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Chemical Mass Balance Source Apportionment of PM_{10} during the Southern California Air Quality Study

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The chemical mass balance (CMB) receptor model was applied to the chemically speciated diurnal particulate matter samples acquired at nine locations in California's South Coast Air Basin (SoCAB) during the summer and fall of 1987 as part of the Southern California Air Quality Study (SCAQS). Source profiles applicable to the Los Angeles area were used to apportion $PM_{2.5}$ and PM_{10} (particles with aerodynamic diameters < 2.5 and 10 μm, respectively) to primary paved road dust, primary construction dust, primary motor vehicle exhaust, primary marine aerosol, secondary ammonium nitrate, and secondary ammonium sulfate. Suspended dust was the major contributor to PM_{10} during the summer, whereas secondary ammonium nitrate and primary motor vehicle exhaust contributions were high during the fall. Secondary ammonium sulfate contributions were uniform across the SoCAB, with average contributions during the fall less than half those found during the summer. Marine aerosol contributions were lower during the fall than during the summer, and were substantially lower at the inland sites relative to the sites near the coast.

INTRODUCTION

The Southern California Air Quality Study (SCAQS) (Lawson, 1990; Fujita, 1993) was conducted by the California Air Resources Board (ARB) during the summer and fall of 1987 to better understand the causes of excessive pollution concentrations in California's South Coast Air Basin (SoCAB). SCAQS was planned (Blumenthal et al., 1987) and executed (Hering and Blumenthal, 1989) to acquire measurements of pollutant and meteorological variables that influence ozone and suspended particulate matter concentrations.

SCAQS acquired simultaneous meteorological, air quality, and visibility measurements at more than 40 measurement locations throughout the SoCAB (Lawson, 1990). Measurements were taken during five episodes of 1- to 3-days' duration (11 days total) between June 19 and September 3, 1987 (termed the summer study) and for three episodes of 1- and 3-days' duration (6 days total) between November 11 and December 11, 1987 (termed the fall study). Chemical compositions of $PM_{2.5}$ and PM_{10} were measured for five periods per day at nine sites during the summer and six sites during the fall (Chow et al., 1994a,b) This paper applies the chemical mass balance (CMB) receptor model to these data to estimate diurnal

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changes in source contributions to PM_{10} levels encountered during SCAQS.

The objectives of this study are: (1) to determine which chemical and physical properties of ambient concentrations and source emissions are most useful for source attribution of receptor concentrations in the SoCAB; (2) to quantify the amounts and uncertainties of source contributions estimated by receptor models; and (3) to determine what portions of $PM_{2.5}$ and PM_{10} are of primary or secondary origin.

The CMB receptor model consists of a least-squares solution to a set of linear equations. This solution expresses each receptor concentration of a chemical species as a linear sum of products of source profile species and source contributions (Friedlander, 1973). Source profiles (the fractional amount of each species in the emissions from each source type) and receptor concentrations, each with realistic uncertainty estimates, serve as input data to the CMB model. The output consists of the contributions from each source type to the total ambient aerosol mass as well as to individual chemical species concentrations and the uncertainties of those contributions.

CMB software currently in use (Watson et al., 1990, 1991) applies the effective variance solution developed and tested by Watson et al. (1984) because (1) it calculates realistic uncertainties of source contributions from both the source and receptor uncertainties, and (2) chemical species measured more precisely in both source and receptor samples are given greater influence in the solution than are less precisely measured species. This software also includes measures developed by Henry (1982, 1992) to evaluate the effects of similarities (collinearity) among source profiles on source contribution estimates.

The CMB receptor model is well documented and tested (e.g., Hopke, 1985, 1991; Gordon, 1980, 1988; Javitz and Watson, 1988; Javitz et al., 1988; Watson, 1979; Watson et al., 1984, 1990, 1991). Watson et al. (1989) and Chow et al. (1993a) summarize the results of several CMB source apportionment studies performed throughout the world. The CMB receptor model has been previously applied to aerosol measurements in the SoCAB (Hidy and Friedlander, 1970; Miller et al., 1972; Friedlander, 1973; Gartrell and Friedlander, 1975; Stelson and Seinfeld, 1981; Cass and McRae, 1983; Gray et al., 1988; Chow et al., 1992a; Zeldin et al., 1990) as summarized by Watson et al. (1994a).

PM_{10} concentrations in the SoCAB often exceed national ambient air quality standards (50 $\mu g/m^3$ annual average and 150 $\mu g/m^3$ 24-hour average). The SCAQS aerosol data offer the first opportunity to examine the diurnal changes in source contributions to 24-hour average PM_{10} concentrations on sequential sampling days at a large number of sampling sites. Previous aerosol measurement programs (e.g., Gray et al., 1986; Solomon et al., 1989; Chow et al., 1992a) acquired 24-hour average concentrations every sixth day for a year. Those studies are more relevant to understanding annual averages than the causes of elevated 24-hour concentrations. The episodic nature of SCAQS sampling complements the data from these previous studies.

SCAQS AEROSOL DATA

A complete description and evaluation of the SCAQS aerosol measurements is given by Chow et al. (1994a). The spatial and temporal distributions of different chemical concentrations are examined by Chow et al. (1994b). Relevant results of these analyses are summarized here. The ambient particulate monitoring network for the SCAQS is shown in Figure 1. Six sampling sites (Burbank, Downtown Los Angeles, Hawthorne, Long Beach, Anaheim, and

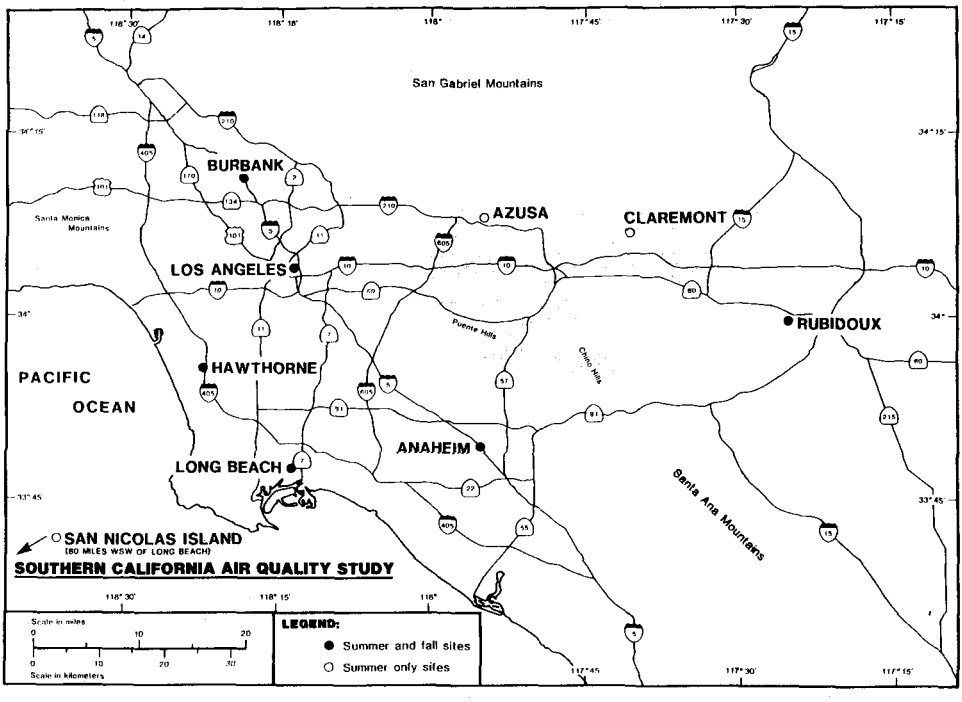

FIGURE 1. Sampling network for the 1987 Southern California Air Quality Study.

Rubidoux) were operated during both the summer and fall; an additional three sampling sites (San Nicolas Island, Azusa, and Claremont) were operated only during the summer. These sampling sites were selected to represent different industrial, commercial, residential, and agricultural land uses in urban, suburban, and background areas, and to characterize source emissions and pollutant transport within the SoCAB. Claremont and Long Beach were research sites at which several particulate sampling systems were collocated with additional meteorological, gaseous, acidity, and visibility measurements (Lawson, 1990).

The summer study emphasized elevated ozone concentrations and west-to-east transport, and included five episodes on 11 sampling days: (1) June 19, 1987; (2) June 24 and 25, 1987; (3) July 13–15, 1987; (4) August 27–29, 1987; and (5) September 2 and 3, 1987. The fall study was designed to investigate air quality during stagnant conditions and consisted of three episodes on 6 sampling days: (1) November 11–13, 1987; (2) December 3, 1987; and (3) December 10 and 11, 1987. Five sample sets were acquired for each episode day. Diurnal sampling using 4- to 7-hour filter-based gas/aerosol samples was conducted during summer (0000–0500, 0500–0900, 0900–1300, 1300–1700, 1700–2400 hours PST) and fall (0000–0600, 0600–1000, 1000–1400, 1400–1800, 1800–2400 hours PST).

$PM_{2.5}$ and PM_{10} filter samples were analyzed for mass concentration by gravimetry (Fitz et al., 1989), for light absorption by the integrating plate method (Lin et al., 1973), for elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Br, Sr, Mo, Cd, Sn, Sb, Cs, Ba, Pt, Hg, and Pb) by X-ray

fluorescence (Dzubay, 1977), for sulfate ($SO_4^=$), nitrate (NO_3^-), and chloride (Cl^-) by ion chromatography (Mulik et al., 1976), for ammonium (NH_4^+) by automated colorimetry (Bolleter et al., 1961), for soluble sodium (Na^+) by atomic absorption spectrophotometry (Rhodes et al., 1989), and for organic carbon (OC) and elemental carbon (EC) by thermal manganese oxidation (TMO) (Fung, 1990). Since ammonium nitrate is known to volatilize during sampling in the SoCAB (Solomon et al., 1992), absorbing substrates were used to catch the volatilized nitric acid and ammonia. Nitric acid, sulfur dioxide, and ammonia gases were measured using combinations of denuders and absorbing substrates. These gases are known precursors of secondary ammonium sulfate and ammonium nitrate. Chow et al. (1994a,b) evaluate the SCAQS aerosol measurement methods and describe their spatial and temporal distributions.

SOURCE PROFILES

With the exception of a tunnel study to evaluate gaseous carbon monoxide, nitrogen oxide, and hydrocarbon emissions (Ingalls, 1989), source testing from known particulate sources was not part of SCAQS. Therefore, $PM_{2.5}$ and PM_{10} source profiles were sought from other sources. Watson et al. (1994a), Gray et al. (1988), and Chow et al. (1992a) show that the source types which contribute to $PM_{2.5}$ and PM_{10} in the SoCAB are (1) geological material (fugitive dust from agriculture, paved and unpaved roads, vacant land, and construction), (2) motor vehicle exhaust (from cars, trucks, and buses fueled with diesel, leaded gasoline, and unleaded gasoline), (3) marine aerosol transported from the Pacific Ocean, and (4) secondary particles (ammonium sulfate, ammonium nitrate, and certain organic compounds). Rogge et al. (1991) and Hildemann et al. (1991) utilized organic compounds to identify meat cooking as a potential contributor to suspended particles. They have not yet achieved quantitative source apportionments, however. Specific organic compounds for meat cooking and secondary organic emissions were not measured on SCAQS samples, and their source contributions cannot be quantitatively calculated. Owing to the highly urbanized areas surrounding the sampling sites, windblown dust from natural surfaces is not considered to be a large contributor to PM_{10} except at the Rubidoux site (Chow et al., 1992a).

A "source type" does not necessarily correspond to a particular emitter. For the primary contributors, several source subtypes may exist within some of these categories which are not easily distinguishable from each other by receptor models using commonly measured chemical species. The source type perceived at a receptor may be a mixture of these different subtypes, and the profile which best explains the receptor measurement should represent this mixture. Several subtype profiles are examined for each source type to determine whether or not they possess enough differences to allow them to be distinguished as separate source types by the CMB receptor model.

Table 1 lists the source types, a short identifier for each specific profile, and a brief description of 27 source profiles which were selected for SCAQS receptor modeling. The short identifiers are used to refer to these particles in the subsequent discussion.

Geological Material

Table 2a lists the geological source profiles from paved roads (Cooper et al., 1987) in the SoCAB. Cooper et al. (1987) also sampled unpaved roads, soil from vacant lots, and a rock crusher. Though Cooper

TABLE 1. Source Profiles Applied in SCAQS $PM_{2.5}$ and PM_{10} Receptor Modeling

Source data base type	Identifier	Description of source profile
Primary geological	PRLBSC[a]	Long Beach paved road sample composite
Primary geological	PRLBPC[a]	Long Beach paved road profile composite
Primary geological	PRDBSC[a]	Burbank paved road sample composite
Primary geological	PRDBPC[a]	Burbank paved road profile composite
Primary geological	PRDNMS[a]	North Main Street paved road dust
Primary geological	PRLAPC[a]	Los Angeles paved road profile composite
Primary geological	PRDRSC[a]	Riverside paved road sample composite
Primary geological	PRSTC[a]	Sepulveda Tunnel paved road dust
Primary geological	PRSCAB[a]	SoCAB paved road profile composite
Primary motor vehicle	MOVES1[a]	SoCAB dynamometer composite
Primary motor vehicle	MOVES2[a]	SoCAB dynamometer composite
Primary motor vehicle	PHRD[b]	Phoenix motor vehicle exhaust: roadside sample average after background
Primary motor vehicle	PHAUTO[b]	Phoenix motor vehicle exhaust: 100% gasoline
Primary motor vehicle	PHDIES[b]	Phoenix motor vehicle exhaust: 100% diesel
Marine aerosol	MAR100[c]	Fresh marine aerosol
Marine aerosol	MAR75[c]	Aged marine aerosol: 25% chloride replaced with nitrate
Marine aerosol	MAR50[c]	Aged marine aerosol: 50% chloride replaced with nitrate
Marine aerosol	MAR25[c]	Aged marine aerosol: 75% chloride replaced with nitrate
Marine aerosol	MAR0[c]	Aged marine aerosol: 100% chloride replaced with nitrate
Secondary solution nitrate	NANO3	Secondary sodium nitrate: $NaNO_3$
Secondary ammonium sulfate	AMSUL	Secondary ammonium sulfate: $(NH_4)_2SO_4$
Secondary ammonium bisulfate	AMBSUL	Secondary ammonium bisulfate: NH_4HSO_4
Secondary ammonium nitrate	AMNIT	Secondary ammonium nitrate: NH_4NO_3
Secondary organic carbon	OC	Secondary organic carbon: 100% organic carbon
Construction	LIME[d]	EPA profile no. 21101 limestone dust
Primary oil combustion	SFCRUC[e]	Santa Fe crude oil boiler
Vegetative burning	VIAGBC[e]	Visalia agricultural burning

[a]Cooper et al. (1987); a composite sample mixes dust aliquots from several different roadways together prior to resuspension and analysis. A profile composite consists of the average and standard deviation from several composite samples.
[b]Chow et al. (1991).
[c]Pytkowicz and Kester (1971).
[d]U.S. EPA (1988).
[e]Houck et al. (1989).

et al. (1987) measured several other geological profiles, OC and EC were measured only on the subset of paved road samples listed in Table 2a. It is evident from these profiles that carbon is a major component of road dust and cannot be ignored. Fortunately, most of the paved road dust profiles with carbon values were derived from samples taken in the vicinity of several of the SCAQS sampling sites.

The profiles were formed by vacuuming road dust from streets in the vicinity of each sampling site, sieving the dried material, resuspending it into a chamber, and sampling the suspended dust through $PM_{2.5}$ and PM_{10} inlets. Cooper et al. (1987) found that typically $< 10\%$ of the paved road PM_{10} was in the $PM_{2.5}$ fraction, and the PM_{10} and coarse particle (PM_{10} minus $PM_{2.5}$) source profiles were

TABLE 2a. Geological Source Profiles (Weight Percent of Mass)[a]

	PRLBSC		PRLBPC		PRDBSC		PRDBPC	
Species[b]	$PM_{2.5}$ (Conc. ± Unc.)[d]	Coarse[c] (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)
Cl^-	0.406 ± 0.020	0.460 ± 0.023	0.337 ± 0.069	0.359 ± 0.101	0.348 ± 0.017	0.355 ± 0.018	0.358 ± 0.020	0.372 ± 0.017
NO_3^-	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400
$SO_4^=$	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400
NH_4^+	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200
Na^+	0.808 ± 0.121	0.858 ± 0.129	0.919 ± 0.111	0.912 ± 0.097	0.760 ± 0.114	0.845 ± 0.127	0.753 ± 0.086	0.831 ± 0.088
TC	21.8 ± 3.2	20.1 ± 1.5	21.8 ± 3.4	20.1 ± 1.5	11.6 ± 1.7	17.8 ± 2.2	11.6 ± 1.8	17.8 ± 2.2
OC	19.6 ± 3.1	19.0 ± 1.5	19.6 ± 3.4	19.0 ± 1.5	10.6 ± 1.7	16.0 ± 2.16	10.6 ± 1.8	16.0 ± 2.2
EC	2.21 ± 0.41	1.19 ± 0.10	2.21 ± 0.43	1.19 ± 0.10	0.999 ± 0.207	1.78 ± 0.22	0.999 ± 0.216	1.78 ± 0.22
Na	0.808 ± 0.121	0.858 ± 0.129	0.919 ± 0.111	0.912 ± 0.097	0.760 ± 0.114	0.845 ± 0.127	0.753 ± 0.086	0.831 ± 0.088
Al	5.19 ± 0.78	5.18 ± 0.78	5.40 ± 0.61	5.43 ± 0.58	4.51 ± 0.68	5.03 ± 0.76	4.29 ± 0.49	4.97 ± 0.53
Si	13.5 ± 2.0	14.3 ± 2.1	15.3 ± 1.9	15.2 ± 1.62	12.7 ± 1.9	14.1 ± 2.1	12.6 ± 1.4	13.8 ± 1.5
P	0.254 ± 0.051	0.227 ± 0.046	0.252 ± 0.037	0.219 ± 0.031	0.223 ± 0.045	0.213 ± 0.043	0.274 ± 0.051	0.248 ± 0.035
S	1.00 ± 0.05	0.903 ± 0.045	0.789 ± 0.213	0.717 ± 0.186	0.872 ± 0.044	0.703 ± 0.035	0.868 ± 0.049	0.702 ± 0.025
Cl	0.406 ± 0.020	0.460 ± 0.023	0.337 ± 0.069	0.359 ± 0.101	0.348 ± 0.017	0.355 ± 0.018	0.358 ± 0.020	0.372 ± 0.017
K	1.22 ± 0.06	1.55 ± 0.08	1.24 ± 0.07	1.59 ± 0.06	0.918 ± 0.046	1.35 ± 0.07	0.877 ± 0.049	1.34 ± 0.05
Ca	4.19 ± 0.21	3.93 ± 0.20	4.01 ± 0.21	3.84 ± 0.14	5.54 ± 0.28	5.73 ± 0.29	4.74 ± 0.80	5.36 ± 0.37
Ti	0.328 ± 0.017	0.404 ± 0.022	0.337 ± 0.018	0.410 ± 0.016	0.334 ± 0.018	0.432 ± 0.023	0.332 ± 0.019	0.436 ± 0.017
V	0.0267 ± 0.0042	0.0164 ± 0.0052	0.0274 ± 0.0032	0.0184 ± 0.0038	0.0207 ± 0.0041	0.0198 ± 0.0055	0.0215 ± 0.0031	0.0197 ± 0.0038
Cr	0.0222 ± 0.0020	0.0273 ± 0.0016	0.0229 ± 0.0017	0.0286 ± 0.0012	0.0195 ± 0.0019	0.0267 ± 0.0016	0.0213 ± 0.0017	0.0889 ± 0.0021
Mn	0.0830 ± 0.0048	0.0922 ± 0.0047	0.0871 ± 0.0049	0.0980 ± 0.0057	0.0759 ± 0.0045	0.0953 ± 0.0049	0.0714 ± 0.0045	0.0934 ± 0.0034
Fe	3.69 ± 0.19	4.31 ± 0.22	3.83 ± 0.20	4.55 ± 0.23	3.32 ± 0.17	4.28 ± 0.22	3.43 ± 0.19	4.45 ± 0.17
Ni	0.0119 ± 0.0016	0.0132 ± 0.0008	0.0130 ± 0.0013	0.0136 ± 0.0006	0.0087 ± 0.0015	0.0128 ± 0.0008	0.0096 ± 0.0011	0.0128 ± 0.0005
Cu	0.0248 ± 0.0021	0.0259 ± 0.0014	0.0248 ± 0.0018	0.0253 ± 0.0010	0.0251 ± 0.0021	0.0262 ± 0.0015	0.0328 ± 0.0077	0.0331 ± 0.0068
Zn	0.223 ± 0.012	0.226 ± 0.011	0.264 ± 0.041	0.249 ± 0.024	0.217 ± 0.012	0.215 ± 0.011	0.242 ± 0.025	0.245 ± 0.030
As	0.0081 ± 0.0094	0.000 ± 0.009	0.0063 ± 0.0098	0.000 ± 0.009	0.0047 ± 0.0107	0.000 ± 0.013	0.0066 ± 0.0097	0.000 ± 0.011
Se	0.000 ± 0.001	0.000 ± 0.001	0.000 ± 0.001	0.000 ± 0.001	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000
Br	0.0066 ± 0.0016	0.0085 ± 0.0006	0.0058 ± 0.0011	0.0089 ± 0.0004	0.0044 ± 0.0015	0.0087 ± 0.0006	0.0063 ± 0.0019	0.0102 ± 0.0016
Sr	0.0379 ± 0.0031	0.0834 ± 0.0042	0.0328 ± 0.0051	0.0681 ± 0.0153	0.0278 ± 0.0027	0.0506 ± 0.0026	0.0234 ± 0.0044	0.0521 ± 0.0019
Mo	0.000 ± 0.008	0.000 ± 0.002	0.000 ± 0.006	0.000 ± 0.001	0.000 ± 0.007	0.000 ± 0.002	0.000 ± 0.005	0.0017 ± 0.0017
Cd	0.000 ± 0.014	0.0080 ± 0.0027	0.000 ± 0.010	0.0040 ± 0.0040	0.000 ± 0.013	0.0108 ± 0.003	0.000 ± 0.009	0.0054 ± 0.0054
Sn	0.000 ± 0.021	0.0080 ± 0.0040	0.000 ± 0.014	0.0074 ± 0.0031	0.000 ± 0.019	0.0125 ± 0.0045	0.000 ± 0.013	0.0063 ± 0.0063
Sb	0.000 ± 0.046	0.000 ± 0.009	0.000 ± 0.031	0.000 ± 0.007	0.000 ± 0.043	0.000 ± 0.010	0.000 ± 0.028	0.000 ± 0.006
Ba	0.000 ± 0.086	0.104 ± 0.018	0.000 ± 0.059	0.0881 ± 0.0158	0.000 ± 0.080	0.0665 ± 0.0186	0.000 ± 0.053	0.0739 ± 0.0121
Hg	0.000 ± 0.002	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.0002 ± 0.0009	0.000 ± 0.000
Pb	0.156 ± 0.010	0.152 ± 0.008	0.229 ± 0.073	0.218 ± 0.066	0.181 ± 0.011	0.225 ± 0.012	0.231 ± 0.050	0.280 ± 0.054
Sum	52.3 ± 3.9	52.4 ± 2.8	54.5 ± 4.0	53.8 ± 2.4	41.2 ± 2.7	51.2 ± 3.2	40.2 ± 2.6	50.8 ± 2.8

TABLE 2a. *(continued)*

Species[b]	PRDNMS		PRLAPC		PRDRSC		PRSCAB	
	$PM_{2.5}$ (Conc. ± Unc.)	Coarse[c] (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)	$PM_{2.5}$ (Conc. ± Unc.)	Coarse (Conc. ± Unc.)
Cl^-	0.352 ± 0.018	0.428 ± 0.021	0.311 ± 0.041	0.364 ± 0.064	0.241 ± 0.012	0.232 ± 0.012	0.298 ± 0.058	0.305 ± 0.059
NO_3^-	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400	0.100 ± 0.400
$SO_4^=$	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400	0.200 ± 0.400
NH_4^+	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200	0.0010 ± 0.0200
Na^+	0.566 ± 0.085	0.659 ± 0.099	0.595 ± 0.070	0.686 ± 0.073	1.12 ± 0.017	0.988 ± 0.148	0.927 ± 0.078	0.966 ± 0.071
TC	20.1 ± 5.5	23.2 ± 1.6	20.1 ± 5.6	23.2 ± 1.6	7.90 ± 1.54	12.0 ± 0.9	15.8 ± 2.0	16.9 ± 1.5
OC	19.3 ± 5.5	21.5 ± 1.63	19.3 ± 5.6	21.5 ± 1.6	7.48 ± 1.53	11.8 ± 0.9	14.7 ± 2.0	15.9 ± 1.5
EC	0.858 ± 0.429	1.72 ± 0.14	0.858 ± 0.432	1.72 ± 0.14	0.419 ± 0.174	0.174 ± 0.051	1.12 ± 0.30	0.973 ± 0.281
Na	0.566 ± 0.085	0.659 ± 0.099	0.595 ± 0.070	0.686 ± 0.073	1.12 ± 0.17	0.988 ± 0.148	0.927 ± 0.078	0.966 ± 0.071
Al	2.89 ± 0.43	3.73 ± 0.56	3.675 ± 0.782	4.30 ± 0.56	8.32 ± 1.25	7.12 ± 1.07	5.70 ± 0.56	5.91 ± 0.44
Si	9.44 ± 1.42	11.0 ± 1.6	9.92 ± 1.17	11.4 ± 1.2	18.6 ± 2.8	16.5 ± 2.5	15.4 ± 1.3	16.1 ± 1.2
P	0.524 ± 0.105	0.496 ± 0.099	0.373 ± 0.150	0.360 ± 0.136	0.228 ± 0.046	0.187 ± 0.037	0.212 ± 0.041	0.184 ± 0.038
S	0.852 ± 0.043	0.782 ± 0.039	0.898 ± 0.056	0.810 ± 0.029	0.739 ± 0.037	0.555 ± 0.028	0.935 ± 0.175	0.706 ± 0.108
Cl	0.352 ± 0.018	0.428 ± 0.021	0.311 ± 0.041	0.364 ± 0.064	0.241 ± 0.012	0.232 ± 0.012	0.298 ± 0.058	0.305 ± 0.059
K	0.663 ± 0.033	1.12 ± 0.06	0.652 ± 0.040	1.08 ± 0.04	1.67 ± 0.08	1.91 ± 0.10	1.03 ± 0.11	1.47 ± 0.09
Ca	3.61 ± 0.18	4.41 ± 0.22	3.24 ± 0.37	4.06 ± 0.35	3.79 ± 0.19	3.59 ± 0.18	3.62 ± 0.26	3.97 ± 0.33
Ti	0.258 ± 0.014	0.354 ± 0.020	0.305 ± 0.047	0.457 ± 0.103	0.458 ± 0.024	0.496 ± 0.026	0.375 ± 0.033	0.473 ± 0.029
V	0.0249 ± 0.0035	0.0190 ± 0.0048	0.0279 ± 0.0033	0.0262 ± 0.0072	0.0283 ± 0.0052	0.0223 ± 0.0059	0.0249 ± 0.0014	0.0174 ± 0.0025
Cr	0.0308 ± 0.0023	0.0393 ± 0.0021	0.0484 ± 0.0176	0.0711 ± 0.0318	0.0245 ± 0.0019	0.0273 ± 0.0016	0.0250 ± 0.0036	0.0330 ± 0.0059
Mn	0.0779 ± 0.0045	0.0888 ± 0.0045	0.0776 ± 0.0051	0.0844 ± 0.0044	0.117 ± 0.006	0.119 ± 0.006	0.0807 ± 0.0056	0.101 ± 0.004
Fe	7.12 ± 0.36	6.13 ± 0.31	5.21 ± 1.91	5.38 ± 0.76	4.79 ± 0.24	5.12 ± 0.26	3.92 ± 0.27	4.93 ± 0.23
Ni	0.0107 ± 0.0015	0.0125 ± 0.0008	0.0292 ± 0.0185	0.0413 ± 0.0288	0.0083 ± 0.0012	0.0084 ± 0.0006	0.0143 ± 0.0024	0.0161 ± 0.0038
Cu	0.0496 ± 0.0032	0.0593 ± 0.0031	0.0526 ± 0.0036	0.0600 ± 0.0022	0.0097 ± 0.0006	0.0097 ± 0.0006	0.0359 ± 0.0074	0.0367 ± 0.0099
Zn	0.398 ± 0.021	0.437 ± 0.022	0.428 ± 0.030	0.431 ± 0.015	0.0870 ± 0.0048	0.0859 ± 0.0044	0.251 ± 0.044	0.246 ± 0.043
As	0.0060 ± 0.0084	0.000 ± 0.010	0.0098 ± 0.0092	0.000 ± 0.010	0.0116 ± 0.0065	0.000 ± 0.006	0.0060 ± 0.0059	0.0000 ± 0.0066
Se	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.000	0.0002 ± 0.0002
Br	0.0018 ± 0.0013	0.0060 ± 0.0005	0.0016 ± 0.0011	0.006 ± 0.000	0.0025 ± 0.0010	0.0067 ± 0.0005	0.0066 ± 0.0020	0.0098 ± 0.0023
Sr	0.0302 ± 0.0027	0.0836 ± 0.0043	0.0211 ± 0.0091	0.0748 ± 0.0088	0.0283 ± 0.0022	0.0441 ± 0.0023	0.0633 ± 0.0251	0.121 ± 0.047
Mo	0.000 ± 0.007	0.0036 ± 0.0018	0.000 ± 0.005	0.0098 ± 0.0062	0.000 ± 0.005	0.000 ± 0.002	0.000 ± 0.0017	0.0016 ± 0.0012
Cd	0.000 ± 0.012	0.000 ± 0.003	0.000 ± 0.009	0.000 ± 0.002	0.000 ± 0.009	0.000 ± 0.003	0.0014 ± 0.0029	0.0035 ± 0.0012
Sn	0.000 ± 0.017	0.0123 ± 0.0043	0.000 ± 0.014	0.0095 ± 0.0031	0.000 ± 0.014	0.000 ± 0.004	0.0004 ± 0.0044	0.0041 ± 0.0014
Sb	0.000 ± 0.039	0.000 ± 0.009	0.000 ± 0.030	0.000 ± 0.007	0.000 ± 0.031	0.000 ± 0.009	0.000 ± 0.0096	0.0025 ± 0.0026
Ba	0.000 ± 0.073	0.0906 ± 0.0178	0.000 ± 0.056	0.0701 ± 0.0205	0.000 ± 0.058	0.0546 ± 0.0171	0.0146 ± 0.0182	0.0918 ± 0.0131
Hg	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.000 ± 0.001	0.000 ± 0.000	0.0003 ± 0.0003	0.0004 ± 0.0002
Pb	0.137 ± 0.009	0.175 ± 0.009	0.209 ± 0.073	0.241 ± 0.066	0.101 ± 0.007	0.114 ± 0.006	0.275 ± 0.083	0.306 ± 0.093
Sum	46.6 ± 5.7	52.9 ± 2.5	45.6 ± 6.1	52.8 ± 2.4	47.8 ± 3.5	48.9 ± 2.9	48.5 ± 2.6	52.5 ± 2.1

[a]See Table 1 for source profile descriptions.
[b]TC = OC + EC; sum does not include Na^+, Cl^-, S, or TC.
[c]PM_{10} minus $PM_{2.5}$.
[d]Conc. is the average abundance (percent of total mass) for several samples of emissions from the same source type. Unc. is the standard deviation of the abundances for these samples.

nearly identical. Both $PM_{2.5}$ and coarse particle source profiles are listed in Table 2a, and though there are some minor differences between these two size fractions, these differences do not result in large differences in CMB source contribution estimates. Each profile results from the average of several samples (typically three) taken around each measurement location. The PRSCAB profile consists of the average and standard deviation from several samples taken throughout the SoCAB.

Approximately 50% of the mass is unaccounted for in these profiles. Presumably, this is due to oxides and water content which are not measured directly by the methods applied to the source or receptor samples. Organic carbon is the most abundant species in each of the SoCAB paved road dust profiles, ranging from 11% to 22% of total mass in these samples. OC usually exceeds EC in these profiles by factors of 15–20. When the typical contributors to paved road dust are considered, this finding is not surprising. Dust on a paved road surface builds up by being tracked out from unpaved areas such as construction sites, unpaved roads, parking lots, and shoulders; by spills from trucks carrying dirt and other particulate materials; by transport of dirt collected on vehicle undercarriages; by wear of vehicle components such as tires, brakes, clutches, and exhaust system components; by wear of the pavement surface; by deposition of suspended particles from many emission sources; and by water and wind erosion from adjacent areas. EC, Al, Si, K, Ca, Ti, and Fe are also present in paved road dust in abundances which exceed 1%.

The abundance of total potassium (K) in geological materials has been found to be approximately 10 times that of soluble potassium (K^+) (Houck et al., 1989). This is an important difference, since soluble potassium is one of the key markers for vegetative burning. Because soluble potassium is not very abundant in geological material, vegetative burning can be distinguished from other sources when soluble potassium is measured in receptor samples. Since soluble potassium was not measured in SCAQS aerosol samples, this identifier cannot be used for vegetative burning, however.

The abundances of Pb and Br in paved road dust are also higher than might be expected in pristine soil, which demonstrates the presence of tailpipe exhaust from vehicles burning leaded fuels. Enrichments in species from clutch and brake wear were absent in these paved road dust profiles. These are often composed of asbestos and/or semimetal carbon composites. Ondov (1974) measured abundances of ~14%, ~2% Ca, ~4% Fe, and ~1% Ba in asbestos brake shoes; Anderson et al. (1973) reported Si abundances of ~10%. Cooper et al. (1987) examined the elemental composition of semimetal brake shoes and found abundances of ~45% Fe, ~2% Cu, ~0.5% Mo, ~0.5% Sn, and ~3% Ba. None of these species is found in the SoCAB paved road dust profiles at levels which exceed abundances in the other geological sources.

When the percent composition for a species is several times larger than its uncertainty, that species is a good marker for that source type. When few other source profiles contain this species, it is very probable that the source types which these profiles represent can be distinguished from each other by CMB modeling. The high concentrations, low uncertainties, and uniqueness with respect to other source types of Al, Si, Ca, Ti, and Fe make it likely that these geological profiles can be easily distinguished from other source types. Paved road dust profiles are too similar to agricultural soil and windblown dust profiles to be distinguished from them. However, the site descriptions given by Chan and Durkee (1989) and Chow et al. (1994a) show that

paved roads in close proximity to all of the sampling sites, except San Nicolas Island and Rubidoux, are the major emitters of geological material.

Motor Vehicle Exhaust

Mobile source particulate emissions are among the most difficult to measure with respect to emission rate and chemical composition. This difficulty arises from (1) different mobile source types (e.g., passenger cars, light duty trucks, diesel trucks, diesel buses), (2) inadequate characterization of the high emitters from the existing motor vehicle fleet, (3) a large number of individual emitters within each type, (4) fuel-use characteristics and emission control technology which have radically changed over the past decade, (5) undefined (and probably undefinable) operating conditions, (6) several emission points on each vehicle (i.e., tailpipe, fuel evaporation, tire wear, brake wear, resuspended dust, and (7) a mixture of primary particles, semivolatile compounds, and secondary particle precursors. Because fuels are constantly changing with time (e.g., lead was being phased out of gasoline at the time of SCAQS, and now is completely absent from gasoline sold in California), it is necessary for motor vehicle profiles to be acquired within a year or two of the study period from vehicles using similar fuels.

Table 2b includes the profiles from the SoCAB (MOVES1 and MOVES2) and from Phoenix, AZ (PHRD, PHAUTO, and PHDIES). Past studies have shown >90% of vehicle exhaust was in the $PM_{2.5}$ size fraction (e.g., Cooper et al., 1987; Houck et al., 1989). Thus, the $PM_{2.5}$ profiles are used to represent contributions in both $PM_{2.5}$ and coarse particle fractions. It is speculated that most of the motor vehicle contributions to the coarse particle fraction are really $PM_{2.5}$ particles which are removed in the $PM_{2.5}$ inlet of the ambient sampler.

The MOVES1 and MOVES2 profiles are weighted averages of separate profiles from light and heavy duty vehicles fueled with unleaded, leaded, and diesel fuels. Tire wear is included in MOVES1 but not in MOVES2. Each profile is weighted by the normalized product of the total particle emission rate measured in the dynamometer tests and the relative number of vehicle types counted for samples taken in a Los Angeles area tunnel (Cooper et al., 1987). MOVES1 and MOVES2 are similar to each other, with approximately equal abundances of OC and EC. The presence of tire dust in MOVES1 raises the organic content slightly, but it does not change the profile very much. Significant amounts of $SO_4^=$, Br, Cl^-, and Pb are detectable in the profile, though Pb levels are much lower than those reported in earlier tests (Watson, 1979; Pierson and Brachaczek, 1976, 1983).

The PHAUTO, PHDIES, and PHRD profiles (Watson et al., 1994b) were acquired at (1) a centralized dynamometer inspection and maintenance station for passenger cars, (2) a centralized dynamometer inspection and maintenance station for heavy-duty diesel trucks and buses, and (3) along urban roadsides, respectively.

Chow et al. (1991, 1992b) used the PHRD and several profiles from other studies, including those from the SoCAB, in CMB modeling of Phoenix and Tucson PM_{10}. None of the SoCAB profiles reproduced the measured ambient concentrations in Phoenix as well as the roadside motor vehicle profile.

Countess (1991) used the mixture of PHAUTO and PHDIES profiles and SoCAB profiles to apportion PM_{10} in Santa Barbara County during 1989. He found that the Phoenix dynamometer profiles explained the ambient data better than the MOVES1 and MOVES2 profiles.

TABLE 2b. Motor Vehicle Source Profiles[a]

Species[b]	MOVES1: $PM_{2.5}$ and coarse[c] (Conc. ± Unc.)[d]	MOVES2: $PM_{2.5}$ and coarse (Conc. ± Unc.)	PHRD: $PM_{2.5}$ and coarse (Conc. ± Unc.)	PHAUTO: $PM_{2.5}$ and coarse (Conc. ± Unc.)	PHDIES: $PM_{2.5}$ and coarse (Conc. ± Unc.)
Cl^-	0.535 ± 0.473	0.029 ± 0.020	1.16 ± 0.75	0.640 ± 0.655	1.62 ± 0.40
NO_3^-	0.000 ± 0.100	0.000 ± 0.100	11.0 ± 10.4	3.89 ± 2.87	0.310 ± 0.400
$SO_4^=$	4.09 ± 2.78	3.11 ± 3.55	6.01 ± 2.09	2.29 ± 1.32	2.44 ± 1.00
NH_4^+	0.000 ± 0.100	0.000 ± 0.100	4.11 ± 2.74	1.67 ± 1.02	0.866 ± 0.126
Na^+	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100
TC	98.1 ± 27.2	104 ± 31	75.5 ± 21.6	43.6 ± 14.7	73.0 ± 10.3
OC	52.8 ± 21.6	49.8 ± 24.2	39.0 ± 18.6	30.1 ± 12.3	40.1 ± 6.6
EC	45.4 ± 16.5	54.2 ± 19.8	36.5 ± 11.0	13.5 ± 8.02	32.9 ± 8.0
Na	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100
Al	0.0760 ± 0.0390	0.0770 ± 0.0510	0.0723 ± 0.5250	0.412 ± 0.205	0.174 ± 0.121
Si	0.645 ± 0.924	0.957 ± 1.391	0.0828 ± 1.1319	1.64 ± 0.88	0.463 ± 0.184
P	0.124 ± 0.103	0.0570 ± 0.0200	0.0837 ± 0.1327	0.115 ± 0.065	0.061 ± 0.058
S	1.36 ± 0.93	1.04 ± 1.18	2.02 ± 0.60	1.01 ± 0.48	1.24 ± 0.28
Cl	0.535 ± 0.473	0.0290 ± 0.0200	0.562 ± 0.409	0.338 ± 0.322	0.0282 ± 0.0613
K	0.0050 ± 0.0060	0.0080 ± 0.0080	0.215 ± 0.229	0.249 ± 0.141	0.0421 ± 0.0332
Ca	0.0560 ± 0.0530	0.0720 ± 0.0790	0.125 ± 0.981	0.707 ± 0.407	0.159 ± 0.063
Ti	0.0060 ± 0.0040	0.0010 ± 0.0030	0.0872 ± 0.4008	0.0654 ± 0.1256	0.0015 ± 0.1530
V	0.0010 ± 0.0010	0.0010 ± 0.0020	0.0233 ± 0.2011	0.0047 ± 0.0538	0.0008 ± 0.0621
Cr	0.000 ± 0.001	0.000 ± 0.002	0.0187 ± 0.0402	0.0151 ± 0.0104	0.0039 ± 0.0147
Mn	0.0180 ± 0.0160	0.0280 ± 0.0240	0.178 ± 0.114	0.105 ± 0.036	0.0082 ± 0.0113
Fe	0.0010 ± 0.0030	0.0010 ± 0.0050	0.934 ± 0.529	0.685 ± 0.423	0.159 ± 0.065
Ni	0.000 ± 0.001	0.000 ± 0.002	0.0189 ± 0.0149	0.0094 ± 0.0093	0.0026 ± 0.0054
Cu	0.0030 ± 0.0020	0.0050 ± 0.0030	0.356 ± 0.135	0.0739 ± 0.0642	0.0132 ± 0.0082
Zn	0.385 ± 0.221	0.0530 ± 0.0280	0.505 ± 0.387	0.273 ± 0.225	0.0699 ± 0.0190
As	0.0030 ± 0.0080	0.0040 ± 0.0120	0.0057 ± 0.0942	0.0021 ± 0.0351	0.0009 ± 0.0208
Se	0.000 ± 0.001	0.000 ± 0.002	0.0042 ± 0.0335	0.0010 ± 0.0090	0.0009 ± 0.0103
Br	0.174 ± 0.106	0.264 ± 0.152	0.0580 ± 0.0339	0.0294 ± 0.0163	0.0023 ± 0.0089
Sr	0.0030 ± 0.0040	0.000 ± 0.003	0.0042 ± 0.0476	0.0070 ± 0.0106	0.0018 ± 0.0132
Mo	0.000 ± 0.008	0.000 ± 0.012	0.0101 ± 0.1058	0.0058 ± 0.0285	0.0019 ± 0.0328
Cd	0.000 ± 0.013	0.000 ± 0.020	0.0270 ± 0.2522	0.0106 ± 0.0680	0.0098 ± 0.0785
Sn	0.000 ± 0.020	0.000 ± 0.031	0.0589 ± 0.4008	0.0149 ± 0.1072	0.0118 ± 0.1238
Sb	0.000 ± 0.045	0.000 ± 0.069	0.101 ± 0.469	0.0189 ± 0.1255	0.0108 ± 0.1444
Ba	0.0010 ± 0.0850	0.000 ± 0.129	0.200 ± 1.502	0.0580 ± 0.4029	0.140 ± 0.467
Hg	0.000 ± 0.001	0.000 ± 0.002	0.0035 ± 0.0798	0.0018 ± 0.0216	0.0019 ± 0.0248
Pb	0.245 ± 0.149	0.373 ± 0.207	0.270 ± 0.126	0.155 ± 0.072	0.0147 ± 0.0294
Sum	105 ± 27	109 ± 32	101 ± 24	56.4 ± 15.1	78.0 ± 10.4

[a]See Table 1 for source profile descriptions.
[b]TC = OC + EC; sum does not include Na^+, Cl^-, S, or TC.
[c]PM_{10} minus $PM_{2.5}$.
[d]Conc. is the average abundance (percent of total mass) for several samples of emissions from the same source type. Unc. is the standard deviation of the abundances for these samples.

Countess (1991) observed that most of the fuel in Phoenix arrives by pipeline from Santa Barbara County's Gaviota Terminal, and that vehicle types, driving patterns, and vehicle inspection and maintenance are similar in Arizona and southern California. Countess (1991) therefore concluded that the Phoenix dynamometer profiles were reasonable representatives for southern California emissions. Lowenthal et al. (1992) confirmed this in CMB sensitivity and collinearity tests on the Santa Barbara PM_{10} samples.

The PHRD profile contains abundances similar to a combination of the PHAUTO and PHDIES profiles. This is expected since there was a mixture of passenger cars and diesel vehicles con-

tributing to the roadside samples. The most abundant species are OC ($39 \pm 10\%$), EC ($36 \pm 11\%$), NO_3^- ($11 \pm 10\%$), $SO_4^=$ ($6 \pm 2\%$), and NH_4^+ ($4 \pm 3\%$). The NO_3^-, $SO_4^=$, and NH_4^+ abundances in the "PHRD" profile are more than twice those of the dynamometer profiles. This is probably due to the longer residence time of the motor vehicle exhaust in the air being sampled at the roadside relative to that sampled from a dynamometer. The abundances of Pb ($0.27 \pm 0.13\%$) and Br ($0.06 \pm 0.3\%$) in the PHRD profile are nearly twice the corresponding abundances in the PHAUTO profile, but similar to those of the MOVES1 and MOVES2 profiles. This implies that the proportion of emissions from leaded gasoline-fueled vehicles was larger during the roadside tests than during the dynamometer facility tests.

Marine Aerosol

Marine aerosol reacts rapidly with nitric acid (Pilinis and Seinfeld, 1987), and unaltered sea salt is rarely a contributor to suspended particles in the SoCAB. Several different marine profiles have been constructed in Table 2c to represent different levels of reaction between marine aerosol and nitric acid. The bulk seawater composition of Pytkowicz and Kester (1971) represents a pure marine aerosol (MAR100). Additional profiles are created from MAR100 by reacting different proportions of the profile mass with nitric acid, assuming negligible chloride depletion over time. This liberates the Cl^- and replaces it with NO_3^-. MAR75 represents the profile when 25% of the sea salt has reacted, MAR50 is the profile with 50% reacted, MAR25 is the profile with 75% reacted, and MAR0 is the profile with 100% of the original marine aerosol reacted with nitric acid. The abundances of nonreacting species are larger in MAR100 than they are in MAR0 owing to the increase in total mass of the aerosol when NO_3^- (molecular weight = 62 g/mol) replaces Cl^- (molecular weight = 37.5 g/mol). A pure sodium nitrate profile is also included for sensitivity testing.

Secondary Sulfate, Nitrate, and Organic Aerosol

Since species such as $SO_4^=$, NO_3^-, and OC can be formed through gas-to-particle transformation in the atmosphere, they cannot be entirely accounted for by primary emissions. Secondary source profiles which consist of "pure" ammonium bisulfate (AMBSUL), ammonium sulfate (AMSUL), ammonium nitrate (AMNIT), and organic carbon (OC) are used to apportion remaining NH_4^+, $SO_4^=$, NO_3^-, and OC which is not apportioned to the primary particle profiles. These secondary source profiles are included in Table 2d. The OC profile does not necessarily represent secondary OC—it accounts for that OC which is not contributed by other source types in the CMB calculations. This might also consist of contributions from cooking, plant parts, or tire wear.

Other Source Profiles

In addition to the source profiles described above, several other profiles are included for sensitivity testing, even though they are not expected to be significant contributors to suspended particles in the SoCAB. Table 2e contains one profile from an agricultural burn (VIAGBC) in Visalia, CA to represent vegetative burning, and another profile from a crude oil boiler (SFCRUC) in Kern County, CA to represent residual oil combustion (Houck et al., 1989). Also included in Table 2e is a lime/gypsum (LIME) profile (U.S. EPA, 1988) which is sometimes used as a surrogate for cement work (i.e., construction projects) when ambient Ca con-

TABLE 2c. Marine Aerosol Source Profiles (Weight Percent of Mass)[a]

Species[b]	MAR0: $PM_{2.5}$ and coarse[c] (Conc. ± Unc.)[d]	MAR25: $PM_{2.5}$ and coarse (Conc. ± Unc.)	MAR50: $PM_{2.5}$ and coarse (Conc. ± Unc.)	MAR75: $PM_{2.5}$ and coarse (Conc. ± Unc.)	MAR100: $PM_{2.5}$ and coarse (Conc. ± Unc.)	NANO3: $PM_{2.5}$ and coarse (Conc. ± Unc.)
Cl^-	0.000 ± 0.030	10.8 ± 1.3	23.5 ± 2.7	38.7 ± 4.4	57.4 ± 6.9	0.000 ± 0.000
NO_3^-	70.5 ± 8.8	57.2 ± 6.8	41.6 ± 4.7	22.9 ± 2.6	0.0037 ± 0.0004	73.0 ± 7.3
$SO_4^=$	5.54 ± 0.69	6.00 ± 0.71	6.55 ± 0.75	7.20 ± 0.82	8.00 ± 0.96	0.000 ± 0.000
NH_4^+	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.000
Na^+	22.2 ± 2.8	24.0 ± 2.84	26.2 ± 3.0	28.8 ± 3.3	32.0 ± 3.8	27.1 ± 2.7
TC	0.000 ± 0.141	0.000 ± 0.141	0.000 ± 0.141	0.000 ± 0.141	0.000 ± 0.141	0.000 ± 0.000
OC	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.000
EC	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.100	0.000 ± 0.000
Na	22.2 ± 2.8	24.0 ± 2.84	26.2 ± 3.0	28.8 ± 3.3	32.0 ± 3.8	27.1 ± 2.7
Al	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Si	0.0062 ± 0.0008	0.0067 ± 0.0008	0.0073 ± 0.0008	0.0080 ± 0.0009	0.0089 ± 0.0011	0.000 ± 0.000
P	0.0001 ± 0.0000	0.0001 ± 0.0000	0.0001 ± 0.0000	0.0001 ± 0.0000	0.0001 ± 0.0000	0.000 ± 0.000
S	1.85 ± 0.23	2.00 ± 0.24	2.18 ± 0.25	2.40 ± 0.27	2.67 ± 0.32	0.000 ± 0.000
Cl	0.000 ± 0.000	10.8 ± 1.3	23.5 ± 2.7	38.7 ± 4.4	57.4 ± 6.9	0.000 ± 0.000
K	0.821 ± 0.102	0.889 ± 0.105	0.970 ± 0.111	1.07 ± 0.12	1.18 ± 0.14	0.000 ± 0.000
Ca	0.846 ± 0.105	0.916 ± 0.108	0.999 ± 0.114	1.10 ± 0.12	1.22 ± 0.15	0.000 ± 0.000
Ti	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
V	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cr	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Mn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Fe	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ni	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cu	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Zn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
As	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Se	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Br	0.138 ± 0.017	0.149 ± 0.018	0.163 ± 0.019	0.179 ± 0.020	0.198 ± 0.024	0.000 ± 0.000
Sr	0.0162 ± 0.0020	0.0176 ± 0.0021	0.0192 ± 0.0022	0.0211 ± 0.0024	0.0234 ± 0.0028	0.000 ± 0.000
Mo	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cd	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sb	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ba	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.0001 ± 0.0000	0.0001 ± 0.0000	0.000 ± 0.000
Hg	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Pb	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sum	100 ± 9	100 ± 8	100 ± 6	100 ± 6	100 ± 8	100.0 ± 7.8

[a]See Table 1 for source profile descriptions.
[b]TC = OC + EC; sum does not include Na^+, Cl^-, S, or TC.
[c]PM_{10} minus $PM_{2.5}$.
[d]Conc. is the average abundance (percent of total mass) for several samples of emmisions from the same source type. Unc. is the standard deviation of the abundances for these samples.

TABLE 2d. Secondary Aerosol Source Profiles (Weight Percent of Mass)[a]

Species[b]	AMSUL: $PM_{2.5}$ and coarse[c] (Conc. ± Unc.)[d]	AMBSUL: $PM_{2.5}$ and coarse (Conc. ± Unc.)	AMNIT: $PM_{2.5}$ and coarse (Conc. ± Unc.)(Conc. ± Unc.)	OC: $PM_{2.5}$ and coarse
Cl^-	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
NO_3^-	0.000 ± 0.000	0.000 ± 0.000	77.5 ± 7.8	0.000 ± 0.000
$SO_4^=$	72.7 ± 7.3	83.5 ± 8.3	0.000 ± 0.000	0.000 ± 0.000
NH_4^+	27.3 ± 2.7	15.7 ± 1.6	22.6 ± 2.3	0.000 ± 0.000
Na^+	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
TC	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	100 ± 10
OC	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	100 ± 10
EC	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Na	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Al	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Si	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
P	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
S	24.3 ± 2.4	27.9 ± 2.8	0.000 ± 0.000	0.000 ± 0.000
Cl	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
K	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ca	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ti	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
V	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cr	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Mn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Fe	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ni	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cu	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Zn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
As	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Se	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Br	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sr	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Mo	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Cd	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sn	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sb	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Ba	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Hg	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Pb	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000
Sum	100 ± 8	99.1 ± 8.5	100 ± 8	100 ± 10

[a]See Table 1 for source profile descriptions.
[b]TC = OC + EC; sum does not include Na^+, Cl^-, S, or TC.
[c]PM_{10} minus $PM_{2.5}$.
[d]Conc. is the average abundance (percent of total mass) for several samples of emissions from the same source type. Unc. is the standard deviation of the abundances for these samples.

centrations cannot be explained by other geological or construction profiles.

MODEL APPLICATION AND VALIDATION

Watson et al. (1990, 1991) describe CMB modeling procedures and an application and validation protocol. The activities carried out to complete the protocol are described in this section.

CMB Model Applicability

The requirements for CMB model applicability are as follows: (1) a sufficient number of receptor samples are taken

TABLE 2e. Other Source Profiles (Weight Percent of Mass)[a]

Species[b]	LIME $PM_{2.5}$ (Conc. ± Unc.)[d]	LIME Coarse[c] (Conc. ± Unc.)	SFCRUC: $PM_{2.5}$ and coarse (Conc. ± Unc.)	VIAGBC: $PM_{2.5}$ and coarse (Conc. ± Unc.)
Cl^-	0.455 ± 0.048	0.410 ± 0.041	0.0240 ± 0.0021	15.4 ± 5.5
NO_3^-	0.000 ± 0.083	0.000 ± 0.083	0.000 ± 0.002	0.349 ± 0.071
$SO_4^=$	1.02 ± 0.104	0.663 ± 0.066	20.3 ± 4.2	1.74 ± 0.87
NH_4^+	0.000 ± 0.153	0.000 ± 0.153	0.0076 ± 0.0054	2.36 ± 1.04
Na^+	0.000 ± 0.044	0.000 ± 0.044	0.762 ± 0.399	1.11 ± 1.50
TC	0.000 ± 1.530	0.000 ± 1.530	0.0894 ± 0.1385	45.4 ± 8.7
OC	0.000 ± 1.443	0.000 ± 1.443	0.0894 ± 0.1184	34.5 ± 8.0
EC	0.000 ± 0.508	0.000 ± 0.508	0.000 ± 0.072	10.9 ± 3.3
Na	0.000 ± 0.044	0.000 ± 0.044	0.762 ± 0.399	1.11 ± 1.5
Al	2.11 ± 0.21	1.20 ± 0.12	0.000 ± 0.009	0.028 ± 0.082
Si	6.50 ± 0.65	3.39 ± 0.34	0.0112 ± 0.0164	0.000 ± 0.052
P	0.126 ± 0.040	0.100 ± 0.029	0.000 ± 0.172	0.000 ± 0.042
S	1.02 ± 0.10	0.663 ± 0.066	5.45 ± 0.39	0.644 ± 0.285
Cl	0.455 ± 0.048	0.410 ± 0.041	0.0240 ± 0.0019	15.4 ± 5.5
K	0.163 ± 0.042	0.135 ± 0.023	0.0444 ± 0.0054	10.0 ± 3.5
Ca	29.5 ± 3.0	29.7 ± 3.0	0.0616 ± 0.0045	0.0137 ± 0.1634
Ti	0.0810 ± 0.1000	0.0530 ± 0.1000	0.0120 ± 0.0019	0.0037 ± 0.0509
V	0.000 ± 0.037	0.000 ± 0.037	0.823 ± 0.058	0.0015 ± 0.0209
Cr	0.000 ± 0.010	0.000 ± 0.010	0.0069 ± 0.0245	0.0025 ± 0.0050
Mn	0.0500 ± 0.0070	0.0280 ± 0.0070	0.0056 ± 0.0010	0.0025 ± 0.0037
Fe	1.04 ± 0.10	0.536 ± 0.054	0.213 ± 0.022	0.0184 ± 0.0104
Ni	0.000 ± 0.004	0.000 ± 0.004	0.789 ± 0.093	0.0010 ± 0.0017
Cu	0.0160 ± 0.0100	0.000 ± 0.010	0.0009 ± 0.0034	0.0006 ± 0.0028
Zn	0.104 ± 0.006	0.0200 ± 0.0060	0.260 ± 0.034	0.0065 ± 0.0044
As	0.0200 ± 0.0130	0.000 ± 0.099	0.0006 ± 0.0007	0.000 ± 0.008
Se	0.000 ± 0.005	0.000 ± 0.005	0.0114 ± 0.0016	0.0009 ± 0.0033
Br	0.0270 ± 0.1000	0.000 ± 0.004	0.0003 ± 0.0002	0.0383 ± 0.0236
Sr	0.0240 ± 0.0050	0.0180 ± 0.0050	0.0015 ± 0.0003	0.0014 ± 0.0031
Mo	0.000 ± 0.011	0.000 ± 0.011	0.0168 ± 0.0023	0.0001 ± 0.0099
Cd	0.0420 ± 0.0450	0.000 ± 0.049	0.0006 ± 0.0020	0.0021 ± 0.0244
Sn	0.000 ± 0.052	0.000 ± 0.069	0.0007 ± 0.0030	0.0010 ± 0.0399
Sb	0.000 ± 0.095	0.000 ± 0.017	0.0006 ± 0.0034	0.0101 ± 0.0462
Ba	0.000 ± 0.256	0.000 ± 0.044	0.0013 ± 0.0111	0.0172 ± 0.1561
Hg	0.000 ± 0.011	0.000 ± 0.011	0.000 ± 0.001	0.0013 ± 0.0114
Pb	0.270 ± 0.027	0.0480 ± 0.1000	0.000 ± 0.001	0.0105 ± 0.0209
Sum	41.6 ± 3.4	36.3 ± 3.4	23.5 ± 4.3	76.5 ± 11.0

[a]See Table 1 for source profile descriptions.
[b]TC = OC + EC; sum does not include Na^+, Cl^-, S, or TC.
[c]PM_{10} minus $PM_{2.5}$.
[d]Conc. is the average abundance (percent of total mass) for several samples of emissions from the same source type. Unc. is the standard deviation of the abundances for these samples.

with an accepted method to evaluate compliance with standards; (2) samples are analyzed for chemical species which are also present in source emissions; (3) potential source contributors have been identified and chemically characterized; and (4) the number of noncollinear source types is less than the number of measured species.

Samples were taken through well-characterized $PM_{2.5}$ and PM_{10} inlets during the SCAQS summer and fall studies. All of these samples were subjected to analysis for mass, elements, carbon, and ion

concentrations. All major source types in the SoCAB have been identified, and profiles which represent their emissions have been assembled. Examination of the chemical profiles shows significant differences among profiles for major source types such as primary geological material, primary motor vehicle exhaust, primary marine aerosol, and secondary sulfates and nitrates. The number of species measured in source and receptor samples is greater than the number of noncollinear sources.

The SCAQS data set was not randomly obtained over a 1-year period, and it should not be used to evaluate compliance with the annual average PM_{10} standard. However, since meteorological conditions on sampled days reflect the conditions most conducive to high PM_{10} concentrations, and since several cases were observed for which the PM_{10} standard was exceeded, the SCAQS data set can be used to determine source contributions to exceedances of the 24-hour standard.

Chow et al. (1994a,b) identify potential negative biases in the X-ray fluorescence and carbon data because the weighted sum of chemical concentrations was substantially lower than the mass concentrations for most samples by ~15%. These biases will probably affect the source contributions from motor vehicle exhaust and geological material, which account for most of the organic carbon and trace elements in SCAQS sources.

Total carbon (TC, sum of OC and EC) is allocated to OC and EC fractions in different proportions in source and receptor samples owing to the different chemical analysis methods, described by Chow et al. (1993b). The TMO method used in SCAQS allocates a smaller portion of TC to EC and a larger portion to OC than do the thermal/optical analysis methods used for the source profiles (Chow et al., 1993b, 1994a). The implications of this incompatibility are explored below.

Initial Source Contribution Estimates

Initial tests with different combinations of profiles determine which profiles best explain the data at each site. Several initial CMB runs were performed at each site for the $PM_{2.5}$ and coarse particle size fractions, and the CMB performance measures were examined to determine how well the ambient concentrations were explained by the source contribution estimates.

Primary geological and marine sources were required in nearly every coarse particle sample to explain chemical measurements. Secondary ammonium nitrate and primary motor vehicle exhaust were often needed to account for a portion of the coarse particles, even though the majority of these are in the $PM_{2.5}$ particle fraction. Sampling inlets do not provide perfect separations at 2.5 μm, and it is expected that some $PM_{2.5}$ material will be found in the coarse particle fraction and vice versa. The lime/gypsum profile was required only at the Rubidoux site, similar to findings reported in previous studies (e.g., Gray et al., 1988; Chow et al., 1992a, 1993a).

Secondary ammonium sulfate, secondary ammonium nitrate, and primary motor vehicle exhaust were always required to account for the chemical concentrations in the $PM_{2.5}$ samples. Small amounts of primary geological material and marine aerosol were needed for a large number of these samples. Primary residual oil combustion and vegetative burning profiles were applied, but the inclusion of these profiles never resulted in source contribution estimates exceeding standard errors (SE) for either the initial source apportionments or any other source apportionments. The secondary OC profile, which contains only OC, was not needed since the primary sources of carbon were sufficient to account for the measured concentrations of OC. This may be an artifact, however, of the need to use

TC rather than OC and EC as fitting species owing to the differences in carbon analysis methods for source profiles and receptor samples. This issue is discussed in greater detail shortly.

The initial source apportionments at each site showed that the following profiles best explained the data across the SoCAB: (1) PRSCAB for primary geological material, (2) PHRD for primary motor vehicle exhaust, (3) MAR0 or MAR25 for primary marine aerosols, (4) AMSUL for secondary ammonium sulfate, (5) AMNIT for secondary ammonium nitrate, and (6) LIME for primary lime/gypsum or cement. As shown below, the source contribution estimates are not overly sensitive to substitution of the other profiles in Table 1 for these default profiles. If the source contribution estimates are overlapping within 1 SE interval, it is preferable to use the same profiles at all sites, so that systematic errors in source contribution estimates are consistent across the SoCAB.

The initial source apportionments also examined the fitting species which would provide the best indication of the presence or absence of sources. The default fitting species selected were Cl^-, NO_3^-, $SO_4^=$, NH_4^+, TC, Na, Al, Si, K, Ca, Ti, V, Fe, Ni, Br, and Pb. The volatilized NO_3^- portion measured by the SCAQS sampler (Chow et al., 1994a) was not considered in this analysis since it is not usually recovered by PM_{10} reference methods. Trace elements which were consistently below detection limits were omitted as fitting species. $SO_4^=$ was used in place of S and Cl^- was used in place of Cl as fitting species owing to the suspected bias in the elemental data and because the soluble fractions of these species are more typical of secondary $SO_4^=$ and marine sources than the total elemental fractions. NH_4^+ and NO_3^- were included as initial fitting species to account for ammonium nitrate, as were Al, Si, K, Ca, and Fe as indicators of soils. V and Ni were also retained, even though their concentrations were low or undetectable, so that residual oil combustion contributions could be sought.

Initial CMB calculations used both OC and EC as fitting species. It was found that ambient OC concentrations were always overpredicted and EC concentrations were always underpredicted. As noted above, this often moved performance measures significantly away from their targets and biased the motor vehicle exhaust source contributions. This discrepancy is due to the incompatibility of the carbon measurements between the ambient data and source profiles. After several trials, it became apparent that only TC was consistent between source and receptor samples. Using TC instead of OC and EC has major consequences for the apportionment of motor vehicle exhaust. Lowenthal et al. (1992) show that the OC and EC abundances are crucial to separating gasoline-fueled exhaust from diesel exhaust. When OC and EC are included in the apportionment of other data sets, it is often possible to assign excess OC to nonvehicle sources of OC, such as cooking or secondary organic aerosol. This is not possible using the SCAQS ambient aerosol data with current source profiles, and any excess OC is attributed to primary motor vehicle exhaust by this modeling. Turpin and Huntzicker (1991) have examined the secondary OC contributions during SCAQS and it was only detected on a few afternoons during the summer study.

Model Outputs and Performance Measures

Watson et al. (1991) define several performance measures which are examined with each CMB to eliminate many profiles from further consideration. There may be more than one combination of profiles which attain the performance criteria to the

same extent. When this is the case, it is necessary to group these individual sources into source types which are not specific to individual sources.

Evaluations of several different combinations of source profiles were made for every $PM_{2.5}$ and coarse particle sample in this data set. An example of the process is given here to illustrate the evaluation process and the grouping of similar profiles into source types. Model outputs, ambient concentrations, source profiles, and modeling software are available from the authors for other researchers to reproduce these tests on this and other examples.

Tables 3a and b show source contribution estimates derived from different combinations of source profiles and fitting species for a typical SCAQS aerosol sample. Numerous tests of this type were made to select initial fitting species and profiles, and the results were comparable to those in Tables 3a and b. The first column in Table 3a shows the "best fit" of source contributions, while trial 1 shows the results with the default set of profiles. Notice that PRSCAB and MAR0 contributions are less than their standard errors, and that their retention or elimination from the CMB fit does not significantly affect the other contributions. Profiles were generally retained in the calculations even if contributions were less than standard errors when no uncertainty/similarity clusters were found. They were removed from the calculation when they appeared in clusters with other profiles and when they had negative values. The standard error in this case offers an upper limit to the actual contribution from its source type.

Trials 2–6 examine the effects of different primary motor vehicle exhaust profiles on the source apportionments. The inclusion of PHAUTO and PHDIES in trial 2 shows obvious collinearity, and demonstrates that these source subtypes cannot be resolved with the current fitting species. Trial 3 vastly overestimates the PERCENT MASS. Trial 4, using PHDIES, provides a result very similar to trial 1, while trials 5 and 6 provide lower estimates, but values which are within overlapping standard errors with the contributions in trial 1. The PHRD profile was found to explain more of the measured mass and it provided a better comparison of calculated and measured chemical species for most samples. MOVES1 would be an equally valid selection for motor vehicle exhaust, however.

Trials 7–9 examine the sensitivity of source contributions to the selection of carbon fractions as fitting species. In trial 7, TC is replaced by OC and EC, and the source contribution estimate of PHRD is 75% of the trial 1 value, though the standard error intervals still overlap. CHI-SQUARE increases from 0.15 to 0.97, reflecting the poorer agreement between calculated and measured OC and EC. Trial 8 substitutes OC for TC and obtains a 20% higher PHRD source contribution than trial 1. Substituting EC for TC in trial 9 reduces the PHRD source contribution by 45%.

Vegetative burning (VIAGBC) and residual oil combustion (SFCRUC) are sought in trials 10 and 11, and are shown to be insignificant contributors to this sample. These profiles were inserted from time to time, especially when V was detected, but a significant contribution was never found from either of them in any of the SCAQS samples. Trials 12 and 13 examine the sensitivity of the motor vehicle exhaust contribution to the removal of Pb and TC. The source contributions do not change significantly.

Table 3b examines source contributions to the coarse particle fraction. Trial 1 shows the contributions with the default profiles, and they are comparable to the best-fit source contributions. Trials 1–3 examine the effect of changing the fraction of marine aerosol which has reacted

TABLE 3a. Sensitivity of $PM_{2.5}$ Source Contribution Estimates Changes in Source Profiles and Fitting Species

Profile[a]	Source contributions ($\mu g/m^3$) at Long Beach on December 10, 1987 at 1400 hours PST								
	Best Fit	Trial 1	Trial 2[g]	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7	Trial 8
PRSCAB		0.6 ± 1.3	−2.3 ± 2.4	−2.0 ± 1.7	0.7 ± 0.8	1.3 ± 0.8	1.4 ± 0.8	0.9 ± 1.1	0.47 ± 1.5
PHRD	20.8 ± 5.1	20.1 ± 5.1						15.6 ± 3.7	23.8 ± 7.7
MOVES1						15.8 ± 4.2			
MOVES2							13.6 ± 3.8		
PHAUTO			40.6 ± 22.8	36.3 ± 10.9					
PHDIES			−3.0 ± 14.9		21.3 ± 3.7				
MAR0		0.06 ± 0.2	0.18 ± 0.27	0.17 ± 0.25	0.07 ± 0.20	0.03 ± 0.2	0.03 ± 0.19	0.05 ± 0.19	0.07 ± 0.21
AMSUL	1.4 ± 0.8	1.4 ± 0.8	1.9 ± 0.9	1.9 ± 0.8	2.3 ± 0.5	2.2 ± 0.7	2.5 ± 0.8	1.8 ± 0.7	1.1 ± 1.0
AMNIT	20.0 ± 2.5	20.0 ± 2.4	20.4 ± 1.1	20.6 ± 2.0	22.2 ± 1.7	22.7 ± 1.7	22.6 ± 1.7	20.5 ± 2.1	19.6 ± 2.8
CHI SQUARE[b]	0.15	0.15	0.19	0.2	0.64	0.4	0.98	0.97	0.98
R SQUARE[c]	0.99	0.99	0.99	0.99	0.98	0.98	0.51	0.51	0.17
PERC MASS[d]	93.7	94.1	129.3	127.3	104	93.9	89.5	86.8	100.5
FITTING SPEC[e] and CLUSTERS[f]			PHAUTO PHDIES					−TCTC +OCTC +ECTC	−TCTC +OCTC

Profile	Trial 9	Trial 10	Trial 11	Trial 12	Trial 13
PRSCAB	1.0 ± 0.95	0.71 ± 1.3	0.6 ± 1.3		
PHRD	11.6 ± 3.3	21.0 ± 5.5	19.8 ± 5.1	19.9 ± 5.1	20.7 ± 8.7
VIAGBC		−0.35 ± 0.67			
SFCRUC			0.31 ± 0.9		
MAR0	0.05 ± 0.19	0.08 ± 0.21	0.04 ± 0.2		
AMSUL	2.1 ± 0.6	1.3 ± 0.8	1.4 ± 0.8	1.4 ± 0.8	1.4 ± 1.0
AMNIT	20.9 ± 1.9	19.9 ± 2.5	10.2 ± 2.5	20.0 ± 2.4	19.9 ± 2.6
CHI SQUARE	0.26	0.13	0.15	0.15	0.17
R SQUARE	0.99	0.99	0.99	0.99	0.98
PERC MASS	79.8	95.2	94.3	92.4	93.8
FITTING SPEC. and CLUSTERS	−TCTC +ECTC		SFCRUC AMSUL	−PBXC	−TCTC

[a]See Table 1 for source profile descriptions.

[b]CHI-SQUARE measures the agreement between calculated and measured concentrations. Watson et al. (1991) set a maximum value of 4.0, but the closer CHI-SQUARE is to zero, the better the fit of source profiles to the ambient data.

[c]R-SQUARE measures the correlation between calculated and measured concentrations. The closer the value of R-SQUARE to the unity, the better the correlation.

[d]PERCENT MASS is the sum of source contributions divided by measured mass. The target value is 1.0. Values significantly < 1.0 indicate missing sources, while values significantly exceeding 1.0 indicate sources which do not belong. For SCAQS receptor modeling, a PERCENT MASS target of 0.8 was sought owing to relatively biased carbon and element concentrations.

[e]FITTING SPECIES are those used to calculate the source contributions. A blank indicates that the default species were used. A minus preceding a species mnemonic indicates that it was removed from the default selection, while a plus indicates the species was added to the selection.

[f]CLUSTERS refers to UNCERTAINTY/SIMILARITY CLUSTERS which identify the potential for collinearity among the profiles which are contained in the CLUSTER. When source profile mnemonics are listed, they appeared together in one or more clusters and are probably collinear.

[g]Similar tests were obtained using OCTC and ECTC instead of TCTC.

TABLE 3b. Sensitivity of Coarse Particle Source Contribution Estimates Changes in Source Profiles and Fitting Species

	Source contributions ($\mu g/m^3$) at Long Beach on December 10, 1987 at 1400 hours PST						
Profile[a]	Best Fit	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6
PRSCAB	10.9 ± 1.1	10.8 ± 1.1	11.0 ± 1.1	10.9 ± 1.1			
PRLBSC					12.2 ± 1.5		
PRLBPC						11.6 ± 1.3	
PRDRSC							9.8 ± 1.2
PHRD	5.2 ± 2.8	7.1 ± 3.5	5.0 ± 3.3	5.7 ± 3.4	4.7 ± 2.8	4.8 ± 2.8	5.9 ± 2.9
MAR0		3.4 ± 0.5					
MAR25	3.1 ± 0.4			3.1 ± 0.4	3.1 ± 0.4	3.1 ± 0.4	3.1 ± 0.4
MAR50			2.6 ± 0.3				
AMSUL		−0.2 ± 0.5	−0.12 ± 0.5	−0.15 ± 0.5			2.7 ± 1.0
AMNIT	2.8 ± 1.0	2.2 ± 1.1	3.4 ± 1.0	2.8 ± 1.0	2.9 ± 1.0	2.9 ± 1.0	
CHI SQUARE[b]	0.29	0.35	0.81	0.3	0.32	0.34	0.27
R SQUARE[c]	0.98	0.98	0.96	0.98	0.98	0.98	0.98
PERC MASS[d]	95.9	101.2	95.1	97.4	99.8	97.7	93.5
FITTING SPEC.[e] and CLUSTERS[f]				MAR25 AMNIT			

[a]See Table 1 for source profile descriptions.
[b–f]See Table 3a for explanations.

with nitric acid. MAR0 and MAR25 explain the data better than MAR50. This was true for all samples at all sites except San Nicolas Island, where MAR100 and MAR75 provided the best agreement between calculated and measured concentrations. Even at sites near the coast such as Long Beach, the majority of the marine aerosol had reacted with nitric acid during SCAQS. Trials 4–6 examine the effects of different paved road dust profiles on the apportionments. These profiles are so similar throughout the SoCAB that it does not really matter which one is used. The SoCAB composite profile (PRSCAB) for primary geological material was selected for consistency. The exception might be at the Rubidoux site, where excessive Ca was found in ambient samples. Unfortunately, samples from geological sources in the vicinity of the Rubidoux site have never been analyzed—certain soils may contain a high abundance of Ca and would be resolvable from other soils by the CMB. The LIME profile is used as a surrogate for these missing Rubidoux profiles.

Deviations from Model Assumptions

The basic assumptions of the CMB model (Watson et al., 1984) are as follows: (1) compositions of source emissions are constant over the period of ambient and source sampling; (2) chemical species do not react with one another (i.e., they add linearly); (3) all sources which may significantly contribute to the receptor have been identified and their emissions characterized; (4) the number of source categories is less than or equal to the number of chemical species; (5) the source profiles are linearly independent (i.e., they are statistically different); and (6) measurement uncertainties are random, uncorrelated, and normally distributed.

The degree to which these assumptions are met in practice depends to a large extent on the types and quality of chemical measurements made at the sources and receptor. The CMB model has been subjected to a number of tests to determine its ability to tolerate deviations from the model assumptions (e.g., Watson, 1979; Gordon et al., 1981; Henry, 1982, 1992; Currie et al., 1984; Dzubay et al., 1984; DeCesar et al., 1985; Javitz et al., 1988; Lowenthal et al., 1992).

Tables 2a–e show that there is substantial variability among individual profiles, and even among profiles from different source types, and that assumption 1 is never completely met. Table 3a shows that for the case presented, the primary motor vehicle exhaust source contribution estimate is not very sensitive to the selection of the MOVES1, MOVES2, or PHRD profile, nor is it sensitive to the removal of Pb or TC. This is despite substantial uncertainties assigned to the abundances in these profiles. Similar sensitivities to changes in motor vehicle profiles were found for many other samples.

With respect to assumption 2, all of the source types are treated as nonreactive. This is definitely the case for primary emissions from geological material and motor vehicle exhaust, in which little change is expected between source and receptor. Though the CMB can estimate the contributions from different secondary aerosol compounds such as ammonium nitrate, ammonium sulfate, hydrogen bisulfate, sulfuric acid, and sodium nitrate, it cannot attribute these compounds to emitters by itself. Watson et al. (1994c) demonstrate how chemical equilibrium modeling might be applied to these secondary aerosol contributions to determine how emissions reductions in their precursors might affect their ambient concentrations.

With respect to assumption 3, it appears from the lower than target PERCENT MASS performance measures for the majority of the CMBs that there is mass which is unaccounted for by the

included sources. However, it has been amply demonstrated that the carbon and elemental data are negatively biased (Chow et al., 1994a,b), and this is a valid explanation for the mass which has not been accounted for.

With respect to assumption 4, 16 chemical species and up to six source profiles were used in each calculation. The number of chemical species always exceeded the number of source types.

The examples in Tables 3a and b show how well assumption 5 could be met and why it is necessary to group specific profiles into source types defined as primary geological material and motor vehicle exhaust. For many cases, the individual profiles within these categories were too collinear to be separated from each other. This was especially the case when diesel and gasoline vehicle exhaust were used together as illustrated in trial 2 of Table 3a.

The effects of deviations from assumption 6 have not been studied to a great extent. Nonrandomness and correlation among measurement errors would result in biases in the calculated concentrations with respect to measured concentrations.

For this study, all of the CMB assumptions are met to the extent that the source contribution estimates can be considered valid.

Identification and Correction of Model Input Errors

In several cases, it was evident that certain chemical species concentrations were physically unreasonable. This was indicated by large CHI-SQUARE values with a large difference between calculated and measured concentrations for the related species. In these cases the Level II data validation summary in Watson et al. (1993) was consulted, and it was usually found that the discrepancy had already been identified by the validation tests. The suspect species was removed from the fit in these cases.

Consistency and Stability of Source Contributions

Separate CMBs were performed on $PM_{2.5}$ and coarse samples for the nine SCAQS sites. The stability of these solutions was tested periodically by adding or dropping fitting species and examining changes in the source contribution estimates. In all but a few cases, the source contribution estimates changed by no more than one uncertainty interval. In those cases where the presence or absence of a single species made a large difference in the source contribution estimates, the species was left in the fit when all performance measures were within target ranges. The species was deleted from the fit when this would bring performance measures into acceptable target ranges.

Source contribution estimates were calculated separately by two independent researchers for all sites. A comparison of the results of the source contribution estimates for geological, motor vehicles, and marine contributions is shown in Figure 2 for the Long Beach and Rubidoux sites. The vertical bars provide the relative magnitude of the standard errors for each of the estimates. A majority of the "old estimates" were calculated first using OC instead of TC as a fitting species with the PRLBSC geological profile. A majority of the "new estimates" were calculated using the default profiles and fitting species described above, with minor modifications. There are slight systematic biases for the geological and motor vehicle exhaust profiles which are consistent with the sensitivity tests in Tables 3a and b. The results show that independent selections of fitting species and source profiles made by separate investigators do not cause significant differences in the source contribution estimates. The results reported below corre-

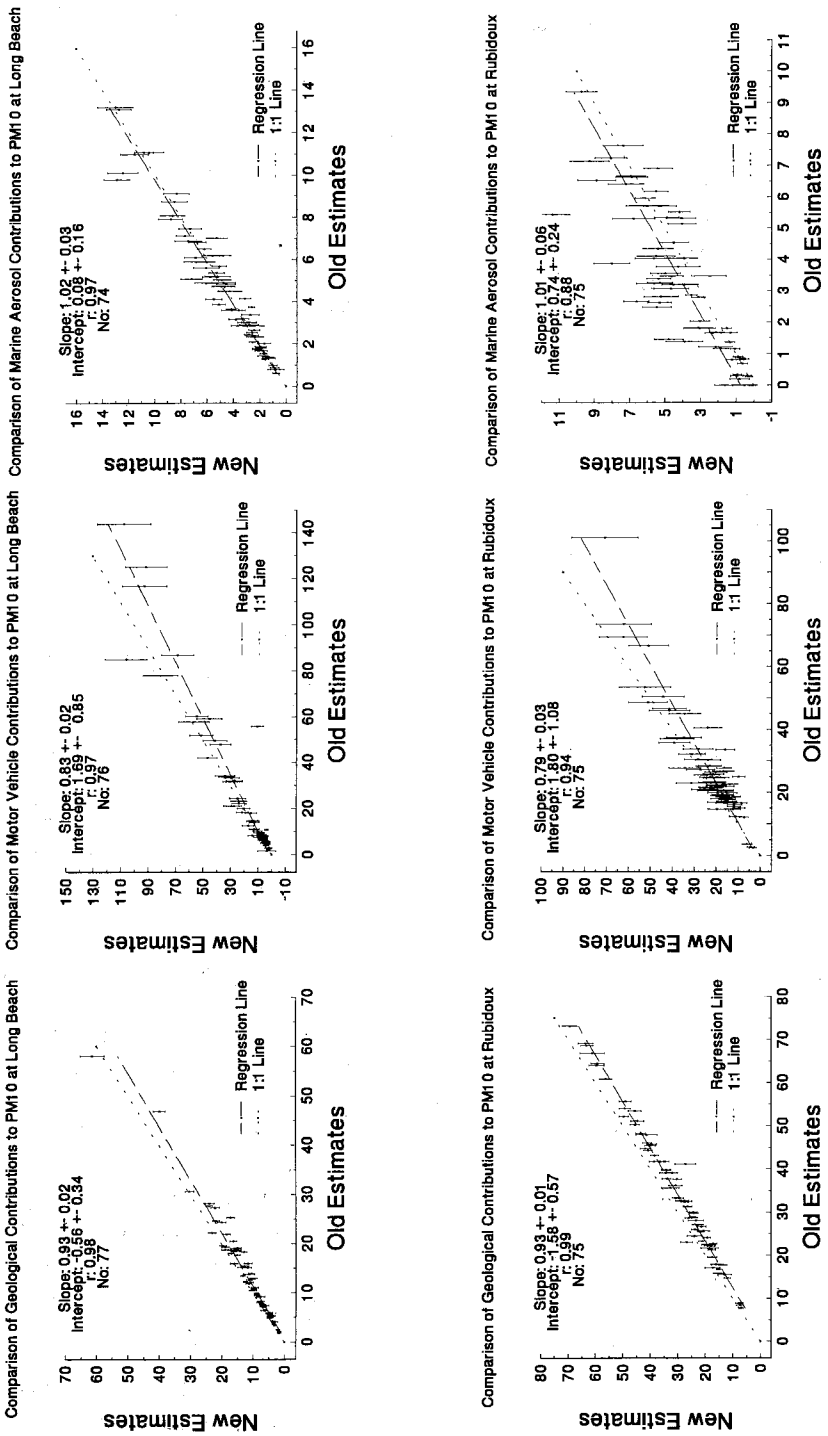

FIGURE 2. Comparison of source contribution estimates calculated from SCAQS aerosol data by two independent researchers.

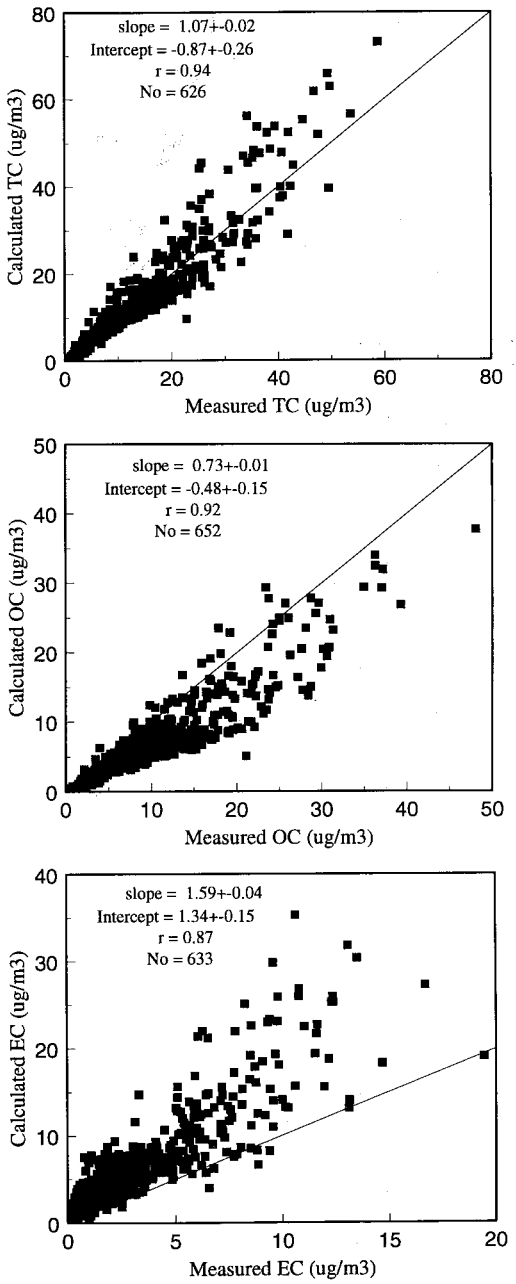

FIGURE 3. Scatterplots of $PM_{2.5}$ calculated versus measured carbon for the SCAQS samples between 6/19/87 and 12/11/87 (TC = total carbon, OC = organic carbon, EC = elemental carbon).

spond to the "new estimates." Figure 3 compares the calculated and measured TC, OC, and EC for all of the $PM_{2.5}$ samples. The effect of differences between profile and ambient carbon measurements is apparent.

Reconciliation with Other Source Apportionment Methods

The source apportionments reported here have not yet been compared with other receptor model source apportionments or with dispersion model estimates of source contributions during SCAQS. This evaluation awaits the publication of other analyses of the SCAQS aerosol data.

SOURCE CONTRIBUTION ESTIMATES

Summaries of CMB source contributions for each sample, including results for $PM_{2.5}$ and PM_{10} (sum of $PM_{2.5}$ and coarse particle apportionments) at each of the nine SCAQS sites, are given by Watson et al. (1993). These summaries include the source contribution estimates and their standard errors for every 4- to 7-hour sample, as well as the 24-hour average source contributions. Most of the discussion here will focus on 24-hour average PM_{10} owing to its importance in standards attainment. Annual or seasonal PM_{10} averages are not applicable due to the episodic nature of this study.

Average Source Contribution Estimates

Average contributions to PM_{10} mass for the summer and fall samples are summarized in Tables 4a and b. The standard deviations of the averages are also given as an indication of the variability of the source contributions. The unexplained portion of these averages is comparable to the unexplained portion found by Chow et al. (1994b) when the weighted sum of chemical concentrations was compared with the mass concentrations.

TABLE 4a. CMB PM_{10} Source Contribution Estimates During Summer

Source	Average[a] source contributions to PM_{10} ($\mu g/m^3$)								
	Burbank	Downtown Los Angeles	Hawthorne	Long Beach	Anaheim	Rubidoux	San Nicolas Island	Azusa	Claremont
Primary geological	14.04 ± 2.82	12.65 ± 3.33	6.81 ± 3.39	11.10 ± 5.27	11.38 ± 3.89	34.86 ± 8.74	1.62 ± 1.67	34.92 ± 6.75	19.40 ± 5.01
Primary motor vehicle	17.02 ± 2.08	16.24 ± 2.71	5.66 ± 1.93	6.30 ± 2.89	8.48 ± 3.15	17.23 ± 4.66	0.85 ± 0.54	15.90 ± 4.26	14.43 ± 3.00
Marine	5.67 ± 2.38	6.53 ± 2.58	6.56 ± 2.72	6.24 ± 2.53	6.54 ± 2.22	5.10 ± 2.16	4.30 ± 2.32	5.74 ± 2.20	4.06 ± 1.83
Primary lime	0.02 ± 0.07	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	4.51 ± 3.14	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Primary residual oil	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.08 ± 0.23	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Secondary ammonium nitrate	6.45 ± 3.22	4.40 ± 2.35	0.58 ± 0.88	0.82 ± 1.06	2.88 ± 1.84	27.36 ± 13.04	0.50 ± 0.47	6.13 ± 4.77	6.27 ± 4.97
Secondary ammonium sulfate	12.41 ± 6.79	13.02 ± 6.94	14.21 ± 7.29	10.91 ± 3.99	8.96 ± 2.47	9.46 ± 3.29	3.66 ± 1.35	11.42 ± 6.17	9.53 ± 4.56
Unexplained mass	16.65 ± 7.01	14.59 ± 4.61	11.70 ± 7.43	10.94 ± 2.53	12.54 ± 2.72	22.67 ± 4.40	6.97 ± 2.13	18.03 ± 5.17	15.68 ± 3.59
Measured mass	72.25 ± 18.59	67.43 ± 15.45	45.91 ± 18.11	46.40 ± 12.05	50.79 ± 10.40	114.78 ± 33.09	17.38 ± 6.17	92.13 ± 16.58	69.97 ± 15.66

[a]Average of 24-hour source contributions plus or minus standard deviation of these source contributions.

TABLE 4b. CMB PM_{10} Source Contribution Estimates During Fall

	Average[a] source contributions to PM_{10} ($\mu g/m^3$)								
Source	Burbank	Downtown Los Angeles	Hawthorne	Long Beach	Anaheim	Rubidoux	San Nicolas Island	Azusa	Claremont
Primary geological	10.99 ± 1.86	9.43 ± 2.96	8.93 ± 1.56	11.31 ± 3.62	13.20 ± 5.07	19.15 ± 7.93	NA	NA	NA
Primary motor vehicle	39.05 ± 14.56	41.09 ± 16.37	35.1 ± 13.63	42.78 ± 21.75	37.24 ± 17.28	30.31 ± 11.31	NA	NA	NA
Marine	1.88 ± 1.40	1.79 ± 1.03	3.65 ± 1.31	2.72 ± 0.97	3.07 ± 1.39	1.05 ± 0.72	NA	NA	NA
Primary lime	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	16.05 ± 3.33	NA	NA	NA
Primary residential oil	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.023	0.00 ± 0.023	0.00 ± 0.00	0.00 ± 0.00	NA	NA	
Secondary ammonium nitrate	25.08 ± 19.41	27.52 ± 19.52	20.44 ± 13.62	23.21 ± 17.95	38.47 ± 30.07	31.57 ± 26.89	NA	NA	NA
Secondary ammonium sulfate	3.12 ± 4.38	3.85 ± 4.90	5.05 ± 4.03	3.77 ± 2.57	3.73 ± 3.27	2.09 ± 2.36	NA	NA	NA
Unexplained mass	18.13 ± 8.14	17.97 ± 4.24	12.28 ± 6.70	13.27 ± 12.21	10.52 ± 7.44	9.59 ± 11.12	NA	NA	NA
Measured mass	94.84 ± 39.20	98.65 ± 43.40	85.08 ± 33.69	96.11 ± 49.33	103.98 ± 56.43	111.98 ± 57.09	NA	NA	NA

[a]Average of 24-hour source contributions plus or minus standard deviation of these contributions.

Primary geological material was the major contributor to PM_{10} during summer at the eastern sites, and its average source contributions at the Rubidoux and Azusa sites were approximately five times the primary geological contribution at the Hawthorne site. The Long Beach, Anaheim, and Burbank sites received primary geological material contributions which were one half to one third of those found at the sites with the highest contributions. Rubidoux was the only site with a primary lime/gypsum contribution. Primary motor vehicle exhaust was the largest contributor to PM_{10} at the Burbank site, the second largest contributor at the Azusa and Claremont sites, and the third largest contributor at the remaining sites. The average primary motor vehicle exhaust contributions at the Burbank, Downtown Los Angeles, Rubidoux, Azusa, and Claremont sites were two to three times those at the Hawthorne, Long Beach, and Anaheim sites.

Secondary ammonium sulfate contributions were fairly uniform across the SoCAB during the summer. The primary marine aerosol contribution also shows a homogeneous distribution across the SoCAB, including its contribution at the San Nicolas Island site. This indicates good west-to-east transport during the SCAQS summer study. The secondary ammonium nitrate contribution stands out at the Rubidoux site, being 5–10 times larger than averages calculated at the other sites. This is true even for nearby sites such as Azusa and Claremont. This is strong evidence that the majority of the secondary ammonium nitrate in the SoCAB is ammonia-limited, and that Rubidoux's proximity to major upwind ammonia sources is the cause of these high nitrate levels. The secondary ammonium nitrate contribution at the Hawthorne site was not detectable—there are few upwind ammonia sources near this site.

The average source contributions to PM_{10} during the fall were substantially different from the summer. Primary motor vehicle exhaust was the major contributor, and secondary ammonium nitrate was the second largest contributor, at all sites during the fall. Secondary ammonium sulfate contributed uniformly across the SoCAB, but its average contribution during the fall was less than half that found during the summer. The primary marine aerosol contribution was lower during fall than during summer and was substantially lower at the inland sites relative to the sites near the coast; this reflects the lack of west-to-east transport during the fall study. Primary geological contributions were much lower during the fall, with the exception of contributions at the Rubidoux site. The primary lime/gypsum contribution at the Rubidoux site nearly equalled the primary geological contribution during the fall study.

Diurnal Variation in Source Contribution Estimates

Figure 4a–c shows the diurnal distributions of source contributions to PM_{10} for each SCAQS episode. The diurnal patterns for PM_{10} mass and the ammonium nitrate contribution follow those observed by Chow et al. (1994b) for individual chemical components. There are a few subtle patterns revealed by the diurnal distribution of source contributions.

The primary geological material contributions follow a diurnal pattern with the highest contributions generally found in the morning samples. These correspond to the morning rush hour and are consistent with paved road dust being suspended by the increased traffic volume. The highest primary lime/gypsum contributions at the Rubidoux site are found in the early morning samples (i.e., 0000–0500 hours PST or 0000–0600 hours PST), however. This is hardly a period during which major construction activities are oc-

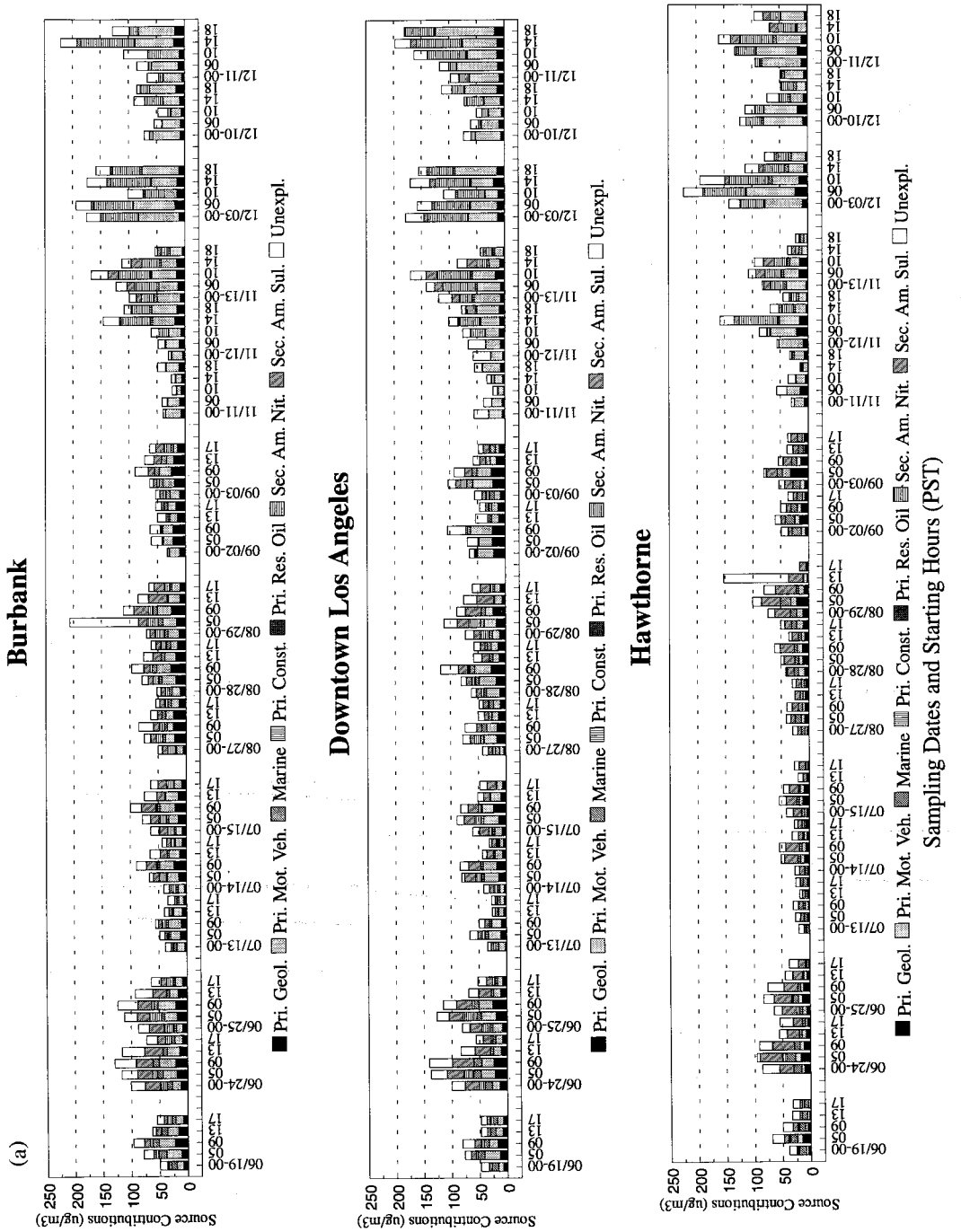

FIGURE 4. (a) Diurnal source contributions to PM_{10} at the Burbank, Downtown Los Angeles, and Hawthorne sites. (b) Diurnal source contributions to PM_{10} at the Long Beach, Anaheim, and Rubidoux sites. (c) Diurnal source contributions to PM_{10} at the San Nicolas Island, Azusa, and Claremont sites.

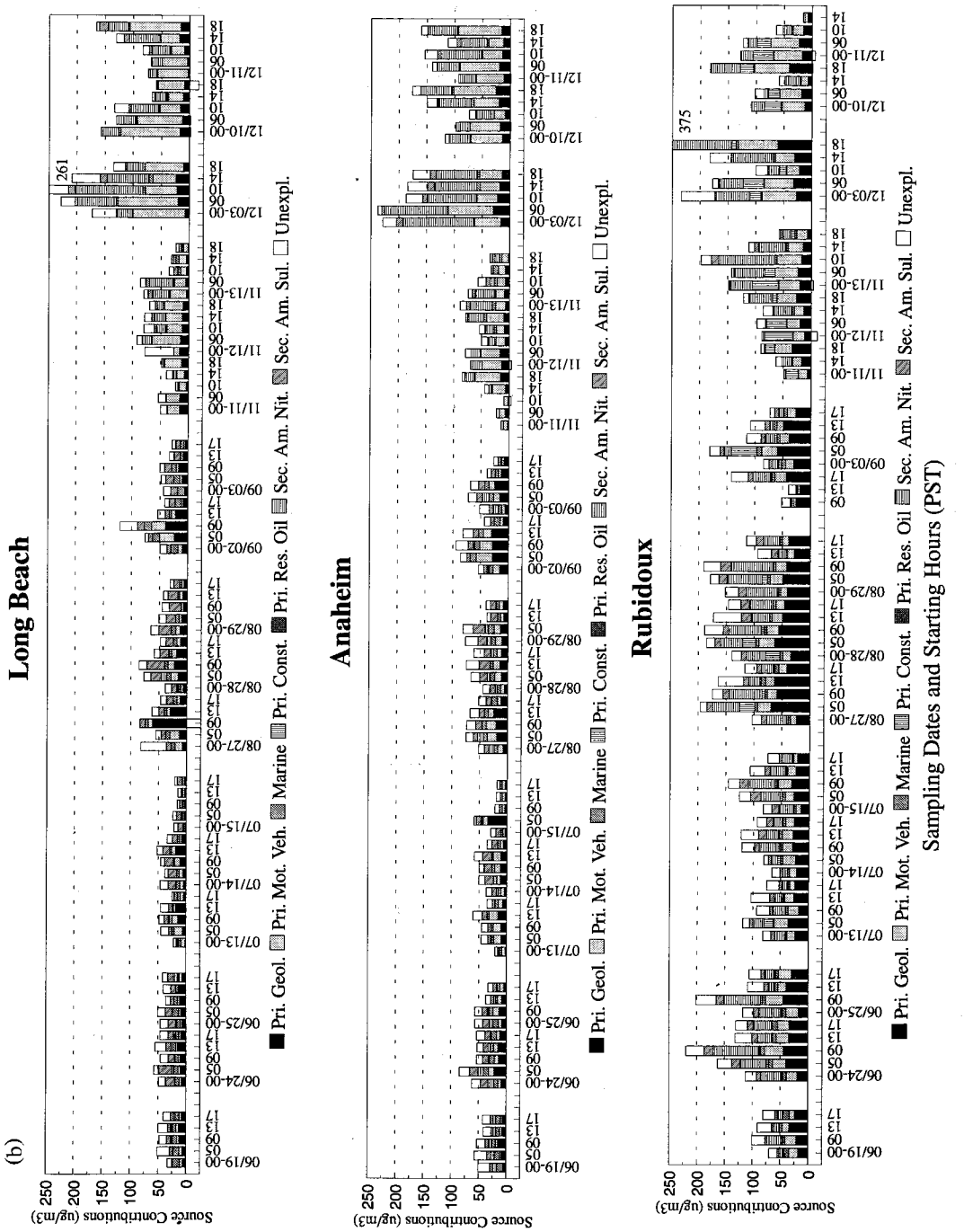

FIGURE 4. (*Continued*)

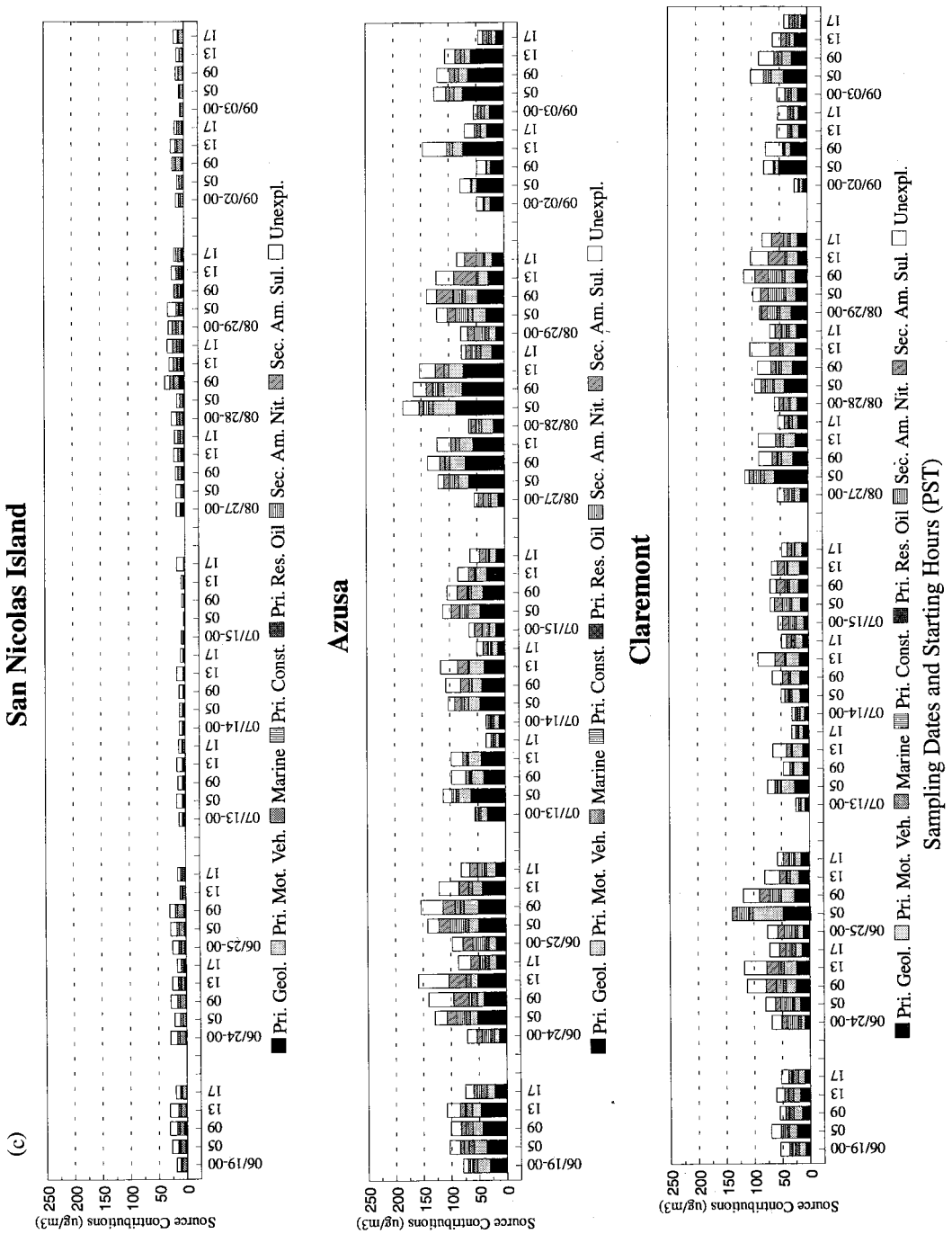

FIGURE 4. (*Continued*)

curring, and traffic counts are lower than at later periods in the day.

Zeldin (1993) examined wind roses and reported a significant increase in wind frequency from the north-northeast, and east-northeast in the fall months, which is the upwind direction for two major cement production facilities. This wind direction is associated with nighttime and early morning "land breezes" (or "drainage winds") which move from the inland areas toward the coast due to radiational cooling during the longer fall nights. During the fall and winter, wind velocities from the north-northeast reflect Santa Ana wind conditions, which over many years, have possibly transported Ca-rich material from the cement facilities, causing Ca enrichment of soils in the vicinity of the Rubidoux site. This would account for noticeable Ca in the summer samples. Paved and unpaved road dust emissions caused by trucks or cars in and around the cement facilities might be transported directly toward the Rubidoux monitoring site during fall drainage wind periods.

Primary motor vehicle exhaust contributions peak in the morning samples, and sometimes in the evening samples. This cycle is expected to be more pronounced in the morning owing to the existence of a surface inversion layer which usually dissipates before the evening rush hour.

(a)

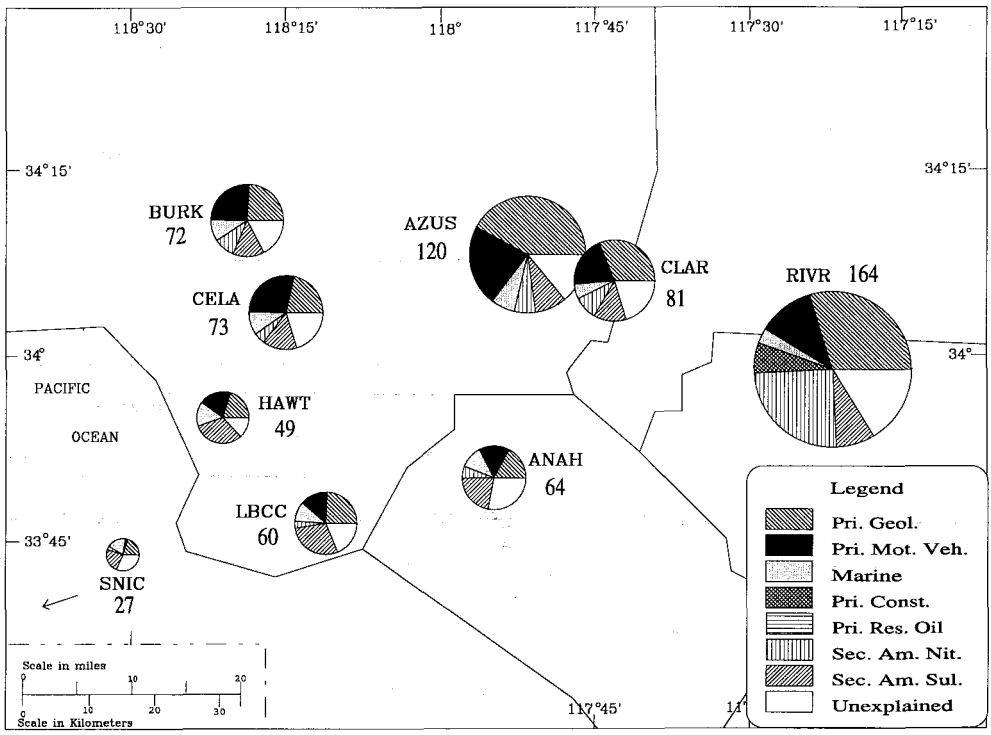

FIGURE 5. (a) Source contributions ($\mu g/m^3$) to 24-hour average PM_{10} mass (the number beside each pie) at nine SCAQS sites on 8/28/87. (b) Source contributions ($\mu g/m^3$) to 24-hour average PM_{10} mass (the number beside each pie) at six SCAQS sites on 12/03/87.

(b)

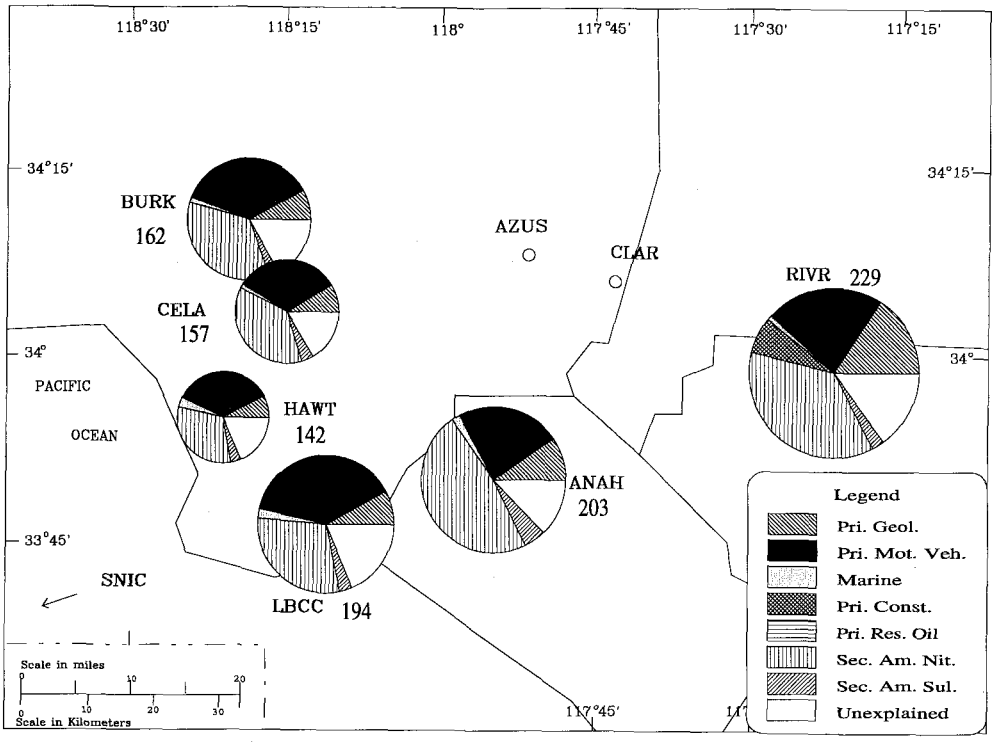

FIGURE 5. (*Continued*)

Contributions to Maximum 24-hour PM_{10}

The spatial distribution of source contributions for the two PM_{10} exceedance days is shown in Figure 5a and b. The contributions to maximum PM_{10} show many of the same characteristics found in the averages. Source contributions generally increase from the western to eastern part of the SoCAB, which reflect the higher emissions densities in the central and eastern portions of the SoCAB, as well as the west-to-east transport patterns during SCAQS (Douglas et al., 1991)—primary geological material, primary motor vehicle exhaust, and secondary ammonium nitrate are the main contributors to these excessive PM_{10} concentrations.

The highest source contributions to PM_{10} mass do not necessarily correspond to the highest PM_{10} concentrations. The largest primary geological contribution of 51 ± 5 $\mu g/m^3$ was found at the Azusa site on August 28, 1987, when PM_{10} was 120 $\mu g/m^3$. The largest primary lime/gypsum contribution was 21 ± 6 $\mu g/m^3$ at the Rubidoux site on November 12, 1987, when PM_{10} was 60 $\mu g/m^3$. The largest primary motor vehicle exhaust contribution of 74 ± 31 $\mu g/m^3$ was found at the Long Beach site on December 3, 1987, when PM_{10} was 194 $\mu g/m^3$. The largest secondary ammonium nitrate contribution of 96 ± 18 $\mu g/m^3$ was found at the Anaheim site on December 3, 1987, when PM_{10} was 203 $\mu g/m^3$. The largest secondary ammonium sulfate contribution of 27 ± 9 $\mu g/m^3$ was found at the Hawthorne site on June 24, 1987, when PM_{10} was 75 $\mu g/m^3$. The largest primary marine aerosol contribution of 11 ± 2 $\mu g/m^3$ was found at the Long Beach site on September 2, 1987, when PM_{10} was 65

$\mu g/m^3$. Only two of these highest contributions correspond to PM_{10} concentrations exceeding 150 $\mu g/m^3$. Several sources contribute at elevated, but not necessarily maximum, levels when 24-hour standards are exceeded.

Comparisons Between the "Original" and "Revised" SoCAB Source Profiles

The "original" source profiles reported by Cooper et al. (1987) for geological material and motor vehicle exhaust did not include ion speciation for sulfate and nitrate. For the geological source profiles presented in Table 2a, the averages and standard deviations were calculated based on the 28 different geological source profiles collected in the San Joaquin Valley by Houck et al. (1989).

Subsequent to completion of the SCAQS CMB modeling described here, "revised" source profiles became available for which NO_3^-, $SO_4^=$, and NH_4^+ abundances were determined (NEA, 1990a,b,c) for the PRSCAB profile. The new abundances for coarse particle fractions are $0.45 \pm 0.17\%$ for NO_3^-, $0.96 \pm 0.12\%$ for $SO_4^=$, and $0.03 \pm 0.05\%$ for NH_4^+. These differ only slightly from the assumed ion abundances for the PRSCAB profile in Table 2a.

Watson et al. (1993) show scatterplots of source contributions derived from revised and original profiles. In all cases, the slopes are close to unity with negligible intercepts. Correlation coefficients are 1.0 for the 18 sample pairs. Substituting the revised for the original profile resulted in negligible changes in the source contribution estimates.

SOURCE SUBTYPES

To develop PM_{10} emissions control strategies, the major source types must be related to specific types of emitters. The differences in profiles for the species measured have not been sufficient to quantify the contributions of their source subtypes. Estimates of their influence can be made, however, by examining the CMB source apportionments in light of knowledge of the meteorology, emissions, and spatial and temporal distribution of source contributions.

Primary Geological Material

For the primary geological material, source subtypes are paved roads, agricultural tilling, construction, and windblown dust. The proximity of the SCAQS sampling sites to paved roads, and their distance from unpaved roads and agricultural activities, implies that most of the measured geological material originated from paved roads. Since Figure 5a and b shows no correspondence between the geological contributions at different sampling sites, and since the distance between the sampling sites is typically 20–40 km, the influence area for the majority of suspended road dust must be less than the distance between samplers. Thus, paved roads within a few kilometers of the sampling site have the greatest influence on PM_{10}.

Major construction activities were noted only near the Hawthorne site during SCAQS. Evidence of construction contributions was not observed, however, in the form of lime/gypsum contributions. The exception is the Rubidoux site, which is in the vicinity of agricultural fields, cement plants, and grading and quarrying activities. As discussed earlier, it is doubtful that the lime/gypsum profile corresponds to construction near the Rubidoux site.

Primary Motor Vehicle Exhaust

Primary motor vehicle exhaust in this study is defined as those particles which are emitted directly from the tailpipe.

Other motor vehicle-related particulate emissions include brake and tire wear. It was noted above that no evidence of brake or tire wear was found in the paved road dust source profiles or in the SCAQS ambient concentrations. These are negligible contributors to PM_{10}.

Since TC rather than EC or OC was used as a fitting species, it is possible that other sources of OC are represented by the motor vehicle exhaust source profiles. Meat cooking emissions and secondary organic aerosol were identified above as potential interferants. The cooking contribution would probably peak during the evening when most meat is cooked; secondary organic carbon would be expected only on photochemically active days (i.e., summer) in the afternoon at sites in the eastern SoCAB. However, this is not observed in the diurnal plots. It would be desirable to allocate the direct tailpipe emissions from motor vehicles to diesel, leaded, and unleaded gasoline-fueled vehicles. It may be possible for the CMB to resolve this with the proper source profiles, but the currently available profiles are not compatible enough with the SCAQS data set to attempt this.

Secondary Ammonium Nitrate

Secondary ammonium nitrate was a major contributor on many occasions. The sources of its precursors in the SoCAB are nitrogen oxides from motor vehicle exhaust (with some from gas-fired power plants and home heating) and ammonia from agricultural operations.

CONCLUSIONS

SCAQS chemical measurements were sufficient to resolve $PM_{2.5}$ and PM_{10} source contributions of primary geological material, primary motor vehicle exhaust, primary marine aerosol, primary lime/gypsum, and secondary sulfates and nitrates. These measurements were also sufficient to determine that industrial sources and vegetative burning were not major contributors to suspended particles during the summer and fall. The aerosol measurements were insufficient to (1) separate secondary organic aerosols and cooking contributions from other source types, (2) allow different types of fugitive dust to be resolved, and (3) distinguish gasoline-fueled vehicle exhaust from diesel fueled vehicle exhaust.

Primary geological material was the major contributor to PM_{10} during summer at the eastern sites, and its average source contributions to PM_{10} at the Rubidoux and Azusa sites were approximately five times those at the Hawthorne site. Primary geological material contributions were significantly lower during the fall, with the exception of contributions at the Rubidoux site. Rubidoux was the only site which was impacted by the lime/gypsum and quarry operations, and the primary lime/gypsum contribution nearly equalled the primary geological contribution during the fall. From the proximity of sampling sites to heavily travelled paved roads, the source of primary geological material was inferred to be paved road dust at all but the Rubidoux and San Nicolas Island sites.

With respect to PM_{10}, primary motor vehicle exhaust was the largest contributor at the Burbank site, the second largest contributor at the Azusa and Claremont sites, and the third largest contributor at the remaining sites during the summer. The average contributions at the Burbank, Downtown Los Angeles, Rubidoux, Azusa, and Claremont sites were two to three times the average contributions at the Hawthorne, Long Beach, and Anaheim sites. Primary motor vehicle exhaust was also a large contributor at all sites during the fall, which showed much lower contributions from this source during the summer.

Primary marine aerosol showed a fairly homogeneous contribution across the SoCAB during summer, including its contribution at the San Nicolas Island site. The primary marine aerosol contribution decreased during the fall and was substantially lower at the inland sites relative to the sites near the coast.

During the summer, secondary ammonium sulfate contributions were fairly uniform across the SoCAB. During the fall, secondary ammonium sulfate also contributed uniformly across the SoCAB, but its average contribution was less than half that found during the summer.

During the summer, secondary ammonium nitrate contributions were five to ten times larger at the Rubidoux site than at the other sites. During the fall, secondary ammonium nitrate was the second largest contributor at all sites. On average, secondary ammonium sulfate and secondary ammonium nitrate contributed 20% to 32% of the PM_{10} during summer and 20% to 38% of PM_{10} during fall. These secondary contributors accounted for one-half to two-thirds of $PM_{2.5}$.

Secondary organic carbon was not detectable in the SCAQS aerosol data set. Other studies performed during SCAQS (Turpin and Huntzicker, 1991) showed that up to 40% of the organic carbon measured in summertime afternoon samples at Claremont might be of secondary origin.

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