SOURCE APPORTIONMENT OF WINTERTIME PM_{10} AT SAN JOSE, CALIF.

By Judith C. Chow,[1] David Fairley,[2] John G. Watson,[3] Robin DeMandel,[4] Eric M. Fujita,[5] Douglas H. Lowenthal,[6] Zhiqiang Lu,[7] Clifton A. Frazier,[8] Glen Long,[9] and James Cordova[10]

ABSTRACT: A pilot air-quality monitoring study was conducted at two locations in San Jose, Calif., between 12/16/91 and 2/24/92, with daytime (0600 to 1800 PST) and nighttime (1800 to next day 0600 PST) PM_{10} (particulate matter with an aerodynamic diameter less than or equal to 10 μm) samples. Source profiles (the fractional chemical composition of emissions) from local paved road dust were combined with source profiles from other studies for input to the Chemical Mass Balance (CMB) receptor model to apportion the measured PM_{10} to sources and to determine the additional information needed to develop emission-reduction strategies. Residential wood combustion was the largest contributor during this period, especially to nighttime samples, and averaged approximately 45% of the PM_{10} mass. Other significant sources included primary motor vehicle exhaust, resuspended road dust, and secondary ammonium nitrate, each contributing between 15% and 20% of the average wintertime PM_{10}. Secondary ammonium sulfate and primary marine aerosol contributions were detectable, but these contributed less than 5% to the average PM_{10}.

INTRODUCTION

The Bay Area Air Quality Management District (BAAQMD) encompasses an area of more than 14,000 km^2, as shown in Fig. 1. The BAAQMD is bounded on the west by the Pacific Ocean, on the east by the Mt. Hamilton and Mt. Diablo ranges, on the south by the Santa Cruz Mountains, and on the north by the northern reaches of the Sonoma and Napa Valleys. The coastal mountains have nominal elevations of 500 m, though major peaks are much higher (Mt. Diablo, 1,173 m; Mt.Tamalpais, 783 m; Mt. Hamilton, 1,328 m).

The BAAQMD manages air quality in Alameda, Contra Costa, Marin, San Francisco, San Mateo, Santa Clara, and Napa Counties, in the southern part of Sonoma County, and in the southwestern portion of Solano County. More than 6,000,000 people, approximately 20% of California's population, reside within this jurisdiction. Major industries and areas of employment include tourism, government/defense, electronics manufacturing, software development, agriculture (vineyards, orchards, livestock), petroleum refining, power generation, and steel manufacturing. Residences are often distant from employment opportunities, and more than 1,800 km of major controlled-access highways and bridges accommodate approximately 240,000,000 vehicle kilometers traveled on a typical weekday.

The U.S. Environmental Protection Agency (EPA) promulgated the National Ambient Air Quality Standards (NAAQS) for PM_{10} in 1987 to protect human health and welfare ("Regulations" 1987). The BAAQMD began long-term routine monitoring of ambient PM_{10} in 1984, and PM_{10} is currently measured at 14 locations. The federal 24 h PM_{10} standard of 150 $\mu g/m^3$ has been exceeded at the San Jose, San Francisco, and Livermore sites. Table 1 summarizes PM_{10} mass, sulfate, and nitrate concentrations at these standard exceedance sites between 1988 and 1992. Analysis of monitoring data reveals that: (1) The 24-h PM_{10} standard is approached or exceeded only during the months of November, December, and January; (2) the federal annual standard of 50 $\mu g/m^3$ is not exceeded at any of the BAAQMD monitoring sites; (3) the highest PM_{10} levels occur in San Jose; and (4) the state 24-h standard of 50 $\mu g/m^3$ is exceeded at every BAAQMD site (Chow et al. 1993a).

PM_{10} mass often exceeds the federal 24-h standard when nitrate concentrations are high. Annual average nitrate concentrations are typically 2–5 $\mu g/m^3$, but maximum nitrate concentrations exceed 30 $\mu g/m^3$ at several sites during wintertime. Maximum PM_{10} nitrate concentrations are two to five times maximum sulfate concentrations.

As a result of the PM_{10} exceedances, the U.S. EPA is expected to redesignate the Bay Area as nonattainment for PM_{10}, thereby requiring submission of a State Implementation Plan (SIP) (PM_{10} 1987). The California Clean Air Act also specifies annual emissions reductions for attainment of the state ozone standard, and it is possible that this might be extended to other state air-quality standards in the future.

Elevated PM_{10} concentrations result from a combination of emissions, transport, transformation, and accumulation of pollutants. Previous studies [e.g., Chow et al. (1992a, 1992b, 1993b, 1993c) and Watson et al. (1994)] have shown that both primary and secondary particles contribute to high PM_{10} levels in many California cities. Primary particles are directly emitted from pollution sources. These particles undergo few changes between source and receptor, and the atmospheric concentrations are, on average, proportional to the quantities emitted. Secondary particles form in the atmosphere from gases emitted by different sources. Sulfur dioxide (SO_2), oxides of nitrogen (NO_x), and ammonia (NH_3) are the most common precursor gases of secondary particles such as sulfate, nitrate, and ammonium, though a portion of secondary organic carbon can also result from total or reactive organic

[1]Res. Prof., Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV 89506.
[2]Statistician, Bay Area Air Quality Mgmt. Dist., Plng. and Res. Div., 939 Ellis St., San Francisco, CA 94109.
[3]Res. Prof., Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV 89506.
[4]Res. and Modeling Mgr., Bay Area Air Quality Mgmt. Dist., Plng. and Res. Div., 939 Ellis St., San Francisco, CA 94109.
[5]Asst. Res. Prof., Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV 89506.
[6]Asst. Res. Prof., Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV.
[7]Grad. Res. Assoc., Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV.
[8]Asst. Res. Chemist, Desert Res. Inst., Univ. and Community Coll. System of Nevada, P.O. Box 60220, Reno, NV.
[9]Sr. Air Quality Engr., Bay Area Air Quality Mgmt. Dist. Plng. and Res. Div., 939 Ellis St., San Francisco, CA 94109.
[10]Air Quality Meteorologist, Bay Area Air Quality Mgmt. Dist., Plng. and Res. Div., 939 Ellis St., San Francisco, CA.

Note. Discussion open until October 1, 1995. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 5, 1993. This paper is part of the *Journal of Environmental Engineering*, Vol. 121, No. 5, May, 1995. ©ASCE, ISSN 0733-9372/95/0005-0378–0387/$2.00 + $.25 per page. Paper No. 7306.

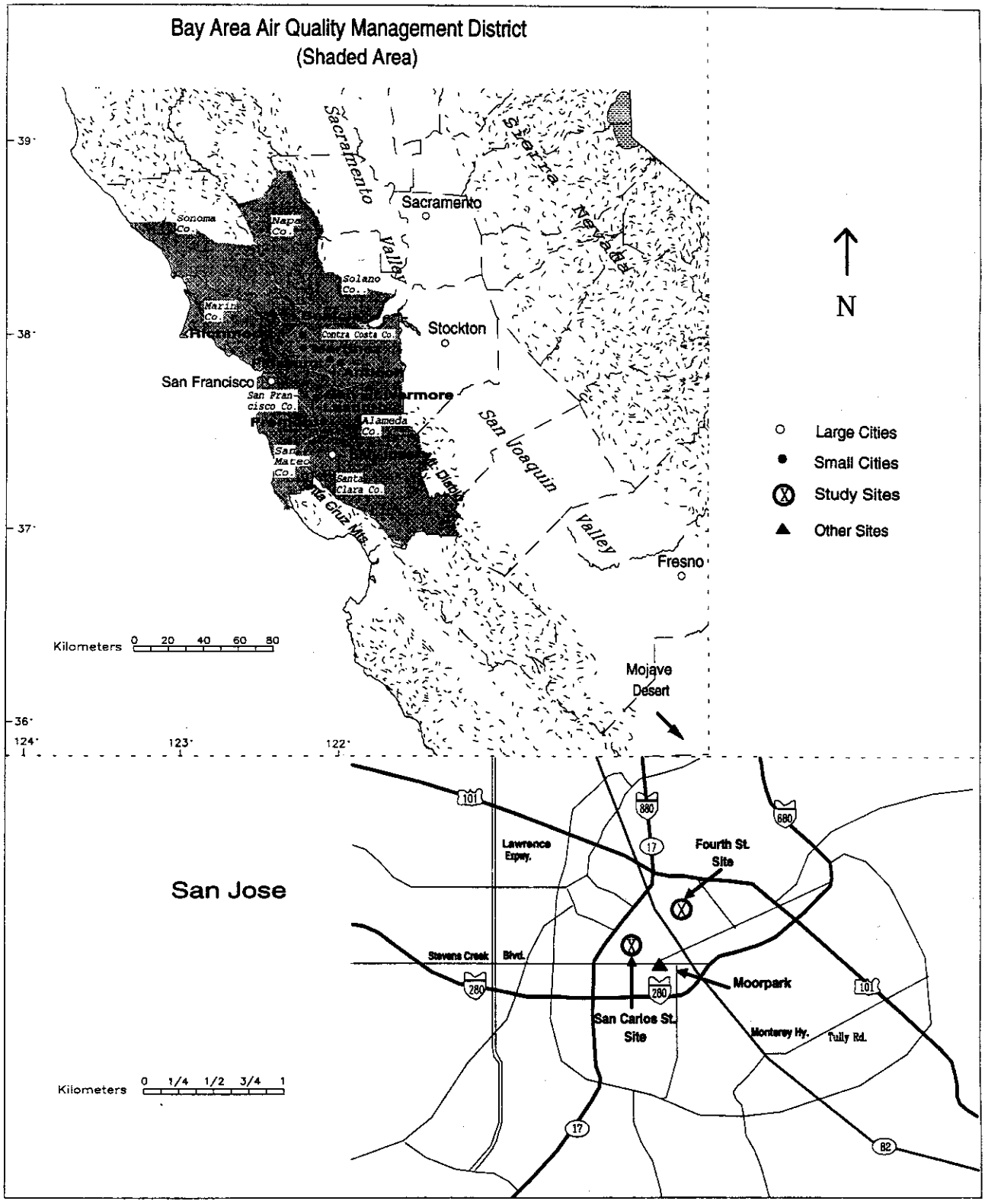


FIG. 1. Bay Area Air Quality Management District Major Landmarks and Fourth St. and San Carlos St. Sampling Sites

gases (TOG, ROG) via atmospheric reactions. Ambient concentrations of secondary aerosol are not necessarily proportional to quantities of emissions since the rate at which they form may be limited by factors other than the concentration of the precursor gases. For example, secondary ammonium nitrate is not a stable compound. Its equilibrium with gaseous ammonia and nitric acid is strongly influenced by temperature and relative humidity (Watson et al. 1994).

A pilot air-quality monitoring study was conducted during wintertime at two sites in San Jose, Calif., to investigate the sources of PM_{10} and to determine the additional information needed to develop emissions-reduction strategies. The ambient chemical compositions and source apportionment results obtained from this study are presented in this paper.

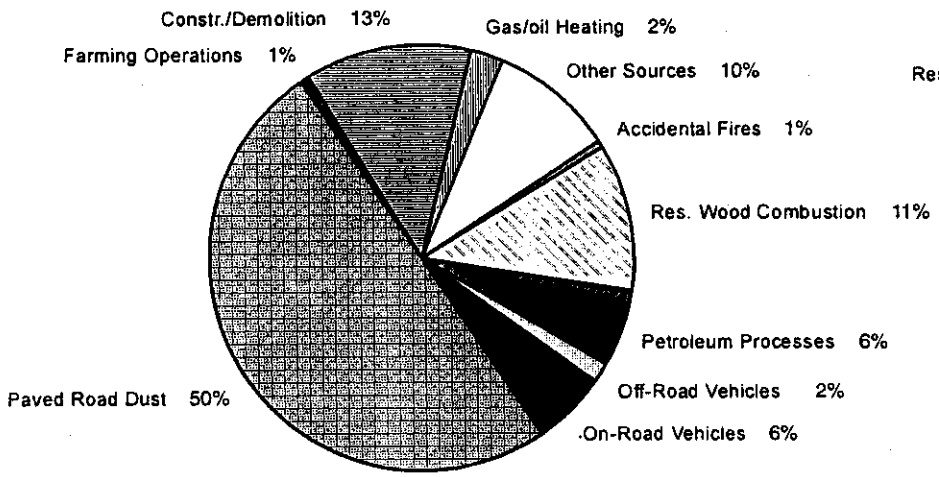
EMISSIONS

Daily emissions of 1,344 tons of TOG, 812 tons of ROG, 536 tons of NO_x, 118 tons of SO_2, 85 tons of NH_3, and 451 tons of PM_{10} were estimated to be released into the atmo-

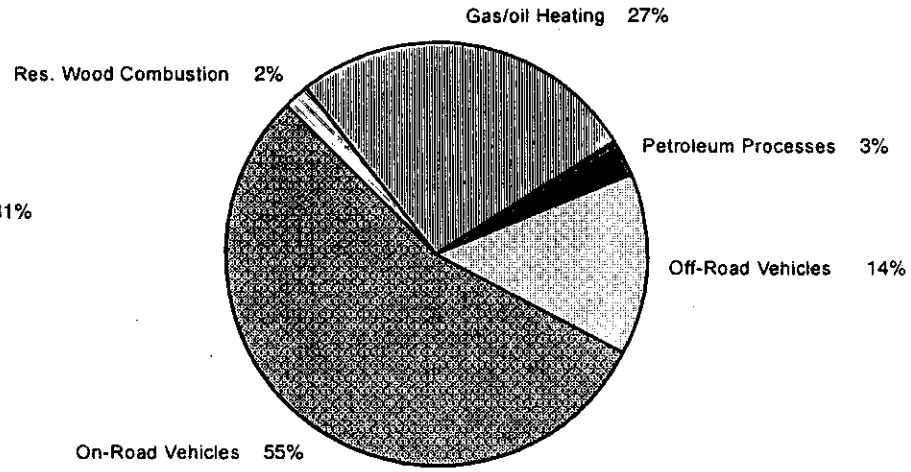
TABLE 1. Annual Statistics for PM_{10} Concentrations between 1988 and 1992

County site (1)	PM_{10} MASS						PM_{10} SULFATE					PM_{10} NITRATE				
	Maximum 24-h ($\mu g/m^3$) (2)	Geometric average ($\mu g/m^3$) (3)	Arithmetic average ($\mu g/m^3$) (4)	Number of Values ($\mu g/m^3$) >150 (5)	>50 (6)	Number of observations (7)	Maximum 24-h ($\mu g/m^3$) (8)	Geometric average ($\mu g/m^3$) (9)	Arithmetic average ($\mu g/m^3$) (10)	Number of values ($\mu g/m^3$) >10 $\mu g/m^3$ (11)	Number of observations (12)	Maximum 24-h ($\mu g/m^3$) (13)	Geometric average ($\mu g/m^3$) (14)	Arithmetic average ($\mu g/m^3$) (15)	Number of values ($\mu g/m^3$) >20 $\mu g/m^3$ (16)	Number of observations (17)
(a) 1988[a]																
Alameda																
Livermore[b,c]	74	25.3	29.8	0	2	19	3.1	1.33	1.51	0	60	14.8	1.34	2.26	0	58
San Francisco																
San Francisco[b,c]	107	25.6	31.5	0	2	19	5.7	1.73	1.95	0	59	26.7	1.03	2.05	1	57
Santa Clara																
San Jose–Moorpark[c,d]	94	30.3	35.0	0	8	40	4.3	1.40	1.65	0	40	8.4	1.47	2.09	0	40
San Jose–4th St.[b]	73	35.9	40.2	0	5	21	4.3	1.58	1.82	0	60	20.6	2.08	3.27	1	58
(b) 1989[e]																
Alameda																
Fremont[b]	77	29.1	32.6	0	5	48	5.5	2.06	2.34	0	48	10.2	1.62	2.22	0	48
Livermore[b]	108	32.7	37.4	0	13	61	16.8	2.05	2.47	1	61	23.0	1.84	2.70	2	61
San Francisco																
San Francisco[b]	101	31.6	36.0	0	13	62	13.9	2.60	2.92	2	61	13.6	1.34	1.84	0	61
Santa Clara																
San Jose–Moorpark[b]	97	32.4	38.0	0	13	61	11.8	2.08	2.44	2	61	27.9	2.05	3.08	2	61
San Jose–4th St.[b,c]	109	29.7[f]	33.8[f]	0	19	135	13.9	2.01	2.35	1	61	26.3	2.29	3.24	3	61
San Jose–W. San Carlos[d]	106	35.6	40.6	0	7	27	4.0	2.15	2.34	0	27	7.7	1.80	2.34	0	27
(c) 1990[g]																
Alameda																
Fremont[b]	136	27.1	32.4	0	10	61	5.0	2.04	2.30	0	61	43.5	2.37	4.09	1	61
Livermore[b]	137	27.5	32.7	0	10	61	6.3	1.84	2.12	0	61	39.9	2.02	3.59	1	61
San Leandro[b]	123	29.3[i]	34.5[i]	0	4	26	4.6	2.15[i]	2.36[i]	0	26	43.0	2.21[i]	4.66[i]	2	26
San Francisco																
San Francisco[b]	165	27.8	34.0	1	12	61	5.3	2.43	2.62	0	61	39.7	1.54	3.08	1	61
Santa Clara																
San Jose-Moorpark[b]	127	29.8	35.4	0	11	61	5.8	1.92	2.17	0	61	33.5	2.53	4.01	1	61
San Jose-4th St.[d]	165	27.1	33.6	1	25	178	7.9	1.78	2.05	0	59	33.1	2.36	4.02	1	59
San Jose-528 Tully[b,c]	122	28.5[h]	35.1[h]	0	5	31	5.9	1.91	2.13	0	61	35.3	2.43	4.09	1	61
San Jose-W. San Carlos[b,c]	134	46.7[h]	55.0[h]	0	5	16	5.9	1.74	1.98	0	60	28.9	2.24	3.58	1	60
(d) 1991[j]																
Alameda																
Fremont[b]	92	27.7	33.7	0	14	59	5.9	2.16	2.43	0	59	23.7	2.95	4.67	1	59
Livermore[b]	155	29.9	36.5	1	12	60	12.1	1.99	2.39	1	60	44.1	2.89	4.91	1	60
San Leandro[b]	99	27.6	32.4	0	10	60	5.5	2.31	2.66	0	60	13.6	2.41	3.71	0	60
San Francisco																
San Francisco[b]	109	29.7	34.9	0	15	60	6.3	2.52	2.78	0	60	30.3	1.75	3.70	1	60
Santa Clara																
San Jose–Moorpark[b]	120	30.6	36.4	0	13	60	5.1	2.07	2.41	0	60	27.7	3.24	5.01	2	60
San Jose–4th St.[d]	153	27.5	33.0	1	26	170	4.5	0.82	1.53	0	98	16.9	0.99	2.51	0	98
San Jose–528 Tully[d]	111	29.1	34.5	0	11	60	7.1	2.03	2.34	0	60	19.7	3.13	4.60	0	60
San Jose–W. San Carlos[d]	111	31.5	37.9	0	14	60	5.0	1.99	2.25	0	60	19.0	3.13	4.58	0	60

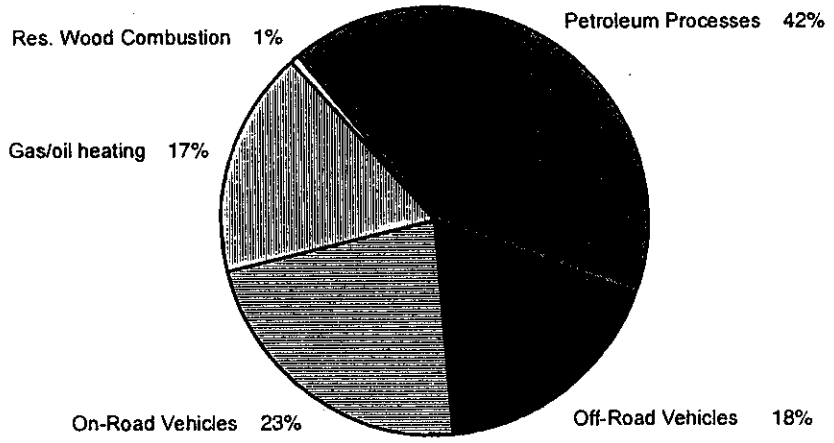
[a]*Air quality* (1989) shows locations of all sampling sites. Sampling sites are grouped by air basin and county.
[b]Gravimetric, Sierra-Andersen Model 1200 high-volume sampler.
[c]Additional annual statistics utilizing a Wedding size-selective inlet are available in Chow et al. (1993a).
[d]Gravimetric, Wedding size-selective inlet high volume sampler.
[e]*Air quality* (1990).
[f]Sampled between 01/01/89 and 08/30/89 with Sierra-Andersen Model 1200 high-volume sampler.
[g]*Air quality* (1991).
[h]Data presented are valid but incomplete in that an insufficient number of valid data points were collected to meet EPA and/or ARB criteria for representativeness.
[i]*Air quality* (1992).



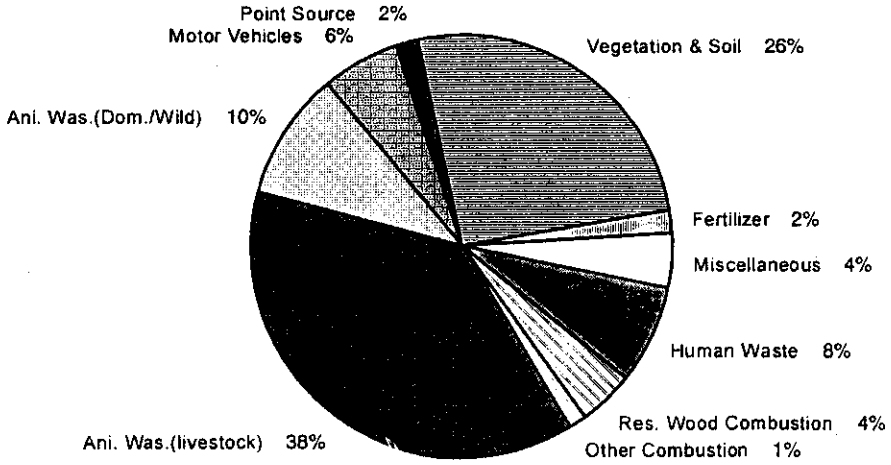
(a) PM10 Total: 451 tons/day



(b) NOx Total: 536 tons/day



(c) SO2 Total: 118 tons/day



(d) NH3 Total: 85 tons/day

FIG. 2. Wintertime (November, December, and January) PM_{10}, Nitrogen Oxides (NO_x), Sulfur Dioxide (SO_2), and Ammonia (NH_3) Emissions Estimates (*1991 Clean* 1992)

TABLE 2. Statistical Summary of Ambient Concentrations during Bay Area Pilot PM_{10} Study

	SAN CARLOS ST.				FOURTH ST.			
	12-h Daytime		12-h Nighttime		12-h Daytime		12-h Nighttime	
Species[a] (1)	Avg (2)	Max[b] (3)	Avg (4)	Max (5)	Avg (6)	Max (7)	Avg (8)	Max (9)
Mass	53.2	92.7	66.7	124.9	56.0	108.5	69.3	115.8
Cl	0.21	0.51	0.99	1.94	0.24	0.59	1.06	2.60
NO_3^-	11.78	18.95	8.29	17.49	12.02	21.46	9.76	21.11
SO_4^{2-}	2.14	6.28	1.94	4.90	2.52	7.25	2.16	5.11
NH_4^+	4.01	8.13	2.89	6.82	4.20	9.92	3.44	7.79
Na^+	0.29	0.65	0.40	1.00	0.34	0.65	0.50	1.34
K^+	0.20	0.39	0.45	0.98	0.26	0.51	0.69	3.57
OC	14.16	20.51	22.65	44.24	14.30	25.98	22.75	39.02
EC	6.20	12.47	9.51	16.93	6.98	14.21	10.19	18.08
Al	0.81	2.00	0.65	1.22	0.93	1.97	0.78	1.28
Si	2.98	6.47	2.39	3.75	2.93	5.74	2.55	3.94
P	0.009	0.047	0.009	0.043	0.006	0.055	0.005	0.059
S	1.139	3.383	0.899	2.296	1.354	4.420	1.037	2.499
Cl	0.156	0.529	1.109	2.666	0.158	0.495	1.179	3.399
K	0.523	0.922	0.910	2.023	0.559	1.032	0.936	1.696
Ca	0.621	1.437	0.518	1.017	0.775	1.552	0.625	1.064
Ti	0.090	0.338	0.086	0.476	0.066	0.121	0.059	0.091
V	0.004	0.011	0.010	0.036	0.004	0.013	0.004	0.010
Cr	0.001	0.004	0.003	0.013	0.003	0.005	0.002	0.009
Mn	0.012	0.026	0.012	0.020	0.014	0.026	0.014	0.022
Fe	0.785	1.601	0.723	1.169	0.824	1.498	0.863	1.307
Co	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Ni	0.002	0.005	0.002	0.006	0.004	0.007	0.004	0.008
Cu	0.020	0.034	0.035	0.072	0.020	0.035	0.030	0.046
Zn	0.053	0.098	0.060	0.108	0.059	0.101	0.073	0.109
Ga	0.000	0.001	0.000	0.001	0.000	0.001	0.000	0.000
As	0.001	0.004	0.002	0.004	0.001	0.002	0.002	0.004
Se	0.003	0.005	0.003	0.006	0.003	0.005	0.003	0.005
Br	0.010	0.026	0.011	0.019	0.011	0.022	0.012	0.022
Rb	0.001	0.003	0.002	0.003	0.001	0.002	0.001	0.003
Sr	0.007	0.014	0.010	0.057	0.016	0.056	0.028	0.112
Y	0.001	0.002	0.001	0.004	0.000	0.001	0.000	0.001
Zr	0.002	0.003	0.001	0.002	0.002	0.003	0.006	0.057
Mo	0.001	0.003	0.001	0.002	0.001	0.003	0.001	0.003
Pb	0.025	0.042	0.034	0.060	0.031	0.054	0.042	0.070
Number in average	9	—	13	—	9	—	13	—

Note: 24-h concentrations, not shown here, are available from the writers.

[a]Species sought but never found above their lower quantifiable limits (defined as three times the standard deviation of the average field blank) were P (<0.0285 μg/m³), Co (<0.0037 μg/m³), Ga (<0.0074 μg/m³), As (<0.0085 μg/m³), Y (<0.0050 μg/m³), Pd (<0.05 μg/m³), Ag (<0.058 μg/m³), Cd (<0.059 μg/m³), In (<0.068 μg/m³), Sn (<0.087 μg/m³), Sb (<0.099 μg/m³), La (<0.46 μg/m³), Au (<0.012 μg/m³), Tl (<0.0094 μg/m³), and U (<0.0091 μg/m³).

[b]Maximum concentrations in the data set. These maxima did not necessarily occur on the same day.

sphere during wintertime in the Bay Area. Alameda, Contra Costa, and Santa Clara Counties (Fig. 1) account for the majority of all emissions, with 59% of TOG, 54% of ROG, 67% of NO_x, 68% of SO_2, 52% of NH_3, and 59% of PM_{10} (*1991 Clean* 1992). As shown in Fig. 2, reentrained road dust is the largest emitter of primary PM_{10}, constituting 50% of the total. Construction and demolition activities account for 13%, residential wood combustion accounts for 11%, and on- and off-road vehicle exhaust accounts for less than 10% of primary PM_{10} emissions in the winter inventory.

Most point-source emissions are located in Contra Costa County, which contains major refineries at Richmond, Martinez, and Benicia, natural-gas-fired power plants at Pittsburg and Antioch, and a steel mill at Antioch. Though these point sources are estimated to emit less than 10% of the primary PM_{10}, they are significant emitters of SO_2 and NO_x. Forty-five percent of SO_2 emissions originate in Contra Costa County. Fig. 2 shows that 42% of district-wide SO_2 emissions derive from petroleum processes. On- and off-road motor vehicles emit over 40% of the SO_2 and more than 70% of the NO_x. Small-scale stationary sources account for less than 25% of NO_x emissions, while large industrial point sources emit less than 5% of total NO_x.

Fig. 2 also shows that 38% of all NH_3 emissions are attributed to livestock waste, 26% to vegetation and soil, 18% to domestic/wild animal and human waste, and less than 10% to industrial point sources and motor vehicle exhaust. Ammonia emissions from wastewater-treatment plants are not included in the current inventory and these may be significant. Actual NH_3 emissions are probably underestimated.

The 1992 BAAQMD emissions inventory is one of the best of its type; however, it does not address temporal distributions for diurnally varying emissions, special circumstances (e.g., plant upsets, specific fires), and intermittent events (e.g., tilling, controlled burns, pesticide applications), which might affect PM_{10} levels at sampling sites near a given source. The inventory does not include some of the source types, such as domestic cooking (e.g., charbroiling and frying) (Hildemann et al. 1991), which might be important contributors to PM_{10} at certain times and places. Although the data in the emissions inventory provide a general understanding of the major emitters, they are not sufficient to determine the major contributors to excessive PM_{10} levels, the chemical composition of PM_{10}, the secondary aerosol contribution to PM_{10}, or the effects of emissions reductions on PM_{10} concentrations. Comparisons with source-contribution estimates and with mi-

croinventories (Pace 1979) in the vicinity of sampling sites are needed to improve estimates of primary and precursor emissions for PM_{10} in San Jose and other parts of the BAAQMD.

METEOROLOGY

The BAAQMD is characterized by complex terrain consisting of coastal mountain ranges, inland valleys, and bays. Temperatures along coastal areas are moderated by the Pacific Ocean and bays, while inland valleys experience greater temperature extremes. Inland valleys experience daytime upslope and nighttime downslope flows.

The summer climate is dominated by the semipermanent east Pacific high-pressure system, and the California coast normally experiences northwest flow and minimal precipitation during summer. A thermal low-pressure area, extending from the San Joaquin Valley to the Mojave Desert, causes onshore flow during most of the summer. The steady northwesterly flow along the eastern edge of the Pacific anticyclone induces upwelling of deep, cold water along the west coast, and air masses cool as they move over the cold coastal water. This cooling is often sufficient to cause condensation, producing frequent summertime occurrences of stratus clouds and radiation fog. Horizontal temperature gradients are largest during the daytime, with moderate temperatures along the coast (~20°C) increasing to ~30°C in the Livermore Valley. Summertime meteorology does not encourage the accumulation of pollutants and it is not conducive to the formation of secondary aerosols.

During winter, the Pacific high weakens and shifts southward, upwelling ceases, onshore flow weakens, and winter storms are frequent, with rain occurring most frequently and with greater intensity from November through April. When the Pacfic high is dominant, surface-based inversions, often due to radiative cooling of the air near the ground, are strong. Light winds and shallow surface layers inhibit the dispersion and dilution of pollutants emitted near the surface. These periods are characterized by radiation fog and winds that flow out of the San Joaquin and Sacramento Valleys into the Bay Area through gaps in the coastal mountains. During winter rainy periods, inversions are weak or nonexistent, winds are often moderate to strong, and air pollution levels are low. The ocean and bays moderate minimum temperatures near these bodies of water. The coldest temperatures are in the sheltered inland valleys, accompanied by strong radiation inversions and limited vertical mixing. The effect of an urban heat island partially counters cooling processes over San Jose in the Santa Clara Valley.

MEASUREMENTS

Samples were taken at two San Jose sites, as shown in Fig. 1, at Fourth St. (downtown commercial district) and West San Carlos St. (commercial residential area, 3 km southwest of downtown San Jose). Daytime (0600 to 1800 PST) and nighttime (1800 to next day 0600 PST) 12-h samples were collected daily from 12/16/91 to 2/24/92 using Desert Research Institute (DRI) sequential filter samples (Chow et al. 1993a) with Graseby-Andersen (formerly Sierra-Andersen) SA 254I medium-volume PM_{10} inlets. Flow rates of 20 L/min were drawn through Teflon-membrane and quartz-fiber filter packs from a total flow rate of 113 L/min through the inlet. Teflon-membrane filters were conditioned under constant temperature and relative humidity for 24-h prior to gravimetric analysis. Quartz-fiber filters were prefired at 900°C for 3 h and refrigerated (<4°C) before and after sampling to minimize organic artifacts.

PM_{10} mass concentrations were measured on Teflon-membrane filters for nearly 150 samples at the two sites. Of these samples, 85 with high (>100 $\mu g/m^3$), medium (~50 $\mu g/m^3$), and low (<25 $\mu g/m^3$) PM_{10} concentrations were selected for chemical analysis to represent all days in the entire sample population. Most, but not all, of these samples were taken on the same day and over the same time interval at both sites (Fairley et al. 1992).

Paved road dust samples were collected adjacent to the Fourth St. and San Carlos St. sites. These samples were dried, sieved, resuspended into PM_{10} size fractions, chemically analyzed, and composited to derive paved road dust source profiles (Chow et al. 1994).

Source and receptor samples were analyzed at the DRI's Environmental Analysis Facility for: (1) mass by gravimetry; (2) 38 elements (Al to U) by X-ray fluorescence; (3) water-soluble chloride (Cl^-), nitrate (NO_3^-), and sulfate (SO_4^{2-}) by ion chromatography; (4) water-soluble ammonium (NH_4^+) by automated colorimetry; (4) water-soluble sodium (Na^+) and potassium (K^+) by atomic absorption spectrophotometry; and (6) organic carbon (OC) and elemental carbon (EC) by thermal/optical reflectance (Chow et al. 1993d; Chow and Watson 1994; Watson and Chow 1994). Ambient and source data are available from the writers in XBase (*.DBF) format on DOS-compatible floppy disks.

CHEMICAL COMPOSITIONS OF PM_{10}

During the pilot study, the highest 12-h PM_{10} concentration of 150.4 ± 7.6 $\mu g/m^3$ was recorded at the San Carlos St. site during nighttime on 12/25/91. The lowest concentration of 8.4 ± 1.0 $\mu g/m^3$ was measured at the Fourth St. site during daytime on 1/12/92. Fig. 3 shows that PM_{10} concentrations for simultaneous samples at the two sites are highly correlated ($r = 0.96$), with slightly lower concentrations at the San Carlos St. site. Pair t-tests showed that statistical differences between PM_{10} measured at the two sites were insignificant ($P > 0.1$).

Twenty-four-hour average PM_{10} concentrations and standard deviations were similar at the two sites: 66.6 ± 28.6 $\mu g/m^3$ at the Fourth St. site and 63.3 ± 28.3 $\mu g/m^3$ at the San Carlos St. site for the chemically analyzed samples. For the entire set of 148 samples, average PM_{10} was 46.2 + 33.7 $\mu g/m^3$ at the Fourth St. site and 47.4 ± 30.1 $\mu g/m^3$ at the San Carlos St. site. Daytime average concentrations were 39.1 ± 32.9 $\mu g/m^3$ at the Fourth St. site, and 37.7 ± 25.6 $\mu g/m^3$ at the San Carlos St. site, while the corresponding nighttime averages were 53.3 ± 36.9 $\mu g/m^3$ and 57.0 + 37.6 $\mu g/m^3$, respectively. Twelve-hour PM_{10} concentrations exceed 100

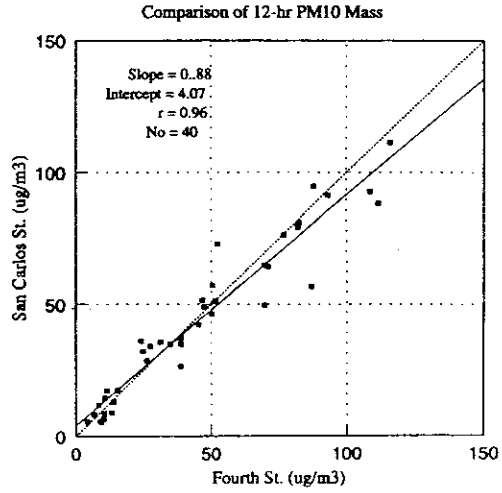


FIG. 3. Comparison of Average 12-h PM_{10} Mass Concentrations at Fourth St. and San Carlos St. Sampling Sites

TABLE 3. Source Profiles Applied in Bay Area Pilot PM_{10} Study (Weight % of Mass)

(1)	Road Dust[a] (SCPVRD) Conc. ± Unc. (2)	Road Dust[a] (SJPVRD) Conc. ± Unc. (3)	Residential Wood Combustion (RWC) (WFIREC1) Conc. ± Unc. (4)	Motor Vehicle Exhaust[c] (PHRD) Conc. ± Unc. (5)	Ammonium Sulfate (AMSUL) Conc. ± Unc. (6)	Ammonium Nitrate (AMNIT) Conc. ± Unc. (7)	Marine Aerosol[d] (MARINE) Conc. ± Unc. (8)
Cl^-	0.160 ± 0.012	0.184 ± 0.014	0.287 ± 0.040	1.157 ± 0.754	0.000 ± 0.000	0.000 ± 0.000	40.000 ± 10.000
NO_3^-	0.000 ± 0.000	0.000 ± 0.000	0.203 ± 0.016	11.025 ± 10.407	0.000 ± 0.000	77.500 ± 7.750	0.005 ± 0.002
$SO_4^{=}$	0.207 ± 0.016	0.107 ± 0.008	0.455 ± 0.036	6.013 ± 2.092	72.700 ± 7.270	0.000 ± 0.000	10.000 ± 4.000
NO_3^-	0.033 ± 0.002	0.024 ± 0.002	0.113 ± 0.014	4.106 ± 2.740	27.300 ± 2.730	22.550 ± 2.255	0.000 ± 1.000
Na^+	0.140 ± 0.010	0.063 ± 0.005	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	40.000 ± 4.000
K^+	0.120 ± 0.011	0.051 ± 0.005	0.521 ± 0.080	0.759 ± 2.315	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
OC	14.526 ± 2.233	12.124 ± 1.864	49.496 ± 5.481	39.003 ± 18.618	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
EC	0.396 ± 0.029	0.545 ± 0.039	21.146 ± 4.581	36.465 ± 10.990	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Al	9.831 ± 2.965	8.883 ± 2.680	0.003 ± 0.010	0.072 ± 0.525	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Si	29.561 ± 9.471	26.516 ± 8.499	0.044 ± 0.017	0.083 ± 1.132	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
P	0.070 ± 0.031	0.055 ± 0.025	0.000 ± 0.005	0.084 ± 0.133	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
S	0.241 ± 0.018	0.243 ± 0.018	0.153 ± 0.017	2.016 ± 0.603	24.270 ± 2.427	0.000 ± 0.000	3.300 ± 1.300
Cl	0.190 ± 0.059	0.097 ± 0.032	0.287 ± 0.040	0.562 ± 0.409	0.000 ± 0.000	0.000 ± 0.000	40.000 ± 10.000
K	2.136 ± 0.438	1.826 ± 0.375	0.635 ± 0.101	0.215 ± 0.229	0.000 ± 0.000	0.000 ± 0.000	1.400 ± 0.200
Ca	4.035 ± 0.708	2.612 ± 0.459	0.066 ± 0.017	0.125 ± 0.981	0.000 ± 0.000	0.000 ± 0.000	1.400 ± 0.200
Ti	0.459 ± 0.033	0.418 ± 0.030	0.001 ± 0.012	0.087 ± 0.401	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
V	0.017 ± 0.019	0.015 ± 0.018	0.001 ± 0.005	0.023 ± 0.201	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Cr	0.015 ± 0.003	0.013 ± 0.004	0.000 ± 0.001	0.019 ± 0.040	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Mn	0.080 ± 0.007	0.090 ± 0.008	0.003 ± 0.001	0.178 ± 0.114	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Fe	5.134 ± 0.363	5.797 ± 0.413	0.004 ± 0.002	0.934 ± 0.529	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Co	0.000 ± 0.074	0.000 ± 0.083	0.001 ± 0.001	0.003 ± 0.089	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Ni	0.014 ± 0.001	0.017 ± 0.001	0.000 ± 0.001	0.019 ± 0.015	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Cu	0.014 ± 0.001	0.015 ± 0.001	0.000 ± 0.001	0.356 ± 0.135	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Zn	0.135 ± 0.010	0.131 ± 0.009	0.076 ± 0.005	0.505 ± 0.387	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Ga	0.000 ± 0.003	0.000 ± 0.002	0.000 ± 0.002	0.007 ± 0.057	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
As	0.002 ± 0.011	0.000 ± 0.015	0.000 ± 0.002	0.006 ± 0.094	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Se	0.000 ± 0.001	0.000 ± 0.001	0.000 ± 0.001	0.004 ± 0.034	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Br	0.001 ± 0.002	0.001 ± 0.001	0.003 ± 0.001	0.058 ± 0.034	0.000 ± 0.000	0.000 ± 0.000	0.200 ± 0.050
Rb	0.007 ± 0.001	0.007 ± 0.001	0.001 ± 0.001	0.002 ± 0.033	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Sr	0.032 ± 0.002	0.041 ± 0.003	0.001 ± 0.001	0.004 ± 0.048	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Y	0.003 ± 0.001	0.002 ± 0.001	0.000 ± 0.001	0.009 ± 0.050	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Zr	0.012 ± 0.001	0.010 ± 0.001	0.000 ± 0.001	0.010 ± 0.063	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Mo	0.001 ± 0.003	0.001 ± 0.002	0.000 ± 0.002	0.010 ± 0.106	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000
Pb	0.062 ± 0.005	0.088 ± 0.007	0.003 ± 0.002	0.270 ± 0.126	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 1.000

[a]Geological profiles of paved road dust from San Carlos St. (SCPVRD) and Fourth St. (SJPVRD).
[b]Residential wood combustion (fireplace and woodstove) profiles from Denver, Colo. (Watson et al. 1988).
[c]Motor vehicle exhaust profiles from Phoenix, Ariz. (Watson et al. 1991b).
[d]Marine profile from U.S. EPA Source Composition Library (*Air emissions* 1990).

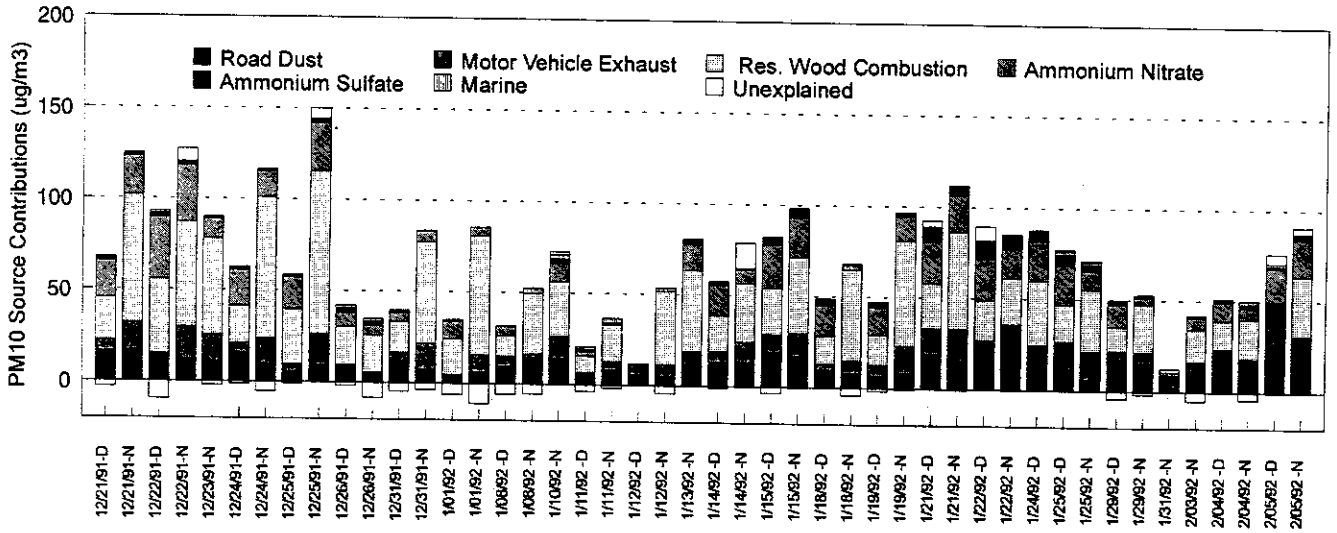


FIG. 4. Daytime (D) and Nighttime (N) PM_{10} Source Contributions at San Jose–San Carlos St. Site (Height of Bars Represents PM_{10} Mass Concentrations; Positive or Negative Unexplained Portions Indicate the Under- or Overestimation of PM_{10} Mass, Respectively, from CMB Model Calculations

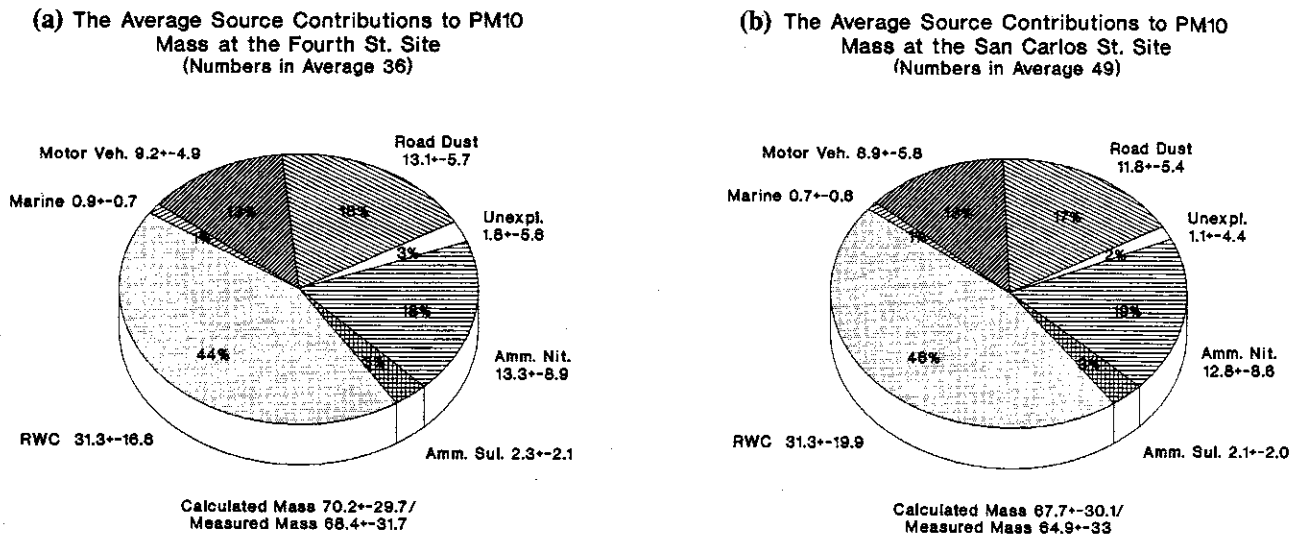


FIG. 5. Average Source Contributions to Wintertime PM_{10} for Primary Paved Road Dust, Primary Motor Vehicle Exhaust, Primary Marine, Primary Residential Wood Combustion (RWC), Secondary Ammonium Sulfate, and Secondary Ammonium Nitrate

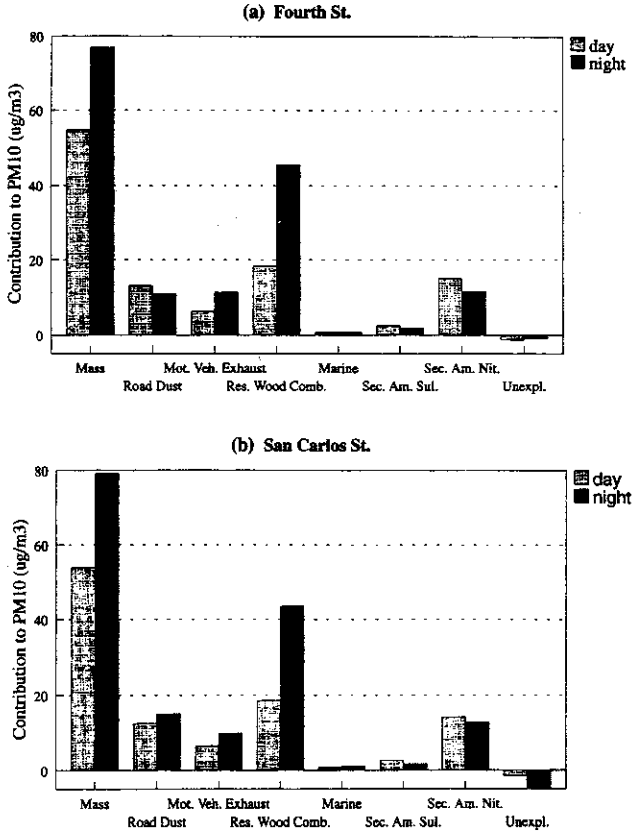


FIG. 6. Day/Night Comparisons of PM_{10} Mass Based on 7 Day/Night Pairs at Fourth St. Site and 19 Day/Night Pairs at San Carlos St. Site

$\mu g/m^3$ (twice the California 24-h standard) on 5% of the days during the study period, with nighttime concentrations consistently ~40% higher than daytime concentrations.

Average and maximum PM_{10} mass and chemical concentrations for the daytime and nighttime are reported in Table 2 for those samples that had paired chemical analysis results for both sites. Table 2 shows that OC, EC, NO_3^-, SO_4^{2-}, and NH_4^+ were the most abundant chemical components and accounted for more than 80% of PM_{10} in the analyzed samples. The sum of the measured chemical species in the analysis subset explains 83 ± 3% of the total PM_{10} mass. Organic carbon (OC) was the most abundant chemical, with an average concentration of 19 ± 6 $\mu g/m^3$ and an average PM_{10} mass fraction exceeding 40%. Average and maximum OC concentrations were 40% and 50% higher at night than they were during the day; the same is true for daytime and nighttime EC concentrations. These wintertime OC concentrations are 30% to 50% higher than annual averages in the South Coast (Solomon et al. 1989) and San Joaquin Valley (Chow et al. 1993b) air basins.

Nitrate is the second most abundant species, with concentrations ranging from 0.5–20 $\mu g/m^3$, and an average of ~10 ± 7 $\mu g/m^3$. Nitrate accounted for ~17% of the average PM_{10} mass. This nitrate average is comparable to annual averages reported in the South Coast (Solomon et al. 1989) and San Joaquin Valley (Chow et al. 1993b) air basins.

Aluminum, silicon, potassium, calcium, titanium, and iron concentrations were also similar at the two sites and accounted for ~15% of the PM_{10} mass. The average PM_{10} silicon concentration was 2.9 ± 1.2 $\mu g/m^3$ at both sites, which is similar to annual average crustal concentrations at South Coast urban sites (Solomon et al. 1989). These concentrations were 30% to 50% lower than those found in annual averages for the San Joaquin Valley (Chow et al. 1993b).

Average soluble potassium (K^+) was 0.61 ± 0.57 $\mu g/m^3$ at the Fourth St. site and 0.37 ± 0.15 $\mu g/m^3$ at the San Carlos St. site. Nighttime average and maximum K^+ concentrations were twice those measured during the day. The average nighttime soluble potassium to total potassium ratio was 0.74 at the Fourth St. site and 0.50 at the San Carlos St. site. This large fraction of potassium, which is soluble, is typical of residential wood combustion contributions from woodstoves and fireplaces (Watson et al. 1988; Chow et al. 1993c).

SOURCE APPORTIONMENT

Using the source profiles listed in Table 3, the Chemical Mass Balance (CMB) receptor model (Watson et al. 1990) was applied to this data set to estimate source contributions to PM_{10} following the U.S. EPA application and validation protocol (Watson et al. 1991a). Fig. 4 summarizes the individual daytime and nighttime source contributions to PM_{10} at the San Carlos St. site. PM_{10} concentrations and source contributions varied fivefold over different day and night periods. The percent mass explained was 100 ± 10% in most cases. Standard errors of source contribution estimates were typically ±15% to ±25% for major contributors. Similar source contributions were obtained at the Fourth St. Site.

Model output is available in computerized form from the writers.

Average PM_{10} source contributions at the two sites are compared in Fig. 5. These source contributions are similar for the two sites. During the pilot study, the largest contributor was residential wood combustion, accounting for ~45% (31.3 $\mu g/m^3$ on average) of the PM_{10} mass for the analyzed samples. Primary geological material was the second-largest contributor, accounting for ~18% (12.5 $\mu g/m^3$ on average) of the PM_{10} mass. Primary motor vehicle exhaust and secondary ammonium nitrate contributed 13–19% (9–13 $\mu g/m^3$ on average) of the PM_{10} mass.

Secondary ammonium sulfate contributions varied from 0 to 10 $\mu g/m^3$, with typical values of 2–3 $\mu g/m^3$ (3–4% of PM_{10} mass). Primary marine-derived aerosol was detected (<1 $\mu g/m^3$), with a maximum contribution (± uncertainty) of 3.6 ± 0.4 $\mu g/m^3$ during the nighttime on 1/11/92 at the Fourth St. site.

Average daytime and nighttime source contributions are compared in Fig. 6. Nighttime residential wood-combustion contributions exceeded twice the daytime contributions. Primary motor vehicle exhaust contributions were 50–80% higher at night than during the day. Contributions from primary geological material and secondary ammonium nitrate were similar for daytime and nighttime samples, however.

Residential wood combustion emissions on cold winter nights and motor vehicle exhaust emissions from morning and evening rush hours, coupled with lower wind speed and less mixing at nighttime during these periods, may result in higher PM_{10} at night.

COMPARISONS BETWEEN PM_{10} SOURCE CONTRIBUTIONS AND ESTIMATED EMISSION RATES

Fractional CMB source contributions to PM_{10} ranged from 24% to 87% from wood combustion, 6% to 49% from road dust, 7% to 53% from vehicle exhaust, and 3% to 40% from secondary ammonium nitrate.

The BAAQMD emissions inventory gives the impression that over 50% of PM_{10} derived from paved road dust, while the CMB resulted in an average of less than 20% of PM_{10} from geological material for the analyzed samples. The inventory estimates ~10% of PM_{10} from residential wood combustion, compared to an average of ~45% from CMB source apportionment. Motor vehicle exhaust accounts for ~13% of PM_{10} mass in the analyzed samples, which is 5% higher than the contribution estimated in the inventory. Furthermore, the source contributions from ammonium nitrate and ammonium sulfate show that the sources of precursor species such as NO_x, SO_x, and NH_3, are just as important to ambient PM_{10} as are the sources of primary particles.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The wintertime pilot study conducted between 12/16/91 and 2/24/92 at two San Jose sites provide a basis for future studies of PM_{10} in the San Francisco Bay Area. Major conclusions to be drawn from measurements and receptor modeling are as follows:

- The highest 12-h PM_{10} concentration was 150.4 ± 7.6 $\mu g/m^3$ at the San Carlos St. site during nighttime on 12/25/91. No 24-h average PM_{10} concentrations exceeded the PM_{10} standard of 150 $\mu g/m^3$ during this pilot study. Twelve-hour PM_{10} concentrations exceeded 100 $\mu g/m^3$ on 5% of the sampled days. Nighttime concentrations were often ~40% higher than daytime concentrations.
- Organic carbon, elemental carbon, nitrate, and ammonium were the most abundant chemical components of PM_{10}, accounting for more than 80% of average PM_{10} mass.
- PM_{10} concentrations and source contributions were similar at the San Jose sites, indicating that one of these sites is sufficient to characterize San Jose neighborhood air quality.
- Primary residential wood combustion was the largest contributor, accounting for ~45% of PM_{10}. Other major contributors were primary geological material, primary motor vehicle exhaust, and secondary ammonium nitrate—each accounting for 15–20% of the average PM_{10}. Secondary ammonium sulfate and primary marine-derived aerosol contributions are generally low, accounting for only a few percent of PM_{10}.
- Current PM_{10} emissions inventories underestimate the residential wood-combustion and motor-vehicle exhaust contributions, and overestimate the road dust source contributions during winter. In addition, the current inventory does not recognize the significance of precursor gas contributions to secondary PM_{10}.

The pilot study identified the following needs for further understanding, which might be obtained in a more comprehensive study:

- Source profiles for primary geological material, primary motor vehicle exhaust, and primary residential wood combustions should be measured.
- Secondary aerosol precursor concentrations for ammonia and nitric acid are needed along with the PM_{10} measurements to determine which precursor gas concentrations should be reduced to minimize ambient secondary ammonium nitrate concentrations.
- Trajectory and secondary aerosol models should be integrated with CMB receptor modeling to further specify source contributions.
- Better temporal resolution (e.g., 0000 to 0500, 0500 to 1000, 1000 to 1600, and 1600 to 2400 PST) is needed for PM_{10} mass, chemical composition, and precursor gas concentrations.
- Additional sampling sites are needed to determine the causes of elevated PM_{10} concentrations in other regions of the BAAQMD.
- Discrepancies between the Bay Area emissions inventory and CMB receptor modeling need to be reconciled.

A comprehensive PM_{10} study plan (Chow et al. 1993a) specifies the measurements, data analysis, and modeling activities needed to develop emission control strategies. This plan is currently being implemented, and the results are anticipated by 1995.

ACKNOWLEDGMENTS

The analysis presented in this paper was sponsored by the FY92 Section 105 Supplemental Grant from U.S. EPA, Region IX, San Francisco, Calif. The writers thank Barbara Bates of U.S. EPA for assisting with the grant application process. The writers are also grateful to William R. Pierson of the Desert Research Institute (DRI) for reviewing the manuscript and supplying valuable technical advice, and to Kimberly Snow and Bridget Ball of DRI for assembling and editing the manuscript.

APPENDIX. REFERENCES

Air emissions species manual. Vol. II: particulate matter species profiles; 2nd Ed. (1990). Prepared for U.S. EPA by Radian Corp., Research Triangle Park, N.C.

Air quality data: summary of the 1988 air quality data gaseous and particulate pollutants; Vol. XX. (1988). Tech. Support Div., California Air Resour. Board, Sacramento, Calif.

Air quality data: summary of the 1989 air quality data gaseous and particulate pollutants; Vol. XXI. (1990). Tech. Support Div., California Air Resour. Board, Sacramento, Calif.

Air quality data: summary of the 1990 air quality data gaseous and particulate pollutants; Vol. XXII. (1991). Tech. Support Div., California Air Resour. Board, Sacramento, Calif.

Air quality data: summary of the 1991 air quality data gaseous and particulate pollutants; Vol. XXIII. (1992). Tech. Support Div., California Air Resour. Board, Sacramento, Calif.

Chow, J. C., Liu, C. S., Cassmassi, J., Watson, J. G., Lu, Z., and Pritchett, L. C. (1992a). "A neighborhood-scale study of PM_{10} source contributions in Rubidoux, California. *Atmos. Envir.*, Vol. 26A, 693–706.

Chow, J. C., Watson, J. G., Lowenthal, D. H., Solomon, P., Magliano, K., Ziman, S., and Richards, L. W. (1992b). "PM_{10} source apportionment in California's San Joaquin Valley." *Atmos. Envir.*, 26A(18), 3335–3354.

Chow, J. C., Watson, J. G., DeMandel R., Chan, W., Cordova, J., Fairley, D., Fujita, E. M., Levaggi, D., Long, G., Perardi, T., and Rothenberg, M. (1993a). "Measurements and modeling of PM_{10} in the San Francisco Bay Area; Vol. I: program plan." *DRI Document 3654.2F*, Prepared for Bay Area Air Quality Management District, San Francisco, Calif., by Desert Res. Inst., Reno, Nev.

Chow, J. C., Watson, J. G., Lowenthal, D. H., Solomon, P. A., Magliano, K., Ziman, S., and Richards, L. W. (1993b). "PM_{10} and $PM_{2.5}$ compositions in California's San Joaquin Valley." *Aerosol Sci. Technol.*, Vol. 18, 105–128.

Chow, J. C., Watson, J. G., Ono, D. M., and Mathai, C. V. (1993c). "PM_{10} standards and nontraditional particulate source controls: a summary of the A&WMA/EPA international specialty conference." *Air & Waste*, Vol. 43, 74–84.

Chow, J. C., Watson, J. G., Pritchett, L. C., Pierson, W. R., Frazier, C. A., and Purcell, R. G. (1993d). "The DRI Thermal/Optical Reflectance Carbon Analysis System: description, evaluation and applications in U.S. air quality studies." *Atmos. Environ.*, Vol. 27A, 1185–1201.

Chow, J. C., and Watson, J. G. (1994). "Guidelines for PM_{10} sampling and analysis applicable to receptor modeling." *EPA-452/R-94-009*, Prepared for Office of Air Quality Planning and Standards, U.S. Envir. Protection Agency, Research Triangle Park, N.C., by Desert Res. Inst., Reno, Nev.

Chow, J. C., Watson, J. G., Houck, J. E., Pritchett, L. C., Rogers, C. F., Frazier, C. A., Egami, R. T., and Ball, B. M. (1994). "A laboratory resuspension chamber to measure fugitive dust size distributions and chemical compositions." *Atmos. Envir.*, 28, 3463–3481.

Fairley, D., DeMandel, R., Rothenberg, M., and Perardi, T. (1992). "Results from the 1991–92 pilot study of wintertime PM_{10} in the San Francisco Bay Area." *Document BAAQMD TM 92002*, Plng. and Res. Div., Bay Area Quality Mgmt. Dist., San Francisco, Calif.

Hildemann, L. M., Markowski, G. R., Jones, M. C., and Cass, G. R. (1991). "Submicrometer aerosol mass distributions of emissions from boilers, fireplaces, automobiles, diesel trucks, and meat-cooking operations." *Aerosol Sci. Technol.*, Vol. 14, 138–152.

1991 Clean Air Plan. Appendix H. (1992). Bay Area Air quality Management District, San Francisco, Calif.

Pace, T. G. (1979). "An empirical approach for relating annual TSP concentrations to particulate microinventory emissions data and monitor siting characteristics." *Document EPA-450/4-79-012*, U.S. Envir. Protection Agency, Research Triangle Park, N.C.

PM_{10} SIP development guideline; EPA-450/2-86-001. (1987). Ofc. of Air Quality Plng. and Standards, U.S. Envir. Protection Agency, Research Triangle Park, N.C.

"Regulations for implementing revised particulate matter standards: 40 CFR parts 51 and 52." (1987). *Federal Register*, 24672.

Solomon, P. A., Fall, T., Salmon, L., Cass, G. R., Gray, H. A., and Davison, A. (1989). "Chemical characteristics of PM_{10} aerosols collected in the Los Angeles area." *J. Air Pollution Control Assoc.*, Vol. 39, 154–163.

Watson, J. G., Chow, J. C., Richards, L. W., Neff, W. D., Andersen, S. R., Dietrich, D. L., Houck, J. E., and Olmez, I. (1988). "The 1987–88 Metro Denver Brown Cloud Study; Vol. II: measurements." *DRI Document 8810.1F2*, Prepared for the 1987–88 Metro Denver Brown Cloud Study, Inc., by Desert Res. Inst., Reno, Nev.

Watson, J. G., Robinson, N. F., Chow, J. C., Henry, R. C., Kim, B. M., Pace, T. G., Meyer, E. L., and Nguyen, Q. (1990). "The USEPA/DRI chemical mass balance receptor model, CMB 7.0." *Envir. Software*, Vol. 5, 38–49.

Watson, J. G., Chow, J. C., and Pace, T. G. (1991a). "Chemical mass balance." *Data handling in science and technology. Volume 7: receptor modeling for air quality management.* P. K. Hopke, ed., Elsevier Press, New York, N.Y., 83–116.

Watson, J. G., Chow, J. C., Richards, L. W., Haase, D. L., McDade, C., Dietrich, D. L., Moon, D., and Sloane, C. (1991b). "The 1989–90 Phoenix Urban Haze Study Volume II: the apportionment of light extinction to sources—final report." *DRI Document 8931.5F1*, Prepared for Arizona Department of Environmental Quality, Phoenix, Ariz., by Desert Res. Inst., Reno, Nev.

Watson, J. G., and Chow, J. C. (1994). "Particle and gas measurements on filters." *Sampling of environmental materials for trace analysis* (B. Markert, ed., VCH-Publisher, New York, N.Y., 125–161.

Watson, J. G., Chow, J. C., Lurmann, F. W., and Musarra, S. P. (1994). "Ammonium nitrate, nitric acid, and ammonia equilibrium in wintertime Phoenix, Arizona." *Air & Waste*, Vol. 44, 405–412.