# 48

# Air Quality

**THOMAS A. CAHILL**
Atmospheric Sciences
Department of Land, Air,
and Water Resources
and
Air Quality Group
Crocker Nuclear Laboratory
University of California
Davis, California

**JOHN J. CARROLL**
Atmospheric Sciences
Department of Land, Air,
and Water Resources
University of California
Davis, California

**DAVE CAMPBELL**
Air Quality Group
Crocker Nuclear Laboratory
University of California
Davis, California

**THOMAS E. GILL**
Atmospheric Sciences
Department of Land, Air,
and Water Resources
and
Air Quality Group
Crocker Nuclear Laboratory
University of California
Davis, California

## ABSTRACT

Air quality in the Sierra Nevada is highly variable in quality: excellent much of the time and in many places, seriously degraded at other times and places. In this chapter, we summarize air quality in the Sierra Nevada both in terms of state and federal ambient air quality standards (ozone, particulate mass, visibility reduction, and so on) which are periodically violated in the Sierra Nevada, and in terms of air quality impacts generally of more ecological import (acid deposition, transport of air toxics, eutrophication of Lake Tahoe, and so on). The emphasis is on well-documented rangewide impacts of human origin. Many other impacts, actually or potentially of no less importance, must be omitted in this short summary because of their more local or limited scope and/or weaker documentation.

At present, the most important deleterious air quality impacts are closely tied to the efficient transport of air pollutants from the Central Valley of California into the western slopes of the Sierra Nevada, up to elevations 6,000 feet or more. This transport is strong in summer and weak or absent in winter, severe in the southern reaches and more modest north of Sacramento, where mountain slopes are more gentle. Of these pollutants, ozone has the best documented and most important effects, especially in its connection to serious injury to the economically important Jeffrey and ponderosa pines. Fine particulate sulfates, nitrates, and smoke are also transported on the same winds, especially between April and October, sharply reducing visibility. Other components in valley air, including nitrates, pesticides, herbicides, and so on, are also efficiently transported into the mountains and deposited on vegetation and in watersheds.

In terms of air pollution sources within the Sierra Nevada, degradation of air quality is one of the difficult questions raised by the potentially increased use of prescribed fire in controlling the high levels of fuel in present Sierras Nevada forests. There is good documentation on degradation of air quality in massive, uncontrolled fires, but other than local data and visual smoke, smoke from prescribed fires is low enough that it is difficult to detect in the rangewide fine particulate mass records since 1988. While smoke from prescribed fires is usually much smaller than that from wildfires, it can, under exceptionally unfavorable conditions, also approximate similar levels.

High-elevation towns of modest population can generate very high levels of fine particles in winter smoke, with concentration levels larger than typically seen even in the largest urban areas of California. Rather surprisingly, there is a rough equality between the maximum mass of fine particles seen in winter urbanized areas, that seen near downwind of massive forest fires, and that from prescribed fires under the most unfavorable conditions. All of these can exceed state and even federal 24-hour particulate mass (PM-10) standards. Lake Tahoe has sharply reduced water clarity and increased algae, some of which is tied to local urban and/or transported air pollutants such as nitrates. Other typically urban air pollutants, such as carbon mon-

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oxide, have been high enough to warrant special air standards to protect respiration at these high-altitude sites.

The rapid desiccation of the eastern Sierra Nevada lakes, Mono and Owens lakes, has resulted in dust storms that in most years generate the highest 24-hour fine dust levels in the United States. Much of this dust is transported into the Sierra Nevada and the White-Inyo Mountains, the latter site being the home of the ancient bristlecone pines. The dust levels near Mono Lake should improve greatly following recent legal and regulatory decisions limiting water export.

On the other hand, acid rain and snow are not as much a problem in the Sierra as in the eastern United States. No permanently acidified lakes or streams occur in the Sierra Nevada, although pulses of acidity can occur during spring snowmelt and during occasional thunderstorms from the southern California desert. In the winter, over much of the nonurbanized Sierra Nevada, levels of some characteristic human pollutants such as sulfates are extremely low, mimicking those at the high-altitude world baseline station on Mauna Loa in Hawaii, which helps explain the modest concentrations of sulfates and nitrates in the snow. Transport of Sierra Nevada smoke downwind into the Colorado plateau national parks appears minor except in catastrophic wildfires.

## INTRODUCTION

The Sierra Nevada has always existed in a dynamic communion with the Earth's atmosphere, responding to changes global, regional, and local, and in turn changing the atmosphere itself. The pace of these dynamic changes has accelerated with man's involvement, modestly in the period of native Americans, but more rapidly at present, threatening responses from the litho-, hydro-, and bio-spheres that may seriously alter the social and economic values of the Sierra Nevada to the state, nation, and world. However, because of its difficult topography, severe weather, relative lack of mineral resources, and low population density, the Sierra Nevada still retains at many times and most places some of the best air quality in the state and the nation. Yet at other times, air pollutants transported into the range, or generated within the range itself, can result in such severe degradation of air quality that at some times and some places, air quality may be as bad or worse than any place in the state or the nation. For example, the highest dust levels seen anywhere in California were near Mono Lake in 1993. Winter smoke levels at Mammoth Lakes resulted in fine particle masses 1.7 times the worst seen all year in downtown Los Angeles. The early morning ozone level (5–10 AM) at Sequoia National Park is usually 2 to 3 times greater than that seen in Fresno. In order to clarify the contradictory nature of air quality in the Sierra Nevada, this report considers three spatial and three temporal scales. The spatial scales are (1) global, (2) regional or directly upwind, and (3) local, within the Sierra Nevada. The effect of the Sierra Nevada itself on air quality downwind of the range is also addressed. The temporal scales are (1) recent historical, past 200 years, (2) present, and (3) near future, next few decades.

This report has as its primary goal the broadest overview of air quality in the Sierra Nevada. Yet in order to make this report useful and readable, it is severely constrained in length and detail. This report has focused on air quality data based on widely dispersed monitoring sites within the Sierra Nevada, largely generated by state and federal air quality programs with multi-year duration. While this decision was based on both statistical relevance and quality assurance considerations, it also represents an effort to make these data more widely available to a research community that tends to emphasize a refereed literature that generally favors studies of more limited scope. In addition, the brevity of this report means that it cannot adequately consider the numerous air quality studies relevant to the Sierra Nevada, the mere listing of which alone would represent approximately many pages of text. Those that are listed and cited must represent many other such studies not cited in this report.

Some important information that will be used repeatedly is given in appendix 48.1, which includes state and federal ambient air quality standards relevant to the Sierra Nevada and a list of California and federal air monitoring sites within the SNEP study region (California Air Resources Board 1972–94). The same source is used for data from sites outside of the study area, such as in the Central Valley of California. The annual reports of the Interagency Monitoring of Protected Visual Environments (IMPROVE 1995) and its NPS/EPA predecessors are the source for much of the federal aerosol data, with individual parks adding specific sites and species. Also important are the annual summaries of the ARB's California Acid Deposition Monitoring Program (CADMP 1995) and the Tahoe Regional Planning Agency.

At many points, choices had to be made regarding what materials could be included. Choices were made that favored well documented, range wide, and significant impacts, (e.g., ozone damage to Jeffrey pines, degraded visibility, ...) while neglecting or only mentioning in passing more local impacts (ozone injury to deciduous vegetation in a specific watershed, geothermal injury near Mammoth Lakes, ...). Detail is often lacking, references truncated to the most important, and judgments made regarding relevance of data to the overall picture. Further, any efforts to even partially achieve such ambitious goals, immediately confront a critical paucity of air quality data in the Sierra Nevada. At most places and most times, no data whatsoever of any type are available. For example, all high altitude (greater than 2,700 meters or 9,000 feet) ozone data are based upon one summer's sampling at one site in Sequoia NP. The paucity of data often demands extrapolations from limited measurements to predict air quality away from the sampling site or sampling times. This is in reality a form of modeling that, of course, becomes even more suspect when one looks into past air quality or tries to predict future air quality (e.g., global climate change, regulatory changes to anthropogenic emissions or ambient levels of criteria pollutants, and so on). Any serious errors or omissions caused by such extrapolations are the sole responsibility of the original author.

Changes in global climate are already occurring, with large (+ 25% for $CO_2$, + 100% for methane, order of magnitude in chlorofluorocarbons, ...) changes in atmospheric chemistry. These may well produce both positive and negative consequences of uncertain magnitude and timing. Some estimate that the most important consequence for the Sierra Nevada is likely to be a shift in the hydrological cycle towards more frequent and intense rain events and away from historical snow patterns. Observed increases in temperature and carbon dioxide, and predictions of increased moisture, could lead to increased bio-productivity. However, recent decreases in the worldwide rate of rise in carbon dioxide, methane, and other "greenhouse gasses" may be harbingers of somewhat lower peak values in the 21st century than some models have predicted, thus limiting changes in climate. While there are many other subtle impacts on the biosphere, it appears that decreases in the northern latitude ozone shield probably are not responsible for the decline in Sierran amphibians. Other, more local, non-atmospheric causes are implicated.

The impacts on Sierran air quality from regional, upwind sources of air pollution are dramatic and easily measurable, from the persistent hazes in summer to ozone damage to Jeffrey and ponderosa pines. The ozone damage is both serious and persistent, and poses both social and economic costs to the Sierra Nevada. Despite massive and costly efforts, the decline in peak ozone values in the Central Valley source regions is slow (unlike the dramatic decreases in the Los Angeles basin), so that relief is not imminent. The persistent hazes have been definitively linked to California sources, and great improvements in visibility could be achieved by a number of proven methods including suppression of summer and fall agricultural burning and controls of sulfur and nitrogen emissions, especially in the Bay Area. The hydrological cycle is dominated by winter snowfall, and the impacts of upwind sources of sulfates and nitrates on mean Sierran snow composition is modest. That does not rule out pulses of moderate acidity at snow melt. It does reflect that winter storm processes do not have the same local connection to California emissions as summer aerosols and ozone.

The impacts on Sierran air quality from local sources, within the study area, are highly variable in magnitude and timing, resulting in major degradation of air quality to levels among the worst in the state and nation superimposed on typical air quality that is so clean as to be the envy of the state and the nation. We consider three major impacts: smoke from fires, influence of urbanized enclaves, and the desiccation of eastern Sierra lakes.

Smoke from major wildfires can be seen for hundreds of miles downwind of the Sierra Nevada, filling valleys (even on occasion the Central Valley) and clearly causing the most obvious and extensive air pollution impact from any local source. This is enhanced by the growing intensity of wildfires caused by fuel build-up over the past decades. Yet, perhaps surprisingly, the impacts of wildfires on the one particulate pollutant subject to state and federal regulation, respirable particulate mass, are not major for several reasons. First, these events are infrequent, so that they have only a modest impact on long-term averages. But perhaps more surprisingly, the maximum smoke impacts of major wildfires fires are generally less in magnitude, and far less in frequency, than smoke impacts in urbanized enclaves such as Mammoth Lakes, South Lake Tahoe, Truckee, and others. The situation is even more favorable for controlled burns designed to limit fuel loading for the major wildfires. First, a great deal of the smoke in the Sierra Nevada during the summer comes from the Central Valley. This smoke is more extensive than that developed by most controlled burns, partially through careful planning of burn periods and burning procedures. Thus, it is our opinion that limits on controlled burning could be relaxed significantly without danger to public health, and with major benefits to public welfare including increased human safety as a result of reduced wildfire events.

The urbanized enclaves referred to above can generate local air pollution that mimics and even surpasses that present in major urban areas of California, but on a much more local spatial scale. Summer levels for standard gaseous pollutants may be significant, while winter urban smoke in small Sierran towns can result in the highest winter particulate mass loading of any site in California, higher even than in the South Coast Air Basin, Bay Area, and San Joaquin Valley. Mass loading at these winter sites may not, however, be directly comparable to those at other warmer, drier sites at times, since measurements have shown that about one-third of the mass can be driven off easily by modestly elevated temperatures. One suspects that trapped water of combustion is retained in very cold climates. The question of other pollutants, such as polyaromatic hydrocarbons (PAHs), is much more important to questions of potential health impacts of wood smoke. The impacts of smoke on local winter visibility are on occasions extreme. Other influences from air pollution in urbanized enclaves include accelerated nutrient input to Lake Tahoe and other pure bodies of water, causing algal growth and lack of clarity. It is our opinion that atmospheric nitrate, a major and occasionally limiting nutrient, from transported, upwind sources is not as important as local nitrate sources around Lake Tahoe, but this is still controversial.

Finally, the influence on local air pollution from the artificially desiccated beds of Mono and Owens lakes is severe, causing in most years the highest respirable dust loading in the entire United States, although for relatively few days per year. The recent Water Resources Control Board ruling on Mono Lake used this air quality information as a component in setting the lake level to a value that should make such events a thing of the past. No such near-term improvements are imminent for the even more severe problems at Owens (dry) Lake.

The next sections will be organized as follows:

1. The Impacts of Global Climate Change
2. The Impacts of Upwind Air Pollutants, generated largely within California
3. The Impacts of Local Air Pollutants, generated within the Sierra Nevada

In addition, we must consider impacts caused by the Sierra Nevada:

4. The Impact of Sierra Nevada Sources on Downwind Areas

## THE IMPACTS OF GLOBAL CLIMATE CHANGE

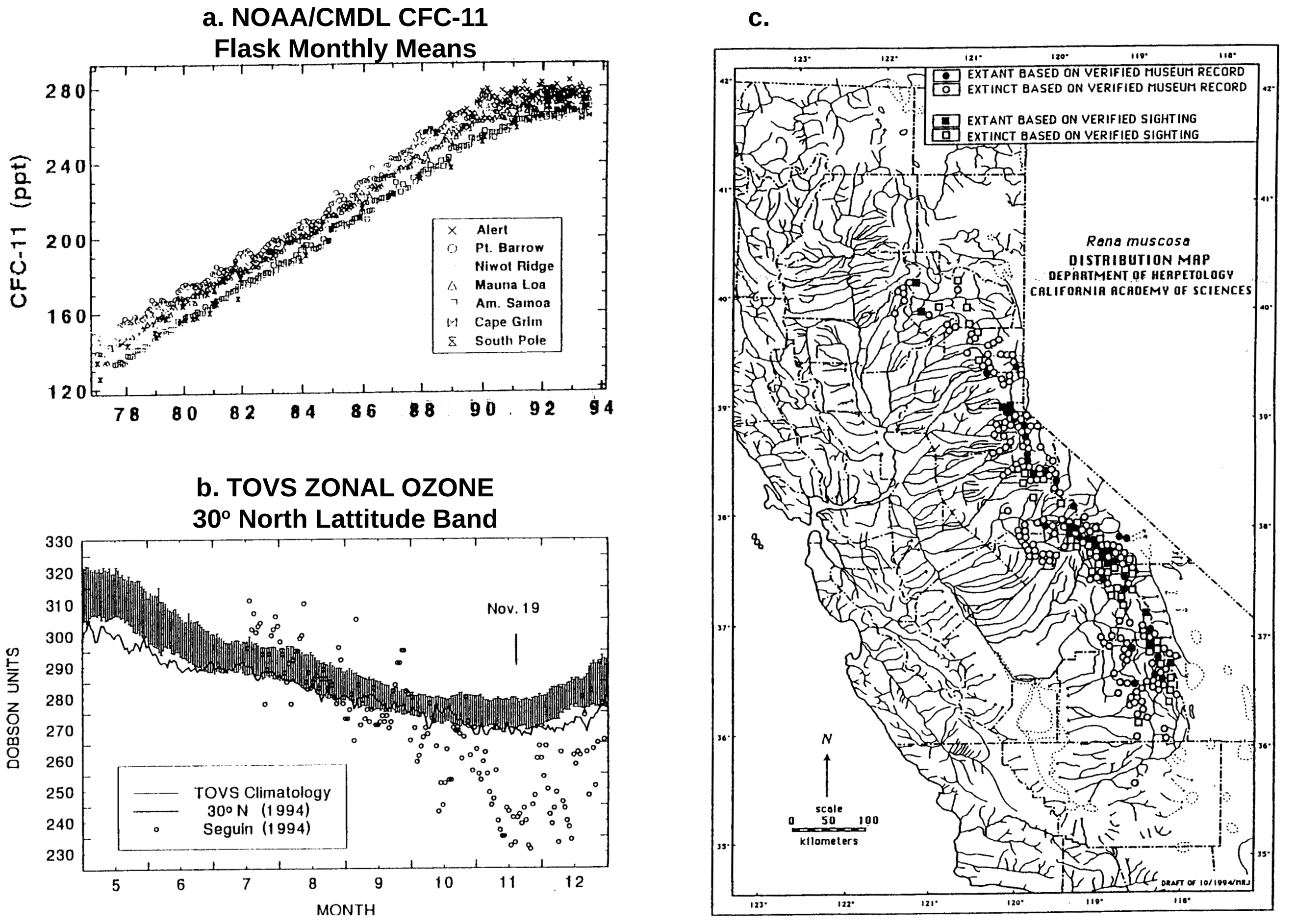
This section will not specifically treat questions of the hydrologic cycle, as that is handled elsewhere. It will deal with possible effects on the Sierra Nevada by factors loosely called "global climate change," or more specifically, "anthropogenic forcing of the global climate." While it is not our intent to delve deeply into global climate debate, it is important to separate those aspects that are certain from those that involve modeling that can verge on pure speculation. The former include changes in global atmospheric chemistry including the 25% rise in $CO_2$, a key nutrient to plants, and a doubling of methane since the late 19th century, massive increases in chlorofluorocarbons after World War II, the Antarctic ozone hole, and other such well documented changes. In an intermediate category are changes that are at the edge of statistical significance but likely to be true, such as the 2% to 3% decrease in the stratospheric ozone shield above the Sierra Nevada, a 0.5°C rise in global temperature (now that the cooling effect of man made aerosols is included in the models), and the transition from the stable, warm climate of 1900 to 1960 into a more highly variable pattern of weather. In the final category, the effect of global climate on local meteorology such as rainfall-snowfall amounts is highly uncertain and while predictions of the models probably contain some guidance, the details are changing rapidly. For a discussion of the topic in depth, a University of California analysis (Knox 1989) discussed many important factors that may be very significant in terms of the amount and timing of rainfall and/or snowfall. In summary, the documented rise in $CO_2$ (carbon dioxide), $CH_4$ (methane), and other "greenhouse gases" raises global temperature and, more importantly, results in greater energy input to the equatorial Pacific, strengthening storms and adding more energy to the southern branch of the jet stream. The "El Nino–Southern Oscillation" (ENSO) events could become more frequent, with more heavy tropical rains in some parts of the cycle and droughts in others. While research on this phenomenon is still in its infancy, the most general and least contested conclusions predict an increase of rain, especially in the southern part of the range, and a decrease in snow in the northern sections. Quantitative uncertainties in such predictions are high, however, and are made more so by recent indications of a slowing down or leveling off of the rise of $CH_4$ and $CO_2$, which if continued, would limit the ultimate temperature rise (NOAA 1995).

A second aspect of global climate change is the direct effect of the observed increases in $CO_2$ levels on the growth of vegetation. In areas in which $CO_2$ is the limiting nutrient, the 25% increase in $CO_2$ since the late 19th century would increase bio-productivity. Research in this area also has not yet delivered a clear and convincing answer, especially since there are many parts of the Sierra Nevada where nitrogen, water, or other factors limit plant growth. Furthermore, local anthropogenic influences can also change growth rates, including pollutants such as ozone, acidic deposition, and alkaline salts from Mono Lake and Owens (dry) Lake. The latter source has, for most of this century, dusted the bristlecone pines (Pinus longaeva) of the White-Inyo Range with alkaline and saline salts. These same trees are used for studies of the effect of globally-enhanced $CO_2$ on growth rates.

A further aspect of global climate change is the observed thinning of the stratospheric ozone layer and the subsequent increase in ground-level ultraviolet radiation. This change has a potential impact on a number of areas, one of which is the global decline of amphibians. In this section, we will discuss this topic in some greater detail as it is needed for discussions of amphibians elsewhere in this report.

Our analysis indicates that increased ultraviolet radiation may not be as big a factor as some predict (Blaustein and Wake 1995). As seen in figure 48.1b, the mean change in the stratospheric ozone shield in the 25° to 35° north latitudes is only about 2% to 3% since 1978 (NOAA 1995), much less than natural variations caused by sunspot cycles, volcanic eruptions like those of Mt. Pinatubo, and even some weather patterns. Further, in figure 48.1a, we see that the recent patterns in the fluorocarbon concentrations that thin the ozone layer show that the rapid growth of the past decades has leveled off, limiting ozone reduction and hence ultraviolet increases in the future if it persists.

The modest decreases in ozone, a few percent at most, would increase in ultraviolet (B) also by only a few percent. When combined with mortality data from recent studies (Blaustein and Wake 1995), this predicts an almost negligible (and certainly undocumented) change in the survival of the eggs of certain amphibian species. Figure 48.1c shows such amphibian extinction rates in the Sierra Nevada. Survival rates of amphibians are closely tied to altitude in the range, with the species with the highest altitudinal range (and thus receiving the highest ultraviolet fluxes) having the highest survival. The survival pattern of the yellow-legged frog (Rana muscosa) is similar to that of other Sierran species, as summa-



Mean total zonal ozone from 25° to 35° North observed by TOVS for November from 1979 to 1993 and for 1994 (error bars denote 1 standard deviation).

Historic and current distribution of the mountain yellow-legged frog (Rana muscosa) in the Sierra Nevada.

**FIGURE 48.1**

Changes in *a,* ozone precursors, and *b,* the ozone shield, 1978–present, along with *c,* historic and current distribution of the mountain yellow-legged frog *(Rana muscosa)* in the Sierra Nevada region.

**TABLE 48.1**

Status of some Sierra Nevada amphibians. (For comparison, the status of the California red-legged frog *(Rana aurora)* at some non-Sierra sites is also shown.)

| Common Name (Scientific Name) | Elevation of Sites (ft) | | Survival at Sites | | |
|---|---|---|---|---|---|
| | Range | Average[a] | Extant | Extinct | % Survival |
| California yellow-legged frog *(Rana aurora draytonii)*[b] | 0–5,000 | 2,500 | 1 | 33 | 3 |
| Foothill yellow-legged frog *(Rana boylii)* | 1,000–6,300 | 3,650 | 0 | Many | 0 |
| Cascade frog *(Rana cascadae)* | 760–8,250 | 4,500 | 3 | 41 | 7 |
| Mountain yellow-legged frog *(Rana muscosa)* | 4,500–12,000 | 8,250 | 44 | 220 | 17 |
| Yosemite toad *(Bufo canorus)* | 6,400–11,400 | 8,900 | 25 | 29 | 46 |
| ***California Red-Legged Frog (Rana aurora)*** | | | | | |
| Los Angeles south (south coastal) | 0–5,000 | 2,500 | 4 | 66 | 6 |
| North of Los Angeles (central coastal) | 0–5,000 | 2,500[c] | 135 | Approx. 65 | Approx. 50 |

[a] Average of elevational extremes of historical range.
[b] Only in the Mt. Lassen–Mt. Shasta region; now extinct in the Sierra Nevada proper.
[c] Most extant sites near sea level.

rized in table 48.1. The amphibian survival rate is closely tied to the absence of planted trout, to ponds that freeze to the bottom in winter, and other local non-atmospheric impacts (Jennings and Hayes 1994). It is also worthy of note that the rapid extinction of amphibians at low- and mid-elevation sites in the southern Sierra Nevada in the 1960s and 1970s (P. B. Moyle, Department of Wildlife, Fish, and Conservation Biology, University of California, Davis, communication with the author, 1995) occurred immediately after the completion of the California aqueducts and vast changes in agricultural practices in the southern San Joaquin Valley (Scheuring 1983). The efficient transport of valley pollutants into the mountains is well established (see next section). In summary, we believe that ultraviolet increases due to global climate change are not a significant factor in the massive decline of some amphibian populations in the Sierra Nevada.

## THE IMPACTS OF UPWIND AIR POLLUTANTS

The Sierra Nevada is closely coupled to upwind air quality by three major factors:

1. The prevailing northwesterly winds
2. The local terrain-generated (upslope-downslope) winds
3. The Central Valley temperature inversions

There is also influence from other directions, probably the most important of which from air quality considerations is transport from the southeast to the eastern slope of the Sierra Nevada. This becomes important for both acidic rain episodes in the summer and alkaline-saline dust from Owens and Mono lakes in the spring and fall. Such events are relatively rare, however, and total impacts are low compared to the close coupling to upwind sources west of the range. In terms of the winds from the west, the prevailing winds dominate local terrain winds in winter, while the local terrain-generated winds dominate in summer. The presence of strong winter inversions in the Central Valley is a major factor in trapping local pollutants near the ground and reducing transport into the range in winter.

In the rest of this section, we will summarize what little is known about air quality upwind of and in the Sierra Nevada before the European settlement, and then consider the present-day air quality of the region.

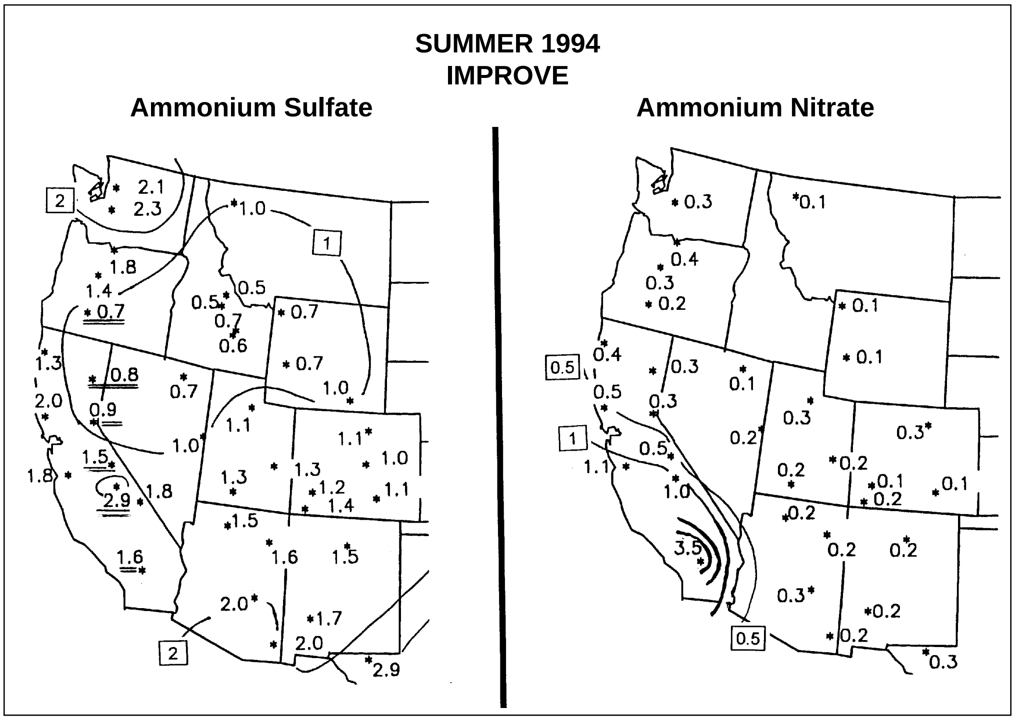
### Natural Status of Air Quality—Pre–European Immigration

Information on the pre-European air quality upwind of the Sierra Nevada is difficult to ascertain at present. No matter which way the wind blows, to the south from the Bay Area, north from the Bakersfield area, or west across the Central Valley, major sources of air pollution now exist that severely modify air quality. However, some information may be inferred from spatial and temporal patterns of both source and effects. The northern Sacramento Valley has a low population and industrial density and receives its incoming air largely from the North Pacific over the Klamath Mountains. With some exceptions, we may extrapolate from the data in this area to natural conditions before European settlement of the Sierra Nevada. The major exception is smoke, which was probably quite prevalent in pre-European times due to lightning-started fires and deliberate fires by native Americans to favor black oak plantations (e.g., the floor of Yosemite Valley). During early decades of European settlement of the Sierra Nevada, anecdotal reports at the time indicated that air quality in the region was considered extremely pure, pristine and therapeutic, and doctors prescribed Sierra Nevada air as a curative (Thompson 1972). However, other reports and photographs indicate significant summer smoke from numerous small fires "of the surface variety" that burned unchecked for extended periods (see section on fires).

### Present Air Quality—Particulate Matter (Fine Aerosols)

The first upwind pollutant that we address is the atmospheric aerosol, fine particles that persist in the atmosphere for hours to days, which range from largely anthropogenic (sulfates, nitrates) to largely natural (soil dusts) in composition. We consider these before ozone, which is biologically more important, because particles retain much information regarding their nature and location of their sources. Ozone, on the other hand, is confounded by multiple sources and complex photo chemistry. Thus, data on fine particles can be used to clarify ozone behavior.

Regional patterns of the two most important constituents of fine ($D_p < 2.5$ microns diameter) aerosols, ammonium sulfate and ammonium nitrate, are shown in figure 48.2. The data are derived from IMPROVE sites (IMPROVE 1995), mostly in national parks, monuments, and wilderness areas, or other sites that represent regional as opposed to local air quality. The nitrate levels in the southern Sierra Nevada and San Bernardino Mountain sites are higher than at any other site in the nation (example: Shenandoah NP, 0.4 $\mu g/m^3$) while even the highest sulfate levels are 20% of those in the east (example: Shenandoah NP, 11.8 $\mu g/m^3$). Conversely, the northern Sierra Nevada values for sulfate and nitrate average only about 40% higher than those at Denali NP in Alaska and the Mauna Loa world baseline observatory in Hawaii. The sulfate levels at coastal California sites have not been corrected for sea spray sulfate, which will sharply reduce most of these values. Note that the Sierra Nevada seems to act as a barrier, limiting transport of Californian aerosols into the largely pristine intermountain area.


SUMMER 1994
IMPROVE

Ammonium Sulfate

Ammonium Nitrate

**FIGURE 48.2**

Spatial patterns of fine particulate ammonium sulfate (µg/m$^3$) and ammonium nitrate (µg/m$^3$) in summer 1994. The doubly underlined sites all occur at elevations above 1,700 m (4,000 feet) and will later be used for north to south spatial trends.

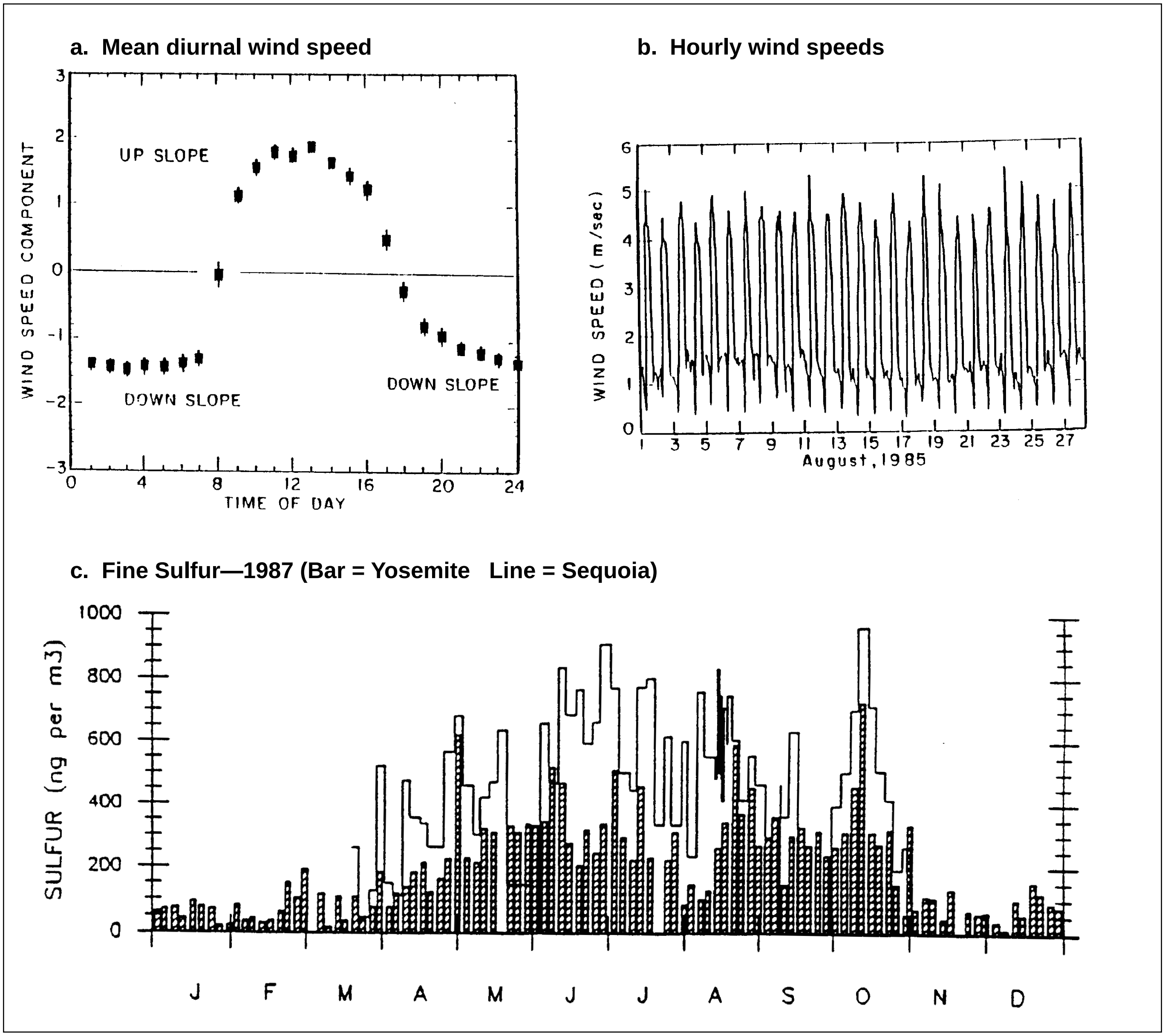
The summer pattern of strong, terrain-driven diurnal winds in the Sierra Nevada is shown in figures 48.3a and b. The regularity of wind direction and velocity are extraordinary, resulting in efficient transport of valley sulfates into the mountains as shown in figure 48.3c. Most other valley pollutants, particles and ozone, show similar behavior.

The diurnal wind patterns are both strong and regular, resulting in strong upslope winds each day and weak downslope winds each night. The concentration of sulfate pollutants in the valley, measured by local air monitoring stations, is relatively constant throughout the year. If anything, it is the inverse of that in the mountains—higher in winter, lower in summer. Clearly, upslope transport from the Central Valley dominates air quality in the mountains, since there are no major sources of sulfate particles within the western slope of the Sierra Nevada. The dominant effect of the Central Valley upon summer air quality on the western slopes of the Sierra Nevada is probably the most important lesson learned from air quality research at mountain sites in the past 20 years. The eastern slopes, on the other hand, can be influenced by air masses moving up from Southern California and Arizona. Summer storms from this direction have shown high acidity.

Further information can be gained through analysis of particulate pollutant patterns as a function of distance along the Sierra Nevada. Figure 48.4 shows the upwind anthropogenic sources of the precursor gasses, sulfur dioxide (SO2) and oxides of nitrogen (NO$_x$), roughly integrated from the Sierra Nevada to the coast along an east-to-west strip.

Figure 48.5 shows annual fine sulfate and nitrate aerosols at mountain sites between 4000 and 7000 feet (1200 to 2100 m) from the San Bernardino Mountains (San Gorgonio / Barton Flats) through the Sierra Nevada into the Cascade Range (Crater Lake National Park). All sites except Sequoia NP lie between 4,000 and 7,000 foot elevation, (1200 to 2100 m). The Sequoia site in 1992 was at elevation 2200 feet (660 m), but using the 1987 particle transects, a 10% correction has been applied to make the data from the present site equivalent to that at Giant Forest at 6,000 feet (1800 m). While there are some similarities between the sources and the resultant fine aerosols, there are also major differences. First, NO$_x$ sources dominate SO$_2$ sources, but sulfate particles dominate nitrate particles. Both types are aerosols in neutralized forms, ammonium sulfate and ammonium nitrate respectively, due to abundant ammonia sources in the Central Valley. Note how rapidly nitrates drop from the very high levels at San Gorgonio (Barton) to low ones at Bliss, Lassen, and Crater Lake. The drop off is much more rapid than for sulfates. San Gorgonio is influenced by the strong and chemically complex upwind sources of nitrogen from the Los Angeles area, but even so, nitrates fall off more sharply than sulfates from Sequoia NP north to Crater lake. This probably reflects that the northern Sacramento Valley is approaching the global background for sulfate aerosols, typically around 0.3 to 0.5 µg / m$^3$, seen at sites like the NOAA world baseline Mauna Loa Observatory (MLO), Hawaii (NOAA 1995). Global baseline values for nitrates are not well established.

Figure 48.6 shows fine particulate mass, which is dominated by sulfates, nitrates and organic matter, and fine soils. Mass has been divided by 10 to show how fine soils are only about 10% of mass at mountain sites.



a. Mean diurnal wind speed

b. Hourly wind speeds

c. Fine Sulfur—1987 (Bar = Yosemite Line = Sequoia)

**FIGURE 48.3**

Terrain-driven diurnal wind patterns *(a, b)* and sulfur aerosols *(c)*, Sequoia National Park, during 1987. A direct comparison is shown for Yosemite National Park, since both sites were near 6,000 feet (1,800 m) elevation.

Table 48.2 contains these data, as well as trace element data, along with comparisons to two urbanized areas, South Lake Tahoe, and, for comparison purposes only, Washington, D.C. All were collected with identical IMPROVE instrumentation and identical analytical and quality assurance protocols (IMPROVE 1995).

The ecological impact of these fine particles is not yet clear. They are acidic and hygroscopic, precursors to acid fogs (generally rare in the Sierra Nevada) and acid rain (generally weak in the Sierra Nevada), and directly involved in foliar dry deposition. However, they are neutralized by the abundant ammonia sources in the valley to ammonium sulfate and ammonium nitrate—common fertilizers.

One impact of these fine aerosols is clear to every visitor; fine particles are the major cause of haze, and severely degrade visibility along and into the western slope of the range (Cahill et al. 1989; Malm et al. 1994). This is especially true downwind of the San Joaquin Valley, a U.S. Environmental Protection Agency "non attainment area" for $PM_{10}$ (particulate matter smaller than 10 μm diameter). The impact of fine particulate matter includes an aesthetic component and may ultimately impact tourism. Such impacts have already oc-

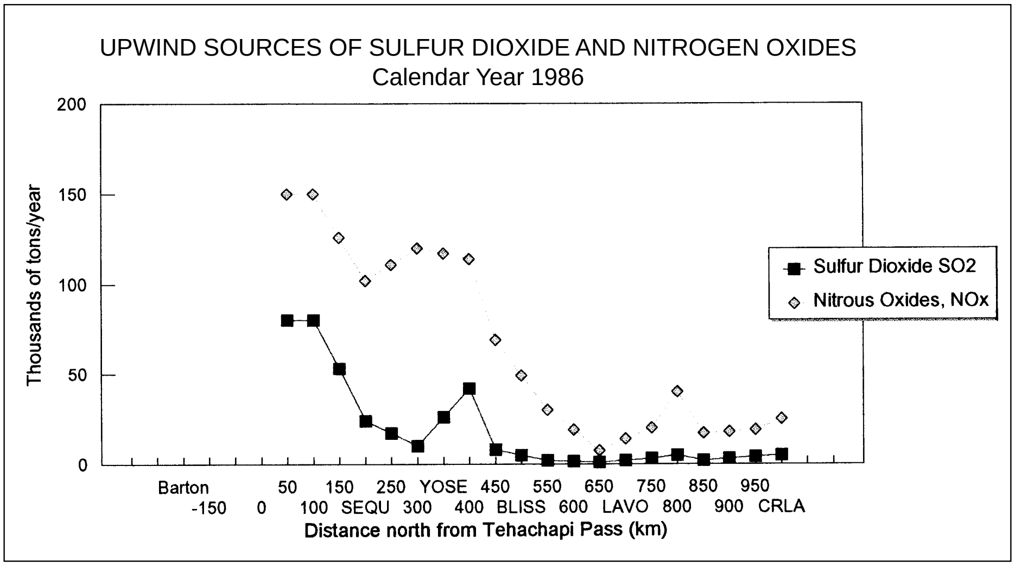


**FIGURE 48.4**

Anthropogenic emissions of sulfur dioxide and nitrogen oxides, gaseous precursors to sulfates and nitrates, on a strip across California roughly 50 km wide, west from the south-to-north transect starting at Tehachapi Pass. Also noted are the approximate locations of Sequoia NP (SEQU), Yosemite NP (YOSE), Bliss State Park at Lake Tahoe (BLISS), Lassen Volcanic NP (LAVO), and Crater Lake NP (CRLA).

curred in several national parks in the eastern U.S.A. (Shenandoah and Great Smoky Mountains), where summer visitation rates have declined in part because tourists literally can't see very much.

An analysis of the impact of fine particles on visibility was performed at 36 national parks, monuments, and wilderness areas as part of the IMPROVE program (Malm et al. 1994). The results of these analyses for western mountain sites is given in table 48.3, with an additional comparison to Shenandoah NP. These results must be interpreted carefully, however, as mountain sites often have extreme summer-winter aerosol differences (figure 48.3c). Thus, an annual average may dilute very poor summertime conditions by adding in almost pristine winter conditions, as happens in the Sierra Nevada and even at Appalachian sites such as Shenandoah NP. Thus, mean summer visibility at Yosemite NP is actually closer to 60 km (38 mi) than to 117 km (73 mi), coinciding with the highest visitor use. At most other types of sites, no such extreme seasonal gradient exists.

Some points are evident. First, visibility is sharply reduced at many Sierran sites, again following a north to south gradient seen in aerosols. Again, Lassen Volcanic (and, it turns out, Bliss State Park) has almost the same visibility as Denali NP in Alaska, one of the best sites in the network. Organic matter is the most important single component, derived at least in part from biomass (mostly agricultural) burning in the Sacramento and San Joaquin Valleys. Sulfates are about a quarter, but are more important than this in summer, about one-third

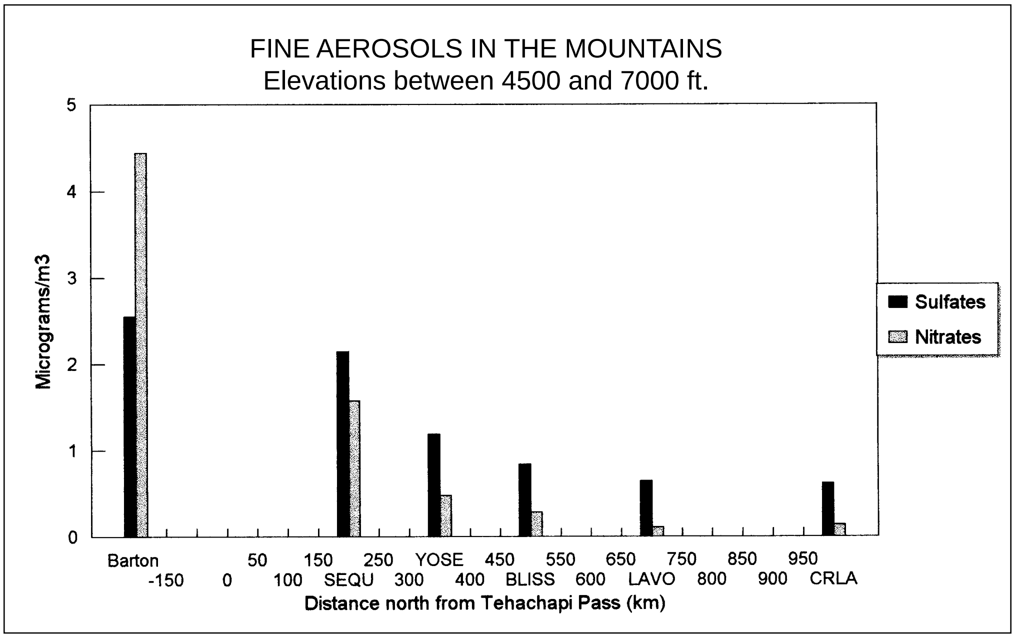
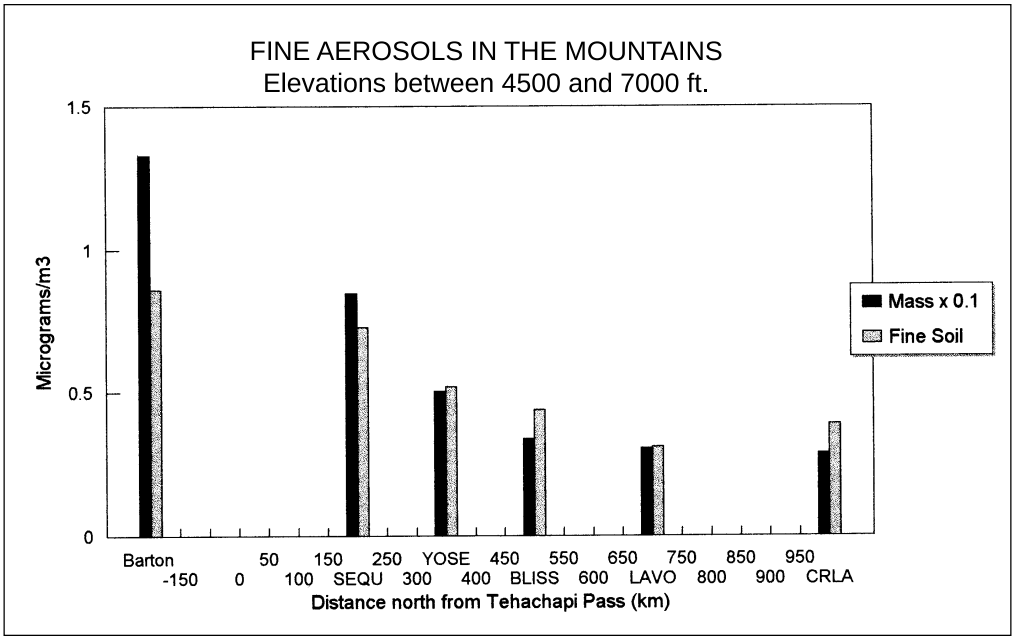


**FIGURE 48.5**

Concentrations of fine sulfate and nitrate aerosols, from San Bernadino NF (Barton Flats/San Gorgonio) to Crater Lake NP, Oregon, for 1992–93. Distances are marked from Tehachapi Pass.

**FIGURE 48.6**

Fine particulate mass, divided by 10, versus fine soils. Soils provide approximately 10% of the fine mass at all sites.



of the haze. Fine soils, nitrates, and soot are the remaining fractions, with the latter also tied in part to biomass burning. San Gorgonio responds to the Los Angeles area with its intense nitrate sources, but more recent data show that Sequoia National Park is also nitrate-impacted.

Figure 48.7 shows three components or tracers of smoke—organic matter, optical absorption, and excess non-soil fine potassium, K-NON. The smoke signature of the Central Valley is very evident even at these high altitude sites.

Note from figure 48.7 the large smoke signature in the Sierra

**TABLE 48.2**

Comparison of Sierra-Cascade aerosol concentrations at high elevations, 1992–93.

| | Sequoia NP (x.09)[a] | Yosemite NP | Bliss SP | South Lake Tahoe[b] | Lassen NP | Crater Lake NP | Washington DC[b] |
|---|---|---|---|---|---|---|---|
| ***Major Constituents (Micrograms/$m^3$)*** | | | | | | | |
| *Coarse Mass* | | | | | | | |
| PM-10 | N.A. | 11.00 | 5.85 | 18.20 | 7.05 | 6.21 | 23.10 |
| *Fine Mass* | | | | | | | |
| PM-2.5 | 8.49 | 5.04 | 3.39 | 9.65 | 3.05 | 2.87 | 19.70 |
| Estimated sum | 6.86 | 4.17 | 2.90 | 9.21 | 2.55 | 2.41 | 18.50 |
| Organics | 2.94 | 1.84 | 1.16 | 5.52 | 1.18 | 0.98 | 5.12 |
| Sulfates | 2.14 | 1.19 | 0.84 | 1.03 | 0.65 | 0.62 | 9.54 |
| Nitrates | 1.58 | 0.48 | 0.29 | 0.53 | 0.11 | 0.14 | 2.41 |
| Soil | 0.73 | 0.52 | 0.44 | 0.88 | 0.03 | 0.39 | 1.03 |
| *Smoke Tracers* | | | | | | | |
| b(abs) (10-8m-1) | 13.50 | 7.83 | 5.66 | 29.30 | 4.99 | 5.25 | 41.80 |
| Estimated mass (micrograms/$m^3$) | 0.14 | 0.08 | 0.06 | 0.29 | 0.04 | 0.05 | 0.42 |
| KNON (ng/$m^3$) | 37.89 | 23.80 | 14.80 | 41.60 | 12.40 | 6.58 | 16.40 |
| ***Trace Elements[c] (Nanograms/$m^3$)*** | | | | | | | |
| Nickel | 0.19 | 0.09 | 0.07 | 0.13 | 0.07 | 0.08 | 3.53 |
| Copper | 1.58 | 0.47 | 0.44 | 1.41 | 2.53 | 0.84 | 4.76 |
| Zinc | 3.12 | 1.55 | 1.29 | 5.13 | 1.52 | 3.33 | 18.60 |
| Selenium | 0.28 | 0.19 | 0.12 | 0.12 | 0.09 | 0.06 | 2.08 |
| Bromine | 2.65 | 1.56 | 1.16 | 1.63 | 0.91 | 0.75 | 5.12 |
| Lead | 1.29 | 0.78 | 0.68 | 1.71 | 0.53 | 0.96 | 6.99 |

[a] Corrects to Giant Forest elevation, 6,000 feet.
[b] Urbanized sites.
[c] Ni, As, and Se often below detectable limit.

**TABLE 48.3**

Causes of haze and visibility loss in the Sierra Nevada, with comparisons to other IMPROVE sites.

| Site Name | Mean Annual Visibility | Soil | Sulfates | Organic Matter | Nitrates | Soot |
|---|---|---|---|---|---|---|
| Denali NP | 154 km (96 mi) | 18% | 43% | 30% | 4% | 4% |
| Crater Lake NP | 139 km (87 mi) | 13% | 26% | 45% | 6% | 10% |
| **Lassen Volcanic NP** | **140 km (88 mi)** | **17%** | **23%** | **41%** | **10%** | **10%** |
| **Yosemite NP** | **117 km (73 mi)** | **15%** | **25%** | **35%** | **15%** | **11%** |
| **Sequoia NP** | **74 km (46 mi)** | — | — | — | — | — |
| San Gorgonio Wilderness Area | 61 km (38 mi) | 14% | 14% | 18% | 44% | 9% |
| Shenandoah NP | 35 km (22 mi) | 3% | 69% | 15% | 8% | 4% |

Nevada is larger than that of either the San Bernardino or Cascade Mountains. This is caused mostly by transport of smoke into the Sierra Nevada from agricultural burning and other anthropogenic sources on the Central Valley floor, not wildfires or controlled burns in mountain forests. This is indicated both by air samples taken on the valley floor, showing persistent smoke, and by the almost total lack of prescribed natural fire or other controlled burns during summer months, June through mid-September. We must be very careful in interpreting these results, for as we investigate pollution sources within the Sierra Nevada, we often find highly polluted mini-urban sites that often serve as the sites for air pollution monitoring stations. The sites chosen for the data above, generally part of the national IMPROVE network, were sited so as to avoid this problem.

## Future Air Quality—Aerosols

Reductions in concentrations of fine particulate matter in the Sierra Nevada would be dramatically reflected in improved visibility throughout the range. This visibility degradation is both serious and anthropogenic (Malm et al. 1994). The Clean Air Act Amendments of 1977, extended by the amendments of 1990, mandate that one must mitigate human sources of haze in mandatory Class I areas. This could be accomplished by limitations of upwind sulfur emissions in the Bay Area, especially by the oil refineries and chemical plants near the Carquinez Strait which dominate $SO_2$ inventories. Continued efforts to control oxides of nitrogen, and tighter controls or elimination of all agricultural burning during summer months would result in sharply improved visibility. This latter policy is in effect in Oregon. On the other hand, increased use of prescribed fire would increase smoke in the mountains, especially during late spring and fall, preferred times for controlled burns.

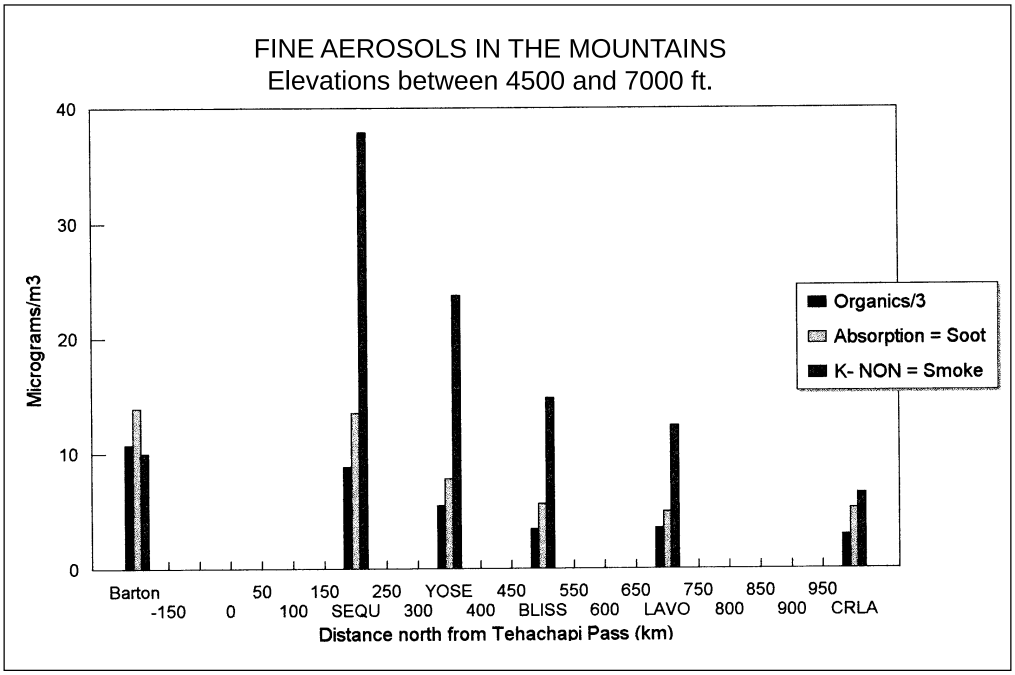


**FIGURE 48.7**

Fine aerosol concentrations for aerosol components that reflect combustion sources.

## Ozone

Of all anthropogenic pollutants, ozone has the best documented impact upon the Sierran biosphere. Injury to trees, especially the Jeffrey pine (Pinus jeffreyi), has been investigated extensively in the past decades, leading to an association with ozone. Due to its importance, a companion chapter by Paul Miller (Miller 1996) deals exclusively with our knowledge of ozone injury to vegetation.

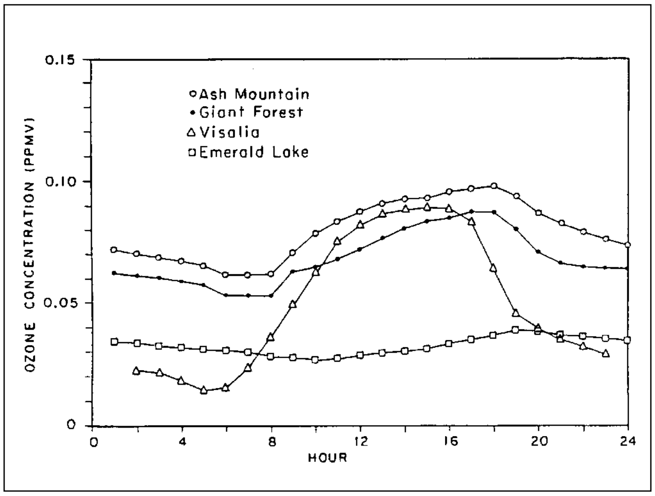
Ozone is generated from emissions of hydrocarbons and oxides of nitrogen that, given sunlight and time, form ozone. The $O_3$ molecule is a very strong oxidizer that, when in contact with biological material, can break up biological molecules, including DNA, destroying their function. The removal of ozone from the air comes from its destruction on surfaces, incorporation into clouds, and scavenging by oxides of nitrogen that destroy it at night. The patterns of ozone are therefore tied to sunlight. Figure 48.8 shows patterns of ozone as a function of time of day, from the valley floor (Visalia) into Sequoia National Park, including Ash Mountain at 2,200 feet (670 m), Giant Forest at 6000 feet (1,800 m) to, at almost 10,000 feet (3,000 m), Emerald Lake.

Clearly, peak daily ozone values at Giant Forest are almost the same as on the valley floor, while ozone values in the key early morning hours, when the stomata of pines open up, are actually much higher at Giant Forest than at Visalia.

Recently, two extensive sets of ozone measurements and analysis have become available, the first covering all western forests (Bohm et al. 1995a, 1995b), and the second an extensive set of ozone measurements at sites on the western slope of the Sierra Nevada (Van Ooy and Carroll 1995). The sites used in the Van Ooy and Carroll study are shown in figure 48.9. Statistical summaries of the data from these sites are shown in figure 48.10.

**FIGURE 48.8**

Mean diurnal variations of ozone vs. elevation from the San Joaquin Valley floor (Visalia) to an alpine site in Sequoia National Park (Emerald Lake) (Cahill et al. 1989).



The patterns are complex, reflecting the presence of urban plumes of increased ozone and efficient transport at some sites. The diurnal patterns are also complex, but fall generally into two categories similar to the several categories of Bohm et al. 1995b. One type was seen before at Sequoia NP, with a sharp daytime peak (figure 48.8), while the other is much flatter, resulting in the narrower of the probability distributions seen at Jerseydale and White Cloud. The value 0.09 ppm (90 ppb), the California standard for peak daily hour, has been highlighted, since it will later be used in exposure and dose calculations.

Miller 1996 has documented ozone injury to forests of the Sierra Nevada, expressed by an Ozone Injury Index (OII). Since the dominant ozone sources are in the Central Valley, one can attempt to match averaged ozone peak values to forest injury. This is done in figure 48.11, with poor results.

The Ozone Injury Index (OII) tends to fall dramatically from Barton Flats in the San Bernardino Mountains, with peaks in the urban plumes of Fresno and Sacramento, until low levels of injury are seen at Lassen Volcanic NP (LAVO). However, the averaged peak hours, typically the 10 worst hours per year averaged in a three-year rolling average (California Air Resources Board 1991; see below), only fall slowly in this profile. The resolution of the problem comes through consideration of exposure and dose.

Now the match between ozone and injury is much more satisfactory, using only hours above 90 pphm (0.09 ppm) for ozone and multiplying the hours by the concentration (figure 48.12). This reflects the fact that the northern Sacramento Valley can have high ozone peaks, but they are of shorter duration than those in the San Joaquin Valley.

There is also the question of transport of ozone into the mountains. The efficient transport of valley ozone into the Sierra Nevada is tied closely to the strength of the terrain winds, which depend in part on the slope of the valley-mountain transport path. As shown qualitatively in figure 48.9, the west-facing slope of the Sierra Nevada is more abrupt by about a factor of two in the southern San Joaquin Valley than it is in the central and northern Sacramento Valley. Theoretically, this should result in stronger terrain winds in the San Joaquin Valley than in the Sacramento Valley, as reflected in the vigorous winds seen at Sequoia NP (figure 48.3), but no systematic study has been made of terrain winds along the entire length of the range.

The second point to note is the slow decline in peak ozone values and rapid decline in ozone dose on the valley floor, which reflect the documented diminution of anthropogenic input gases needed to create ozone (illustrated in figure 48.4, nitrous oxides) but also may reflect the location of the sampling site vis à vis an urban plume. We discount to some extent the role of peak temperature as a major cause of the profile, since summer daily maximum temperatures in the northern Sacramento Valley are roughly equivalent to those in the southern San Joaquin Valley.

In summary, it appears that serious ozone injury, based on

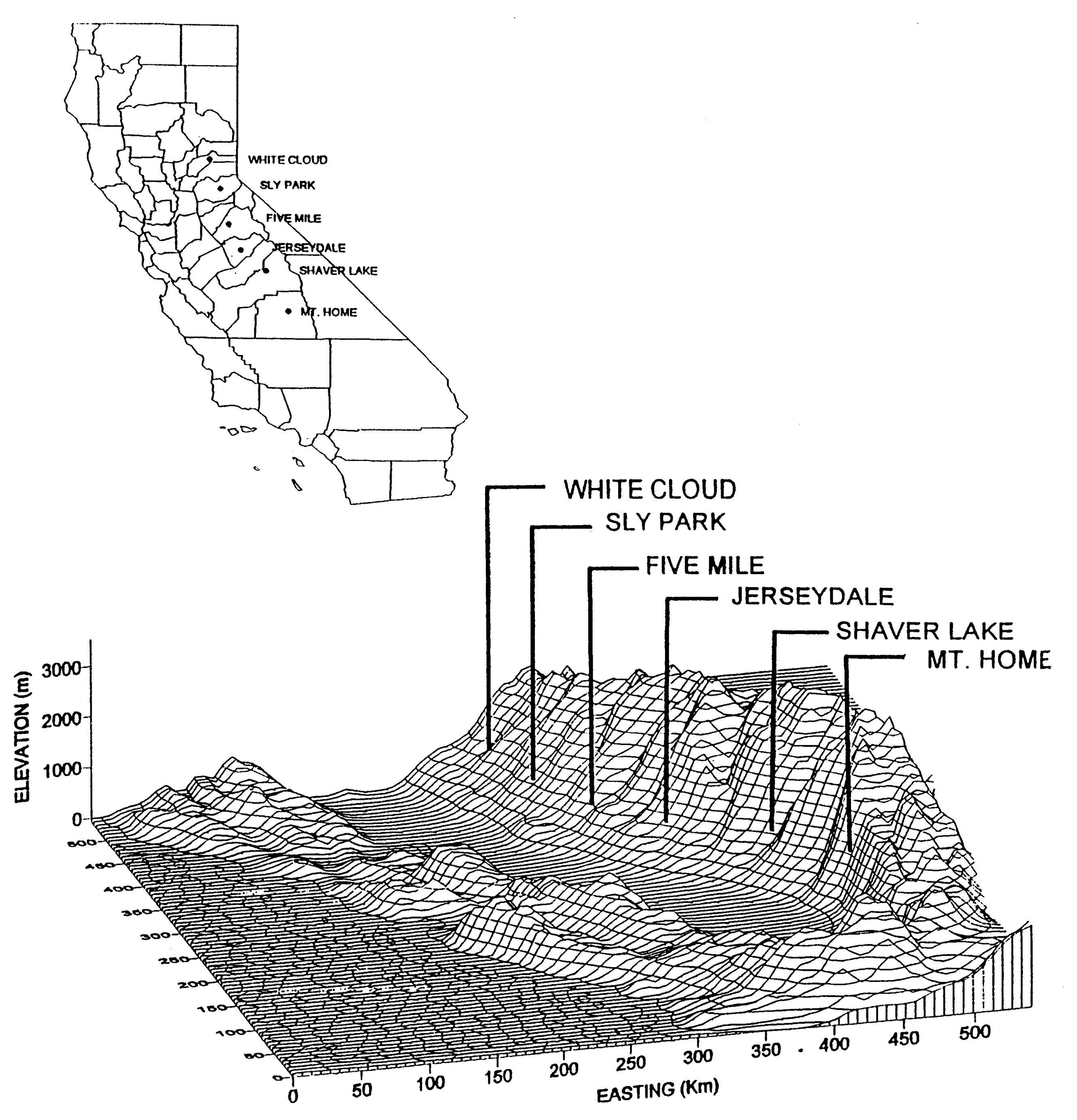


FIGURE 48.9

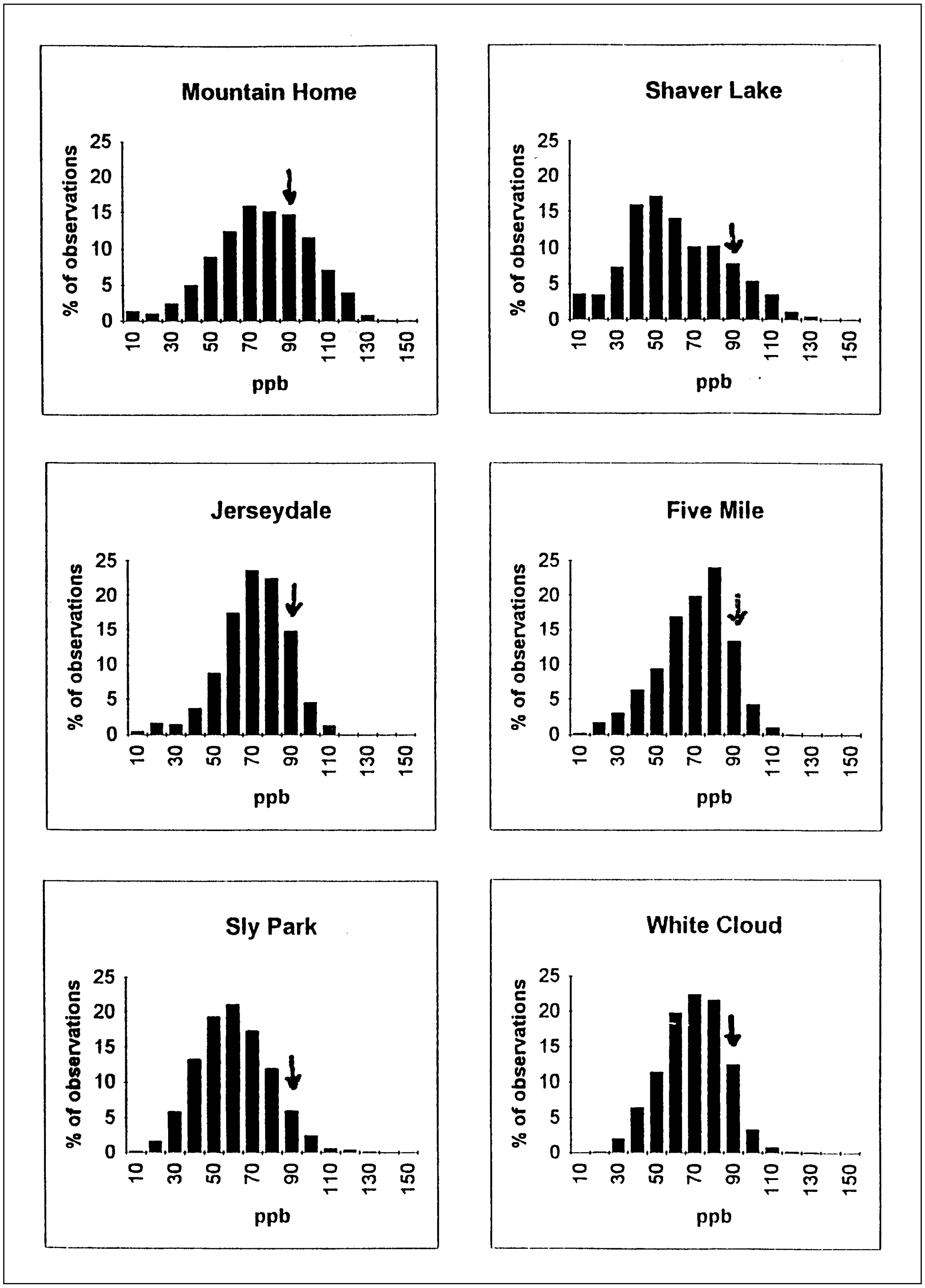
Perspective view of central California, showing approximate site locations. Horizontal area shown is 530 km on a side. Vertical exaggeration is a factor of 3.

the ozone injury index (OII) occurs on the most sensitive but also economically important species, ponderosa pine (Pinus ponderosa) and Jeffrey pine, when the average peak hour valley ozone concentration exceeds 0.09 ppm, which is the California state standard. Injury severity is best reflected by a dose calculation, based upon the product of the concentration times all hours during which the concentration exceeds 0.09 ppm.

Note that neither dose nor average peak ozone values reflect the individual daily-hour peak values upon which health standards are based. Figure 48.13 shows the daily peak ozone

FIGURE 48.10

Probability plots for ozone concentrations in the Sierra Nevada (Van Ooy and Carroll 1995).



values for Sacramento in summer 1992. Average peak hourly values were 0.069 ppm, while peak hour levels as high as 0.12 ppm occurred. The peak hour values may now be compared with the 0.12 ppm national standard and the 0.09 ppm California standard. The state standard was equaled or exceeded on about one-quarter of all days in summer 1992. It is therefore plausible that by achieving the state health standard of 0.09 ppm ozone at valley floor sites for peak hours, we would also achieve a value that would largely protect an important Sierran bio-resource, the ponderosa and Jeffrey pine forests of the western slope.

The ozone profiles in the Central Valley also bring us back to the question with which we started. What was the ozone value in pre-settlement times, and what will it be in the future? A general consensus appears to be developing that average daily peak summer ozone levels at pristine, mid-northern latitude sites are about 0.03 to 0.04 ppm, based upon remote sites used in global monitoring studies such as

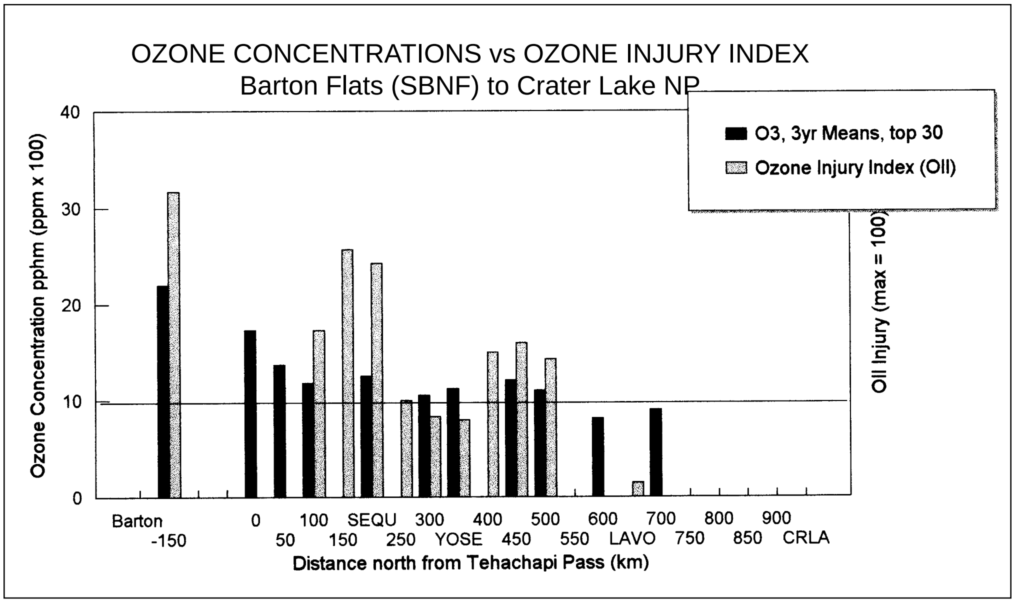


**FIGURE 48.11**

Comparison of averaged peak ozone hours versus ozone injury. The California standard, 0.09 ppm, is 9 on this scale (pphm).

NOAA's Mauna Loa Observatory, Hawaii. If true, we can infer that since summer ozone levels in the northern Sacramento Valley are approaching those levels (0.059 ppm, Redding; 0.052 ppm, Chico; 0.069, Sacramento) and anthropogenic influences are modest (figures 48.3 and 48.4), then the pre–European settlement ozone levels in the central and southern Sacramento Valley were somewhere between 0.035 and 0.05 ppm. We are thus seeing roughly a doubling to tripling of ozone upwind of the Sierra Nevada from historical levels.

## Future Air Quality—Ozone

We can also infer something about the future ozone values from this information and current ozone trends on the valley floor. Figure 48.14 shows recent trends in ozone in the San Joaquin Valley and Sacramento Valley air basins, 1981–90 (California Air Resources Board 1991). These were the data used in figure 48.11.

What is evident is that the dramatic decline of peak ozone

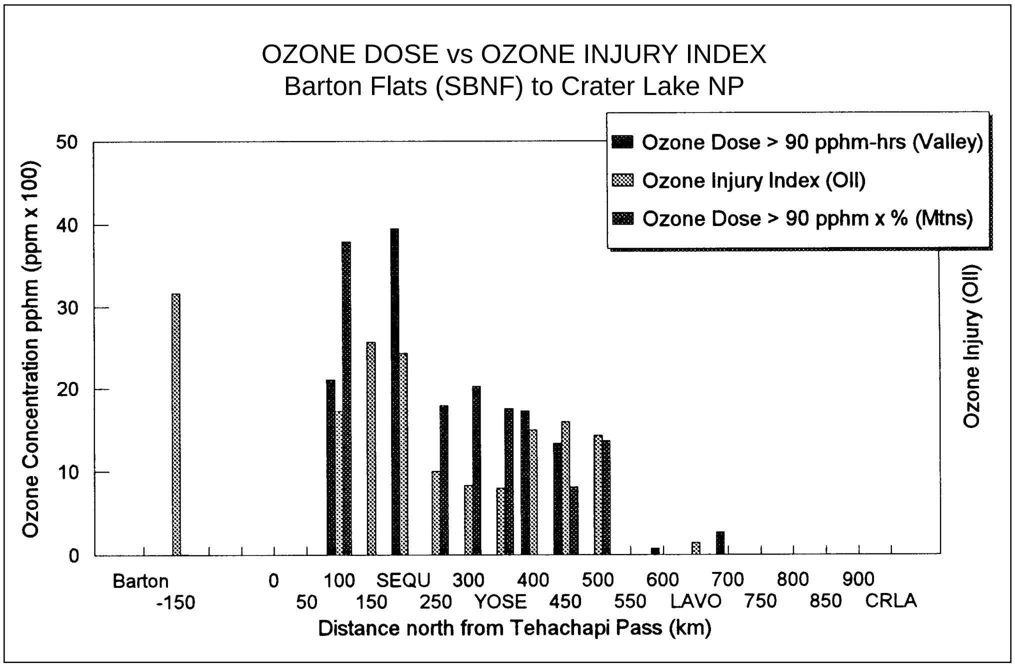
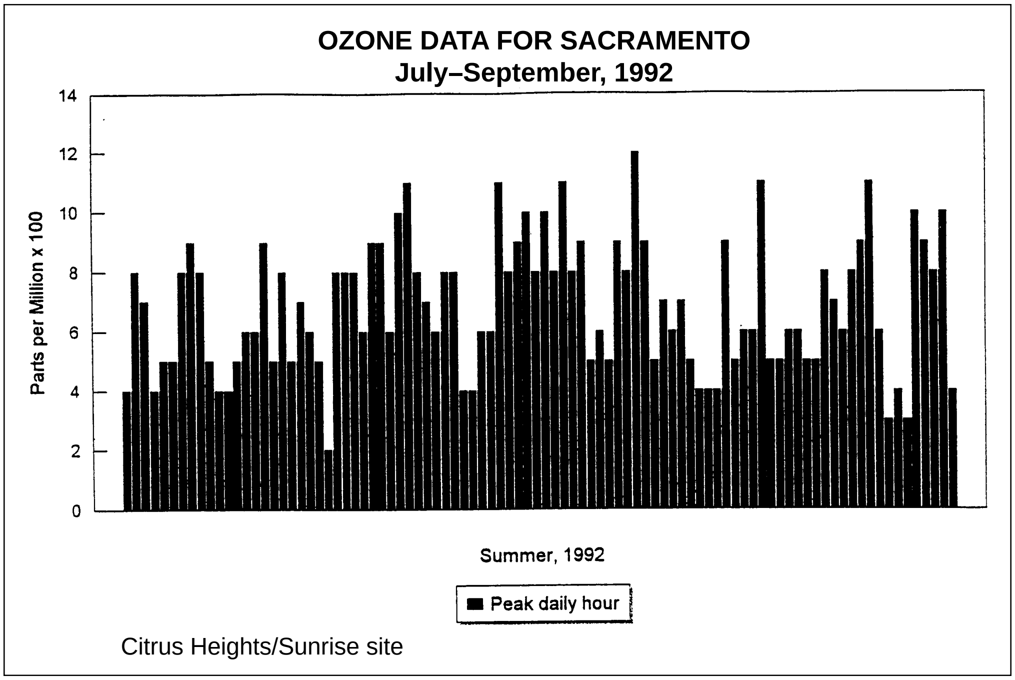


**FIGURE 48.12**

Comparison of ozone exposure (valley sites), ozone exposure (mountain sites), and the ozone injury index (OII) taken from mountain sites.

FIGURE 48.13

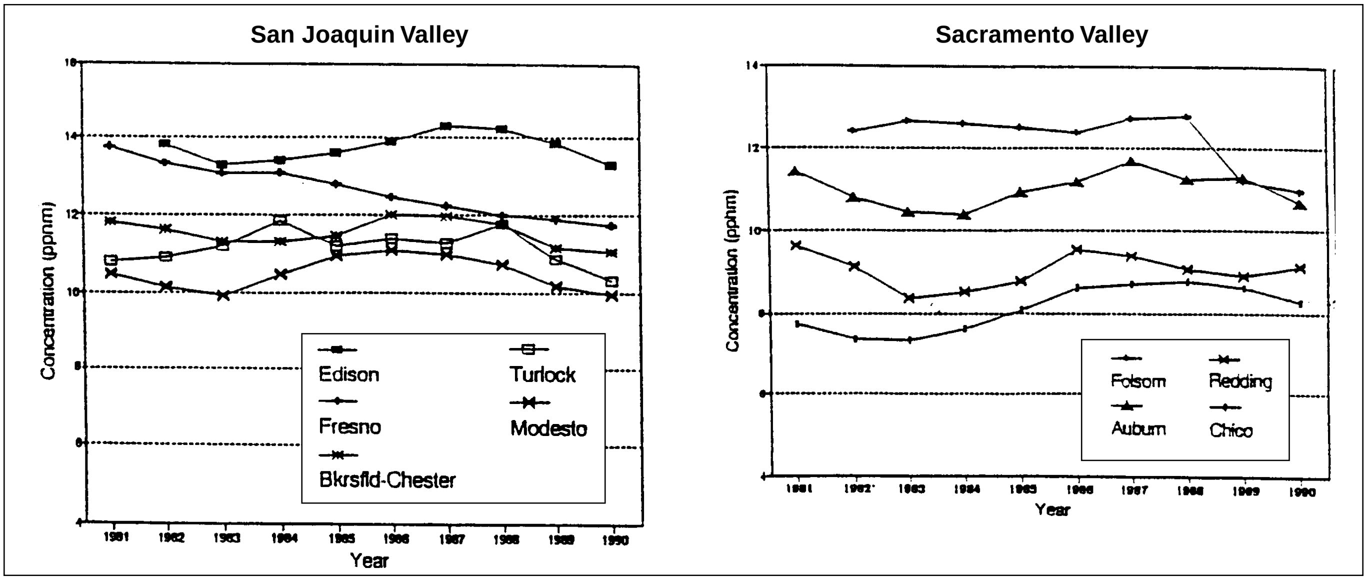
Peak daily hour ozone concentration for Sacramento (Citrus Heights–Sunrise site), July–September 1992.



concentration seen in places such as the Los Angeles Basin (1981–90) is not seen in the Central Valley. Since both areas share much of the same controls on vehicular emissions, and since there has been roughly comparable (fractional) growth in vehicular miles per year in both areas during this time, this probably indicates that mobile source emissions are somewhat less of a factor in the Central Valley than in Los Angeles. Certainly, the intense biological activity of the valley floor, prehistoric to a degree and agriculturally enhanced in the present, introduces biological sources of hydrocarbons and ozone precursor gases such as nitrous oxide that are much less important in the anthropogenically dominated Los Angeles Basin. Certainly, peak summer temperatures are somewhat higher and persist longer, and pollutant retention times are longer, in the Central Valley, allowing pollutants to more fully convert to ozone. It is important to note that ozone ex-

FIGURE 48.14

Mean of top 30 ozone concentrations (parts per hundred million), three-year averages, Sacramento Valley and San Joaquin Valley air basins, 1981–90.



posure values have decreased in the Central Valley since 1980, more so than peak values. The reasons are complex and still under intense investigation. What is clear is that there is a serious ozone problem in the Central Valley, and the state and federal air quality agencies will continue to pursue ozone control measures. Based on the past decade, however, all indications are that progress will be slow.

The situation is not without hope. Recent studies confirm the impact of a small number of "grossly emitting" vehicles (~10%) that generate perhaps two-thirds of all automotive emission. New technologies allow these vehicles to be identified on the road, allowing very effective reductions of emissions (Beaton et al. 1995). Until these gross emitters have been removed from the highway, little improvements in automotive emissions could be achieved by much more expensive technologies like "zero emission vehicles" (electric) that pose new types of environmental problems (Lave et al. 1995).

In winter, ozone levels in the Sierra Nevada are, on average, higher than those on the Central Valley floor, which fall to near-zero levels due to fog, lack of sun, and intense scavenging by anthropogenic gases and particles (CARB 1994; South Lake Tahoe site). The ozone patterns at high elevations do not fit typical summertime patterns, with peaks occurring at strange times and places (i.e., at night). More and more evidence indicates that these winter ozone levels, though moderate, may be partially caused by subsidence of stratospheric ozone (the "good" ozone that stops ultraviolet) down to high elevation sites such as Lake Tahoe. Since these ozone concentrations are not high, and since the biosphere is largely quiescent, the effects are assumed to be modest.

## Other Upwind Pollutants

The same conditions that efficiently transport particulate matter and ozone from the Central Valley into the Sierra Nevada also transport other valley pollutants including gaseous pollutants ($NO_x$ [nitrogen oxides], etc.), other photochemical compounds (PAN [peroxyacetyl nitrate], etc.), herbicides, pesticides, and other air pollutants. Gaseous pollutants can be converted into more damaging substances such as PAN, which could be a significant factor in declining forest health. Only limited data are available on these other valley floor pollutants, but they are surely present. The importance of their presence is unknown, but should be the focus of future studies.

## Winter Conditions

In winter transport from the valley is cut off by persistent valley inversions, photochemistry is weak, and local sources are quiescent. As shown in figure 48.2, aerosols are at very low values in remote (non-urban) areas. But it is this time that most of the annual water input to the Sierra Nevada occurs in the form of snow. The best information on pollutants in precipitation is probably derived from snow surveys.

Figure 48.15 shows snow survey results for sulfates and nitrates, after Laird et al. 1986. We have plotted using the spatial scale of figure 48.4, which shows the upwind sources. Clearly, a very different pattern is shown in the sulfate and nitrate content of snow, measured near the end of the snowfall season in February and March. The pattern is now relatively flat from north to south, and even flatter if one factors in the amount of snowfall at each site (higher in the north). Thus, net deposition of sulfates and nitrates in the snow is relatively constant, as expected from the nature of the synoptic winter storms which respond to nitrate and sulfate sources, natural and anthropogenic, over a very wide area upwind of California.

The introduction of nitrates and sulfates into the Sierra Nevada hydrological cycle leads to the possibility of perma-

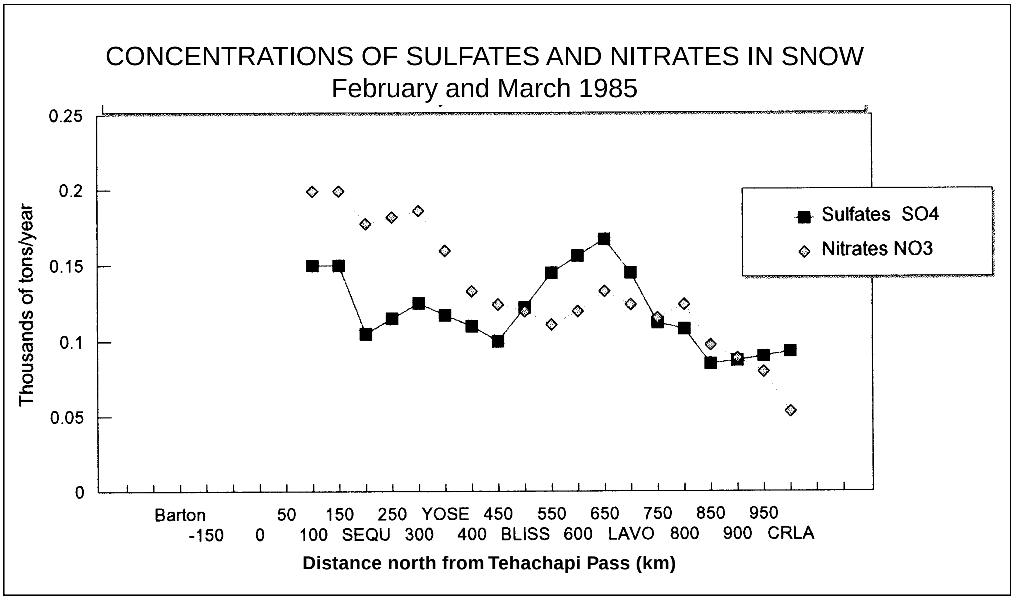


**FIGURE 48.15**

Sulfate and nitrate concentrations in snow on a south-to-north transect along the Sierra Nevada (after Laird et al. 1986).

nent or ephemeral acidification of lakes and streams, exacerbated by the generally low buffering capacity of high Sierra granite watersheds. Extensive work has been done on this problem in the past decade, most notably by and for the California Air Resources Board's Research Division. The results of the California Acid Deposition Monitoring Program (CADMP) are summarized annually (CADMP 1995) and provide an excellent basis for evaluating the impact of acidic deposition. The results show that "In contrast to the Eastern U.S., no permanently acidified lakes and streams have been found in California" despite the observation that ". . . many California lakes exhibit a very low buffering capacity" (CADMP 1995). This was attributed to the relatively un-acidified winter storms that dominate total annual precipitation in the Sierra Nevada. Highly acidified storms have been observed, such as those in Sequoia N.P. (Cahill et al. 1989), originating over the southern California desert, some carrying effluents attributed to the Arizona copper smelters. However, total precipitation from such events is, on the average, only a modest contribution to total precipitation.

Averaging over the hydrological cycle for the years 1984–88, CADMP found that pH in the Sierra Nevada was 5.26 +/- 0.04. This can be compared to the cleanest California sites on the Northwest coast, 5.33 +/- 0.02, close to the weak acidity of pristine rainfall in equilibrium with atmospheric $CO_2$. Another measure of human impact is nitrate and non–sea salt sulfate. The sulfate deposition was 1.4 times higher at the southern sites, Lake Isabella through Sequoia N.P., than at the northern sites, Lake Tahoe through Quincy, while nitrates were higher by a factor of 1.8 at the southern sites than the northern sites. Recall the equivalent ratios for aerosols were, respectively, about 2.5 for sulfates, and 8.0 for nitrates. One striking pattern did emerge—a strong dependence upon the elevation at which the precipitation was collected. The well documented Sequoia N.P. transect from Ash Mountain (2200 ft) through the Giant Forest (6,000 ft) to Emerald lake (10,000 ft) used previously for ozone and aerosols showed a strong gradient in acidic deposition; Ash Mountain, 7.1 and 16.6 µeg/L for sulfates and nitrates, respectively; Giant Forest, 4.5 and 8.4 µeg/L, and Emerald Lake, 3.0 and 3.5 µeg/L.

These data are in accord with the results of the national Acid Deposition Assessment Program, which also found that only one western lake out of 10,393 surveyed showed even marginal acidity, below 6.0, and that lake was geothermal in origin. "It appears that there are virtually no acidic lakes in these (western) areas" (NAPAP 1991).

None of this contradicts results showing that in the spring melt, pulses of acidity can surge through streams and lakes. But it does put into context the far more important acidic dry deposition of gasses and particles during the long, generally dry summers of the Sierra Nevada. Highly acidic fogs can occur in California, but generally they are rare in the Sierra Nevada region since they are generally trapped in the valley floor inversions.

### Summary of Present-Day Effects of Upwind Air on Sierra Nevada Air Quality

The present status of air quality in the Sierra Nevada can be conveniently separated into summer and winter conditions. In summer, the southern parts of the western slope of the range are highly impacted, as terrain winds pull into the mountains, to altitudes of at least 6,000 feet, all the air pollutants of the San Joaquin and Sacramento valleys. In the winter, the Sierra Nevada's non-urban air is very clean. This occurs because in clear air conditions under high pressure, a strong inversion closes off the Central Valley floor and prevents transport into the range. In winter storm conditions, the inversion is broken, but air motion and mixing are extremely vigorous while precipitation rapidly strips the air of pollutants. Such storms come off the Pacific, and thus have a very limited time over land to pick up anthropogenic pollutants.

Thus, in terms of regional impacts of upwind sources:

> Summer: highly impacted air quality in the south (for ozone, among the worst in the nation), but fair to good air quality, especially north of Sacramento
>
> Winter: very clean air, close to pristine quality, both in terms of wet deposition (snow) and aerosols (sulfates, nitrates, etc.)

## THE IMPACTS OF LOCAL AIR POLLUTANTS

There are significant sources of air pollution generated within the Sierra Nevada, strongly affecting local air quality, and more weakly affecting downwind sites in the Great Basin deserts of Nevada and California. These will be considered in the following order:

1. smoke from forest sources, both wildfire and controlled burns
2. pollutants from urbanized enclaves, including nutrients from urban sources (Lake Tahoe)
3. particulate matter (fugitive dust) generated by human modification of water resources at Mono and Owens lakes on the east slope of the Sierra Nevada

While the global and upwind sources of air pollution are important, local sources can be, on occasion, extreme, resulting in some of the highest particulate levels seen in the United States.

## Prehistoric Air Quality

There is a paucity of data on factors within the Sierra Nevada that affected air quality in prehistoric times. Clearly, there were no urban centers, so that component was absent. Mono and Owens lakes were in slow decline after the Pleistocene "ice ages," and without exposed playas, were generally a minor source of dust to air quality that was generally very good. Deep Springs Lake and other lakes at the western edge of the Great Basin that had larger natural cycles probably had some blowing dust. However, the situation is very different for smoke. From historical data on fires and the natural timing of lightning-induced fires, we can infer that there was two to four times as much area burned on an average summer day than in present times, with removal of timber plus present-day catastrophic fires redressing the biomass balance (see the following section on fires). Thus, we expect that there was much more summer smoke in the past, and less smoke in spring and fall, the time where prescribed natural fires and controlled burns are now encouraged (California Department of Fish and Game 1994). An example can be found in the Blue Mountains of northeastern Oregon, which were noted and named in the past for having much fire smoke commonly present in the summer. Another example is in historical pictures of the Lake Tahoe area, many of which show smoke. However, at the time of these pictures (late 19th century) massive human impact was evident as this was the peak of the Comstock lumbering period. There would also be changes in the nature of the smoke due to changes in the temperature of the fires.

The extent of transport of smoke into the Sierra Nevada from the Central Valley, a major factor at present (figure 48.7), is not known from presettlement times. All one has are a few logs from the first Spanish explorers. It may have been less than at present, based upon statements on what the explorers could see. However, native Americans were known to encourage fires to favor generation of oaks and for other purposes.

## Present-Day Air Quality: Effect of Forest Fire Smoke within the Sierra Nevada on Air Quality

This section derives much of its information from the previous sections on fire, and they should be used for the more detailed and definitive discussion of the role of fire. Here we examine what is known about present and proposed air quality impacts of forest burning in the Sierra Nevada based on data taken in or near the Sierra Nevada. There is also a very large and important state and federal effort to model smoke emissions from fires, and this will not be discussed here. However, the modeling, if successful, will be constrained by the actual measurements that are reported herein.

There are many ways to categorize forest fires, but the following classifications appear the most widely used at present. Fires are categorized as:

> Wildfires: These are large, sometimes catastrophic crowning wildfires that burn all before them. They may be initiated by lightning, accidents, and arson. The 24,500 acre Cleveland fire mostly in the El Dorado NF in 1992 is an example, used several times in this section. Such fires are predominantly in late summer, with dry fuel, high temperatures, but relatively vigorous smoke dispersal.
>
> Prescribed fires: Prescribed fires, sometimes called prescribed burns or controlled burns, are human-initiated fires that burn under some prescription that involves weather, terrain, location, fuel moisture, fuel configuration (piles) and especially meteorology. These fires are used in national forests, usually in spring and fall, and are often keyed to an approaching rainstorm that will both disperse smoke and prevent loss of control.
>
> Prescribed natural fires: These are lightning-initiated forest fires that are allowed to burn under some prescription. Lightning-started fires are most common in summer, and such fires are allowed to burn in national parks and wilderness areas. Sometimes the terms 'control and contain' are used for such fires.

The second and third types are also generally "surface burns" that spread only occasionally to tree crowns, and thus represent an approximation of historical patterns of fire that existed before human impacts.

Other terms have recently arisen that categorize the types of prescribed fires, namely 'ecological burns' and 'activity burns' (WESTAR Council 1995). There was some suggestion that the former may be considered differently from the latter in terms of federal air quality regulations since the former merely returns the forest to a more natural situation that avoids smoke from the otherwise inevitable and much more damaging wildfires.

There are two other source of smoke in the Sierra Nevada—the transport of smoke from the central valleys into the mountains, generally in summer and early fall, generally from biomass (agricultural, levee maintenance, and so on) burning (see earlier), and the heavy but localized smoke in late fall and winter in urban enclaves, especially those in valleys, derived largely from wood stoves and fireplaces (see later).

It is surprisingly difficult to establish the effect of each of these smoke sources on air quality in the Sierra Nevada. Smoke has a visual impact all out of proportion with the mass of smoke present, so that smoke levels must be extreme before the record of particulate mass reflects a major impact. Yet the only 24-hour federal particulate standard is for particle mass below 10 micrometers in diameter (PM-10), which is not violated until visibility drops to about 2 miles. Most of the air particulate air sampling in the Sierra Nevada measures only PM-10 mass, and thus is of limited use in identifying small and moderate smoke impacts. These sites only operate on a one-day-in-six cycle, and due to urban locations, are of little use to establish non-urban smoke levels. Further, the data on how many acres are burned each day from either wildfires or prescribed burns are often difficult to access. Meteorological measurements in the mountains are scarce, and terrain effects major.

The IMPROVE data base is somewhat better in several regards. The measurements are PM-2.5, a better match to the size of smoke. The sites operate Wednesday and Saturday, in non-urban , non-valley locations, and have full meteorology, chemical, and optical analysis. However, as can be seen in appendix 48.1, there are only two such sites in the Sierra Nevada—Sequoia and Yosemite N.P. Fortunately, the paired stations at Lake Tahoe, operated for the Tahoe Regional Planning Agency (TRPA) using full IMPROVE protocols, provide a very important third site, as well as an invaluable non-urban to urban comparison. Finally, data are extended by using similar sites in the Cascade and San Bernardino Mountains. It is this data set that we must use for long-term data on Sierran smoke, supplemented by local studies.

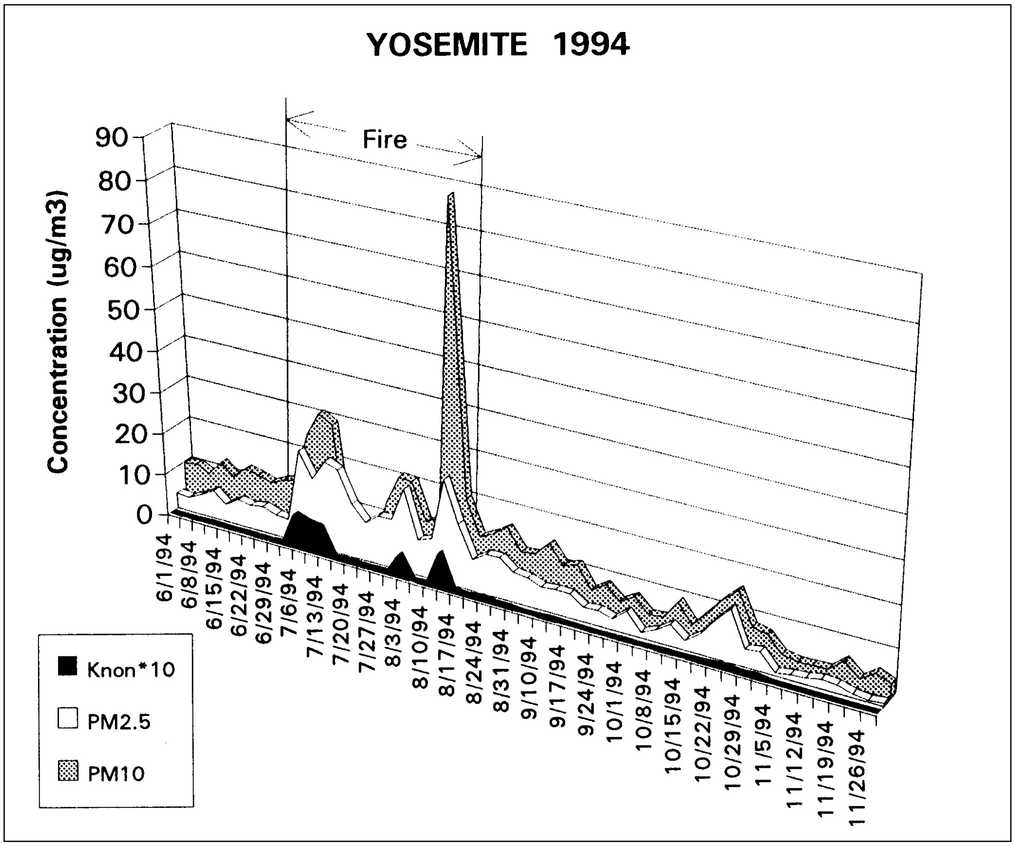
Analysis of aerosol data from several sites in the Sierra Nevada indicates that the most severe impacts on air quality occur from large wildfires, but shows little effect of controlled fires at remote locations. Using figure 48.16 (data from the IMPROVE air sampler at Turtleback Dome, Yosemite N P) as an example, it is evident that the highest levels of particulate pollution occurred during a prescribed natural fire that burned in the park from July 3 to August 18, 1994. On only one occasion, however, did the pollution exceed the state air quality standard of 50 $\mu g/m^3$ for $PM_{10}$. The presence of smoke at the site during these episodes is evident from the unusually high peaks in non-soil potassium (K-non), a tracer of biomass smoke, and from human observations. Relatively low levels of particulate matter were seen (figure 48.16) during the subsequent fall season when the majority of agricultural waste burning is occurring in the San Joaquin Valley as well as controlled burning in nearby forests for fire suppression and silviculture.

In contrast, high levels of $PM_{10}$ occur frequently in the heavily developed Yosemite Village (in Yosemite Valley) during the same period, even when no large fires are burning in the area, as shown in figure 48.17. The presence of many small local sources (campfires, fireplaces, and vehicles) and the micro meteorology of the valley, which tends to trap air under a nighttime inversion, result in a high background level of pollution.

Another comparison of local, anthropogenic sources versus wildfires and controlled burns occurs in the Tahoe Basin. Air quality data taken near the relatively urbanized Highway 50 corridor in South Lake Tahoe show high levels of aerosol pollution in the winter. Large peaks occur in both organic matter and in K-non (non-soil potassium) indicating wood smoke as the source (figure 48.18). At D. L. Bliss State Park, located in a largely undeveloped area on the west shore of

**FIGURE 48.16**

Some components of air quality (concentrations of non-soil potassium and particulate matter) at Turtleback Dome, Yosemite National Park, June through November 1994, showing impact of fires.



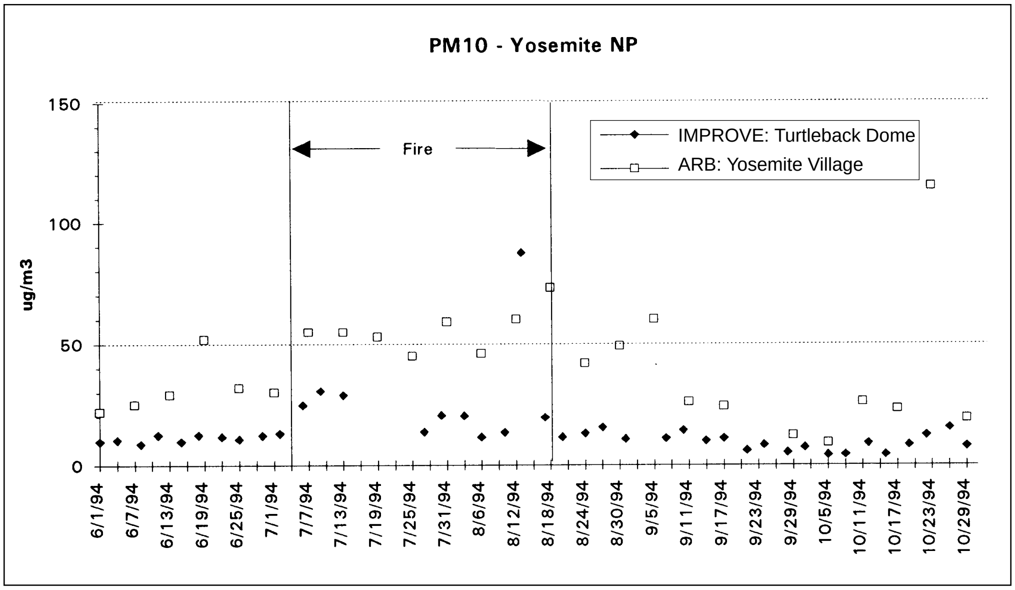


**FIGURE 48.17**

PM10 concentrations in Yosemite Village, Yosemite National Park, June through November 1994, as measured by California Air Resources Board (ARB) and UC Davis IMPROVE sampler (IMPROVE).

the lake, the winter is the cleanest season (figure 48.19). This suggests that residential wood combustion is the primary source at South Lake Tahoe. The only period in which occasional elevated levels of smoke are detected at both sites, indicating a source outside the basin, is the late fall when large amounts of cropland are being burned in the Sacramento Valley and controlled burning in the surrounding national forests is at its peak. But the smoke levels even in these conditions are far less than the winter peaks at South Lake Tahoe roughly 20%, and of much shorter duration.

A final direct comparison between wildfires and residential wood burning is shown in figure 48.20 for Truckee, Cali-

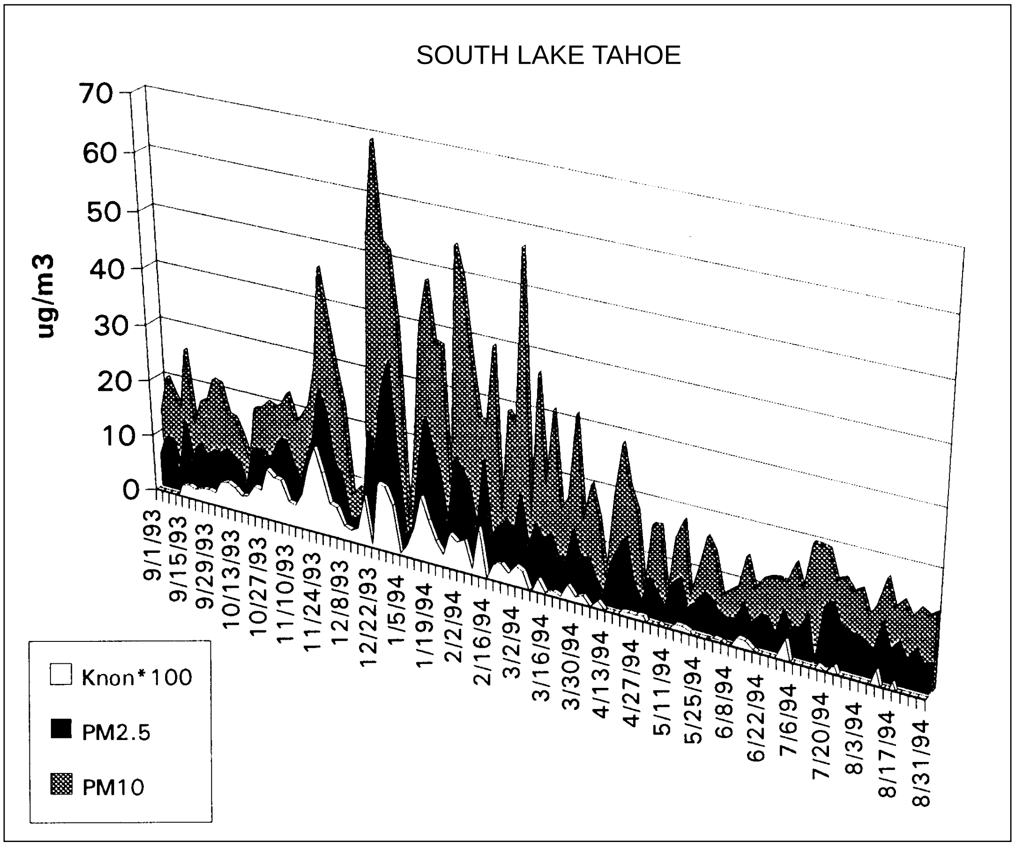
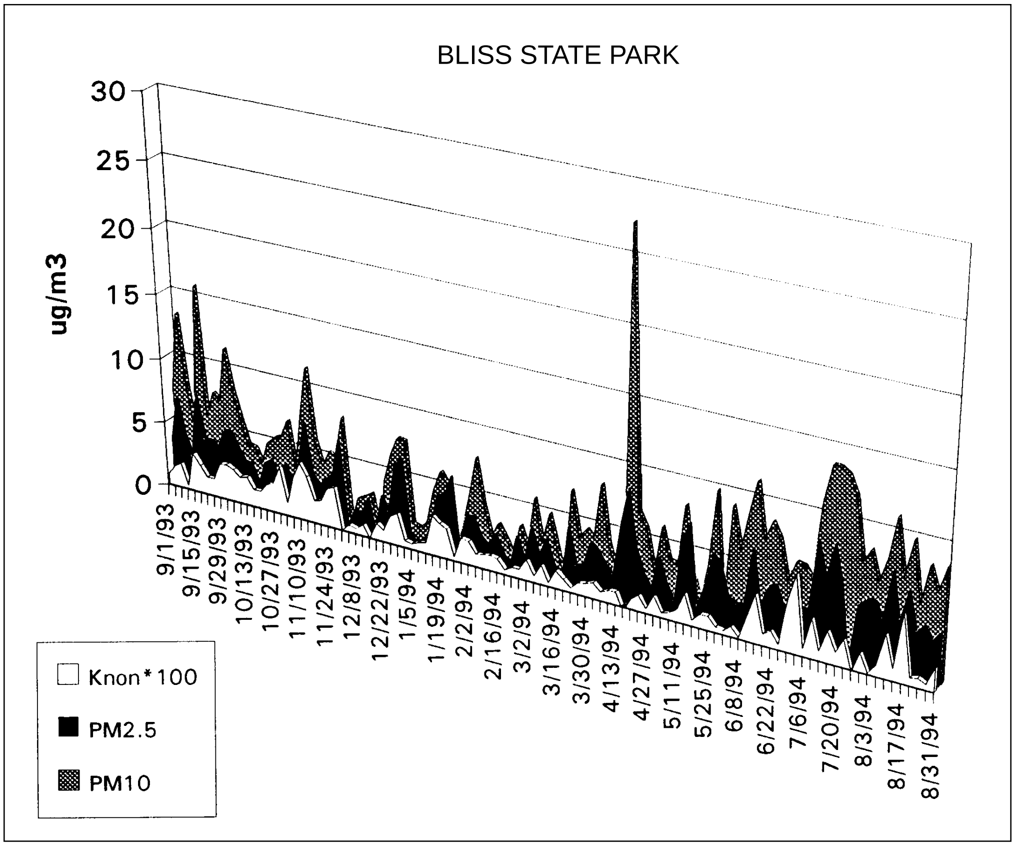


**FIGURE 48.18**

Some components of air quality (concentrations of non-soil potassium and particulate matter) at South Lake Tahoe, September 1993 through August 1994, showing impact of smoke.

**FIGURE 48.19**

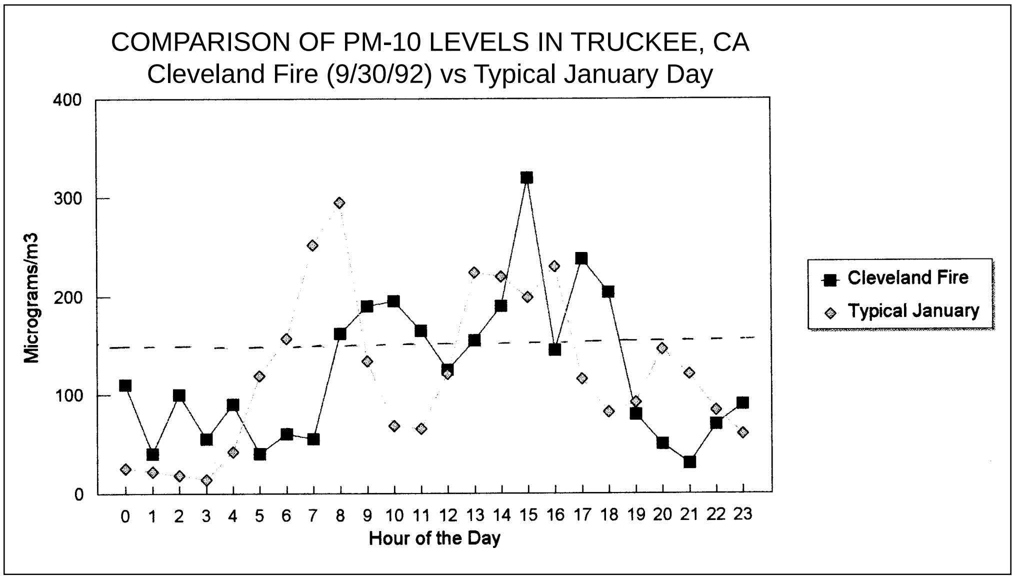
Some components of air quality (concentrations of non-soil potassium and particulate matter) at D. L. Bliss State Park, September 1993 through August 1994, showing impact of smoke.



fornia. The availability of a new type of particulate measuring unit, a TEOM, allows hourly measurements to be made of mass. In figure 48.20, the intense Cleveland fire of 1992, located south of Interstate 80 and upwind of Truckee, is compared to winter smoke levels in the city. The Cleveland fire burned 5,500 acres on September 29, 7,000 acres of September 30, and 7,500 acres on October 1, when a light rainfall (0.1 inch) greatly aided fire suppression, limiting further acreage to roughly 3,500 acres until it was declared out about 1 week later (McKey 1995). Not only are the levels comparable for these two cases, 121 $\mu g/m^3$ for the Cleveland fire, 124 $\mu g/m^3$ for a typical January day, one has to remember that the Cleveland fire lasted for only a few days, while winter smoke episodes at Truckee are extremely common under the charac-

**FIGURE 48.20**

Comparison of hourly $PM_{10}$ levels at Truckee, CA, for the peak day of the Cleveland wildfire (9/30/92) and a typical January day (1/16/92).



teristic winter subsidence inversion common to almost all high mountain valleys. The peak winter day in Truckee, January 1992, was 179 µg/m$^3$, measured by TEOM. But the TEOM probably understates the equivalent filter mass by 30% since the TEOM filter is heated, which drives off some of the water. Thus, in terms of person-dose, a typical winter is at least a factor of 10 or greater more important to health than a major local forest fire.

On the same day as the Truckee data, September 30, 1992, samples were taken at Bliss State Park as part of the regular Wednesday-Saturday IMPROVE-compatible protocol for TRPA. Bliss was not nearly as impacted as Truckee, since the wind was driving the smoke northeast. However, it recorded 13 µg/m$^3$ of PM-10, versus the 121 µg/m$^3$ for Truckee during the Cleveland fire. Even so, it was the highest PM-10 recorded on 16 sampling days between September 2 and November 30, 1992, more than double the annual average of 5.85 µg/m$^3$ recorded 1992–1993. The corresponding fine mass was 5.35 µg/m$^3$, versus an annual average of 3.39 µg/m$^{3.}$ A strong nitrate signal was received, in fact the highest level seen all year, 1.45 µg/m$^3$, versus an annual average of 0.29 µg/m$^3$. This raises the question of whether the strong nitrate peak seen in South Lake Tahoe in winter could have a significant component from residential combustion of pine wood. Another more likely possibility is that the nitrate resulted from the volatilization of dry deposited nitrate on pine needles. Other species reached the highest level during the fire, including trace amount of chloride, arsenic, selenium, and bromine. The non-soil potassium smoke tracer, K-NON, reached its second highest level on June 30, supporting the heavy transport of valley smoke into the mountains since grass smoke has a K-NON/ mass ratio of at least ten times that of pine.

The results of the Cleveland fire help put into context the smoke from controlled burns, which for an entire season might total 7,000 acres, roughly as much was consumed per day in the Cleveland fire. In addition, the Cleveland fire occurred at a dry, hot period of the summer, without the meteorological mitigation built into controlled burns. Hence, the absence of any obvious signature due to controlled burns at Bliss, along with only one day of moderate impact at Yosemite, can now be readily understood since so little fuel is burned per day as compared to the uncontrolled Cleveland fire.

The relative importance to human health of local wood burning, as compared to forest fires, can be explained by the (by definition) higher population densities in urban areas, the regular pattern of residential wood fires, and the penchant for these urbanized areas to be in valleys rather than ridges, and the common nighttime inversions that trap smoke close to the ground. Wildfires, by their very nature, generate lots of heat, and tend to loft much of their pollutant load into the sky.

The smoke produced by biomass combustion is composed of water vapor, other gases, and particles less than 2.5 µm in diameter, but a significant amount of larger particles may also be produced by large, intense fires due to entrainment of soil and partially combusted matter in the strong updrafts. Significantly larger particles present little threat to health or visibility, and typically do not persist in the atmosphere for more than a few hours before they settle out due to gravity. Fine particles (smaller than 2.5 µm), however, are very effective in reducing visibility because they scatter light and aid the condensation of water vapor in the air. These smaller particles also contain a significant quantity of organic compounds known collectively as polycyclic aromatic hydrocarbons (PAH) which include a number of toxic and potentially carcinogenic substances. Since the fine particles are readily inhaled and retained in the lungs, and may settle onto the surface of vegetation, increased concentrations of smoke represent a potential hazard to both human health (Larson and Koenig 1994) and the environment. These concerns are not limited to emissions from forest fires. Research data indicate that burning of grasses, agricultural wastes, and other types of wood produce even higher concentrations of PAH (Jenkins et al. 1995b).

Woodburning emits a variety of gaseous pollutants (Jenkins et al. 1995a). These are composed primarily of $CO_2$ and $H_2O$, with the remainder dominated by CO (carbon monoxide) and a variety of hydrocarbons, including PAHs. Since carbon monoxide is relatively inert and disperses readily, it should not have any significant impact on air quality beyond the immediate area of the fire. Hydrocarbons, on the other hand, can be transported over large areas and contribute to ozone formation in the presence of other pollutants. $NO_x$ is also produced, as in all combustion, but in relatively small concentrations in comparison to their emissions from vehicles and industrial sources.

Finally, there is evidence that part of the water of combustion of wood smoke may be trapped in the smoke, especially in cold, humid, winter conditions (Molenar et al. 1996), and seen also in the 30% difference between TEOM and standard $PM_{10}$ filters (above). If even a small fraction of the water is trapped, it can greatly raise the smoke mass. More detailed analyses (see above) are needed before this can be resolved. Nevertheless, a certain caution should be retained about ways to reduce wood smoke by reducing temperature of combustion and air flow, as opposed to an oxygen-rich open flame. Low temperature smoke is far more chemically complicated than high temperature smoke, retaining compounds that are known mutagenic (and perhaps carcinogenic) agents.

Fall 1995 saw a good deal of activity in the area of fire pollution. First, the fall was exceptionally dry, with the first significant rain occurring in early December. The meteorology was stable, with weak winds and strong inversions forming in the Central Valley. Several prescribed natural fires and controlled burns persisted into periods of poor ventilation, with major smoke impacts on local communities. This occurred for fires in and near Sequoia N.P., which totaled about 9,000 acres by early December. Prescribed fires were ignited near Mineral King and in a chaparral zone about 10 miles upslope of Three Rivers. Heavy smoke was recorded in local communities, resulting in four violations of the 150 µg/$m^3$ federal 24-hour PM-10 regulations, with the maximum value of 194 µg/$m^3$ (D. Ewell, Sequoia National Park, communication with the author, 1995). Another fire burned for about a month in the Lake Tahoe basin, in Bliss State Park near the TRPA aerosol site. Smoke impacts were regularly reported (B. Mahern, Tahoe Regional Planning Agency, communication with the author, 1995). Both of these fires represent patterns of prescribed and controlled burns that may become more likely in the future, and the experience gathered in these events will be useful in avoiding such impacts. Clearly, the concentration of so much burn acreage in a single watershed of air basin at times of poor ventilation resulted in unacceptable levels of smoke, although the anomalous weather of fall 1995 was a major factor in these episodes.

Finally, there was a major wildfire/prescribed fire workshop sponsored by the WESTAR Council, an association of air resource agencies from western states, Alaska to the Dakotas, San Francisco, November 27–29, 1995. While the reports and recommendations of this meeting are not yet released, minutes of the presentations have several points of interest (WESTAR Council 1995). One of these was the conceptual separation by a speaker from the U.S. Environmental Protection Agency on various options, including separation of smoke from "ecological burns" and "activity burns" and possible trade-offs against wildfire smoke. The logic is that the ecological burns are really a way of avoiding future smoke from the much more serious crowning wildfires, as well as a way to maintain a healthy forest. The consensus also was reached that the nuisance effects of smoke, including visibility reduction, will become more important as a constraint on burning than possible violations of federal fine particulate air quality standards.

Overall, current data suggest that controlled forest burns are not as major a source of particulate mass in populated areas of the Sierra Nevada as residential wood combustion and campfires. Large wildfires produce severe short-term impacts on air quality, but because they are rare, average smoke dose to individuals is generally limited. Prescribed or controlled burns are more common, but the amount of materials burned is more modest, and the measures to limit human smoke impacts are generally quite effective, leading to very low contributions to $PM_{10}$ particulate loading in inhabited areas. Thus it would appear that prescribed fires are usually performed in such a way as not to cause a significant threat to regional air quality as measured by fine particulate mass. The obvious exception is for some local visibility reduction, but this must be compared to improved air quality by decreasing the impacts of major wildfires. Given that fire is a natural part of the Sierra Nevada ecosystem (Phillips 1995), the beneficial effects on the Sierra Nevada ecosystem of increased fire use should not result in widespread violations of state and/or federal fine particle health standards.

The very real problems of perceived smoke and visibility reduction must be addressed, however. One way is to couple the presence of modest summer smoke with the overall health of the forest and the reduced chances of major wildfires, which cause drastic reductions of visibility and direct and indirect health effects. The other is to ascertain the relationship between visibility reduction and smoke mass, showing that even in visibly dense smoke, mass loadings are modest. Using results of studies of Oregon and Washington fires (Radke et al. 1990), a relationship was measured. Visibility due to smoke must be reduced to 3.0 +/- 1.8 km (1.9 +/- 1.1 mi) before one reaches the federal particulate air quality standard of 150 µg/$m^3$ six miles before one reaches the California standard of 50 µg/$m^3$. The same relationship is found for IMPROVE's fine (Dp< 2.5 mm) particulate mass. A "best fit" between visibility and mean annual mass at 44 sites gives 3.0 kilometers (1.9 miles) for the federal standard of 150 µg/$m^3$, assuming no contribution from particles greater 2.5 µm diameter (S. Copeland, U.S. Forest Service, Fort Collins, Colora-do, communication with the author, 1995). The corresponding visibility at the 50 µg/$m^3$ California standard is 9.1 km (5.7 miles). The problem of visibility is compounded for fires that occur in scenic areas by the fact that people are used to seeing many miles. Thus, visibility reductions are obvious. The plumes tend to be well above the ground, which makes them more visible as it reduces ground level mass concentrations. The same effects do not occur for the even greater smoke densities in towns like Truckee during the winter, for example, since the densely populated core of the town is less than one mile long.

There are also indirect effects of fires, in which they act as a means of transporting materials from one location to another. An example is agricultural burning in the central valleys of California. The mass of smoke by itself may not be a serious factor in terms of particulate mass, but health effects are reliably reported when smoke impacts cities, such as visits to doctors by asthmatics (Betty Turner, American Lung Association, communication with the author, 1995). The answer appears to be in the reactions of sensitive populations to all the other materials lofted into the atmosphere with the smoke, which in the valleys include pollens, fungal spores, partially pyrolized pesticides and herbicides, and other components.

## Effect of Urbanization within the Sierra Nevada on Air Quality

The ecological and touristic values of the Sierra Nevada have naturally generated areas of moderate population density in small cities, towns, and other areas. These areas in turn modify the local environment in many ways, including impacts on air quality associated with increased traffic, changes in land use, heating, and other activities. It was not anticipated, however, that the focusing of developmental pressures on areas of especially high scenic value would then generate quasi-urban areas with traffic and population densities similar to other, larger cities in California. Examples include the Lake Tahoe literal, Yosemite Valley, and Mammoth Lakes, but there are others. These quasi-urban areas then in turn degrade to a greater or lesser degree the values that drew the population in the first place, and even lead to levels of air pollution that result in violations of state and federal air quality standards. Visitors became clearly aware of other impacts of urbanization, including traffic jams, parking problems, smoke from fires, etc. But most casual observers would be startled to realize that some of the highest particulate mass loadings in California occur in the Sierra Nevada.

### Health and Regulatory Air Quality Issues

***Summer, Lake Tahoe Sites.*** In response to heavy and congested traffic levels at South Lake Tahoe, and a few air samples that showed high particulate lead levels, a study was mounted in summer 1973 by the California Air Resources Board at sites all around the Lake Tahoe Basin. While the results showed a wide variation in air quality at sites around the lake, it was clear that sites near the Nevada state line, the locus for casinos and the target of much of the daily traffic, had levels of gaseous and particulate pollution that were typical of other, much larger areas in California.

Table 48.4 shows a representation of the ARB data, placed into a comparison with other California sites (Goldman and Cahill 1975). One entry in the table is incorrect, although that was not known at the time. The lead value for Los Angeles, submitted to the ARB, had been arbitrarily divided by a factor of 2.8 in order to maintain continuity with earlier (erroneous) measurements. Thus, the true Los Angeles lead value is actually 2.7 $\mu g/m^3$. Nevertheless, the fact that even some air pollution levels at some Tahoe sites were worse than in downtown Los Angeles was a cause of considerable comment, leading to a designation of a special Lake Tahoe Air Basin, special, stricter standards for both visibility and carbon monoxide, establishment of a permanent air pollution site, and several state and federal air quality studies that continue to this day, including major efforts by the Tahoe Regional Planning Agency (TRPA).

The key question that immediately arose was the attribution of air pollution to anthropogenic sources within the basin, potentially amenable to mitigation, versus either natural sources or anthropogenic sources upwind of the Lake Tahoe area. Figure 48.21 shows the results of recent TRPA studies that address this question.

Comparisons of a site at Bliss State Park that responds only to pollutants coming across the mountains from upwind sites, versus at site at South Lake Tahoe, give a convincing answer to the question. Since the sulfur (sulfate) particles are essentially the same at both sites, this pollutant comes from upwind sources. Organic matter (smoke, ...) and nitrates appear to be largely from upwind sources in the summer, but of strongly local sources in the winter. A similar analysis using ARB data shows that, in the summer, ozone behaves like sulfur and responds to upwind sources, while most other gaseous pollutants are largely local in origin. Methane has a significant (roughly 50%) natural source, as do coarse particles that respond to pollen, bio-debris, etc. Soils are largely local, especially in winter and spring when road sanding debris is present.

Since the early 1970s, the air pollution at South Lake Tahoe has been reduced due to improved auto emissions, control of road surfaces, and other efforts. Lead is essentially absent, while NO, $NO_2$, and CO have been cut roughly in half. No such improvement has been seen for ozone, which has actually risen slightly in this period, though still representing moderate levels.

Nevertheless, visibility at Lake Tahoe has degraded since the base year of 1982 as both transported and local sources of fine particles have increased. This is a serious source of concern and closely tied to the enjoyment of the extraordinary vistas for which Lake Tahoe is justly famous. Studies are un-

**TABLE 48.4**

Air quality at two Lake Tahoe sites, with comparison to other California cities. Gaseous data were collected over the month of July 1973.

| | | | **For Comparison Purposes** | | |
|---|---|---|---|---|---|
| **Pollutant**[a] | **Incline** | **Stateline** | **Monterey** | **Sacramento** | **Los Angeles** |
| Oxidant (ppm) | 0.063 | 0.049 | 0.04 | 0.09 | 0.11 |
| Carbon monoxide (ppm) | 1.5 | 6.4 | 1.0 | 2.0 | 6.0 |
| Sulfur dioxide (ppm) | — | — | — | — | 0.04 |
| Nitrogen dioxide (ppm) | 0.009 | 0.051 | 0.00 | 0.040 | 0.11 |
| Nitric oxide (ppm) | 0.003 | 0.024 | 0.02 | 0.020 | 0.10 |
| Oxides of nitrogen (ppm) | 0.012 | 0.068 | 0.03 | 0.060 | 0.17 |
| Hydrocarbons (ppm) | 2.5 | 5.2 | — | 2.0 | 3.0 |
| Hydrocarbons (ppm) (non-methane) | 0.17 | 1.97 | — | — | — |
| Lead particulate (micrograms/$m^3$) | 0.203 | 1.72 | 0.23[b] | 0.49 | 0.95 |
| Suspended particulates (micrograms/$m^3$) | 95 | 87 | 36 | 78 | 116 |

[a] The values for the gaseous pollutants (the first 8) are in parts per million of air, maximum hour averaged over the month, while the particulate values are 24-hour averages taken at random times throughout the month and averaged, expressed as micrograms of material per cubic meter of air. (—) indicates pollutant not measured at that site.

[b] Data averaged from two nearby sites, since lead was not measured at Monterey.

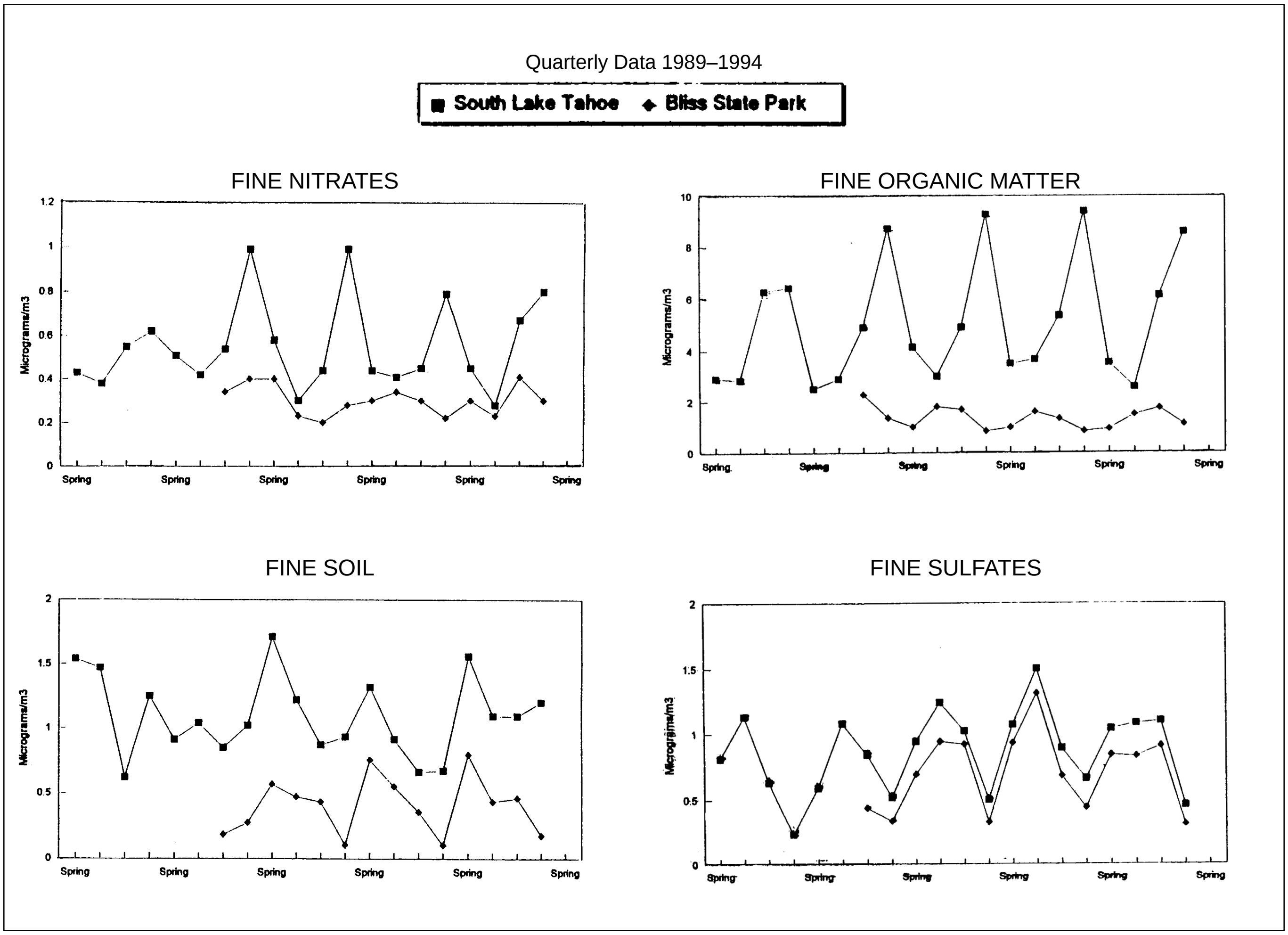


**FIGURE 48.21**

Aerosols at two Lake Tahoe sites.

derway to identify exactly which factors are dominant in this problem (Molenar et al. 1996). Note that similar problems of urban haze occur in Yosemite Valley from a combination of local smoke and transported San Joaquin Valley air pollution.

***Winter, Lake Tahoe, Mammoth Lakes, and Yosemite Valley.*** The question of the relative impact of urban versus non-urban wood smoke has been largely addressed above, in the section on fires. These data also show, however, that there are additional sources of smoke in the urbanized areas that are not wood smoke. This is shown by analysis of the optical opacity of the smoke as compared to the known smoke tracer, K-NON, at South Lake Tahoe and Bliss, suggesting some fossil fuel/diesel source contributions. But wood smoke dominates the mass of smoke particles.

The mass concentrations in smoke levels in winter are elevated, often exceeding state and federal air quality standards as well as causing intense haze. This is a fact also realized at other winter resorts such as Aspen and Vail, Colorado, which have initiated vigorous controls on residential woodburning. Examples were shown above at Yosemite Valley and Truckee. As a further example, the city of Mammoth Lakes, California, achieved levels of particulate matter that ranked among the highest urban values in California, and gross violation of state and federal standards. Figure 48.22 shows that not only are such levels high in the peak days, but they are also high on average, unlike the intense but infrequent episodes of wildfires. Since 1990, serious efforts at smoke suppression have been in place, with some success.

### Ecological Impacts: The Case of Lake Tahoe

As seen in figure 48.21, there are significant concentrations of airborne particulate nitrates at Lake Tahoe sites, along with much smaller levels of phosphorous, both limiting nutrients in the nutrient-poor lake. Some of this material will enter this lake through dry and wet deposition, thus fertilizing the lake and contributing to the roughly 30% degradation in water quality observed since 1958 (Goldman 1994). Clearly, the question of local versus transported sources becomes critical, as does the ratio of these nutrients to those contributed to runoff from urbanized areas and soil disturbance from development. This is the subject of active investigation at this time, and a clear consensus has yet to be achieved.

The location of the sources of particulate nitrates has largely been resolved (figure 48.21). During spring, summer, and fall, most particulate nitrate is transported from upwind sources. During this time, most gaseous nitrogen, $NO_x$, is of local, motor vehicle origin (Cahill et al. 1977). In winter, both the particulate nitrate and the gaseous nitrate is local in origin, with heavy transportation sources but also including other forms of combustion.

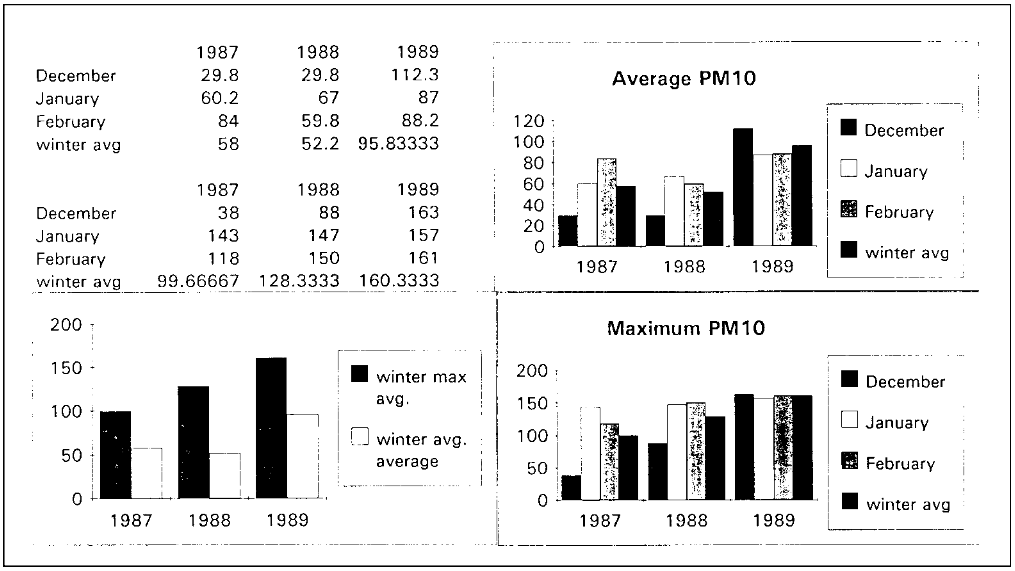
One opinion is that atmospheric deposition is a major factor in nitrate input to the lake, resulting in a tons/year prediction of nitrate input to the lake. In comparison to the nitrate input in streams and run-off, this gives it an atmospheric source that dominates nitrate input to the lake. However, dry deposition measurements are notoriously difficult to do accurately, and questions remain on input pathways of nitrogen (Jassby et al. 1994).

From the atmospheric data given in figure 48.21, we made calculations of dry deposition from the measured nitrate concentrations (Sehmel 1980). Using a mean transported nitrate concentration of 0.3 μg/m$^3$, from the Bliss site but averaged over the entire lake surface, yields deposition values between 0.4 and 1.0 ton/year, well below those inferred from the TRG measurements (Jassby et al. 1994). Adding in the local anthropogenic particulate nitrate, 0.3 μg/m$^3$, inferred from the South Lake Tahoe site after subtracting the transported component, assuming a somewhat larger particle size for humid, winter conditions, and averaging over that portion of the lake near urbanized areas, yields an additional 0.1 to 0.3 tons/year. In contrast, using local gaseous $NO_x$ concentrations from vehicles, and the same type of calculations but this time over a 1 km wide band around the lake, yields a mean $NO_x$ concentration of 22.6 μg/m$^3$, roughly 75 times the concentration of transported particulate nitrate. If only 10% is scavenged onto trees and surfaces to eventually reach the lake in spring snow melt, this yields on the order of 20 (or more) tons/year into the lake, with a spatial pattern that closely matches observed maxima in algal growth. Since there are major uncertainties in making sub-surface nitrate measurements from urban runoff, direct observation of this effect is difficult.

Even these factors do not appear to explain the increasing turbidity of Lake Tahoe, since $NO_x$ levels have been steadily decreasing over the past 20 years while the lake is getting steadily worse. A good match is seen, however, when one compares development around the lake, with soil disturbance and mobilization of phosphorous, to algal growth. Local traffic will also be driven in part by this development.

## Dust Storms Caused by the Desiccation of Mono and Owens Lakes

At the interface of the Sierra Nevada and the Great Basin lie several saline lakes or playas (dry lake beds), remnants of large "pluvial lakes" that stored glacial melt water and runoff from the Sierra Nevada during the Pleistocene ice ages. As stated previously, a certain amount of airborne dust is generated from some of these playas (such as Deep Springs and Honey Lakes), but this material has a limited impact, and, as it is of natural occurrence, is not an air pollutant per se. However, when saline lakes are desiccated by human action, any dust generated is considered "fugitive" and subject to the National Ambient Air Quality Standards (NAAQS). Wind-driven sand moving across unvegetated, recently exposed playa surfaces kicks up dust plumes composed of silicate



| | 1987 | 1988 | 1989 |
|---|---|---|---|
| December | 29.8 | 29.8 | 112.3 |
| January | 60.2 | 67 | 87 |
| February | 84 | 59.8 | 88.2 |
| winter avg | 58 | 52.2 | 95.83333 |

| | 1987 | 1988 | 1989 |
|---|---|---|---|
| December | 38 | 88 | 163 |
| January | 143 | 147 | 157 |
| February | 118 | 150 | 161 |
| winter avg | 99.66667 | 128.3333 | 160.3333 |

**FIGURE 48.22**

Particulate matter ($PM_{10}$) at Mammoth Lakes, California, winter, 1987–89. All values are in micrograms/m$^3$. The California 24-hour standard is 50 micrograms/m$^3$, while the federal 24-hour standard is 150 micrograms/m$^3$.

minerals and salts. About half of the mass of playa dust aerosols is contained in particles of diameter less than 10mm ($PM_{10}$), small enough to be transported long distances and inhaled deeply into the human respiratory tract. Fugitive dust storms from playas are a problem in several areas around the globe, of which the Sierra Nevada region possesses several significant examples (Gill in press). Water diversions from the Truckee and Walker rivers flowing out of the Sierra Nevada have resulted in minor blowing dust at Pyramid and Walker lakes in Nevada. However, serious $PM_{10}$ problems exist at Mono and Owens (Dry) lakes at the Sierra Nevada's eastern base (table 48.5). These areas are two of the three "non-attainment areas" for $PM_{10}$ formally designated by the U.S. EPA within the Sierra Nevada region; the third is the community of Mammoth Lakes in Mono County, which is impacted by wood smoke.

All significant dust storms from the playas of Mono and Owens lakes are dependent on one major factor external to the Sierra Nevada—sustained winds caused by synoptic (large-scale) weather systems affecting the region. A few dust events, generally minor and short-lived and especially at Owens Lake, can be caused by mesoscale (regional) atmospheric circulation (upslope-downslope winds and convective storms) caused or enhanced by the steeply-sloping topography of the Sierra Nevada itself (Cahill et al. 1994).

As much as 65 $km^2$ of playa has been exposed along the shore of Mono Lake (directly east of Yosemite National Park) since water diversions by the Los Angeles Department of Water and Power (LADWP) began in 1940. When no dust is observed (in recent years, more than 90% of all days), the air in the Mono Basin is among the "cleanest" in California. But when the lake was near its historical low, average dust concentrations on the remaining days exceeded the then-existing California standard for particulate matter by a factor of six (Kusko and Cahill, 1984). Mono dust storms can violate the California airborne sulfate standard, and may contain sufficient arsenic to elevate cancer risk in humans (Cahill and Gill 1988). The occurrence and significance of dust storms from Mono Lake's northeastern playa has been a major factor in the legal and environmental battle over LADWP's water rights and protection of the Mono Lake ecosystem.

**TABLE 48.5**

Air quality impact of dust storms downwind of Mono and Owens Lakes, 1979–83[a] (all values in $\mu g/m^3$).

| | Mono Lake[b] | Owens Lake |
|---|---|---|
| Maximum 24-hour $PM_{10}$ concentration | 1,650 | 2,092 |
| Worst 1.3% of all days | 912 | 1,098 |
| Worst 5% of all days | 416 | 599 |
| Worst 11% of all days | 265 | 315 |
| Remaining 89% of all days (non-dust storm days) | 9 | 14 |
| Maximum short-term $PM_{10}$ concentration, $\mu g/m^3$ from UC Davis field measurements | N.A. | 40,620[c] |
| U.S. EPA 24-hour standard for $PM_{10}$, 150 $\mu g/m^3$ | | |
| California 24 hour standard for $PM_{10}$, 50 $\mu g/m^3$ | | |

[a] Based on GBUAPCD data, in Kusko and Cahill (1984) converted from Total Suspended Particulates to $PM_{10}$.
[b] Level of Mono Lake, 6,373 +/- 1 feet above MSL, 1979–82.
[c] Based on calculations in Cahill et al. 1994, 1995.

Although the level of Owens Lake (in the shadow of Mt. Whitney) was already slowly receding due to Owens River water withdrawals for Owens Valley agriculture, LADWP diversions into the Los Angeles Aqueduct caused the lake's complete desiccation. The water transfer began in 1913, and dried Owens into a 280 $km^2$ playa within fifteen years. The outer third of the playa, a zone of crystalline salts, clays, and fine silts, is vulnerable to severe wind erosion by the abrasion of blowing sand; Owens Lake dust events represent the highest estimated $PM_{10}$ levels recorded to date in the U.S.A., a 24-hour $PM_{10}$ average of 4,184 $\mu g/m^3$ at the town of Keeler and a 2-hour $PM_{10}$ concentration on the lakebed exceeding 40,600 $\mu g/m^3$ (Cahill et al. 1994, in press). For comparison, the U.S. EPA 24-hour limit for $PM_{10}$ is 150 $\mu g/m^3$; this standard is exceeded at least 48 days per year downwind of Owens Lake (Great Basin Unified Air Pollution Control District [GBUAPCD] 1994). Just as in the Mono Basin, on dust-free days air quality in the Owens Valley is generally very good, with $PM_{10}$ levels on the order of 10 $\mu g/m^3$ or less.

Dust plumes from Owens Lake tend to blow north or south and hug the eastern slope of the Sierra Nevada, blocking scenic views of the mountains with white dust haze, occasionally disrupting traffic on U.S. Highway 395, and constituting a general nuisance to local residents. Saline, alkaline dust from Owens Lake is known to encrust the needles of pines and leaves of other plants in the White-Inyo Range, and is deposited within the borders of Death Valley National Park. Owens dust is transported onto the eastern slope of the Sierra Nevada, impacting the John Muir, Golden Trout, South Sierra and Dome Lands Wilderness Areas and adjacent parts of Inyo National Forest before spilling over the crest of the range. To the south, the dust clouds enter the Indian Wells Valley east of Walker Pass, affecting the city of Ridgecrest (120 km south of the playa), and occasionally suspend operations at the Naval Air Weapons Station, China Lake, causing millions of dollars in economic losses each year. The total amount of dust emitted by the playas of Owens and Mono lakes may exceed 8 million tons per year. This represents perhaps 3% to 5% of the total mass of particulate air pollution produced in North America (and is several times greater than the sum total of all regulated air pollutants in the Los Angeles air basin), presently placing these two dry lake beds among the largest individual sources of fugitive dust in North America (Gill in press).

The health effects of $PM_{10}$ in general are becoming well known, and chronic or acute exposures to Owens and Mono Lake dust storms are bound to be deleterious to humans. However, there is little specific data on human health effects of mineral dust, even less known about the effects of saline, alkaline particles from lake beds, and only anecdotal data at

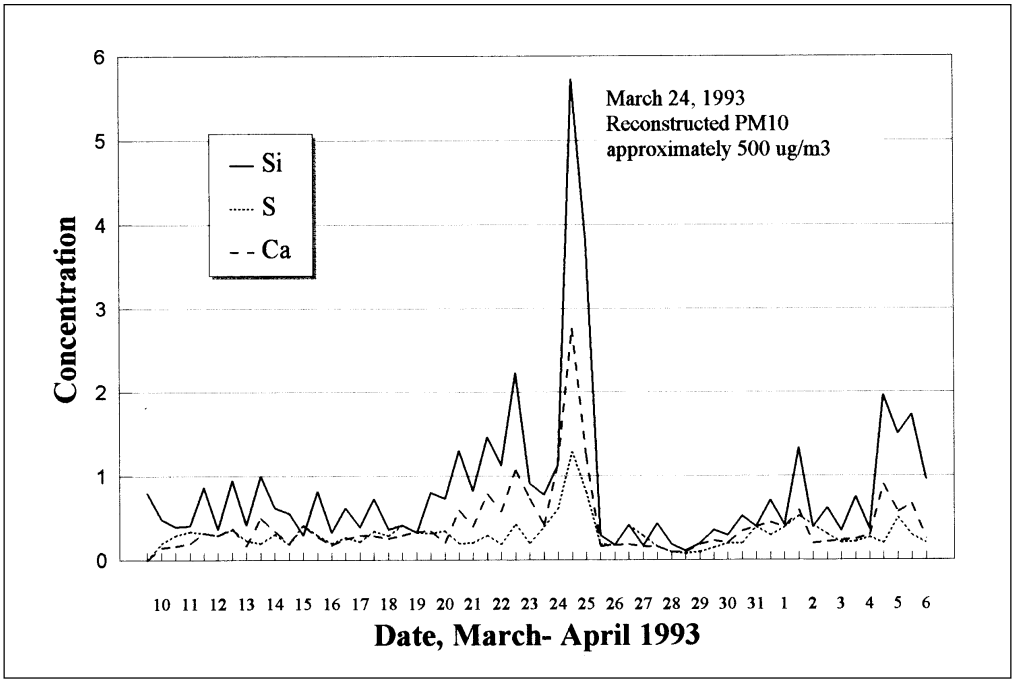


**FIGURE 48.23**

Elemental chemistry of dust for silicon, sulfur, and calcium at Schulman Grove, Ancient Bristlecone Pine Forest, March–April 1993, showing impact of March 24 Owens Lake event; concentrations in $\mu g/m^3$, data for particles 2.5 µm or smaller collected with UC Davis SMART sampler (after Cahill et al. 1994).

best on specific health effects of Mono-Owens aerosols. The effects of this dust on ecosystems are also not well known, though we can make inferences from other studies. Prolonged deposition of alkaline dust causes chemical, physical and biological changes in soil profiles and eventually changes vegetation communities and ecosystem structure; there is anecdotal evidence that such changes have started to occur in the Mono Basin (Cahill and Gill 1988). Alkaline, saline dust coating needles or leaves limits plant germination, growth, respiration, transpiration, and photosynthesis; blocks the stomata; exacerbates secondary stresses such as drought, insects and pathogens; modulates the uptake of toxic metals and other air pollutants; and may cause visible injury and even cell death to needles, leaves and bark (Farmer 1993). No detailed monitoring for these problems has been undertaken in the Inyo National Forest, but dry deposition of $PM_{10}$ from Mono and Owens lakes is known to occur on its slopes. Since the most damaging effects of dust take place on arctic-alpine vegetation (Farmer 1993), it may well have some of the aforementioned effects on high-altitude ecosystems of the Sierra Nevada.

A significant fraction of the soil in alpine environments in the White-Inyo Range, including the Ancient Bristlecone Pine Forest Area of Critical Ecological Concern, was created by the fallout of fine airborne sediments originating in the Owens and / or Mono basins in the geological past (Marchand 1970). The enhanced input of $PM_{10}$ to these areas from dust storms (figure 48.23) simulates these soil-building episodes of the geologic past (Gill in press), and should have some effect on the health and growth of bristlecone pines. Since bristlecone pine growth in the White Mountains is being used to evaluate global climate change, and prevailing wind trajectories into the groves pass through the Mono Basin and Owens Lake areas, the impact of Owens Lake and Mono Basin dust could provide a "false signal" to this system.

Ruling D-1631 of the State Water Resources Control Board in 1994 provided that water exports from the Mono Basin must be restricted in a manner to "result in the water level of Mono Lake rising to a level of 6,391 feet in approximately 20 years." When this occurs, blowing dust from the Mono Lake playa will be significantly reduced and will be unlikely to have a serious environmental impact.

Figure 48.24 shows all measured values of air pollution downwind of Mono Lake, 1979–1993, with corrections to convert to the maximum $PM_{10}$ values on the land around Mono Lake. These corrections include conversion from total suspended particulates (TSD), measured for 1979 through 1986 to $PM_{10}$, measured at present using a multiplicative factor of 0.47. It also includes corrections for drought, 1987–1993, using Owens Lake as a model (about a factor of 2) and conversion for the Simis Ranch site to the maximum site, generally near Warm Spring, using (1) the Fugitive Dust Model (FDM) used by Jones and Stokes, the WRCB contractor, (2) the Industrial Source ISC2 model used by the GBUAPCD's contractor, and (3) the Mono-Owens Davis Dust Model (MODDM) based on the Davis work (Cahill and Gill 1988).

The latter model (figure 48.24), based as it is on a linear fetch hypothesis closely tied to sand motion, and calibrated against observed dust levels 1979–1983, is not as sensitive to the source strength assumptions inherent in the first two models, neither of which was designed for the two-step dust resuspension process that dominates dust loadings at Mono (and Owens) Lake. In addition, there are other factors not considered in the models of $PM_{10}$ mass, including the questions of interior and persistent dust, multiple pathways for arsenic input from the dust, and even the magnitude of the extraordinary dust events. All these support a high lake level for elimination of blowing dust from the playas.

At Owens Lake, even though federally mandated, $PM_{10}$ mitigation may take much longer. While the early UCD/ARB work (Barone et al 1979; Kusko and Cahill 1984) identified the cause, and mitigation studies were undertaken as early as 1982 (State Lands Commission WESTEC Report, 1984), progress has been slow. Several techniques, including flood irrigation, deployment of sand fence arrays, and re vegetation, are presently being tested on the Owens Lake playa for dust storm suppression, (State Lands Commission 1991; GBUAPCD 1995), but control of the massive clouds of dust is deemed not feasible in the short term by the local agency (GBUAPCD 1995).

## EFFECT OF THE SIERRA NEVADA ON DOWNWIND AIR QUALITY

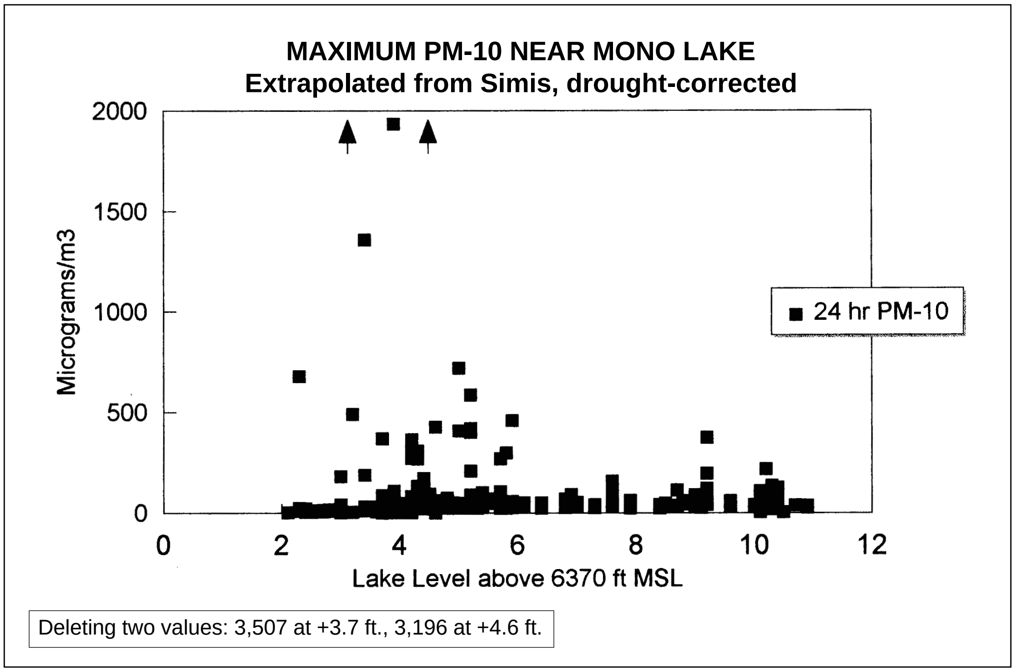
The three major sources of air pollutants within the Sierra Nevada are forest smoke (wildfires, prescribed natural fires, controlled burns), urban sources (again mainly smoke, some vehicular) and the partially/completely desiccated lake beds of Mono Lake and Owens Lake (alkaline/saline dusts). The urban sources are, however, minor in total emissions (tons/year), and their high winter concentrations are due mainly to severely limited dispersion. Thus, there is no theoretical or empirical evidence that their influence is much more than local.

The other two sources, however, are large enough so that their influence is well documented. The impact of Sierran forest smoke on the Central Valley of California has been mentioned earlier, a consequence of nighttime downslope winds that may be especially important in fall due to decreased ventilation in the valleys, which increases the residence time of smoke, combined with prescribed natural fires and controlled burns in the mountains. This period, however, is also a period that has significant acreage of agricultural burning in the valleys, many hundreds of thousands of acres each fall. Renewed interest in the impact of these Sierra Nevada sources on air quality downwind (east) of the range is partially a consequence of the activities of the Grand Canyon Commission, charged under the Clean Air Act amendments of 1990 to evaluate all sources of visibility reduction in that area. The commission's task groups are aware of plans to increase burning in forested areas, and is looking actively at sources such as the Sierra Nevada.

Data from the Sierra Nevada can place this evaluation in perspective. The results at lake Tahoe show efficient transport of smoke aerosols (and other components such as ozone) from the California Central Valley into the Tahoe Basin, across passes at roughly 7,000 feet and around mountains that rise to 10,000 feet. This occurs during much of each spring, summer, and early fall. These pollutants certainly influence the Great Basin air quality, although levels are modest. The results of the Cleveland fire of 1992 show massive transport of smoke downwind of the range, but such events are infrequent. Conversely, the valley to mountain transects in Sequoia NP,

**FIGURE 48.24**

Maximum $PM_{10}$ near Mono Lake, extrapolated from Simis, drought-corrected.



Deleting two values: 3,507 at +3.7 ft., 3,196 at +4.6 ft.

1987 (Cahill et al. 1989) show a sharp reduction in ozone and aerosols between Giant Forest at 6,000 feet and Emerald lake at 10,000 feet. The Emerald Lake site is west of the Great Western Divide, and the peaks to the east of it rise to over 14,000 feet. This supports a very limited pollutant transport efficiency over the mountains to downwind sites in the central and southern Sierra Nevada, both for local forest smoke and valley smoke. Finally, there is well-documented transport across Tehachapi Pass into the Mojave Desert (Pitchford et al, 1984) as the elevation drops to around 4,000 feet. As temperatures drop each fall, all mountain transport processes weaken and smoke of all kinds tends to stay in the Central Valley. This was certainly the experience in the dry fall of 1995, when smoke from the Sequoia N.P. prescribed fires drifted downslope into the valley. It is highly unlikely that any significant amount of this smoke ever made it to the Grand Canyon. In summary, fires that burn under summertime conditions can contribute smoke downwind of the range, while spring and fall fires tend to have greatly reduced transport east of the mountains and, conversely, the greatest local impact. The wintertime inversions in the Central Valley, and lack of fires in the Sierra Nevada, indicate little Sierra Nevada influence at downwind sites.

A final piece of evidence concerning transport into the intermountain area can be gathered by comparing aerosols at Bliss State Park, Lake Tahoe, with the Great Basin and Grand Canyon National Parks. The characteristic signatures of wood smoke are, in order of uniqueness, excess fine potassium (KNON), organic carbon from carbon (C) and hydrogen (H), optical absorption, and elemental carbon. The mean values for each are shown in table 48.6 (IMPROVE 1995).

Thus, there is no convincing evidence that there is major transport from the Sierra Nevada into the great basin region or the Grand Canyon N.P., since such long scale transport would cause values to decrease as particle are lost during transit. Further, since the highest values at Bliss occur in summer, and these come from the Sacramento valley floor, a better case could be made for the impact of agricultural burning in California on air quality in the great basin region.

Finally, transport of aerosols from Mono and Owens Lake into the mountains and then downwind into the Great Basin reported photographically by aerosol measurements and by satellite (Cahill et al. in press). While these events are infrequent, occurring about 11% of all days (Kusko and Cahill 1984) they are intense and carry a great deal of fine alkaline/saline dust into this region. The source at Owens Lake alone is estimated to represent on the order of 5% of all the fine dust generated in the United States each year (Gill and Gillette 1991). They tend to occur preferentially in spring and fall, but they can occur at any time in the year. The Mono Lake source is being effectively mitigated, and efforts are underway to control Owens Lake, which, at the very least, will not be getting any worse. The particles are also coarser than smoke, typically around 5 μm diameter, as opposed to smoke at 0.3 μm, and thus get removed more readily during transport. Thus, interest in this source is not as keen as for forest smoke, which at least in some situations may be increasing in future years.

**TABLE 48.6**

Mean values of aerosols at Bliss State Park, Great Basin NP, and Grand Canyon NP.

| | Bliss State Park, CA | Great Basin NP | Grand Canyon NP |
|---|---|---|---|
| KNON | 8.77 ng/m$^3$ | 6.70 ng/m$^3$ | 7.83 ng/m$^3$ |
| Organic carbon (C) | 1.12 μg/m$^3$ | 0.79 μg/m$^3$ | 0.63 μg/m$^3$ |
| Organic carbon (H) | 1.17 μg/m$^3$ | 1.01 μg/m$^3$ | 0.87 μg/m$^3$ |
| Optical absorption | 5.42 Mm$^{-1}$ | 4.18 Mm$^{-1}$ | 4.26 Mm$^{-1}$ |
| Elemental carbon[a] | 0.15 μg/m$^3$ (?) | 0.12 μg/m$^3$ (?) | 0.09 μg/m$^3$ (?) |

[a] The (?) indicate values close to the detectable limit and thus statistically weak.

## CONCLUSIONS

Air quality in the Sierra Nevada is, at times, as good as that found anywhere in the world, and, at times, as bad as that found anywhere in the world. Fortunately, good air quality is much more common than bad air quality, but the present impacts are important and future threats serious.

Changes in air quality from past values have accelerated with man's involvement, modestly in the period of native Americans, but more rapidly at present, threatening responses from the litho-, hydro-, and biospheres that may seriously alter the social and economic values of the Sierra Nevada to the state, nation, and world.

Changes in global climate are already occurring, with both positive and negative consequences of uncertain magnitude and timing. The most important is most likely to be a shift in the hydrological cycle towards intense rain events and away from historical snow patterns. Observed increases in temperature and carbon dioxide ($CO_2$), and predictions of increased moisture, could lead to increased bioproductivity. However, recent decreases in the worldwide rate of increase in $CO_2$ and methane ($CH_4$) may be harbingers of somewhat lower peak values in the 21st century than some models have predicted, and thus limiting changes. While there are many other subtle impacts on the biosphere, it appears that decreases in the northern latitude ozone shield are probably not responsible for the decline in Sierran amphibians. Other, more local, non-atmospheric causes are implicated.

The impacts on Sierran air quality from upwind sources of air pollution are dramatic and easily measurable, from the persistent hazes in summer to ozone damage to Jeffrey and ponderosa pines. The ozone damage is both serious and persistent, and poses both social and economic costs to the Sierra Nevada. Despite massive and costly efforts, the decline in peak ozone values in the Central Valley source regions is slow (unlike the dramatic decreases in the Los Angeles basin), so that relief is not imminent. The persistent hazes have been definitively linked to California sources, and great improvements in visibility could be achieved by a number of proven methods including suppression of summer and fall agricultural burning, further controls of sulfur emissions in the Bay Area, and increased efforts to reduce $NO_x$ emissions, including nonvehicular sources. The hydrological cycle is dominated by winter snowfall, and the impacts of upwind sources of sulfates and nitrates on mean Sierran snow composition is modest and no acidified lakes and streams are found. That does not rule out pulses of moderate acidity at snow melt. It does reflect that winter storm processes do not have the same local connection to California emissions as summer aerosols and ozone.

The impacts on Sierran air quality from local sources are highly variable in magnitude and timing, resulting in major degradation of particulate air quality to levels among the worst in the state and nation superimposed on typical air quality that is so clean as to be the envy of the state and the nation. We consider three major areas: smoke from fires, influence of urbanized enclaves, and the desiccation of eastern Sierra lakes.

Smoke from major wildfires can be seen for hundreds of miles downwind of the Sierra Nevada, filling valleys (even on occasion the Central Valley) and clearly causing the most obvious and extensive air pollution impact from any local source. This is enhanced by the growing intensity of wildfires caused by fuel build-up over the past decades. Yet, perhaps surprisingly, the air pollution impacts of wildfires on state and federal fine particulate mass standards is generally not major for several reasons. First, these events are infrequent, so that they have only a modest impact on long-term averages. But perhaps more surprisingly, the maximum smoke impacts of major fires are generally less in magnitude, and far less in frequency, than smoke impacts in urbanized enclaves such as Mammoth Lakes, California, South Lake Tahoe, Truckee, and others. The situation is even more favorable for controlled burns designed to limit fuel loading for the major wildfires. First, there is a great deal of smoke in the Sierra Nevada range from the Central Valley. This is in fact more extensive than that developed by most controlled burns, partially through careful planning of burn periods and burning procedures. Thus, it is our opinion that limits on controlled burning could be significantly relaxed without danger to public health, and with major benefits to public welfare including increased human safety from reduced wildfire events.

The urbanized enclaves referred to above can generate local air pollution that mimics and even surpasses that present in major areas of California, but on a much more local spatial scale. Winter urban smoke can result in the highest winter particulate mass loading of any site in California. Yet we believe that using mass loading alone may be misleading, since there is growing evidence that the abundant water of combustion in low temperature burning of wood, especially pine wood, becomes trapped in the smoke in cold conditions and gives misleading values for mass that may not have equivalent health impacts to equal mass loading in other urban areas of California. The question of other pollutants, such as polyaromatic hydrocarbons (PAHs), is much more important to questions of potential health impacts of wood smoke. The impacts of smoke on local winter visibility are on occasions extreme.

Other influences from air pollution in urbanized enclaves include accelerated nutrient input to Lake Tahoe and other pure bodies of water, causing algal growth and lack of clarity. It is our opinion that atmospheric nitrates, a major and occasionally limiting nutrient, from transported, upwind sources, are not as important as local nitrate sources in Lake Tahoe, but this is still controversial.

Finally, the influence on local air pollution from the artificially desiccated beds of Mono and Owens lakes is severe, causing in most years the highest respirable dust loading in the entire United States, although for relatively few days per year. The recent Water Resources Control Board ruling (D-1631, 1994) on Mono Lake used this air quality information as a component in setting the lake level to a value that should make such events a thing of the past. No such near-term improvements are imminent at the even more severe problems at Owens (dry) Lake.

Returning to the very beginning of this report, one final conclusion must be proposed. Any future studies of air quality in the Sierra Nevada would be improved immeasurably by rectifying deficiencies in the air quality data set. These should be based on the importance of the ecological effects and impacts on the mountains, as well as human health considerations. For example, ozone transects from valley floor to high elevation should be routinely done at three or four sites (perhaps Visalia through Sequoia National Park, Merced through Yosemite, Sacramento through Lake Tahoe, and Chico east, plus Redding through Lassen Volcanic National Park in the Cascades) in order to document ozone dose for comparisons to ozone injury. These same sites might well allow for measurements of other valley pollutants, including herbicides and pesticides from agricultural operations. Much more information is needed on smoke from fires in the forest, especially the smoke from the historic/prescribed surface based fires proposed for increased use in fuel control. Some effort should be expended to study health effect in winter urban smoke episodes and blowing alkaline dust from Owens (dry) Lake. Ultraviolet measurements of all kinds are almost totally lacking. Other examples come to mind.

## ACKNOWLEDGMENTS

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## APPENDIX 48.1

# Air Quality Standards and Monitoring Stations

### SUMMARY OF AMBIENT AIR QUALITY STANDARDS ESPECIALLY RELEVANT TO THE SIERRA NEVADA

| Species | Averaging Period | California | Federal, Primary | Comment |
|---|---|---|---|---|
| Ozone | 1 hour | 0.09 ppm | 0.12 ppm | |
| Carbon Monoxide | 8 hour | 9.0 ppm | 9.0 ppm | Lake Tahoe, 6.0 ppm |
| Carbon Monoxide | 1 hour | 20.0 ppm | 35.0 ppm | |
| Nitrogen Dioxide | 1 hour | 0.25 ppm | 0.053 ppm (annual average) | |
| Suspended Particulate Matter (PM-10) | Annual | 30 $\mu g/m^3$ | 50 $\mu g/m^3$ | |
| Suspended Particulate Matter (PM-10) | 24 hour | 50 $\mu g/m^3$ | 150 $\mu g/m^3$ | |
| Visibility Reducing miles | 8 hour (day) | ~10 miles | | Lake Tahoe, ~35 |

(also sulfur dioxide, lead (30 day average, 2.5 $\mu g/m^3$), hydrogen sulfide, and vinyl chloride)

### AIR MONITORING STATIONS

Air monitoring stations in the Sierra Nevada Ecosystem Project (SNEP) study region, the southern Cascade Mountains, and San Bernardino Mountains, in operation for all or part of 1993.

| | California | | Federal | | | |
|---|---|---|---|---|---|---|
| **Site Name** | **Gases** | **Particles $PM_{10}$** | **Particles, $PM_{10}$** | **Particles, $PM_{2.5}$** | **Other** | **Comments** |
| ***Cascade Mountains*** | | | | | | |
| Burney, Shasta County | Yes | Yes | | | | closed 3/93 |
| Lassen Volcanic National Park | Yes | No | | | Yes, IMPROVE | |
| ***SNEP Region*** | | | | | | |
| Chester, Plumas County | No | Yes | | | | |
| Quincy, Plumas County | Yes | Yes | | | | |
| Graeagle, Plumas County | No | Yes | | | | closed 9/93 |
| Loyalton, Sierra County | No | Yes | | | | |
| Nevada City, Nevada County | Yes | Yes | | | | closed 6/93 |
| Grass Valley, Nevada County | Yes | Yes | | | | 4 sites |
| Truckee, Nevada County | | Yes | Yes | | | 2 sites |
| Colfax, Placer County | Yes | Yes | | | | |
| Lake Tahoe, Placer/El Dorado County | Yes | Yes | | | Yes, TRPA | 4 sites |
| Placerville, El Dorado County | Yes | Yes | | | | |
| Jackson, Amador County | Yes | No | | | | |
| Sonora, Tuolumne County | | | Yes | No | | |
| Yosemite, Camp Mather, Tuolumne County | | | Yes | No | | |
| Yosemite National Park | Yes | Yes | | | Yes, IMPROVE | 3 sites |
| Mono Lake, Mono County | | | No | Yes | | 2 sites |
| Mammoth Lakes, Mono County | Yes | Yes | | | | |
| Wilsonia, Tulare County | Yes | No | | | | |
| Sequoia National Park | Yes | No | | | Yes, IMPROVE | 2 sites |
| ***San Bernardino Mountains*** | | | | | | |
| Lake Gregory, San Bernardino County | Yes | Yes | | | | |
| San Gorgonio Wilderness | No | No | | | Yes, IMPROVE | |

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