater Lake and Mt. Lassen, while winter levels at South Lake Tahoe, developed under intense inversions, are as much as 20 times higher than the regional winter nitrate concentrations.

Yosemite and Sequoia have a similar relationship to that between Bliss and South Lake Tahoe, however the basin nitrate source in this case is the San Joaquin Valley. Winter nitrate is very high in the San Joaquin Valley due to intense winter inversions, but unlike the Tahoe basin, the San Joaquin Valley is also very large NO_x source, so the better-mixed summer months show similarity in nitrate concentrations between Yosemite and Sequoia, but at concentrations five to ten times the regional levels measured at Crater Lake and Mt. Lassen.

Figure B-12. Fine nitrate (<2.5 µm diameter) concentration frequency distributions.
 (The geometric means are marked with bars and the Crater Lake mean is repeated on all plots for comparison.)

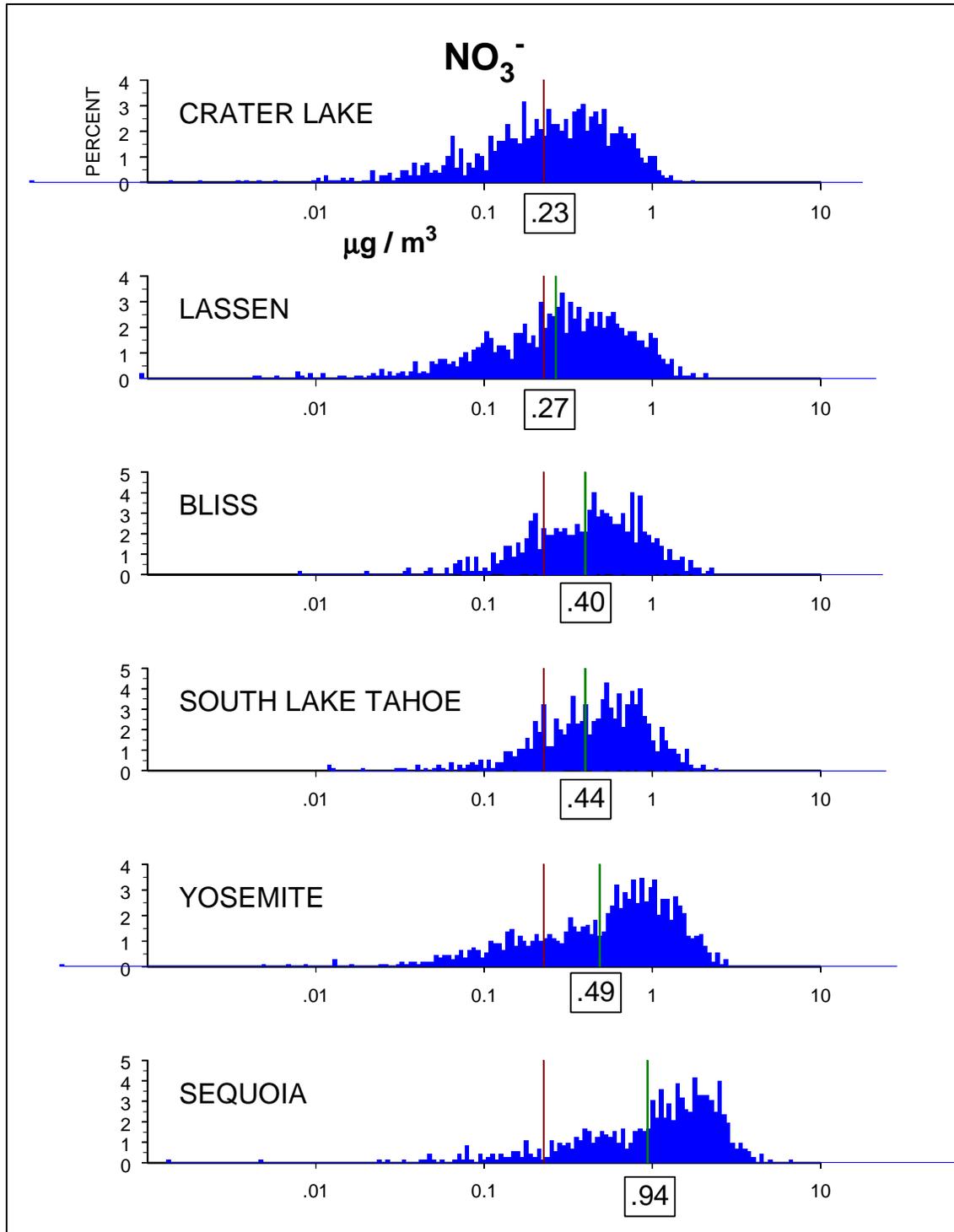
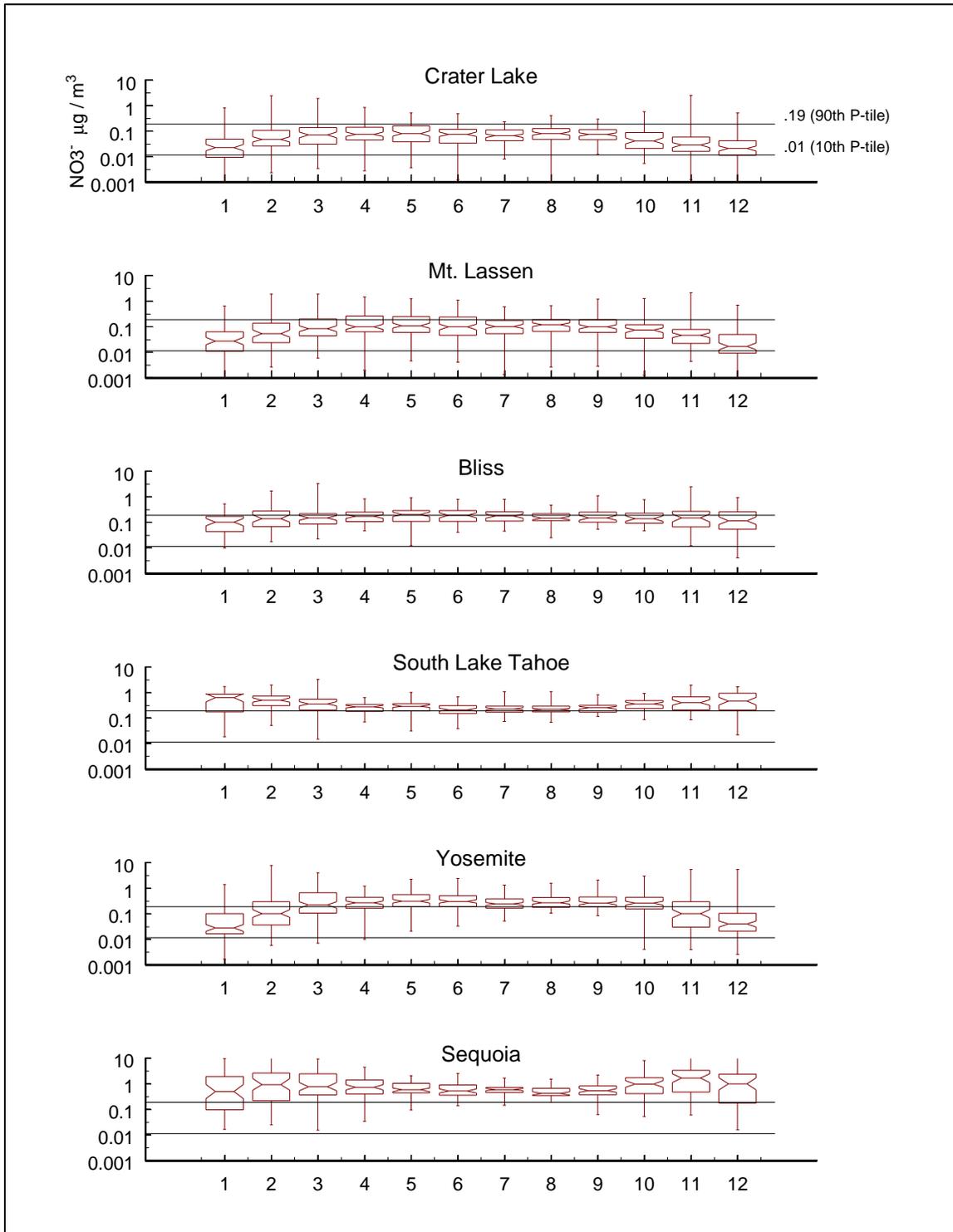


Figure B-13. Seasonal distributions of fine nitrate ($\mu\text{g}/\text{m}^3$).
(Reference lines at Crater Lake 10th and 90th percentiles.)



3.6 Four General Sierra-Cascade Aerosol Types

The comparative analysis in the previous sections indicates that there are four general aerosol influences in the Sierra Nevada – Southern Cascade mountain chain:

1. Hemispheric aerosol: this material is the widely dispersed tropospheric aerosol found at high altitude throughout the western U.S. It dominates at Crater Lake and Mt. Lassen and provides a regional baseline at Bliss and Yosemite. It consists of soil, combustion products, especially carbonaceous aerosols, secondary sulfate, a small amount of nitrate, and trace metals indicative of coal and petroleum use. Recent research indicates that this material is primarily from Asian sources, transported across the Pacific Ocean by the prevailing westerly winds (VanCuren, 2003).
2. Montane rural aerosol: the result of emissions generated in the mountains themselves (e.g. wild fire, slash burning, etc.). Biomass smoke is its dominant component, with a small amount of dust in late summer (VanCuren, 2003)
3. Local community aerosol: the material generated in the populated areas of the mountain region, such as Quincy, Mammoth Lakes, and South Lake Tahoe. This consists primarily of motor vehicle exhaust, road dust, and chimney smoke.
4. California subregional aerosol: the downwind product of pollutants generated in the agricultural and urban areas of central California, including the San Francisco Bay metropolitan area, the San Joaquin Valley, and the Sacramento Valley. This material is virtually absent at Crater Lake and Mt. Lassen, but increases in importance moving down in altitude or southward along the range, with small impacts at Bliss, moderate impacts at Yosemite, and very strong impacts at Sequoia. It consists of coarse and fine soil, organic and elemental carbon, sulfates, nitrates, and various trace metals.

The individual contributions of these aerosol sources to observed aerosol burdens are not directly measurable. Rather, major aerosol components - such as dust, smoke, or vehicle exhaust – must be allocated to them by a combination of statistical inference and logical tests.

The following sections focus on recognizing patterns in the data with the goal of distinguishing among these sources as they impact aerosol concentrations in the Tahoe Basin.

4 Aerosol within the Lake Tahoe Basin

4.1 *The Apparent Local Component at South Lake Tahoe*

A simple first-order model for recognizing locally generated aerosols in the Tahoe Basin is to assume that the Bliss data represent the well-mixed regional air and that South Lake Tahoe represents regional air plus intra-basin emissions. This implies that the difference between Bliss and South Lake Tahoe represents the intra-basin aerosol. The gross concentration, PM_{2.5} composition, and annual concentration cycle of the local aerosol as determined by this method is shown in **Figure B-1**. The data reflect the strong seasonality of the inversions that hold local pollutants in the basin in winter, but also show that the local aerosol has a distinctive composition, dominated by carbonaceous aerosol in the fine mode and a large coarse particle component.

The large organic carbon difference in winter suggests wood smoke as well as other fuel combustion. The absence of any significant sulfate difference and the small nitrate difference suggest that local primary pollutants dominate the difference, and secondary particle formation is minimal except in mid winter.

The fine soil difference does not track the winter pattern of the other components; rather it peaks twice, once in March, and again in July. This pattern is difficult to visualize in **Figure B-1** due to July being at one end of the X-axis. This probable source is road dust since the South Lake Tahoe sampling site is next to one of the most heavily used roads in the basin. This is examined further in Section 4.2

Although the IMPROVE data do not report the chemical composition of the coarse particle mode, it is probably anthropogenic since natural aerosol sources in the basin (soil dust, tree pollen, etc.) are suppressed by wet soil and snow cover in winter, and biologic activity is also at a minimum in winter.

4.2 *Local Mineral Dust*

4.2.1 *Fine Dust*

The IMPROVE fine soil calculation does not distinguish among soil sources, so there is no direct measure of imported vs. local soil dust. Fortunately, the local dust in the Tahoe basin and elsewhere in the Sierra-Cascade region has a distinctive chemical signature that differentiates it from the tropospheric dust. This is evident throughout the range in late summer and at South Lake Tahoe in winter, where the iron/calcium ratio provides a chemical “marker” that can be used to estimate the daily fraction of local vs. imported fine soil in the IMPROVE samples.

Figure B-1. Cumulative plots of monthly mean differences between South Lake Tahoe and Bliss IMPROVE aerosol data.

(The x-axis runs from July to June to better show the winter maximum. Note that fine soil peaks in March and again in July, while the others have only the single winter maximum, with nitrate differences confined to only the November-February period.)

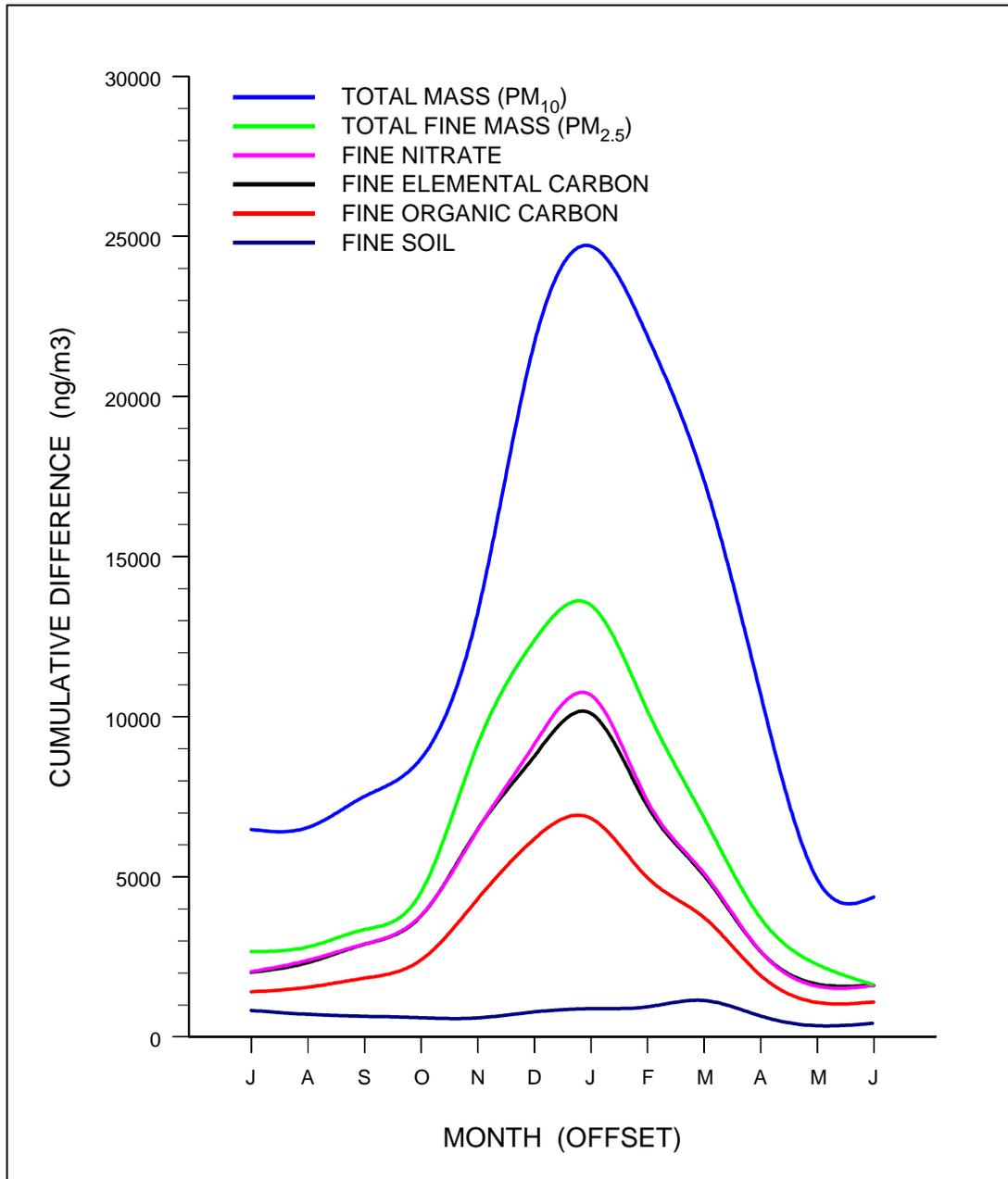


Figure B-2 shows the seasonal cycle of Fe/Ca ratios at Mt. Lassen, Bliss, and South Lake Tahoe. **Figure B-3** shows how the chemical difference is used to develop a

mixing model to distinguish between local and regional mineral aerosol. **Figure B-4** shows the seasonal fine soil concentrations calculated for Bliss and South Lake Tahoe using the mixing model.

Conceptually, the tropospheric soil should be roughly equal at the two sites. Experiments with different values for the mixing model found that BLIS and SOLA tropospheric soil concentrations diverge (violating the requirement that they be equal) when the tropospheric soil Fe/Ca ratio specified in the model exceeds 1. This implies that the “bump” on the winter SOLA frequency distribution (dashed red line in upper panel of **Figure B-3**) is, in fact, due to days with low local soil during the winter season. The model was insensitive to specification for the local Fe/Ca ratio. The mixing model as applied to generate the results in **Figure B-4** assumes that samples with Fe/Ca >1.8 are purely local, and those with Fe/Ca <1.0 are purely tropospheric, and assumes mixing at intermediate values.

Qualitatively, the mixing model seems to work. The model meets the equivalency criterion (6 percent difference between site means for tropospheric soil at SOLA and BLIS compared to the 15 percent uncertainty of the means themselves) and produces the same temporal pattern for tropospheric soil at both sites.

These results indicate that local soil sources are dominant at the South Lake Tahoe monitoring site, accounting for more than two thirds (69%) of the annual fine soil load. Local fine soil at Bliss is much less, accounting for about only one quarter (26%) of the annual soil load. Taking local population density as a rough surrogate for soil generation, it seems likely that the values at Bliss are representative of other relatively undeveloped areas in the basin, while the more densely developed areas probably experience dust loadings comparable to those at SOLA.

4.2.2 Coarse Soil

Although the IMPROVE data do not report the chemical composition of the coarse fraction, it is nonetheless possible to estimate the coarse mass related to the modeled local soil by multiple regression of the modeled fine soil components against the accompanying coarse mass. This regression gives a highly significant, albeit noisy result ($P < .000$; $r^2 = .44$) for SOLA. Daily fraction calculations based on this regression indicate that, on average, local soil constitutes between 66 and 90 percent (83 ± 17) of the coarse mass in South Lake Tahoe. The lower coarse mass at BLIS makes this regression much noisier, ($P < .000$; $r^2 = .24$) but indicates that the mean local soil fraction there is between 13 and 35 percent (24 ± 11) of coarse mass.

Figure B-2. Annual cycles of Fe/Ca ratios at South Lake Tahoe, Bliss, and Mt. Lassen. (The tropospheric aerosol has a characteristic ratio near 1. The local soil peaks in the dry summer months at all sites, shown by ratios near 2. Heavy winter activity (road sanding, mud track-out) in the basin adds a marked winter peak at South Lake Tahoe and a smaller impact at Bliss. Winter activity at Mt. Lassen is minimal by comparison to the Tahoe Basin.

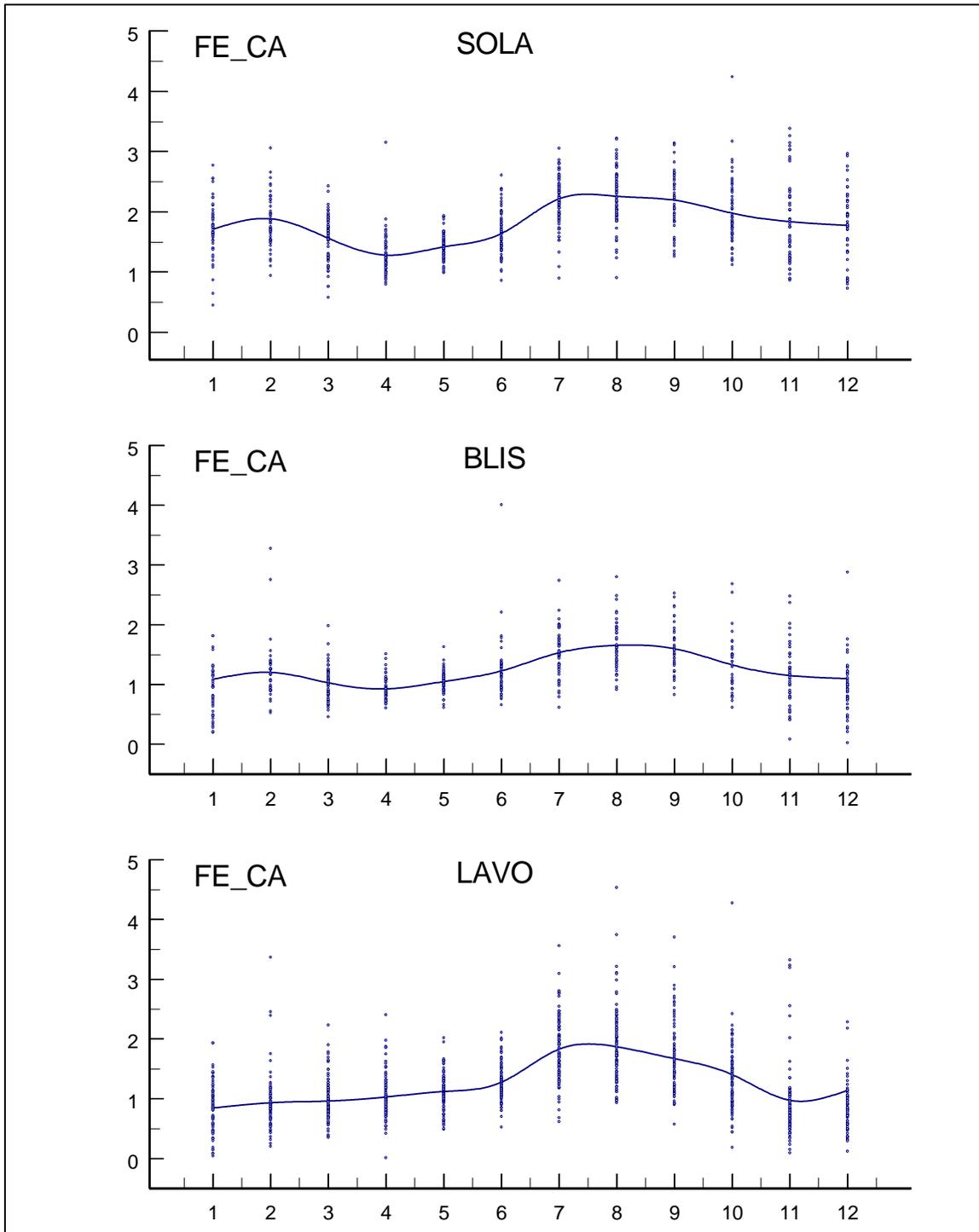


Figure B-3. Top - Frequency distributions of Fe/Ca ratios. Bottom – Simple mixing model using Fe/Ca ratios of 1.0 and 1.8 to represent pure tropospheric and pure local soils, overlain on Fe/Ca ratio distribution for all days at SOLA.

(Blue is tropospheric aerosol, represented by all days with Asian dust at Crater Lake and Mt. Lassen. Red is local dust represented by winter (DeB-Jan-Feb) at South Lake Tahoe. The Fe/Ca ratios peak at 1.1 and 1.8, respectively, and the distributions are very different, having only 20% overlap. The frequency curves suggest that each data set contains a small number of samples of the other type – note the “bump” below 1.1 on the SOLA winter data and the “shoulder” above 1.4 on the Crater Lake/Lassen data)

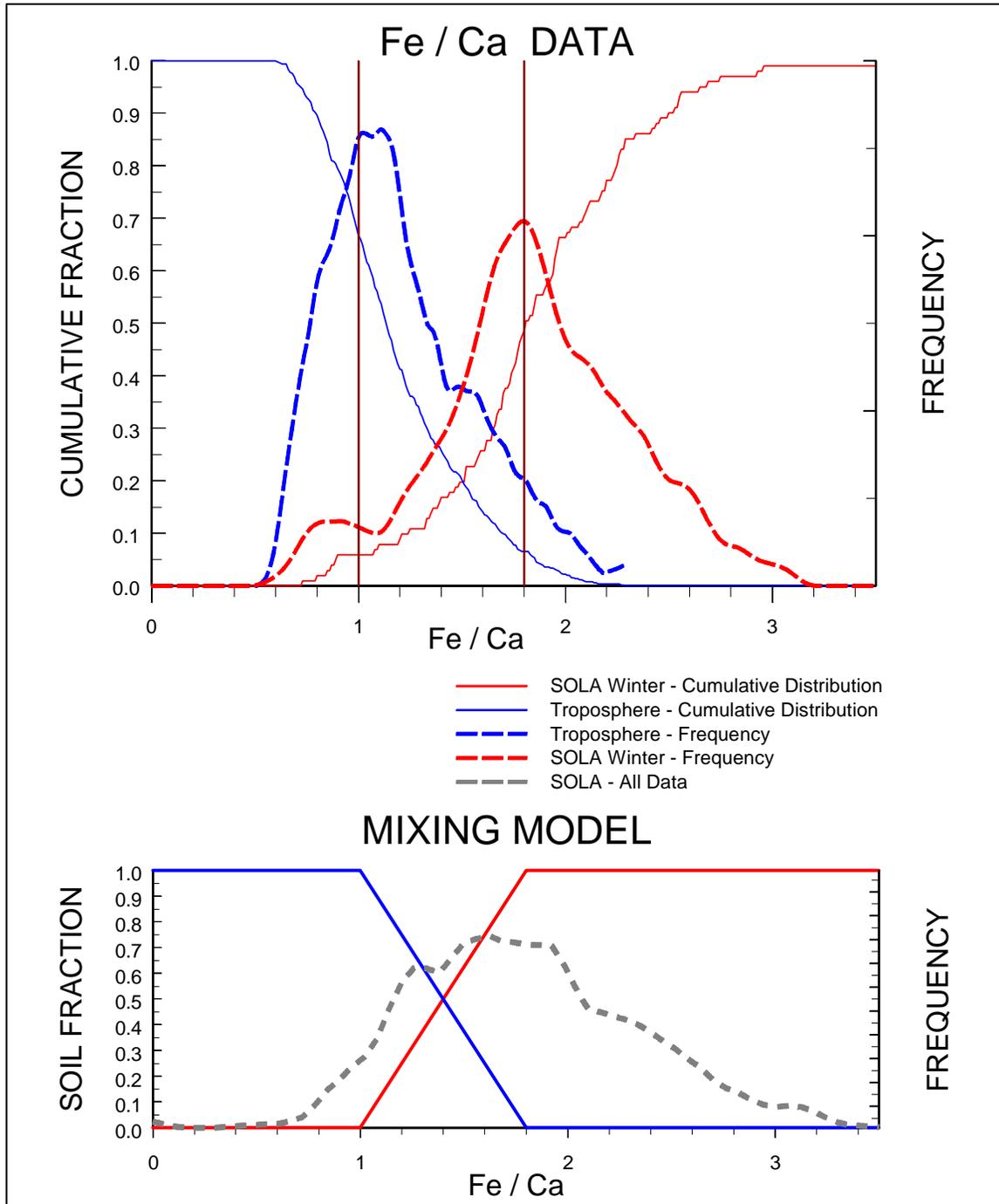
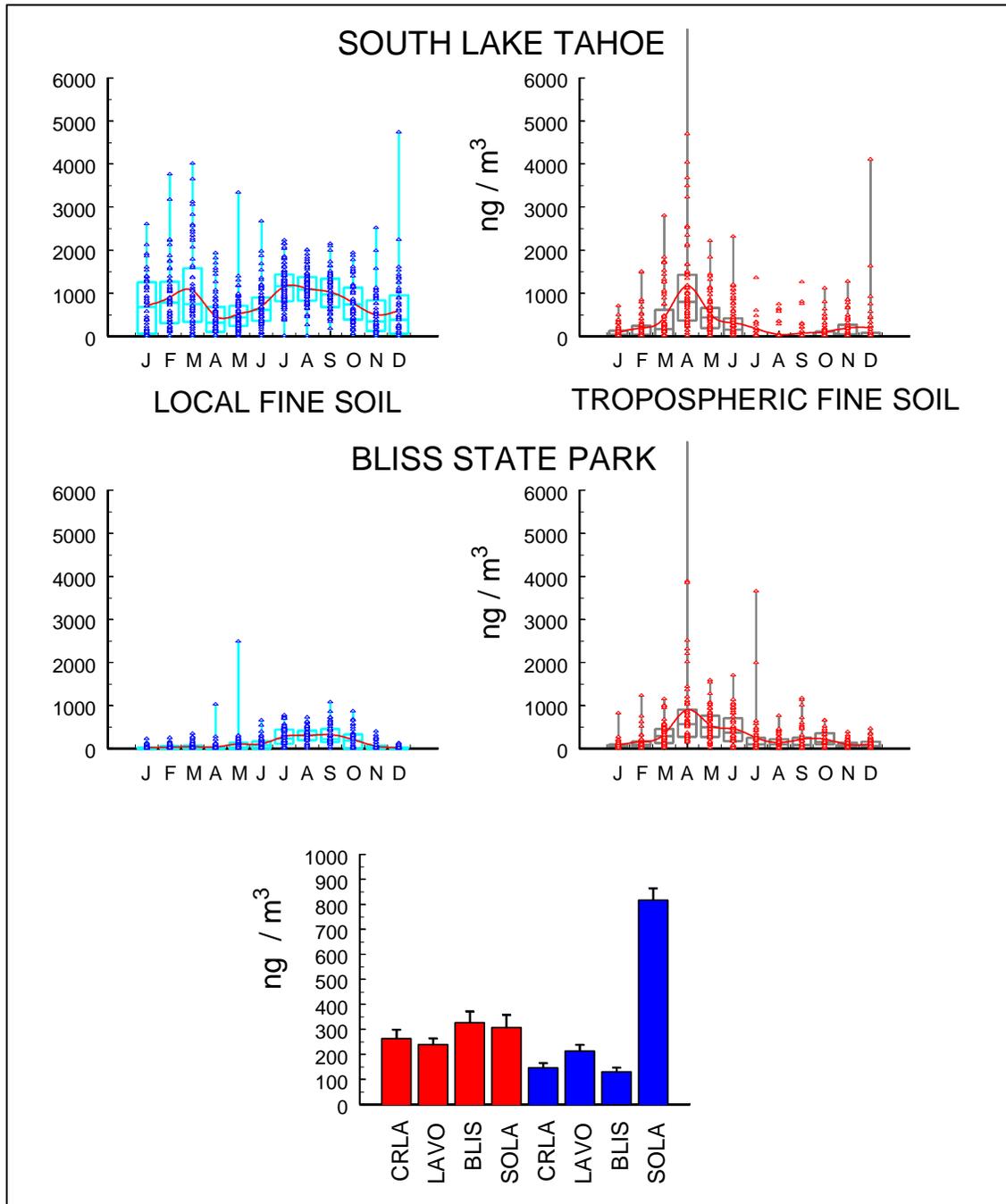


Figure B-4. Modeled local and tropospheric fine soil concentrations (ng/m^3) at Bliss State Park and South Lake Tahoe.

(Symbols are daily values; curves connect monthly means; background box-whisker plots show quartiles. Overall modeled mean tropospheric and local dust concentrations for CRLA, LAVO, BLIS, and SOLA at bottom. Difference between SOLA and BLIS tropospheric means is less than their uncertainty.)



4.3 Carbon

Carbonaceous material dominates the fine aerosol collected at SOLA. Elemental carbon averages 16 percent and organic carbon about 47 percent of fine mass; together they account for nearly two thirds of fine mass. This contrasts sharply with BLIS, where only about one third of fine mass is carbon, and the “clean” comparison sites (Crater Lake and Lassen) where it is about one quarter.

Chemical signatures can be used to distinguish between the carbonaceous aerosol from fossil fuels and that from biomass. Since such calculations rest on approximate assumptions about chemical processes and emissions, this analysis presents two independent estimates of the fossil-biomass carbon allocation. Neither method is, by itself, definitive, but together they define the range of possible contributions from these two sources to total aerosol loading in the Tahoe Basin.

4.3.1 The Carbon / Sulfate Ratio

In the discussion of **Figure B-10** and **Figure B-11**, it was noted that sulfate is predominantly a long-range transport pollutant, with minimal sources within the Sierra-Cascade mountain chain. The source of this sulfate is primarily combustion of fossil fuels, so that there is a strong link between transportation and industrial emissions and aerosol sulfate (Polisar *et al.*, 1996).

Conversion of gaseous sulfur oxides in exhaust streams to ambient aerosol sulfate takes one of two pathways, either gas-phase conversion through reaction with hydroxyl radicals and ozone, or through aqueous conversion within cloud droplets or wet aerosols (Seinfeld, 1986). The former is too slow to create significant in situ sulfate from local fuel combustion in the mountains, so sulfate in dry air in the mountains is necessarily due to transport from upwind urban or industrial areas in California or across the Pacific. On the other hand, wet conversion is quite rapid, but California's summer transport season is dry, making wet conversion unlikely to contribute much to season-long summer sulfate levels. Local sulfate in the mountains may arise from local conversion during the wet seasons (winter and early spring).

In summer, the meteorological conditions that transport urban and industrial aerosols into the mountains are regularly repeated (climatological stability) and transport times are long enough for conversion to be essentially completed by the time air masses reach the IMPROVE sampling sites. This implies, however, that the particular ratio of sulfate to other fossil fuel aerosols may vary geographically and seasonally.

In winter, local wet conversion should be near stoichiometric, so that local sulfate should be correlated with local fuel use when humidity is high, but the numerical relationship is probably unstable under dry conditions.

Taken together, these considerations suggest that sulfate can be used as an approximate marker for fossil fuel combustion aerosols, since, on average, it will be roughly proportional to other fossil fuel aerosols. However, this relationship comes with one significant caveat: sulfate only sets a lower bound on total fossil fuel aerosols

because local fossil fuel combustion may emit primary particles without accompanying gaseous sulfur emissions being converted to sulfate.

These concepts regarding sulfate are employed in the following sections to roughly separate biomass aerosol from fossil fuel aerosol in the Sierra-Cascade region.

4.3.2 Fossil Fuel Aerosols

4.3.2.1 Sulfate

Figure B-5 shows the annual cycle of sulfate concentrations for two San Joaquin Valley cities (Fresno and Stockton) and the two Tahoe Basin IMPROVE sites (BLIS and SOLA). The mean values in winter are lower than in summer at all sites, but wet sulfate conversion causes peak winter values to exceed summer at Fresno and Stockton, and to equal them at SOLA and BLIS. Since there is no significant transport to BLIS and SOLA in winter, the peak values reflect that season's local sulfate. In summer the BLIS and SOLA sulfate data appear to be dominated by transport.

4.3.2.2 Carbon/Sulfate Ratios in the Sierra-Cascade Region

Figure B-6 shows the annual cycles and frequency distributions of C/SO₄= ratios for a suite of sites in the Sierra-Cascade region.

Long term statistics from the Crater Lake and Lassen IMPROVE data indicate that smoke-free days with typical well-aged tropospheric aerosols have C/SO₄= ratios in the range of 0.7 to 5 with a mean of 2.6.

In spring and early summer the low population montane sites experience low regional smoke. These conditions result in carbon/sulfate (C/SO₄=) ratios typical of fossil fuels (1 to 3). Although sulfate concentrations at SOLA and BLIS are virtually identical throughout the year, the strong residential smoke source in the Tahoe Basin drives ratios at SOLA from three to thirty times above the fossil-fuel baseline.

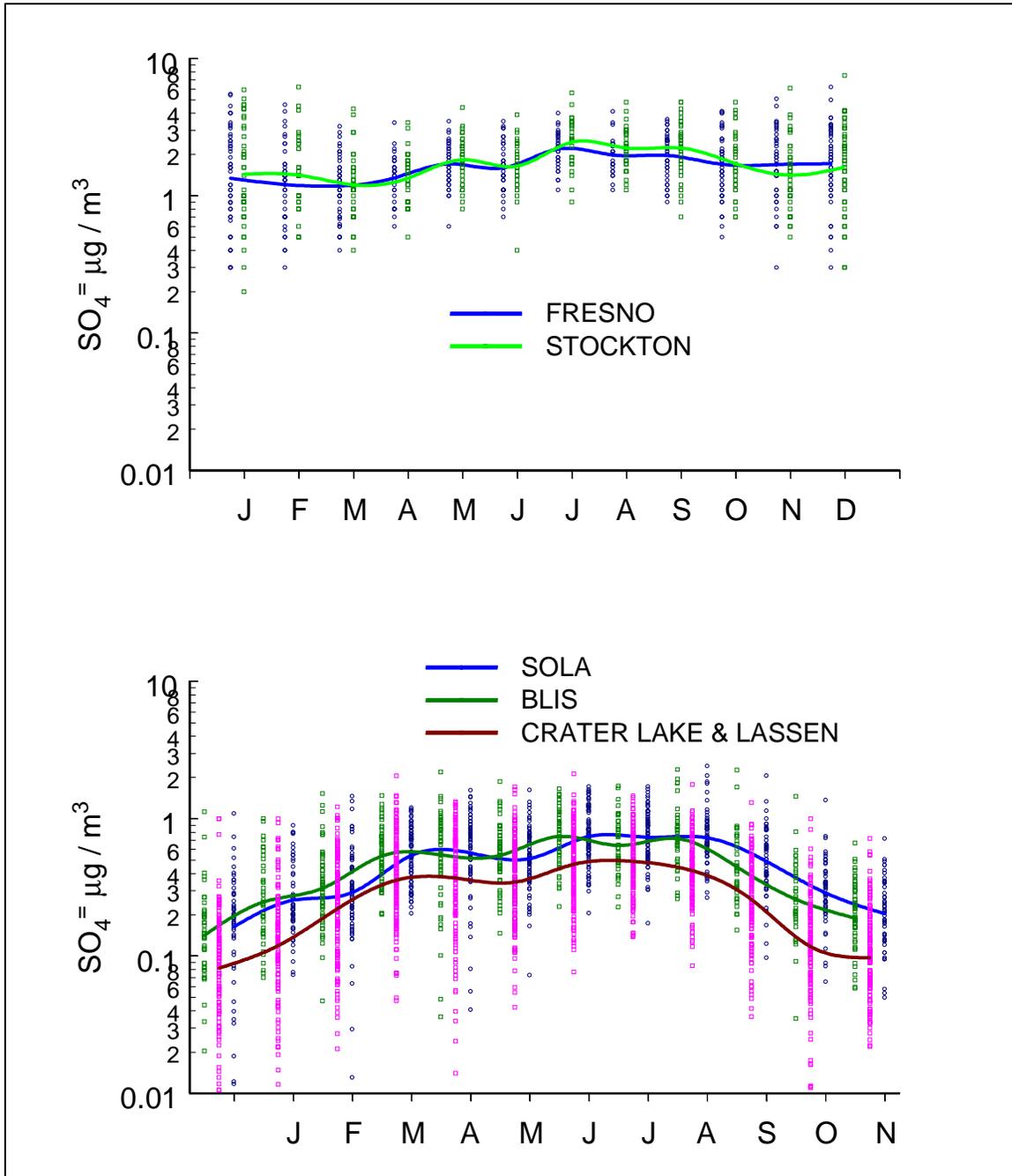
4.3.3 Biomass Carbon/Sulfate Ratios

4.3.3.1 Vegetation Burning

In situ profiles for wildfire smoke isolated from smoke events observed at Mt. Lassen and Crater Lake exhibit carbon/sulfate ratios ranging from 12 to 60 with a mean near 30 (VanCuren, 2003). This mean is approximately the same as that of a published smoke profile for slash burning near Medford Oregon (Core, 1989), suggesting that this ratio can represent wildland biomass fires ranging from slash to major regional fires.

Figure B-5. Annual cycles of sulfate for two San Joaquin Valley cities (Fresno and Stockton), the two Tahoe Basin IMPROVE sites (BLIS and SOLA), and the two “clean” National Park sites (CRLA and LAVO pooled data).

(The mean values in winter are lower than in summer at all sites, but wet sulfate conversion causes peak winter values to exceed summer at Fresno and Stockton, and to equal them at SOLA and BLIS. Note offset between Tahoe Basin sites and CRLA/LAVO.)



4.3.3.2 Residential Wood Combustion

Similar in situ data will not be available for chimney smoke in the Tahoe Basin until current field studies are completed. A chimney smoke profile from Medford published as a companion to the slash profile (Core, 1989) is adopted here as a reasonable “first guess” for domestic heating emissions in the Tahoe Basin since residents there burn wood of similar species composition to that used in southern Oregon. The Medford residential smoke profile has about half the sulfate of the open burning with carbon-sulfate ratios in range from 26 to 122 and a mean of 56.

4.3.3.3 A Carbon-Sulfate Mixing Model for Smoke

Analysis of the simple case of smoke vs. tropospheric aerosol at Crater Lake and Lassen (VanCuren, 2003) indicates that biomass smoke is absent in samples with carbon sulfate ratios below 2, and overwhelming in samples with ratios greater than 20. A simple mixing model for fossil and biomass carbon at BLIS and SOLA can be constructed from the reported profile ratios and the carbon/sulfate ratio data from these sites.

Figure B-6 shows frequency distributions and the annual trend of carbon/sulfate ratios for Crater Lake and Lassen compared to those for BLIS and SOLA, and presents a mixing model based on these data. **Figure B-7** shows monthly mean fossil and biomass carbon concentrations derived by applying the model. The general agreement among sites ranging from Yosemite to Lassen for the well-mixed spring-summer period suggests that the model works reasonably well. However the lack of sulfate conversion in winter at SOLA causes the model to overstate winter biomass carbon and understate winter fossil fuel carbon.

4.3.4 The Elemental / Organic Carbon Ratio (EC/OC)

Elemental / organic carbon ratios reflect the nature of the fuels being burned and the degree of completeness of combustion. While individual sources are highly variable, ambient carbonaceous aerosol can be generally classified by this ratio.

4.3.4.1 Fossil Fuel EC/OC Ratios

Industrial burners (heaters, boilers, etc.) and internal combustion engines use fuels that are high in carbon, easily ignited, and low in water and non-combustible materials. High temperatures volatilize most organic molecules and nearly complete mixing of fuel and air promotes their combustion. As a result, the unburned fraction in exhaust streams from most fossil-fuel combustion tends toward “soot” (elemental carbon and low volatility organic molecules).

Aerosol emissions from motor vehicles in the Tahoe basin are highly uncertain. Modern gasoline vehicles produce very little particulate pollution when tested under warm, sea level conditions. In-use testing of motor vehicles (California’s Smog Check program)

focuses on gaseous pollutants. Limited testing conducted in Colorado (Coburn, 1998; Cadle *et al.*, 1999) suggests a significant increase in particulate emissions from light duty motor vehicles running under cool, high altitude conditions, but the applicability of these data to the California vehicle fleet have not been established. Diesel vehicles are significant sources of particulate emissions at sea level, and are a likely source in the Tahoe basin as well, but emissions rates for Tahoe conditions are uncertain. Overall, there are no definitive data on high altitude emissions of vehicles in California.

Lacking data on motor vehicle emissions under Tahoe conditions, fleet EC/OC ratios cannot be built “from the ground up”. However, they can be approximated by using observed ambient EC/OC ratios from sites where fossil fuel carbon is thought to dominate the samples. The Medford OR study, cited above for wood smoke chemistry, also reported a “composite transportation” profile; the EC/OC ratio in that profile is 0.6. Similar ratios (.45-.50) have been reported from monitoring data collected in southern California, where warm weather and high vehicle traffic argue against significant biomass influence.

Looking for direct evidence in the Tahoe data, there appears to be a break point in the frequency distribution for SOLA between 0.6 and 0.7, and the mean for August, when the motor vehicle signature at the roadside SOLA site should be strongest, is also about 0.6.

4.3.4.2 Biomass Fuel EC/OC Ratios

Biomass fuels tend to have high intrinsic ash and water content, and are usually burned at low temperatures, often with poor air-fuel mixing. These conditions promote incomplete combustion and the distillation of organic compounds (vaporization followed by condensation in the exhaust stream).

Data reported in the Medford, OR study indicate that dry wood burned in the semi-controlled conditions of residential wood heating produces typical EC/OC ratios around 0.3. This fraction’s applicability to the Tahoe Basin is supported by the sharp rise between 0.25 and 0.3 in the EC/OC frequency distribution at SOLA (**Figure B-8**).

Wildland fuels (slash, wildfire) are usually burned with low efficiency due to high moisture content (wild fire) and/or poor ventilation (piles). The EC/OC ratio calculated from the Medford study data on timber harvest slash is 0.16. The data from the low-population sites (Crater Lake, Lassen, Bliss) in **Figure B-8**, where wildland smoke is expected to be more frequent than chimney smoke, indicate that this ratio is typical of smoke throughout the Sierra-Cascade range.

Figure B-6. C/SO₄= ratios for Crater Lake and Mt. Lassen compared to BLIS and SOLA and interpreted for a mixing model for fossil fuel vs. biomass carbon.

(The aerosol is assumed to be 100 percent fossil fuel derived for values below 2, a mixture of fossil and biomass from 2 to 20, and pure biomass for values over 20.)

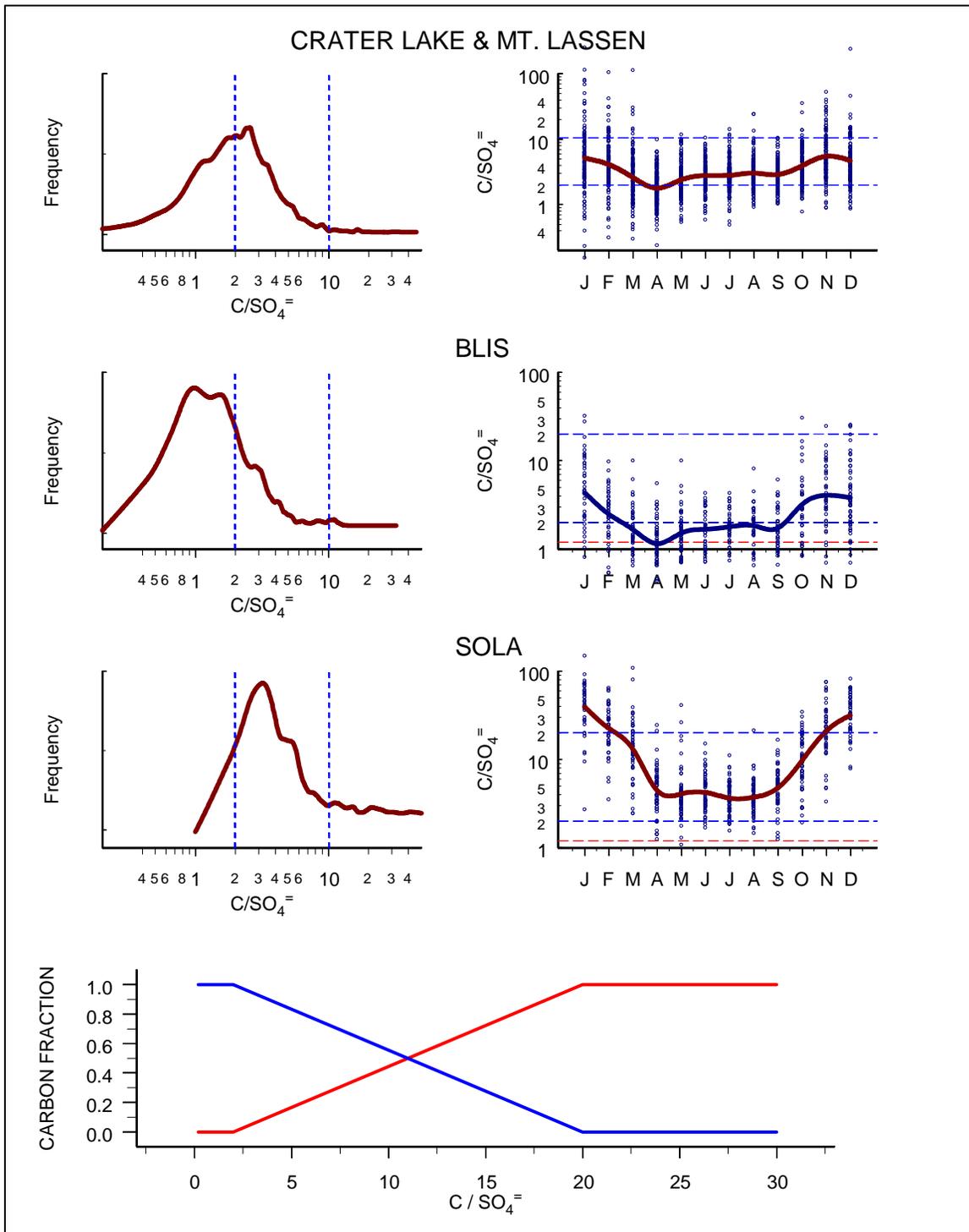
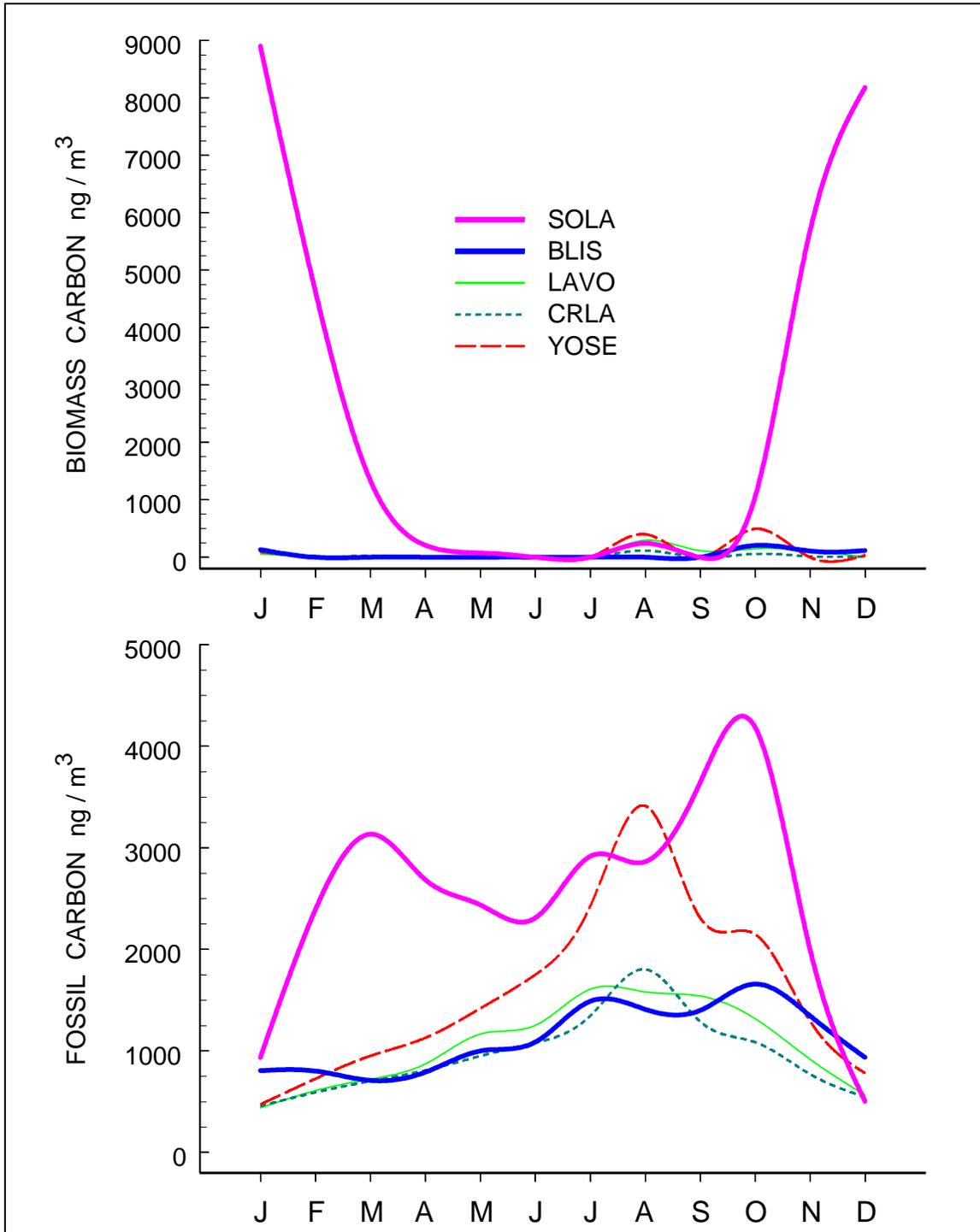


Figure B-7. Modeled biomass and fossil carbon concentrations based on C/SO₄= mixing ratios.

(The spring-summer smoke burden equalizes between SOLA and the surrounding mountain areas. Late season smoke at Yosemite, Bliss, Lassen, and Crater Lake is indicative of typical wildfire and forestry prescribed burning patterns in the Sierra-Cascade region. Model performs poorly in winter due to lack of sulfate conversion on dry days, causing almost all carbon to be assigned to smoke.)



4.3.4.3 An EC/OC Mixing Model for Smoke

The data in **Figure B-8** and the reported differences between chimney smoke and wildland smoke suggest that two models are needed -- one for low population sites exposed to regional smoke and a second for populated areas where chimney smoke is more prevalent.

Modeled fossil-biomass allocations reported as monthly mean carbon concentrations are shown in **Figure B-9**. The biomass baseline used at SOLA was 0.3, while 0.16 was used at all other sites (SOLA results are reported for both baselines). As with the carbon/sulfate model, the well-mixed spring-summer conditions in the range show up well. Unlike the previous model, the EC/OC model appears to properly track the increased concentration of all pollutants during winter in the basin.

4.4 Consensus Carbon Allocation in the Tahoe Basin

The two mixing models for smoke permit the following generalizations regarding carbonaceous aerosol in the Tahoe Basin.

1. Wild- and prescribed-fire smoke is a diffuse regional pollutant spring through fall, as well as an infrequent but intense local one. Biomass smoke is present throughout the range from spring through fall. It is highly variable in concentrations, but is, on 24-hour average, less than $1 \mu\text{g}/\text{m}^3$.
2. Concentrated chimney smoke is generally confined to the basin floor. Average chimney smoke impacts at Bliss, 200m (600 ft) above the lake and far from population centers, are on the order of $\frac{1}{2} \mu\text{g}/\text{m}^3$.
3. Chimney smoke is at a minimum in spring, averaging about $2 \mu\text{g}/\text{m}^3$ or less. Reduced mixing causes average in-basin smoke concentrations to roughly double by late summer and fall. Intense inversions in winter cause smoke concentrations in that season to average about $6 \mu\text{g}/\text{m}^3$.

Fossil fuel carbon tracks the seasonal cycle of smoke in the basin. At the roadside SOLA site it approaches the level of chimney smoke. Vehicular carbon is probably a smaller fraction of total carbon in low-traffic areas in the basin, but the difference cannot be quantified from the available data. In summer, half or more of fossil carbon may be due to transport, whereas it is dominated by local sources in winter.

Figure B-8. Carbon biomass/fossil fuel allocation model derived from EC/OC ratios. Upper plots: EC/OC histories for Crater Lake – Lassen, BLIS, and SOLA; bottom plot: fractionation model and EC/OC frequency distribution for SOLA.

(Reference lines: 0.16 - typical ratio for wildfire and slash burning; 0.3 - typical ratio for residential wood heating; 0.6 – ratio for urban transportation (Medford, OR profiles)).

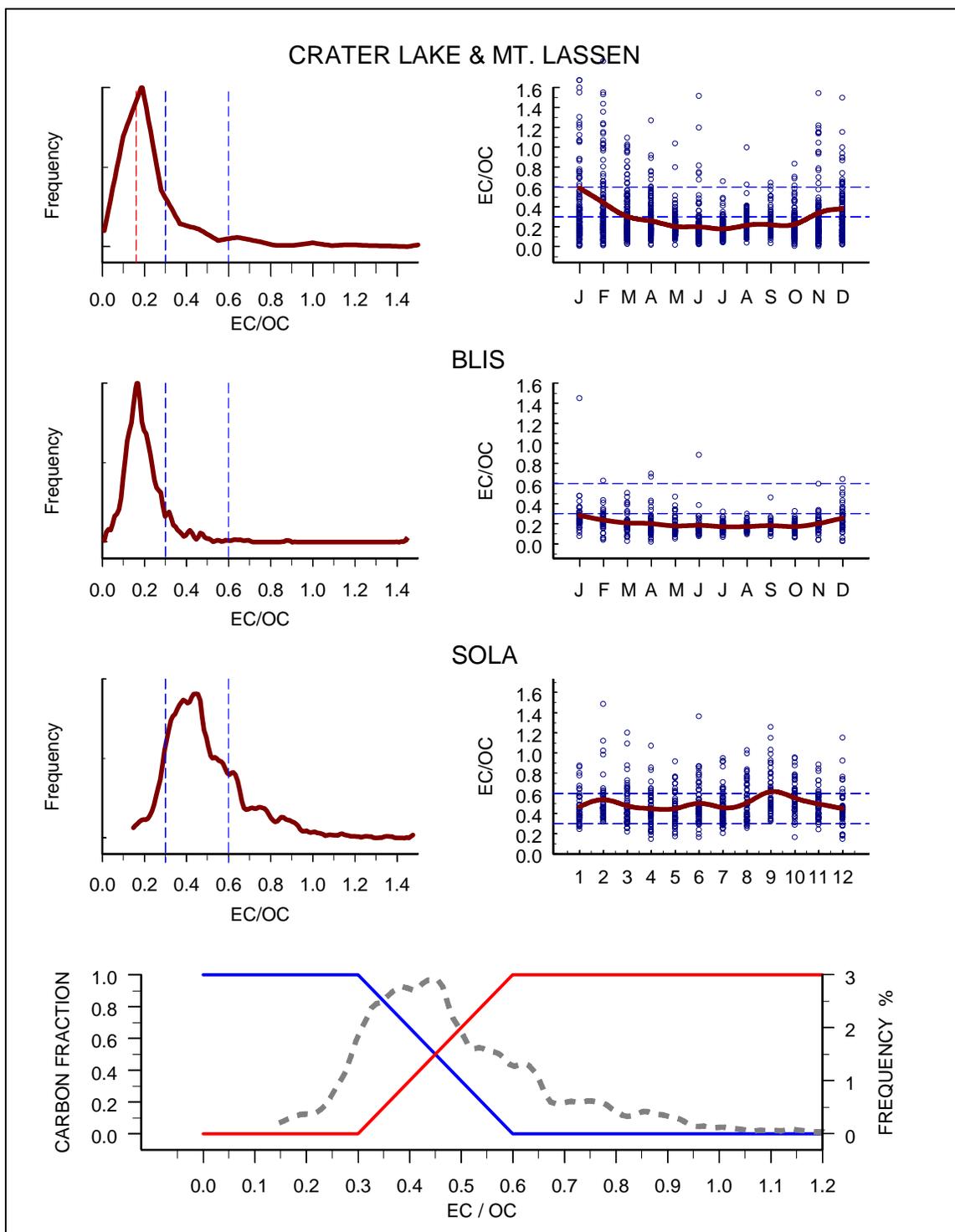
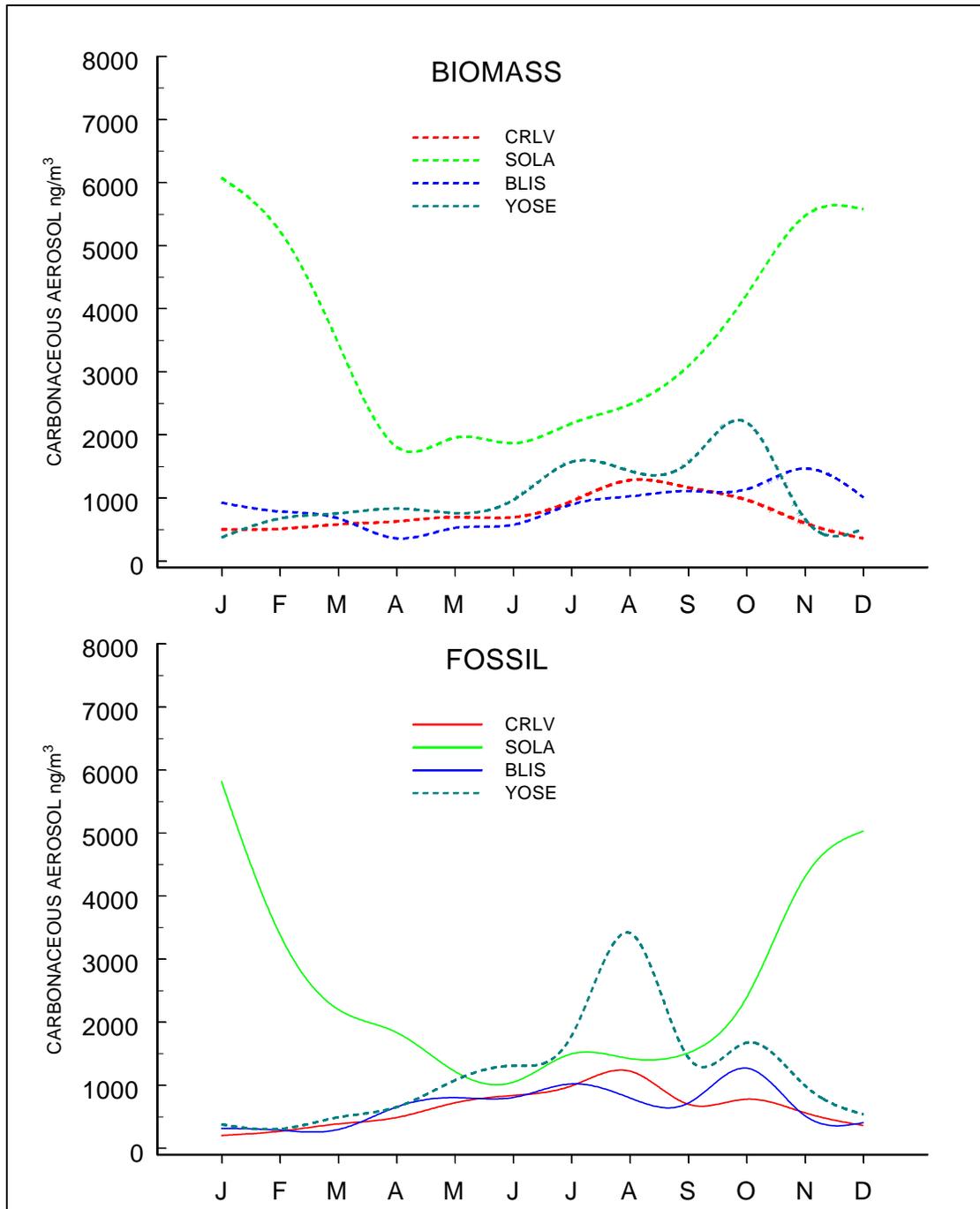


Figure B-9. Modeled mean monthly biomass and fossil carbonaceous aerosol concentrations 1989-1999 based on EC/OC mixing ratios.

(The spring and early summer regional smoke and transported fossil carbon are roughly equal among Bliss and the National Parks. Not even in mid summer does the smoke signature equalize between SOLA and the surrounding mountain areas. Late season smoke at Crater Lake/Lassen and Yosemite is indicative of typical wildfire and forestry prescribed burning patterns in the Sierra-Cascade region. Late summer transport of Californian pollutants to Yosemite shows as fossil peak July to September. Note small winter increase of smoke at Bliss.



5 Transported Pollutants in the Tahoe Basin

An upper bound on the transported fraction of aerosols in the Tahoe Basin is roughly approximated by the monitoring data from the BLIS site. Regional airflow patterns work to minimize local effects at BLIS.

In summer, the dominant wind direction in the region is from the southwest; thus pollutants arriving from Asia or upslope from the lowland areas reach this site without significant local enhancement from in-basin sources. In-basin sources impact the Bliss site only when the local inversion is deeper than the sites' elevation above the lake or when there is no inversion present. As a result, local sources (other than Highway 89) are strongly diluted at Bliss. In winter, the persistent temperature inversion in the basin tends to isolate the BLIS site from local impacts much of the time. Occasional local impacts in winter slightly increase average smoke concentrations.

Besides the small local effects of traffic on Highway 89 and intermittent recreational activity at Emerald Bay and Bliss State Park, the dominant sources of aerosols at the Bliss site are the tropospheric aerosol, transport from upwind areas of California, and regional fires. Chimney smoke generated within the basin is only a secondary contributor at Bliss.

5.1 Tropospheric “Background” – The Asian Component

An extensive analysis of the composition and temporal distribution of aerosol impacts from transoceanic transport has been developed for Crater Lake and Mt. Lassen. The Asian continental aerosol plume has been shown to dominate the aerosol “climate” at these sites from March to October. **Table B-2** shows the estimated partial contributions of major aerosol sources at Crater Lake and Mt. Lassen compared to the identified components in the Bliss aerosol.

The same meteorological processes that bring Asian continental aerosols to the National Park sites should impact Bliss with roughly the same frequency. The data presented support this assumption, as does statistical comparison of BLIS data with LAVO. BLIS and LAVO fine mass correlate at 0.5 for their entire set of overlapping days, and sulfate correlates at 0.65 between the sites. These are very strong correlations considering that the sites are about 200 km (125 mi.) apart.

Bliss experiences slightly less coarse material than do the National Park sites (about $\frac{1}{2}$ $\mu\text{g}/\text{m}^3$), but receives a little more fine aerosol (about $\frac{1}{3}$ $\mu\text{g}/\text{m}^3$). This is consistent with greater vehicle traffic near the National Park monitoring sites and occasional winter smoke exposure at Bliss.

Based on the data in **Table B-1**, the tropospheric aerosol contribution to the Tahoe Basin appears to be about $4\frac{1}{2}$ $\mu\text{g}/\text{m}^3$, of which roughly $2\frac{1}{2}$ are fine and 2 are coarse. Based on the annual cycle of total fine mass at Bliss, winter contributions appear to be minimal.

5.2 Upwind California

The data in **Table B-1** indicate that Bliss experiences somewhat less coarse mass than do the National Park sites, but somewhat more fine aerosol. Since the estimated fine smoke and dust concentrations at Bliss are lower than the National Park sites, the fine mass difference (about 1.7 $\mu\text{g}/\text{m}^3$) is probably due to stronger transport from the upwind areas of California (primarily the Sacramento Valley and San Francisco Bay areas) and/or greater exposure to smoke. This difference represents a “first guess” estimate of the mean fine aerosol impact of upwind areas of California on the Lake Tahoe basin.

Table B-1. Modeled total, coarse, and fine mass ($\mu\text{g}/\text{m}^3$) for the transport season (March - October) for Crater Lake and Mt. Lassen 1989-1999 compared to observed and modeled components for Bliss State Park as reported above.

(Regressing fine particle chemistry against coarse mass is inherently weak, so fine fraction results are more reliable. The Crater Lake / Lassen models have R^2 of .10 for coarse mass and .84 for fine mass; overall R^2 is .53 (low correlations and effects of temporal exclusion - Asian and local source impacts tend to alternate - cause some totals to exceed 100%). BLIS fine aerosol estimates are based on the mixing models; coarse chemistry from regression against fine chemistry.)

	CRATER LAKE & LASSEN			BLISS		
	MEAN	S. D.	MEAN %	MEAN	S. D.	MEAN %
TOTAL MASS (PM10)	7.5	5.8		7.1	3.5	
ASIAN PLUME	4.5	4.1	60			
SMOKE	0.69	0.87	9			
ROAD DUST & MOTOR VEHICLE	1.8	1.7	24	0.70	0.60	10
LOWLAND AGRICULTURE	0.18	0.46	2			
SEA SALT AND LOWLAND SOIL	0.76	0.70	10			
COARSE MASS (PM10-2.5)	3.8	3.8		3.2	2.2	
ASIAN PLUME	1.8	1.9	47			
(ASIAN DUST)	0.41	0.79	11			
(ASIAN CARBONACEOUS)	0.51	0.40	13			
SMOKE	0.02	0.45	0			
ROAD DUST	1.1	1.3	29	0.54	0.39	17
MOTOR VEHICLE	0.16	0.45	4			
SEA SALT AND LOWLAND SOIL	0.87	0.85	23			
LOWLAND AGRICULTURE	0.08	0.26	2			
FINE MASS (PM2.5)	3.6	2.4		3.9	2.0	
ASIAN PLUME	2.6	3.0	72			
(ASIAN DUST)	0.26	0.50	7			
(ASIAN CARBONACEOUS)	0.65	1.00	18			
TOTAL SULFATE	0.36	0.29	10	0.57	0.34	15
(ASIAN SULFATE)	0.30	0.24	8			
SMOKE	0.76	1.1	21	1.4	1.1	36
ROAD DUST	0.26	0.39	7	0.13	0.21	3
MOTOR VEHICLE	0.12	0.35	3	0.05	0.19	1
LOWLAND AGRICULTURE	0.07	0.18	2			
SEA SALT AND REGIONAL SOIL	0.05	0.07	1			

5.3 Intra-State Sulfate

Within the uncertainty of this analysis Bliss only differs from the National Park sites in having a little less coarse mass, and a little more smoke and sulfate. The winter drop-off and the closely matched annual distributions of sulfate concentrations at Bliss and South Lake Tahoe (**Figure B-5**), indicate that it is unlikely that the excess sulfate at Bliss is due to in-basin sources; rather it appears that the sulfate at both sites is primarily transported. The year-round increase in sulfate at the Tahoe Basin sites compared to the Crater Lake/Lassen data indicates that there is a small flux of California sulfate into the range throughout the year. Average concentration of this intra-state sulfate varies from $0.3 \mu\text{g}/\text{m}^3$ in winter to about $3 \mu\text{g}/\text{m}^3$ in summer.

5.4 Regional Smoke

The modeled smoke allocation in **Figure B-9** suggests that the smoke increase relative to the Crater Lake and Lassen sites occurs primarily in November, December, and January. Since regional burning is minimal in winter, this indicates that the excess smoke at Bliss is at least in part due to winter in-basin sources.

Referring, again, to **Table B-1**, the mean spring-to-fall smoke concentration at Bliss is roughly $1/6 \mu\text{g}/\text{m}^3$ (this estimate is derived by dividing the modeled March-October mean biomass carbon by the carbon mass fraction in the Medford smoke profiles - about 65 percent). This small mean smoke concentration, coupled with the very large standard deviation, suggests that regional smoke impacts, although severe on occasion, are not significant contributors to mean aerosol loading in the Tahoe basin. In fact, Bliss seems to be more strongly influenced by intra-basin smoke. The modeled winter smoke concentrations at Bliss have a mean of $0.47 \mu\text{g}/\text{m}^3$ and a standard deviation of 0.76.

6 Summary of Aerosol Data

The data presented at the beginning of this section show that the Lake Tahoe Basin is somewhat cleaner than the upwind lowland areas of California, but that it has considerably higher aerosol loading than non-urban sites in the Sierra-Cascade mountain chain.

Analysis of the data collected in the Tahoe Basin shows that local sources dominate for smoke and road dust, but are less significant for typical secondary urban/industrial pollutants such as sulfate.

Transport into the Tahoe Basin comes primarily from the tropospheric “background”, which consists of continental aerosols derived from Asia. This source is ubiquitous in the higher elevations of Sierra-Cascade range, and provides a small (on average $4\frac{1}{2} \mu\text{g}/\text{m}^3$) baseline aerosol concentration wholly outside the influence of activities anywhere in California (VanCuren, 2003).

Transported aerosols originating within California appear to contribute, on average, about $2\frac{1}{2} \mu\text{g}/\text{m}^3$ (VanCuren, 2003)

Fires outside the Tahoe Basin occasionally deliver large amounts of smoke to the basin, but they appear to have minimal impact on average aerosol loading. Pollutants produced within the Tahoe Basin are concentrated by shallow inversions overlying Lake Tahoe. Local sources are not strong enough to have significant impacts when the inversion is absent.

Further study is needed to determine the spatial distribution of pollutants within the basin; the data from the Bliss and South Lake Tahoe monitoring sites probably represent the extremes of pollutant concentrations in the basin.

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