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LAKE TAHOE VISIBILITY STUDY

by

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Prepared for Region IX

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ABSTRACT

Visibility monitoring and airborne particulate sampling in the Lake Tahoe Basin were used to document present visual air quality levels and to assess the relative impacts of major contributing emission source categories. Visibility data were obtained by long path contrast and particle scattering techniques. Particles were sampled in two size ranges at three locations and were analyzed for mass concentration and elemental composition (elements greater in atomic weight than Na). Statistical analysis showed fine particle concentration (particle diameter less than 2.5 μm) to be related to visibility. Measured elements plus the mass of material assumed to be associated with them accounted for only 20 percent of the fine particle concentration. The remaining 80 percent was assumed to be nitrates and carbonaceous materials; the latter associated with wood smoke, terpenes and transport from upwind areas. A model was developed to apportion all of the fine particle mass to source categories. The results of this effort were then used to determine an optical extinction budget.

This study indicates 70 percent of the basin-wide visibility impact and 30 percent of the South Lake Tahoe visibility impact are caused by natural and long range transported emissions. Residential wood smoke emissions are responsible for the majority of the remaining impact; at South lake Tahoe automotive emissions are also significant.

CONTENTS

FIGURES

TABLES

LAKE TAHOE VISIBILITY STUDY

INTRODUCTION

In recognition of the potential threat to the unique environment of the Lake Tahoe Basin by increased urban and commercial developments, Congress enacted the Tahoe Regional Planning Compact (Public law 95 551). This legislation directed the Tahoe Regional Planning Agency (TRPA) to "establish environmental threshold carrying capacities and to adopt and enforce a regional plan and implementing ordinances which will achieve and maintain such capacities while providing opportunities for orderly growth and development consistent with such capacities." Atmospheric visibility, which relates to the airborne particulate carrying capacity of the atmosphere, is one of many environmental qualities for which TRPA is responsible.

The U.S. Environmental Protection Agency designed and conducted a visibility study in the Lake Tahoe Basin to support TRPA in the establishment of a threshold for visibility. The objectives of the study were to 1) measure present visibility levels, 2) determine sources of visibility impairment and 3) provide a means to estimate visibility impacts of proposed activities. A major time constraint was imposed on the study. Results were required within 12 months of the funding of the program. The sparsity of pertinent historical data dictated that a major portion of the study be directed towards monitoring. This was followed by an intensive period of interpretive analysis. The following is a description of the visibility monitoring program, a summary of the techniques employed to interpret the data and the results of the interpretive analysis.

MONITORING PROGRAM

The monitoring program was designed to accommodate the geography and emission source configuration thought to be of importance to visibility for the Tahoe area. The Lake Tahoe Basin is an area of approximately 1300 km^2 located in the Sierra Nevada and Carson Mountains (see Figure 1). The lake, at about two km elevation above sea level, covers approximately 40 percent of the basin, with the remainder being primarily coniferous forest. Mountains, up to one km above the lake's surface, surround the basin. Tourism is the basin's primary industry.

Estimates of air pollution emissions from local anthropogenic sources were available in an emissions inventory prepared by EPA's regional office in San Francisco. The major local anthropogenic sources are the products of fuel combustion for vehicles and space heating, and suspended soil from transportation and construction activities. Urban population in the Basin is primarily at the south and north ends of the lake, with the south having the larger population. Major natural sources include suspended soils, forest fires and terpenes (from the coniferous forest). Long range transport of pollutants from upwind sources is also expected to impact the basin.

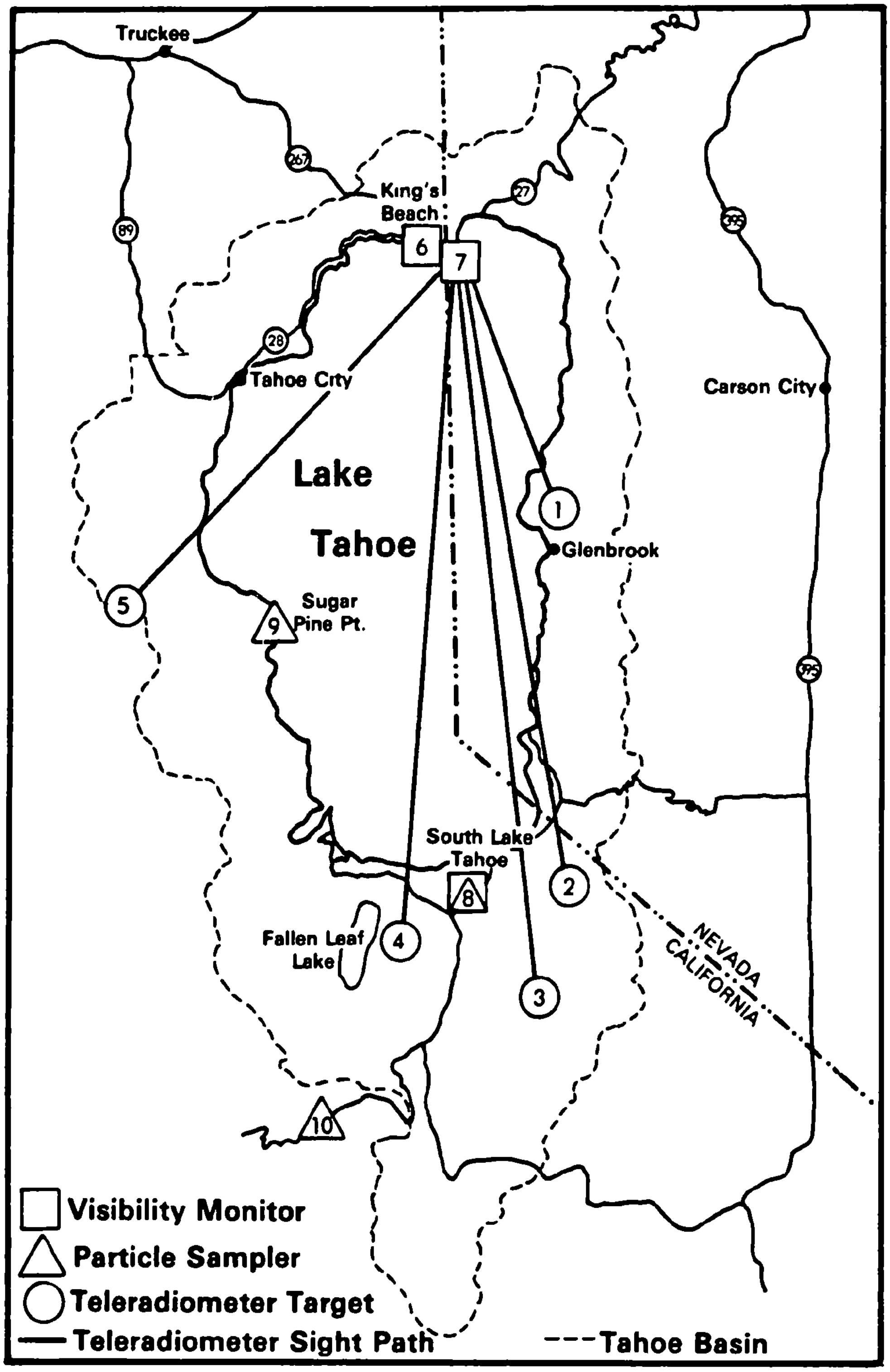

Figure 1. Lake Tahoe Basin with visibility study monitoring locations indicated. Site numbers refer to Table I

The air pollutants of importance to visibility are airborne particulates and NO_2. The contribution of NO_2 to visibility impairment is important only in plume optics, not in well mixed layers[1] or in urban-influenced areas[2-5]. It was assumed therefore that NO_2 was not an important factor in Lake Tahoe visibility degradation.

The field program consisted of visibility and particle monitoring. Table I indicates the instruments and their deployment. A number of different types of instruments were employed to characterize various aspects of visibility at Lake Tahoe. Teleradiometers provide a measure of apparent contrast, C_r, of a distant target against its background (typically the sky). This along with the distance to the target, r, and its inherent contrast, C_0, can be used to estimate extinction coefficient, b_{ext} by

$$b_{ext} = -1/r \ln C_r/C_0. \qquad 1)$$

Visibility is often expressed in terms of visual range, the greatest distance at which a dark object is visible. Visual range, VR, is related to extinction coefficient by

$$VR = 3.912/b_{ext}. \qquad 2)$$

Integrating nephelometers make a point measurement of scattering coefficient, b_{scat}, which is a portion of the extinction coefficient.

$$b_{ext} = b_{scat} + b_{abs}, \qquad 3)$$

where b_{abs} is the absorption coefficient. If the absorption coefficient is assumed to be small compared to the scattering coefficient, then b_{scat} can replace b_{ext} in equation 2 in order to calculate visual range. A more complete discussion of these two measurement techniques is available elsewhere.[6-10]

Spectacular views of the lake and surrounding mountains are a highly valued resource at Lake Tahoe. Color slides were selected to provide an overall qualitative means to document basin-wide visibility. The long path measurements of the teleradiometer also monitored basin wide visibility. Though restricted to contrast measurements of a limited number of elements in a scene, a teleradiometer provides quantitative data required for interpretive analysis. The two north Lake Tahoe locations for camera and teleradiometer monitoring were at different elevations (lake level and 240 meters above lake level), thus allowing a view from within and above low lying haze layers. The light scattering measurements made by the nephelometer at South Lake Tahoe (at the Tahoe Y) provided data representative of the higher pollutant concentrations expected in the urban area.

Particle sampling was accomplished with stacked filter units similar to those described by Cahill et al.[11-12] They segregate sampled particles into two size ranges (coarse particles 15 μm to 2.5 μm diameter and fine particles less than 2.5 μm diameter), collecting each on separate filters. Gravimetric and particle-induced x-ray emission (PIXE) analysis were performed on each filter. The former gives the mass concentration while the latter provides the elemental composition for elements greater in atomic weight than sodium.

Particle sampling sites were selected to provide a variety of necessary information. Sugar Pine Point State Park was chosen as representative of

TABLE I. LAKE TAHOE VISIBILITY MEASUREMENT AND PARTICLE SAMPLING EQUIPMENT, SAMPLING FREQUENCY, AND LOCATIONS

Activity	Instrument	Sampling Frequency	Location (Map # and Name)	
Contrast Measurements of Distant Mountains	MRI 3010 Multiwavelength Teleradiometer	Three times daily (0900, 1200, & 1500)	Targets	1 Deadman Point 2 Gunbarrel Ski Run 3 8455 foot peak 4 Tahoe Mountain 5 Ellis Peak
			Measurement Locations	6 Kings Beach 7 Stateline Fire Lookout
Color Slides	Olympus OM-2 with 50 mm lens, manually operated	Two times daily (0900 & 1500)	From	6 Kings Beach 7 Stateline Fire Lookout
			Toward	8 South Lake Tahoe* 5 Ellis Peak - Northwest Shore
Color Slides	Two Olympus OM-2 automatic timer operated; south-looking with 50 mm lens, north-looking with 135 mm lens.	Two times daily (0900 & 1500)	From	9 Sugarpine Point State Park
			Toward	6 Kings Beach 8 South Lake Tahoe
Light Scattering Coefficient Measurement	MRI 1550 Integrating Nephelometer	Continuous, hourly average data		8 South Lake Tahoe
Particle Sampling in Two Size Ranges	Stacked Filter Unit compatible with gravimetric, elemental analysis	48-hour samples every two days		8 South Lake Tahoe 9 Sugarpine Point State Park 10 Sierra Ski Ranch, Echo Summit

*Also photographed with 135 mm lens.

basin averaged concentrations. Data from this site were expected to relate well to the teleradiometer measurements. The South Lake Tahoe particle sampler colocated with the nephelometer was necessary both to relate to the optical data provided by the nephelometer and to provide information on the composition and concentrations of particles generated in the urban area. A third site at Sierra Ski Ranch, on Echo Summit, was expected to be relatively uninfluenced by pollutant sources within Tahoe Basin. This site is ≈400 meters above the lake and generally upwind of the Basin though exposed to the same distant upwind sources as the Basin. Comparison of data from this site with data from the two basin sites was intended to yield insight into the nature of particles transported into the Basin. These three locations are among nine that have been used in a previous particle monitoring program[13]. Results from the earlier research influenced the choice of sites for the visibility study.

In addition to the information collected directly for this program, daily maximum and minimum temperature data at Sugarpine Point and daytime hourly surface observations (temperature, visibility, dewpoint, wind speed and direction, altimeter setting and sky condition) at South Lake Tahoe airport were obtained. Forest Service records of wildfire and controlled burns in the Basin during the study were also obtained.

The field monitoring program was divided into two six month periods. The first (summer/fall), running from June to the end of November 1981, was the intensive monitoring period during which all of the activities indicated in Table I were performed. This six month period of sampling was designed to form the basis for interpretive analysis, the results of which were required by the spring of 1982. A second six-month period (winter/spring) of less intensive monitoring immediately followed the first. The objective of this monitoring was to assess the degree to which the first period represented a full year. Equipment operated during the second period consisted of the automatic camera system and particle sampler at Sugarpine Point plus the nephelometer at South Lake Tahoe.

Teleradiometer measurements and data analysis, photography, and particle sampler operation were conducted under a cooperative agreement with the John Muir Institute (JMI). Particle sample gravimetric and elemental analysis was conducted under a cooperative agreement with Crocker Nuclear Laboratory, University of California-Davis (UCD). The nephelometer operation and data processing was conducted by the California Air Resources Board.

Each of the monitoring groups prepared and followed standard operating and quality control procedures. Additionally JMI and UCD participated in an external quality assurance program involving system and laboratory analytical audits performed by Rockwell International and field audits performed by Lockheed Engineering and Management Services Company; both under EPA contract.

RESULTS

Teleradiometer Measurements

Figure 2 shows the time plots of the daily-average visual range as calculated from teleradiometer contrast measurements at Stateline Fire Lookout and Kings Beach. Daily mean values from the two observation sites are highly

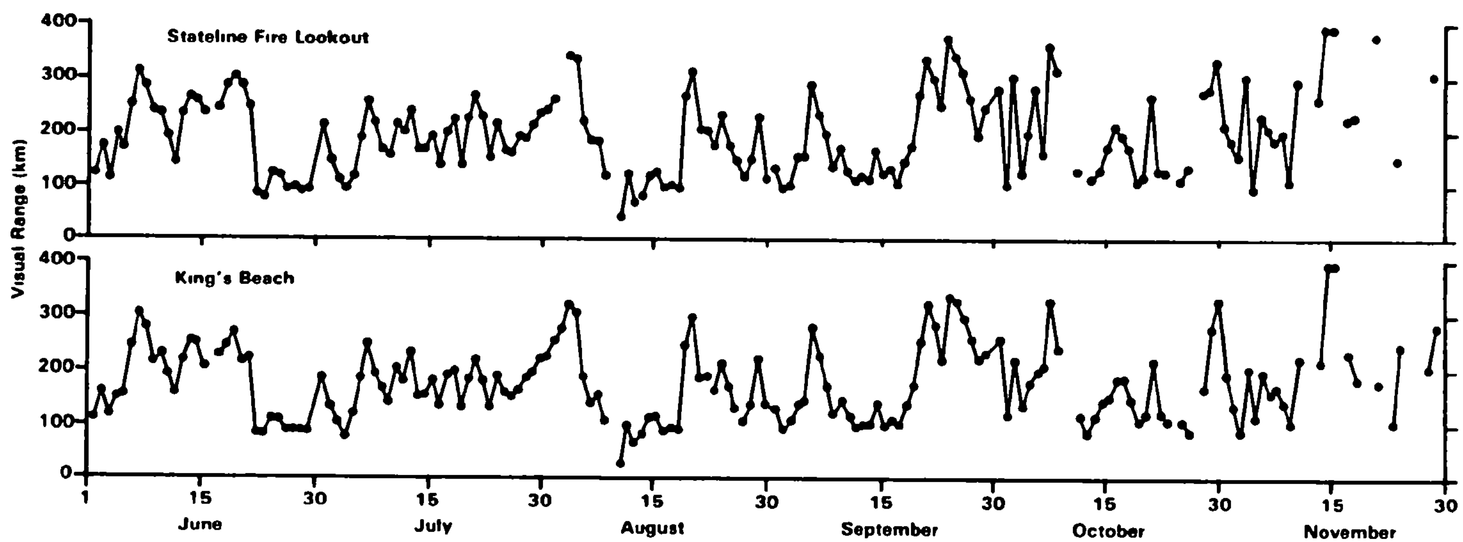

Figure 2. Daily averaged visual range (km) as determined by the teleradiometer measurements versus time for Stateline Fire Lookout and King's Beach sites

correlated. The Stateline Fire Lookout site, which is higher in elevation than the Kings Beach site, has a systematically higher visual range. The low visual range values from June 19 to June 29 and from August 6 to August 14 were associated with impacts from the Napa and Wrights Lake forest fires. Due to the sporadic and largely uncontrolled nature of forest fires as pollution sources, data during these two periods were not included in subsequent interpretive analysis. Inspection of the target-specific teleradiometer data indicates that the data from targets number 1 and number 5 showed greater disagreement with the target-averaged values than data from the other targets. These differences were attributed to the sensitivity of teleradiometer measurements to inherent contrast errors for short path length measurements (targets 1 and 5 are 15 and 24 km from the observation points). They may also have been due in part to a spatially inhomogeneous distribution of visibility-reducing pollutants since sight paths for targets 1 and 5 cross only the northern half of the Basin.

Extinction coefficient values derived from contrast measurements of target numbers 2, 3, and 4 were averaged to create the basinwide visibility data base used in subsequent interpretive analysis. Figure 3 shows the cumulative frequency distributions of these values for the Stateline Fire Lookout and King's Beach sites. Data from the King's Beach observation site were selected for analyses combining teleradiometer and particle data since its sight paths are lower in elevation than corresponding sight paths for Stateline Fire Lookout and thus likely to be more highly related to ground-level measured particle concentrations.

Nephelometer Measurements

Cumulative frequency distributions of summer/fall and winter/spring visibility data from the nephelometer at South Lake Tahoe are shown in Figure 4. Data during the periods influenced by the two major forest fires were removed. Scattering coefficient data, measured at 500 nm wavelength, were adjusted to 550 nm to correspond more closely to human eye and teleradiometer peak response characteristics[14]. The summer/fall period had somewhat poorer average visibility than the winter/spring period. The seasonally averaged diurnal behavior of scattering coefficient at South Lake Tahoe is shown in Figure 5. Winter and spring have large diurnal fluctuations while fall has a less dramatic variation. Summer has no significant diurnal variation in scattering coefficient. Trapping of the pollutants below a nocturnal radiation inversion is apparently responsible for the increasing scattering coefficient in the late afternoon and evening. However, the decrease of the values occurs too early in the morning to correspond the breakup of the inversion. This suggests some systematic local circulation which disperses the pollutants. Summer scattering coefficient values seem uninfluenced by either mechanism.

The nephelometer-measured visibility at South Lake Tahoe is significantly lower than the teleradiometer-measured Tahoe Basin visibility as seen in the cumulative frequency distributions (Figures 3 and 4). To determine whether this was due in any great part to instrument bias, an examination was conducted of data from several periods of time during which some degree of spatial uniformity in the concentration of visibility-reducing pollutants might be expected. June 13 to June 22 was a period of very good visibility. It is expected that the meteorological conditions during such an episode of high visibility would tend to discourage spatially inhomogeneous pollutant distributions. The mean nephelometer scattering coefficient and teleradiometer extinction coefficients were the same for this clean period (0.08 km^{-1}). By

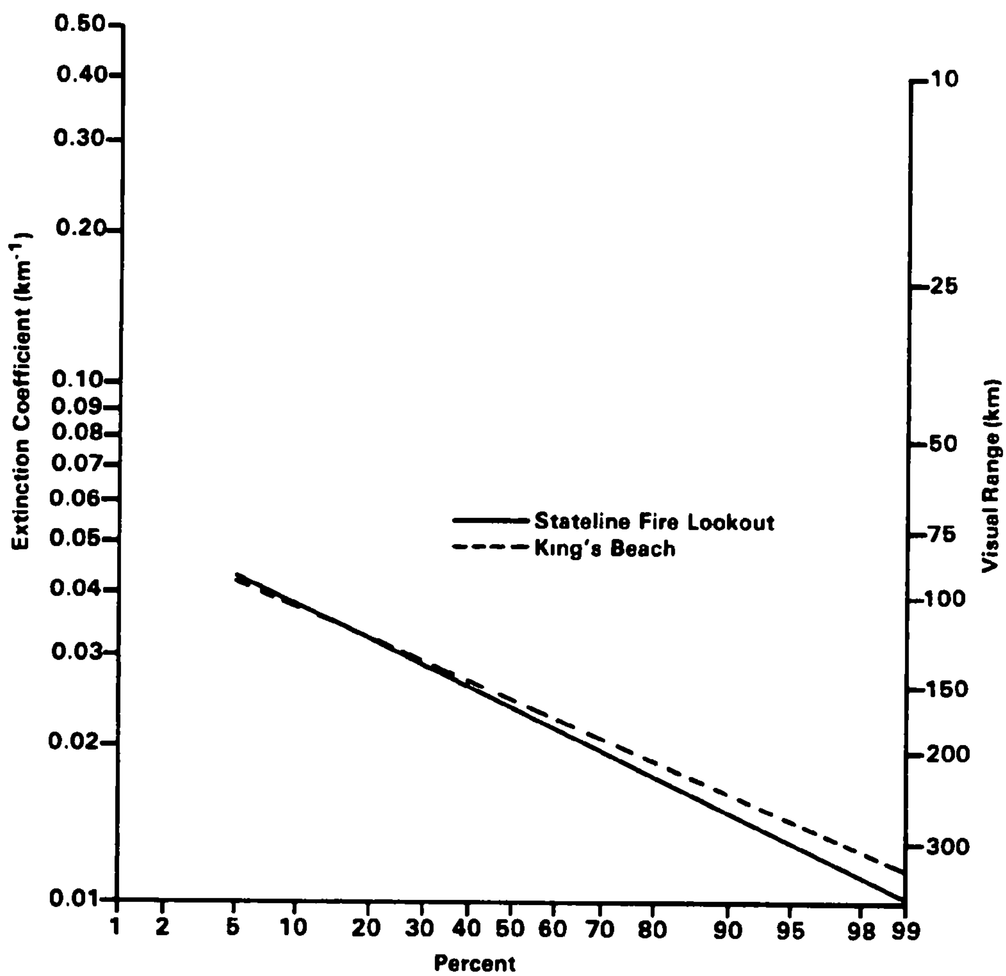

Figure 3. Cumulative frequency distribution of extinction coefficient (km^{-1}) as determined by teleradiometer measurements for Stateline Fire Lookout and King's Beach sites for the summer/fall period. Equivalent visual range scale from equation number 2 of text

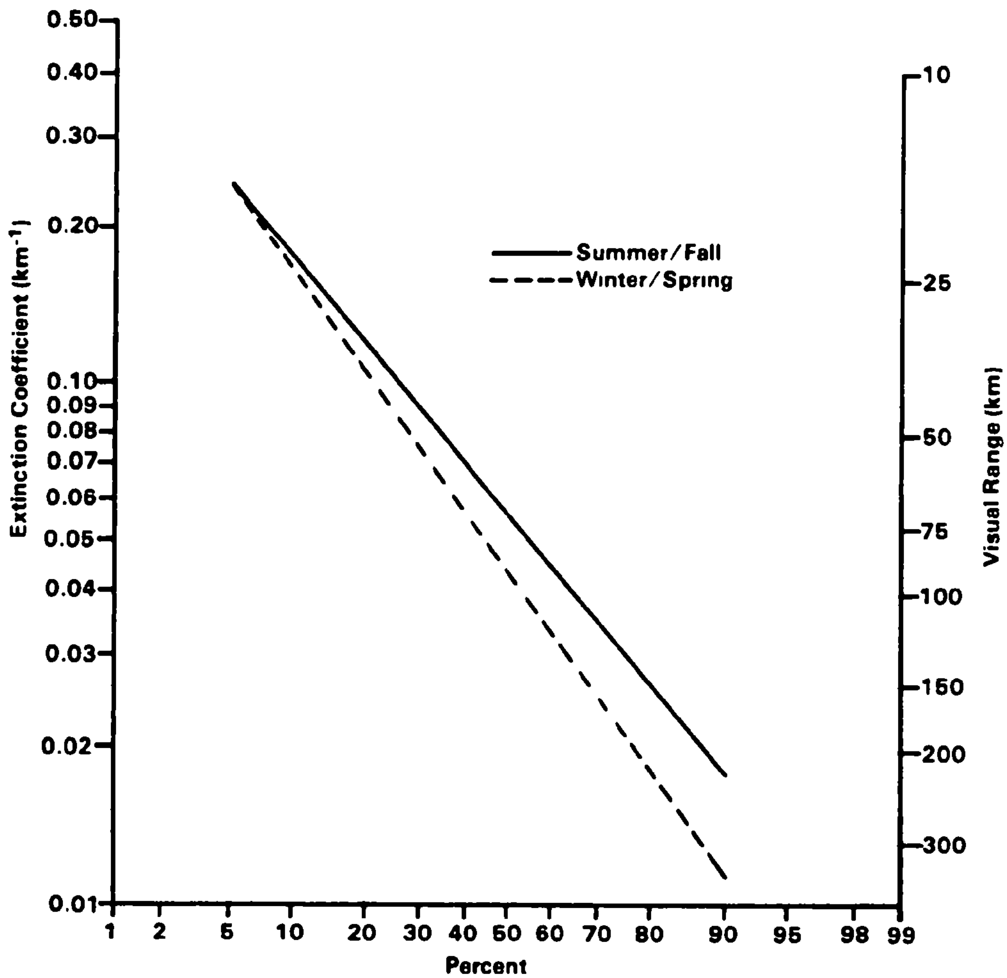

Figure 4. Cumulative frequency distributions of extinction coefficient (km^{-1}) as determined by the integrating nephelometer (assumes extinction coefficient equals scattering coefficient) at South Lake Tahoe for two six month periods. Equivalent visual range scale from equation number 2 of text

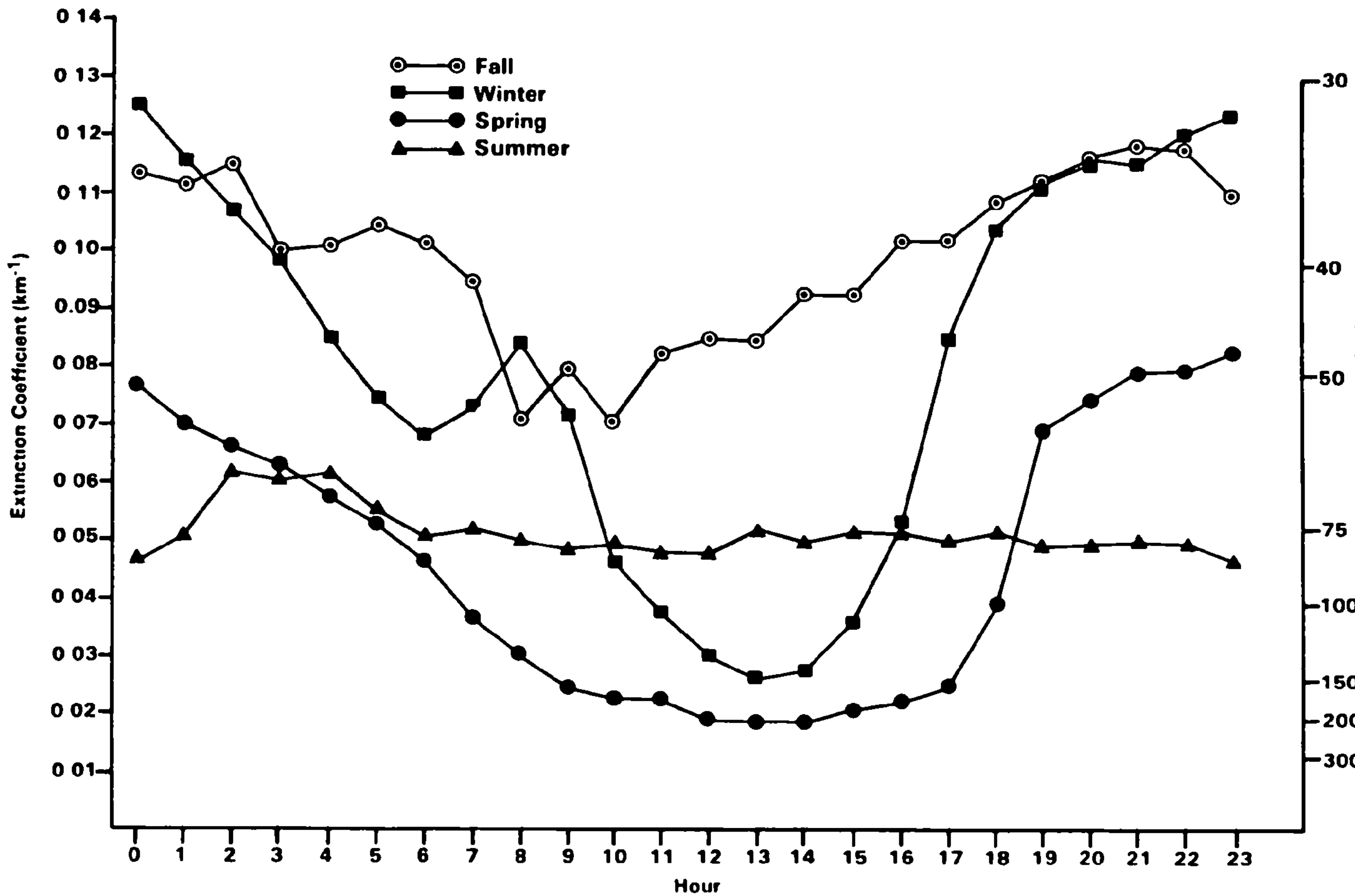

Figure 5. Seasonal averaged diurnal variations in extinction coefficient as determined by the integrating nephelometer (assumes extinction coefficient equals scattering coefficient) at South Lake Tahoe. Equivalent visual range scale from equation number 2 of text

assuming that the impact of the major forest fires was uniform over the Basin and that it was intense enough to overwhelm the impacts of local sources, a comparison on poor air quality days was possible. The average scattering coefficient value from the nephelometer for August 12 to August 14 was 0.078 km^{-1} while the extinction coefficient from the teleradiometer was 0.053 km^{-1}. These values are close by comparison to differences in the cumulative frequency distributions for the two instruments on the poor visibility end of the scale (compare Figures 3 and 4). By comparison, October 21 was selected by the appearance in photographs of a visible layer of pollutants over the southern end of the Basin suggesting a spatially inhomogeneous pollutant distribution. On that date the average scattering coefficient at South Lake Tahoe was 0.423 km^{-1} and the basin-averaged extinction coefficient was 0.039. Thus, in at least a semi-quantitative sense, the two methods seem to agree (and disagree) as expected. Diurnal visibility variations may be another factor contributing to the different mean values since the nephelometer provides a 24 hour-a-day measurement while the teleradiometer has discrete 9 a.m., noon, and 3 p.m. measurements. As seen in Figure 5, except in summer, the South Lake Tahoe visibility during these hours is considerably better than the daily average. A subset of the nephelometer data was compared to the teleradiometer data to investigate this factor. Using only paired data (hourly averaged nephelometer data for hours corresponding to each valid teleradiometer value), the ratio of the mean nephelometer derived extinction coefficient to the mean teleradiometer derived extinction coefficient is 2.0 overall, 1.7 for summer, and 3.0 for fall.

Photography

The photographic documentation of visibility at Lake Tahoe resulted in nearly 3000 color slides. Though they have not been used in a quantitative sense, they have been a valuable aid in the interpretation of other measurements. They have also been used to communicate visibility information to those unfamiliar with more quantitative measures of visibility. The importance of photography in a study such as this cannot be overemphasized. Policy makers have the opportunity to "see" a variety of visibility conditions, and know, by associating them with quantitative measurements, the frequency with which they occur. Figures 6, 7, and 8 are photographs representative of unusually good, average and unusually poor basin-wide visibility. An example of good basin-wide visibility coupled with a perceptable haze layer over the south end of the lake is shown in Figure 9.

Particle Sampling

Means and standard deviations of particle data are presented in Tables II, III, and IV for Sugarpine Point, South Lake Tahoe, and Sierra Ski Ranch sites respectively. At Sugarpine Point, the values for the two six-month monitoring programs can be compared. The coarse and fine particle mass concentrations are greater during the intensive (summer/fall) period than the following six-month period. This is consistent with the lower visibility measured by the nephelometer in summer/fall compared to winter/spring. The largest measured elemental contributors to the coarse mass concentration are soil-related elements (i.e., Al, Si, K, Ca, and Fe). For the fine size range, sulfur and soil-related elements are important contributors. In both size ranges, the major portion of the mass must be contributed by light elements (lower in atomic weight than sodium) which are not measured by PIXE analysis. The light elements constitute a greater portion of the fine size particles than the coarse. Fine

Figure 6. View from Stateline Fire Lookout towards the south end of the lake, 9:00 a.m., August 4, 1981. Approximately 98 percent of the time teleradiometer determined visual range is less than the 320 km corresponding to this photograph

Figure 7. View from Stateline Fire Lookout towards the south end of the lake, 9:00 a.m., June 4, 1981. Approximately 50 percent of the time teleradiometer determined visual range is less than the 160 km corresponding to this photograph

Figure 8. View from Stateline Fire Lookout towards the south end of the lake, 9:00 a.m., August 13, 1981. Approximately 1 percent of the time teleradiometer determined visual range is less than the 60 km corresponding to this photograph

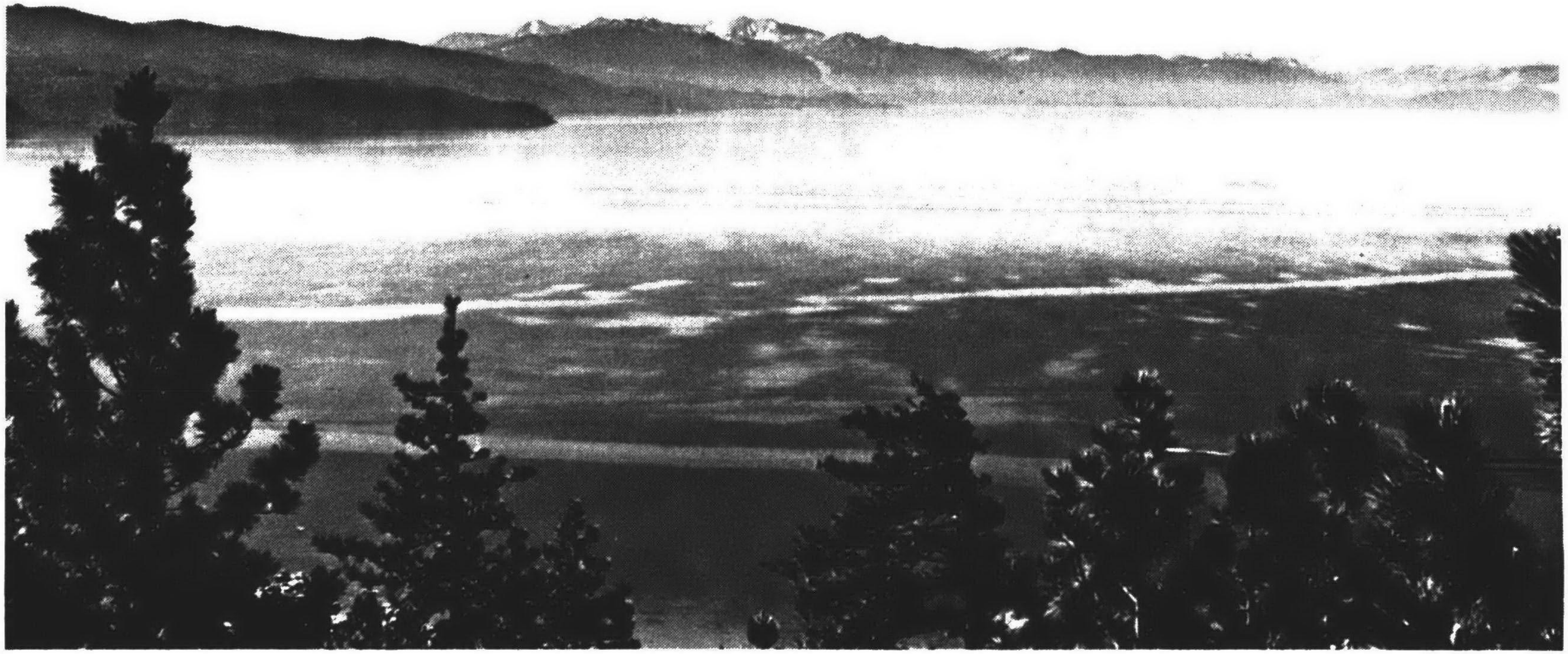

Figure 9. View from Stateline Fire Lookout towards the south end of the lake, 9:00 a.m., June 21, 1981. Basin-wide visual range from the teleradiometer is approximately 240 km while South Lake Tahoe visual range from the nephelometer is approximately 150 km

TABLE II. SUGARPINE POINT AVERAGE AND STANDARD DEVIATION OF ELEMENTAL COMPOSITION WHEN ABOVE DETECTION LIMITS FOR AT LEAST 50% OF SAMPLES ($\mu g/m^3$)

	Summer/Fall		Winter/Spring	
	Coarse	Fine	Coarse	Fine
Al	0.76±0.53	0.06±0.05	0.38±0.47	0.06±0.07
Si	1.26±0.74	0.11±0.09	0.78±0.89	0.14±0.15
S	-	0.22±0.14	0.08±0.04	0.18±0.16
Cl	-	-	0.07±0.07	-
K	0.15±0.10	0.06±0.03	0.13±0.10	0.08±0.13
Ca	0.20±0.12	0.03±0.01	0.22±0.25	0.04±0.04
Ti	-	0.004±0.002	-	0.01±0.01
Mn	-	-	0.03±0.01	0.01±0.01
Fe	0.32±0.26	0.04±0.03	0.26±0.26	0.04±0.05
Zn	-	0.002±0.001	-	-
Br	-	0.004±0.003	-	-
Pb	-	0.02±0.01	-	0.03±0.02
Mass	10.9±5.8	7.1±2.6	8.0±7.0	5.2±3.7

TABLE III. SOUTH LAKE TAHOE AVERAGE AND STANDARD DEVIATION OF ELEMENTAL COMPOSITION WHEN ABOVE DETECTION LIMITS FOR AT LEAST 50% OF SAMPLES ($\mu g/m^3$)

	Summer/Fall	
	Coarse	Fine
Al	1.22±0.58	0.05±0.04
Si	2.48±1.15	0.12±0.09
S	0.06±0.03	0.13±0.11
Cl	0.13±0.33	-
K	0.26±0.13	0.05±0.03
Ca	0.38±0.19	0.03±0.01
Ti	0.06±0.04	0.004±0.002
Mn	-	0.001±0.001
Fe	0.57±0.29	0.04±0.03
Cu	-	0.001±0.004
Zn	0.01±0.01	0.003±0.002
Br	0.03±0.01	0.03±0.01
Pb	0.08±0.04	0.10±0.04
Mass	17.9±7.9	7.5±3.2

TABLE IV. SIERRA SKI RANCH AVERAGE AND STANDARD DEVIATION OF ELEMENTAL COMPOSITION WHEN ABOVE DETECTION LIMITS FOR AT LEAST 50% OF SAMPLES ($\mu g/m^3$)

	Summer/Fall	
	Coarse	Fine
Al	1.09±0.88	0.09±0.08
Si	1.86±1.47	0.20±0.16
S	0.08±0.05	0.27±0.20
Cl	0.23±0.54	-
K	0.27±0.28	0.07±0.04
Ca	0.56±0.85	0.06±0.10
Ti	-	0.006±0.004
Mn	-	0.003±0.004
Fe	0.49±0.47	0.07±0.06
Cu	-	0.001±0.003
Zn	-	0.002±0.002
Pb	-	0.004±0.003
Mass	20.1±14.5	7.6±3.6

particle mass concentrations are similar at the three sites during the first six months, though coarse mass concentrations are much lower at Sugarpine Point than at the other sites.

INTERPRETIVE ANALYSIS

This section describes the methods and results of interpretive analysis of data collected during the intensive monitoring period from June through November of 1981. Data taken during the two periods of major forest fire influence were not used. The overall objective of this analysis was to relate measured visibility to particulate pollution sources. Basically, this was accomplished by determining the relative contribution of sources to the particle concentration, then applying multiple linear regression techniques to the source contribution and visibility data to relate them.

Multiple linear regressions performed with a standard computer routine provide the basis for this work. In general, multiple linear regression of a dependent variable Y on independent variables $X_1, \ldots, X_n$ determines coefficients $a_1, \ldots, a_n$ which minimize the mean square error. The linear model considered here is

$$Y = a_0 + \sum_{i=1}^{n} a_i X_i + \varepsilon \qquad 4)$$

where the ε denotes the error. The error is considered to have a mean of zero. The variance σ^2 and the errors corresponding to the various Y's are assumed to be independent. The level of significance of the coefficients can be determined using a t test, while an F test is used to determine the overall significance of the linear model. The proportion of total variation in Y accounted for by the regression model is given by the coefficient of determination, R^2.

$$R^2 = \frac{\text{Sum of Squares Regression}}{\text{Sum of Squares Total}} \qquad 5)$$

A more detailed discussion of multiple linear regression is available elsewhere.[15]

Preliminary Analysis

First, an assessment of the relative importance of coarse and fine particles to visibility was conducted. This was accomplished using a model of the form.

$$b_{p,ext} = A_c M_c + A_f M_f \qquad 6)$$

where $b_{p,ext}$ is the particle extinction coefficient, M_c and M_f are the coarse and fine mass concentrations and A_c and A_f are the regression coefficients determined in the analysis. The $b_{p,ext}$ values are determined by averaging the b_{ext} values corresponding to the particle sampling periods and subtracting the appropriate Rayleigh scattering coefficient (scattering by gas molecules in an unpolluted atmosphere). The intercept, a_o, was forced to be zero because particle extinction will be zero when particle concentration is zero.

Table V shows the results of this model for teleradiometer data paired with particle data from Sugarpine Point samples and nephelometer data paired with particle data from the South Lake Tahoe sampler. The R^2 values indicate that 84 and 88 percent of the variation in particle extinction (teleradiometer and nephelometer respectively) is explained by the particle mass concentration. In both cases, the fine particle coefficient is significant while the coarse particle coefficient is not.

A dependence of visibility on fine particle concentration has been demonstrated by other investigators.[16] However, testing of the coarse particle influence on visibility is required before it can be dismissed.[17] Since fine particles alone demonstrate a significant relationship to visibility, the coarse particle data will not be included in any subsequent analysis.

Source Characterization

In order to assess the causes of visibility impairment in the Tahoe Basin, it is necessary to identify the sources of fine particles. One approach involves using compositional characteristics of sources to identify their contribution to the ambient particle loading.[18] This technique was used to specify "Soil," "Sulfate," and "Automotive" source categories. The equations used to calculate the contribution by these sources are specified in Table VI. Also shown in this table is a category known as "Other" which contains materials from a variety of minor (in some cases unknown) sources. For each category, some measured elemental concentration (or concentrations) is adjusted based on known or assumed compositional characteristics of sources. In the case of "Soil" the measured concentrations of a half dozen elements are multiplied by numbers which adjust for the additional mass of oxygen assumed to be associated with them in soil minerals. Since fine potassium (K) is thought to be from both soil and vegetative burning, iron (Fe) concentration times 0.48 (the ratio of coarse K to Fe at Lake Tahoe) is used for the contribution to soil by K.

The "Sulfate" value is similarly determined by adjusting the sulfur concentration to account for the added oxygen mass. Lead is used as a tracer for the exhaust products of automobiles. In this case, the multiplicative factor accounts primarily for hydrocarbons associated with auto exhaust. The factor of 12 for "Auto" is based on information from Trijonis and Davis.[18] The category labeled "Other" is also determined by adjusting measured elemental concentrations to reflect the mass of the associated unmeasured elements.

The same type of approach was tested on another source category, "vegetative burning", but was not used. Other investigators have used non-soil-related fine K as a tracer for smoke from vegetative burning.[20] An average K to Fe ratio calculated from the coarse particle data is assumed to represent the relative proportions of those elements in the soil. This ratio multiplied by fine Fe represents the fine K from soil and the difference between it and the total fine K is assumed to be related to vegetative burning. Application of this technique to samples taken during the impact of the two major forest fires indicated that the excess fine K (total fine K minus soil related fine K) to smoke concentration was not constant. The impact, in terms of enhanced fine particle concentration, of the Napa fire was accompanied by a significant increase in excess K while the even greater impact from the Wrights Lake fire had only a minor increase in excess K above background levels. There are two notable differences between the two fires. The Napa fire was 200 km from Tahoe and was fueled by grass, shrubs and hardwood forest while the Wrights

TABLE V. RESULTS OF MULTIPLE LINEAR REGRESSION ON EQUATION NUMBER 6 OF TEXT FOR TELEPHOTOMETER VISIBILITY/SUGARPINE POINT PARTICLE DATA AND NEPHELOMETER VISIBILITY/SOUTH LAKE TAHOE PARTICLE DATA

	A_c	t-test significance	A_f	t-test significance	R^2	n
Teleradiometer	-0.00015	0.430	0.00236	0.000	0.84	57
Nephelometer	0.00048	0.443	0.00448	0.039	0.88	19

TABLE VI. EQUATIONS FOR CALCULATION OF FINE PARTICULATE PARAMETERS (Note: Chemical symbols are used for each measured element)

1.	Soil
	Soil = Mg x 1.66 + Al x 1.67 + Si x 2.14 + Ca x 1.44 + Mn x 1.44 + Fe x 1.40 + (Fe x 0.48) x 1.21
2.	Sulfate
	Sulfate = S x 3.0
3.	Auto
	Auto = Pb x 12
4.	Other
	Other = P x 2.29 + V x 1.78 + Cr x 1.46 + Ni x 1.27 + Cu x 1.25 + Zn x 1.25 + Cl x 1.65 + Se

Lake fire was adjacent to the Tahoe Basin and primarily consumed coniferous forest. A special study was performed, in which samples containing smoke from conifer wood was compared to hardwood smoke and grass smoke samples. The ratio of K to total mass concentration for the conifer wood smoke was much smaller and more variable than the other two. Therefore, without information concerning the types and mix of fuel involved, excess K could not be used in a quantitative way as a tracer.

At this point in the analysis, all of the heavy elements (larger in atomic number than 11, sodium) and light elements which are assumed to be associated with them are accounted for as "Sulfate," "Auto," "Soil" or "Other." However, only about 20% of the mass of the Lake Tahoe fine particle samples is explained by these sources. The 80% unexplained is composed of light elements. It is most likely that the major portion of this mass is carbonaceous in nature, with a good share of that being organic hydrocarbons. Nitrates may also be a significant contributor to the unexplained fraction. Some portion of the unexplained mass may be water bound to the particles. This is not thought to be a major component.

The sources contributing to this unexplained category can be classified as either of local origin or the result of transport. Nitrates and hydrocarbons can be transported into the Tahoe Basin in much the same way as sulfates from upwind sources in California. As with sulfates, nitrates are assumed to result from transport from distant sources. Thus, the local sources primarily provide hydrocarbons. Based on calculated emissions for the basin, the major contributors to hydrocarbons are burning wood for residential heating and aerosols resulting from the terpene emissions by coniferous trees. On the basis of their estimated emissions, these two local sources dominate all the other hydrocarbon sources in the basin, including diesel, which has about one half the expected emissions of "Auto". Another class of short term hydrocarbon sources is wild fires and prescribed burning. Except for impacts from occasional major wild fires, wood burning for residential heating represents the overwhelming fraction of wood consumed in the Tahoe Basin.

A model was developed to apportion the unexplained fraction of the fine mass concentration to three classes of sources: the transported light elements, the terpenes, and the residential wood smoke. The transported light element concentration is assumed to be proportional to the sulfate concentration, since it is also assumed to result from transport. A proportionality constant of two was derived from typical measured values for the ratio of nitrates + total hydrocarbon to sulfates for the Sacramento Valley.[21] The remainder of the unexplained mass is assumed to be terpenes plus residential wood smoke. The production of smoke from residential burning of wood is assumed to be proportional to degree-heating hours. This is an extension of the empirical relationship between fuel demand for residential heating and degree heating days.[22] The assumptions were that the proportion of wood to other fuels is independent of temperature or season, that wood smoke emissions are proportional to wood consumed and that degree-heating hours would more faithfully represent fuel demand in an area with frequent large diurnal temperature fluctuations than degree heating days. The hourly temperature values used to calculate degree-heating hours were derived from a sinusoidal fit to the measured daily high and low temperatures, with the period of the sine function controlled by the time between sunrise and sunset. Terpene emission rates increase exponentially with temperature.[23] Using the hourly temperature values, the relative emissions of terpenes can be calculated for any period of time.

The following equations relate the various components of the model.

$$U = TLE + NTU \qquad 7)$$
$$TLE = 2 \times SO_4 \qquad 8)$$
$$NTU = aD + bT \qquad 9)$$

where, U, TLE, and NTU are the unexplained, transported light elements and non-transported unexplained concentration. SO_4 is sulfate concentration. "D" and "T" are the degree heating hour and relative terpene emissions respectively. Wood smoke concentration is the product "aD" while terpene concentration is "bT." By making the assumption that "a" and "b" are constants, they can be determined by multiple linear regression analysis on equation number 9. In this way the gross variations of NTU with temperature can be accounted for (NTU generally increases with increasing temperature at Sugarpine Point and Sierra Ski Ranch and decreases at South Lake Tahoe). However, ambient concentrations are not directly proportional to emissions. The use of constant "a" and "b," determined by regression analysis, results in over or under predicting the NTU concentration for a typical day in spite of a good average prediction. To avoid this situation, a further adjustment is made to the constant values determined from multiple linear regression. For each sample period these values are multiplied by the ratio of the observed to the predicted concentration of the non-transport unexplained mass, $(\frac{NTU}{aD+bT})$. This adjustment term could be interpreted physically as a meteorological factor. The term is greater than one when the meteorology promotes stagnation resulting in higher than average concentrations of pollutants from local sources. When the term is less than one the meteorology retards the concentration of pollutants from local sources (i.e., increases their dispersion, dilution or deposition).

The model was applied to non-wildfire related particle data from each of the three Tahoe particle sampling sites. The degree of success of these applications of the regression portion of the model are demonstrated by the high level of significance for the two regression coefficients (less than 0.05% chance of the null hypothesis being true for all except "a" at Sierra Ski Ranch with 14%) and the high multiple R^2 value, 0.81 at Sugarpine, 0.73 at South Lake Tahoe and 0.68 at Sierra Ski Ranch. The physical significance of the adjustment term is supported by photographs which show rain during many of the periods where the term is considerably less than one. Apparently the washout by the rain prevented the higher levels of terpene and wood smoke predicted on the basis of temperature alone.

Tables VII, VIII and IX present the results of the source characterization assessment techniques described above for the three particle monitoring sites. The "Sulfate" and "Transported Light Element" source categories were combined and labeled "Long Range Transport." One of the more striking results is the difference between the "Residential Wood Smoke" estimate at the three locations. As one might expect, the highly developed South Lake Tahoe urban area has higher smoke concentrations from residential heating than at the more remote basin site at Sugarpine. The "Residential Wood Smoke" concentrations for Sierra Ski Ranch located at Echo Summit are lower than either of the two basin sites. The "Long Range Transport" is greatest at Sierra Ski Ranch on Echo Summit perhaps as a result of its exposure to transport from the west. The difference in transport values at the two basin sites might result from enhanced vertical mixing at the south end of the basin. This might also explain why the mean "Terpene" concentrations which are about the same at Sugarpine and Sierra Ski Ranch are about a factor of two higher than at South Lake Tahoe.

TABLE VII. SUGARPINE POINT FINE PARTICLE SOURCE CHARACTERIZATION (Data excludes Napa and Wrights Lake Fire Periods)

Source	Overall		Summer		Fall	
	µg/m^3	%	µg/m^3	%	µg/m^3	%
Soil	0.46	6.4	0.67	7.8	0.32	5.1
Auto	0.19	2.7	0.12	1.3	0.24	3.8
Long Range Transport	2.0	28	2.0	23	2.0	32
Residential Wood Smoke	1.2	17	0.73	8.4	1.6	25
Terpene	3.3	46	5.1	59	2.1	34
Other	0.02	0.3	0.02	0.2	0.02	0.3
Total	7.15	100	8.65	100	6.20	100

TABLE VIII. SOUTH LAKE TAHOE FINE PARTICLE SOURCE CHARACTERIZATION (Data excludes Napa and Wrights Lake Fire periods)

Source	Overall $\mu g/m^3$	Overall %	Summer $\mu g/m^3$	Summer %	Fall $\mu g/m^3$	Fall %
Soil	0.46	6.1	0.67	9.3	0.35	4.5
Auto	1.2	15	0.76	11	1.4	18
Long Range Transport	1.2	16	1.5	21	1.0	13
Residential Wood Smoke	3.0	40	1.6	22	3.7	49
Terpene	1.7	23	2.7	38	1.2	15
Other	0.03	0.4	0.02	0.2	0.04	0.5
Total	7.51	100	7.18	100	7.67	100

TABLE IX. SIERRA SKI RANCH SOURCE CHARACTERIZATION (Data excludes Napa and wrights Lake Fire periods)

Sources	Overall $\mu g/m^3$	Overall %	Summer $\mu g/m^3$	Summer %	Fall $\mu g/m^3$	Fall %
Soil	0.80	11	1.2	13	0.49	7.5
Auto	0.17	2.2	0.13	1.5	0.21	3.2
Long Range Transport	2.4	32	2.5	28	2.4	36
Residential Wood Smoke	0.70	9.2	0.46	5.2	0.90	14
Terpene	3.5	46	4.6	52	2.5	39
Other	0.02	0.3	0.02	0.2	0.02	0.3
Total	7.61	100	8.89	100	6.51	100

An alternate explanation for low terpene at South Lake Tahoe may be related to the expected lower ozone values in the more urbanized South Lake Tahoe area caused by higher NO concentrations. Ozone is highly reactive with terpene causing the gaseous terpene to form fine particles.[24] This would result in a lower ratio of particle to gaseous terpenes at South Lake Tahoe than the other locations in the area. The "Auto" concentrations are nearly the same at Sugarpine and Sierra Ski Ranch and as expected are much smaller than at South Lake Tahoe. Mean "Soil" concentrations are about the same for the two basin sites, though nearly half the values for Sierra Ski Ranch. This may have resulted from the somewhat less ground cover and ski area maintenance during the summer at the latter location.

Visibility/Fine Particle Relationship

The optical extinction efficiency of particles from distinct source categories are not necessarily the same. The size distribution, shape, density and index of refraction characteristics of particles emitted by a source will determine its optical affect per unit mass concentration[25]. The product of the extinction efficiency for a collection of particles and its mass concentration is the particle extinction coefficient associated with those particles. The particle extinction coefficients associated with particles from each of the sources which impacts an air parcel can be summed to obtain the total particle extinction for that parcel. Lack of detailed physical information on particles associated with each source makes it impractical to calculate the corresponding extinction efficiencies. However, it is possible to estimate them using multiple linear regression.

The multiple linear regression model employed has particle extinction, derived by visibility measurement, as the dependent parameter and the mass concentration of particles associated with the various source categories as independent parameters. The coefficients determined by the regression analysis are the estimates of the extinction efficiencies for the particles associated with various sources. A satisfactory model is obtained by this method when 1) a large fraction of the variation in the dependent variable is explained (i.e., a high R^2 value), 2) the regression coefficients are statistically significant and 3) it is physically meaningful. These conditions are often not met upon the initial application of regression analysis. If this is the case, a process of trial and error is employed in which independent parameters are eliminated or combined and re-evaluated in the multiple linear regression model. A simple example of this was the elimination of coarse particles from the visibility analysis because the coefficient relating it to particle extinction was statistically indistinguishable from zero.

Data from the Kings Beach teleradiometer location for targets number 2 through 4 and particle data from the Sugarpine Point site were used to develop a regression model for basin-wide visibility. The teleradiometer-derived particle extinction values corresponding to each of the particle sampling periods were averaged. The mean particle extinction was the dependent variable; the independent variables were the particle emission source categories. A series of multiple linear regressions were run on the data trying different combinations of source categories for independent variables in an attempt to find a satisfactory model. The most useful set of source classifications tested as independent variables are "Long Range Transport," "Wood Smoke" and sum of "Soil", "Auto", "Terpene" and "Other". The last of these is referred to as "Non-Transport-Non-Smoke." The following equation results from the multiple linear regression analysis performed on these parameters.

$$b_{p,ext} = 0.00451 \text{ LRT} + 0.00374 \text{ RWS} + 0.00074 \text{ NTNS}$$

The $b_{p,ext}$, LRT, RWS and NTNS are the particle extinction, "Long Range Transport," "Residential Wood Smoke" and "Non-Transport-Non-Smoke" parameters. The R^2 value for this model is 0.84. All the coefficients are significant at the 90% level or better and the F-ratio indicates a highly significant regression.

Table X shows the results of employing this model to determining the particle extinction budget using the mean particle values shown in Table VII. Comparing the percentage values in the two tables reveals several interesting results. Though "Terpenes" represent the highest source contribution they contribute less to the extinction than "Long Range Transport" and less than "Residential Wood Smoke" except in summer. This is due to the enhanced capacity of transport and smoke-related particles for impacting visibility as indicated by their regressions coefficients which are five to six times greater than the coefficients for the rest of the particles at Tahoe. The disparity in optical properties may be the result of the size distribution of the particles in question. The smoke and transport-related particles are probably in the 0.5 to 1.0 μm diameter size range which is highly effective for light scattering.[25] The terpenes are most likely smaller (less than 0.5 μm diameter) and therefore less efficient at scattering light. Fine soil-related particles are too large for efficient scattering. While the auto-related particles may be in the proper size range, apparently their low concentrations prevented them from surviving the earlier multiple linear regression attempts as a separate independent parameter. Another factor which may share the responsibility for some particle source categories having higher efficiencies than others is their spatial distributions, especially in the vertical. If the concentration of particles associated with a source fell off rapidly with height, then the 200 m average height difference between the teleradiometer sight paths and the particle sampler would result in a lower "effective" optical extinction efficiency than the true extinction efficiency. Near surface emissions for "Soil", "Terpene" and "Auto" would suggest that their concentrations decrease with height and thus result in a lower effective than true extinction efficiency.

A similar analysis was performed on nephelometer and particle data from the South Lake Tahoe site. Nephelometer derived particle extinction values corresponding to each of the particle sampling periods were averaged. No satisfactory model was found which could encompass the six month period. Two seasonally dependent models were required to adequately explain the visibility, a summer model based on "Long Range Transport" and a fall model based on "Residential Wood Smoke." The following equations resulted from the analysis.

$$b_{p_s,ext} = 0.00963 \text{ LRT} + 0.00509 \text{ NLRT}$$

$$b_{p_f,ext} = 0.02031 \text{ RWS} + 0.00619 \text{ NRWS}$$

TABLE X. LAKE TAHOE BASIN PARTICLE EXTINCTION BUDGET

Source	Overall km^{-1}	Overall %	Summer km^{-1}	Summer %	Fall km^{-1}	Fall %
Soil	0.0003	2.0	0.0005	3.1	0.0002	1.4
Auto	0.0001	0.9	0.0001	0.5	0.0002	1.0
Long Range Transport	0.0089	54	0.0090	56	0.0089	53
Residential Wood Smoke	0.0046	28	0.0027	17	0.0058	35
Terpene	0.0024	15	0.0038	24	0.0016	9.3
Other	0.0000	0.1	0.0000	0.1	0.0000	0.1
Total	0.0165	100	0.0161	100	0.0167	100

the $b_{p_s,ext}$, LRT, NLRT represent the summer particle extinction, "Long Range Transport," and "Non-Long Range Transport" parameters, while $b_{p_f,ext}$, RWS, NRWS represent the fall particle extinction "Residential Wood Smoke" and "Non-Residential Wood Smoke" parameters. The multiple R^2 values for the summer and fall regressions are 0.87 and 0.85 respectively.

Table XI shows the results of employing these models to determine the particle extinction budget using the mean particle values shown in Table VIII. As a comparison of the two tables shows, the wood smoke is the major contributor overall (average of summer and fall) to both the source and the extinction budget, however the contribution is roughly 3 times greater in the fall than in the summer. The long range transport and terpene parameters are approximately equal in both summer and fall. The values of terpene and transport are lower in the fall than in the summer.

SUMMARY AND CONCLUSIONS

Results of this study indicate generally good visibility at Lake Tahoe with a summer/fall median visual range for the basin greater than 150 km. Somewhat poorer visibility in the urbanized South Lake Tahoe area with median visual range for the same period of about 70 km, demonstrates an effect on visibility from local pollutant sources. Basin wide visibility was measured only during the summer/fall intensive monitoring season. The degree to which this six month period is representative of annual basin wide visibility remains an area of speculation. The nephelometer measurements at South Lake Tahoe indicate better visibility in the winter/spring period than in summer/fall (median visual ranges of about 90 km and 70 km respectively). Assuming the same trend for the basin wide visibility would lead to the conclusion that annual basin wide median visual range is greater than that reported for the summer/fall monitoring period.

Multiple linear regression analysis indicates that visibility is significantly related to fine particle concentration but is not related to coarse particle concentration. Automotive emission, soil, and sulfates account for approximately 20 percent of the mass of fine particles. The remaining 80 percent is composed of elements lighter in atomic weight than sodium. These were assumed to be composed of nitrates from out of basin sources, and carbonaceous material resulting from residential wood burning and terpene emissions by coniferous forest. A model was developed to estimate the relative contribution of each of these materials for each particle sampling period. Except at South Lake Tahoe, terpenes represented nearly half the fine particle mass, long range transport (nitrates + sulfates + hydrocarbons) represented 30 percent and wood smoke 10 to 20 percent. In the South Lake Tahoe urban area, residential wood smoke, terpenes, and long range transport accounted for approximately 40, 25, and 15 percent of fine particle mass concentration respectively.

Since fine particles from different sources do not necessarily have the same optical extinction efficiency, the relationships between visibility and source categories were determined using multiple linear regression. For basin wide visibility the most important sources of impact are long range transport, residential wood smoke and terpenes, accounting for approximately 50, 30, and

TABLE XI. SOUTH LAKE TAHOE PARTICLE EXTINCTION BUDGET

Source	Overall km^{-1}	Overall %	Summer km^{-1}	Summer %	Fall km^{-1}	Fall %
Soil	0.0027	4.0	0.0034	7.8	0.0021	2.0
Auto	0.0062	8.8	0.0039	9.0	0.0084	8.4
Long Range Transport	0.0103	14	0.0142	33	0.0064	6.4
Residential Wood Smoke	0.0418	58	0.0079	18	0.0757	76
Terpene	0.0105	15	0.0138	32	0.0072	7.1
Other	0.0001	0.2	0.0001	0.2	0.0002	0.1
Total	0.0716	100	0.0433	100	0.1000	100

15 percent of the visibility impact respectively. In South Lake Tahoe residential wood smoke accounts for nearly 60 percent of the impact while long range transport and terpenes account for about 15 percent each and automotive accounts for nearly 10 percent.

The implications of these findings are that approximately 70 percent of the basin-wide visibility impact and 30 percent of the South Lake Tahoe visibility impact are caused by sources beyond the reasonable control of Tahoe Regional Planning Agency (i.e., natural and long range transport emissions). Of the controllable sources, wood smoke for residential heating affords the greatest degree of potential visibility improvement. This is especially true at South Lake Tahoe in the colder seasons. Though automotive sources and to some degree wind blown soil sources are controllable, their share of the extinction budget is quite small and therefore the potential visibility improvement by their control is also small.

Further studies of visibility and particles are warranted at Lake Tahoe. Characterization by analytical techniques of the light element fraction of the fine particles would be an important check on the estimation technique employed in this work. In such work, it's expected that distinguishing between wood smoke and terpene carbonaceous materials would not be triveal since smoke from coniferous wood contains a large quantity of terpene hydrocarbons[26]. Particle sampling and visibility monitoring should be conducted in a routine way for at least two years so that yearly variations can be investigated. This would also allow a much better evaluation of the relationships between visibility and particle source categories on a seasonal basis.

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