CONTROL OF ATMOSPHERIC FINE PRIMARY CARBON PARTICLE CONCENTRATIONS

Thesis by

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to my family

and Melissa

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ABSTRACT

The adverse health effects and urban visibility degradation associated with atmospheric carbon particle concentrations suggest that control of this class of air pollutants is desirable, especially in the event of an increase in the usage of diesel vehicles. In this study, procedures for the engineering design of fine carbonaceous particulate matter abatement strategies have been developed and tested in the Los Angeles area. Carbon particle abatement strategies are evaluated based on the results of an emissions to air quality model, the performance of which is verified by comparison to measurements of ambient aerosol concentrations taken in the South Coast Air Basin during 1982.

As a result of this research, the long-term average behavior of fine aerosol carbon concentrations has been characterized in the Los Angeles area for the first time. The highest concentrations of fine particulate total carbon were observed in areas of heavy traffic density. The annual average fine total carbon concentration at downtown Los Angeles was 12.2 $\mu g\ m^{-3}$ during 1982, which constituted 37% of the fine aerosol ($d_p < 2.1\ \mu m$) mass collected at that location. Aerosol carbon concentrations were observed to decrease with distance inland from downtown Los Angeles. The 1982 annual average fine total carbon concentration at Rubidoux, which is about 80 km east of Los Angeles, was only 8.2 $\mu g\ m^{-3}$. There is a pronounced winter peak and summer minimum in carbonaceous aerosol concentrations in the western portion of the air basin. The monthly average fine total carbon

concentration at downtown Los Angeles reached a high of 22.3 μg m^{-3} during December 1982, and dropped to 7.4 μg m^{-3} during June 1982. At eastern locations in the air basin, the seasonal trend becomes less significant, with monthly average fine total carbon concentrations at Rubidoux observed to be between 6.4 and 10.8 μg m^{-3} during all months of 1982.

Elemental carbon in the atmosphere is inert and is due solely to direct (primary) aerosol emissions from sources, while organic carbon could be directly emitted as primary aerosol or could be formed in part from condensation of the low vapor pressure products of atmospheric chemical reactions (secondary formation). Examination of the spatial and temporal trends of the ratio of fine total carbon to fine elemental carbon concentration leads to the conclusion that secondary organic carbon aerosol formed in the atmosphere from hydrocarbon precursors was not the overwhelming contributor to overall long-term average total carbon levels in the Los Angeles area during the year 1982. At downwind locations, such as Azusa or Rubidoux, it was found that, at most, between 16% and 22% of the annual average total carbon concentration (or 27% to 38% of the organic carbon) may be due to secondary aerosol formation in excess of that found at Lennox (a near-coastal site next to a heavily travelled freeway source of primary aerosol). Comparison of fine elemental and organic carbon particle concentrations against the ratio of those two aerosol species found in basin-wide source emissions further indicates that, over long averaging times during 1982, primary aerosol carbon particle emissions

are responsible for the majority of atmospheric carbon particle concentrations.

The particulate air quality data collected during 1982 were used to verify the performance of a mathematical model for long-term average air quality. The Lagrangian particle-in-cell air quality model previously developed by Cass (1977, 1981) was improved to handle near-source dispersion from ground level sources. The model was tested against emissions, elemental carbon air quality, and meteorological data for 1982 in the Los Angeles area. It was found that the model adequately predicts the long-term average concentration of this primary pollutant. The predictions and observations of monthly average elemental carbon particle concentrations have a positive correlation coefficient of 0.78. The model also determines the source classes responsible for fine carbon particle air quality. Many source types, including highway vehicles, charcoal broilers, and fireplaces contribute to primary total carbon particle concentrations, while elemental carbon concentrations are due mostly to emissions from diesel engines.

The source class contributions computed by the air quality model were used to determine the optimal emission control strategy for attaining any desired level of improved carbon particle air quality. Linear programming techniques were employed to solve for the least costly set of emission control measures which would enable an air quality goal to be met. Solutions indicate that application of a few control measures, aimed almost entirely at diesel engines, will reduce the basin-wide maximum annual average fine elemental carbon concentration approximately by half at an annual cost of about $69 million. The maximum annual average fine primary total carbon concentration may be reduced by about 35% at a cost of $102 million per year. A control program for visibility improvement would preferentially require the reduction of atmospheric fine elemental carbon particle concentrations, whereas a program designed to control fine aerosol mass would benefit from total carbon particle concentration reductions. It was determined that a control strategy that is optimal for total carbon control may be near-optimal for elemental carbon control. However, an emissions control strategy designed to optimize for elemental carbon control may produce peak total carbon concentrations that exceed those which would result from a control strategy optimized for total carbon by as much as 8%.

In summary, it has been demonstrated that the air quality model is useful both in predicting long-term average carbon particle air quality and in determining the sources responsible for that air quality outcome. It was found that emissions from diesel engines were responsible for a large portion of the atmospheric fine carbon particle concentrations in the Los Angeles area during 1982. Control of emissions from diesel engines is therefore important, and it was determined that the least costly set of emission control measures for reducing carbon particle concentrations includes many diesel engine emission controls.

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GLOSSARY

Coarse particles - airborne particulate matter with particle sizes greater than 2.1 µm in diameter.

Elemental carbon - black carbonaceous particulate matter with a chemical structure similar to impure graphite and that is non-volatile below 600°C in an inert atmosphere (helium).

Fine particles - airborne particulate matter with particle sizes smaller than 2.1 µm in diameter.

Particulate organic carbon - the carbon content of airborne organic compounds present as particulate matter in the atmosphere.

Particulate total carbon - The summation of the airborne particulate carbon content due to all particle types present, including organic carbon, carbonate carbon and elemental carbon.

Primary aerosol carbon - that fraction of the airborne carbonaceous particulate matter that was emitted to the atmosphere from its source as particulate matter (eg. as a solid or liquid) rather than as a hydrocarbon gas.

Secondary aerosol carbon - carbonaceous particulate matter formed in the atmosphere from the low vapor pressure products of reactions involving gaseous hydrocarbon precursors.

CHAPTER 1

INTRODUCTION

1.1 Problem Definition

Particulate air pollutants residing in particle sizes below about 2 μm aerodynamic diameter are largely responsible for the severe visibility deterioration observed in the South Coast Air Basin that surrounds the Los Angeles area (Hidy et al. 1974, White and Roberts 1977, Cass 1976, Conklin et al. 1981). Particles in that size range are easily respirable (Task Group 1966) and thus contribute to many of the adverse health effects attributed to high levels of total suspended particulate matter in the atmosphere (Middleton et al. 1969). Control of the fine particle fraction of the ambient aerosol is, therefore, a particularly important problem facing state and local air pollution control agencies.

Studies show that most of the fine particulate matter in the atmosphere of the South Coast Air Basin consists of sulfates, nitrates, and carbonaceous particles (Hidy et. al 1974). As will be seen in Chapter 2 of this study, aerosol carbon alone accounts for about 40% of the total fine particle mass in that air basin. Hence, its control is critical to any attempt to meet present total suspended particulate matter and future fine particle air quality standards. Black graphitic (elemental) carbon particles have been found to be the predominant light-absorbing aerosol species in the atmosphere (Rosen et al. 1977) and are responsible for a major portion of the Los Angeles visibility problem (Conklin et al. 1981). Polynuclear aromatic hydrocarbons that are adsorbed onto soot particles have been shown to be carcinogenic in experimental animal studies (IARC Working Group 1980). Thus an assessment of approaches to reducing atmospheric soot concentrations may provide valuable insights concerning the control of toxic substances in the atmosphere.

Despite the importance of aerosol carbon particles as contributors to particulate air quality and visibility standard violations, relatively little is known about how to control such pollutants effectively. Routine air monitoring data bases sufficient to support aerosol carbon control strategy studies do not presently exist for the Los Angeles area (Wadley and Witz 1981, Tsou 1981). Inventory procedures for defining organic and elemental carbon emissions are in their earliest stages of development at present (Cass et al. 1982). Air quality modeling approaches designed to assess the sources responsible for atmospheric carbon particle concentrations previously have been limited to rollback and receptor model calculations that cannot be verified easily because the elemental composition of emissions from many different carbonaceous particulate source types is virtually identical. The problem is compounded due to the presence of secondary organic aerosol that is formed in the atmosphere from the low vapor pressure products of reactions involving gaseous hydrocarbon precursors (Grosjean and Friedlander 1975, Schuetzle 1975, Cronn et al. 1977, Grosjean 1977, Appel et al. 1979).

Better air quality modeling approaches are needed. Methods for identifying the least costly combination of control technologies required to attain any desired level of aerosol carbon air quality should be developed. Control strategies aimed at abating fine total carbon particle mass might look quite different than strategies directed at abating the visibility-reducing potential of elemental carbon particles alone.

The pursuit of methods for controlling atmospheric carbon particle air quality is particularly important in Los Angeles at this time. As noted by Pierson (1978), Los Angeles air quality is likely to be heavily affected by increased soot emissions if large numbers of diesel passenger cars are introduced into the vehicle fleet. Engineering research into control of aerosol carbon concentrations is needed before conversion of more of the vehicle fleet to diesel engines occurs.

1.2 Approach of the Present Study

The objective of the present study is to develop methods for the design of emission control strategies that can be employed to reduce atmospheric primary carbonaceous aerosol loadings, thereby improving visibility and reducing exposure to respirable fine particles. Methods developed will be tested during a case study of aerosol carbon abatement alternatives in the South Coast Air Basin.

At the start of this research effort, an air quality data base suitable to support control strategy development in the Los Angeles area did not exist. As part of this study, a routine sampling program is conducted during the calendar year of 1982. Twenty-four hour average ambient fine particulate matter samples are collected at six-day intervals at ten monitoring locations in the South Coast Air Basin. The samples are analyzed for total carbon and elemental carbon (total carbon = elemental carbon + organic carbon) by the method of Johnson et al. (1981). Measurement of the trace metal content of samples provides the ability to use receptor modeling techniques (Cooper and Watson 1980, Gordon 1980) to confirm source class contributors to observed air quality. Measurement of $SO_4^=$, NO_3^-, and NH_4^+ ion concentrations completes a mass balance on the major aerosol components of the samples. The sampling program described in Chapter 2 results in a representative set of air quality data that is used to characterize an annual cycle of fine carbon particle air quality in the Los Angeles area. The air quality data set also can be used to verify the predictions of an air quality model describing the transport of primary pollutants in an urban airshed.

The relative importance of secondary organics formation is assessed in Chapter 2 by comparing measured ambient (primary plus secondary) total carbon to elemental carbon concentration ratios with the same ratios observed at emission sources (which yield primary aerosol only). Development of new methods for evaluating the magnitude of secondary aerosol formation is extremely important. The extent to which primary particulate sources versus gas phase hydrocarbon sources should be controlled depends on the outcome of such an inquiry, and present methods for making such determinations have led to longstanding scientific disputes (Gundel 1978).

A mathematical description of the atmospheric transport of fresh emissions of a non-reactive pollutant over an air basin is developed in Chapter 3. The model employs a Lagrangian particle-in-cell technique to predict long-term average concentrations of an inert pollutant, such as elemental carbon. The calculation procedure is formulated to simulate atmospheric transport processes including ground-level dry deposition and vertical diffusion. Particular attention is given to the mixing of pollutants in the vertical direction at locations close to sources.

In Chapter 4 the model is used to predict 1982 monthly averaged fine carbonaceous particle concentrations in the Los Angeles atmosphere. Data requirements for the model application are outlined and satisfied. An inventory of fine carbonaceous particulate emissions is compiled for an 80X80-km (50X50-mile) grid centered over the western portion of the South Coast Air Basin. Over 70 source types are identified, and carbonaceous aerosol emissions are matched to the model in such a way as to represent spatial and temporal emissions trends. Source samples are collected and analyzed for a few source types to further improve inventory accuracy. Meteorological data are collected, and the characteristics of ventilation in the air basin are summarized. Other data requirements and approximations necessary for execution of the air quality model are discussed.

Results of the modeling exercise are examined in the latter part of Chapter 4. Since elemental carbon particles are chemically very stable and are due solely to primary emissions, the non-reactive air quality model is verified by focusing on the comparison between predicted and observed fine elemental carbon particle air quality. The comparison of fine primary total carbon concentration predictions to fine total carbon concentration observations provides a new method for estimating the amount of secondary organics present in the atmosphere (i.e., organic particles formed from the condensation products of atmospheric hydrocarbon gas phase reactions). By subtracting calculated primary organic aerosol concentrations from the measured total organic aerosol present, an estimate of the magnitude of the secondary organics present can be obtained.

From the air quality modeling exercise, the contribution from each of many source types to primary aerosol carbon air quality is determined at a number of receptor sites. This source-to-receptor information is combined with data on emission control opportunities to evaluate alternative strategies for aerosol carbon air quality improvement. In Chapter 5, a linear programming algorithm is developed to identify optimal control strategies that provide the least costly combination of aerosol carbon emission control measures needed to attain any desired level of primary aerosol carbon air quality.

The trade-off implied by choice of a strategy optimized for control of total carbon particle concentrations versus an optimal strategy for elemental carbon particle concentrations is examined in

Chapter 5. The effects on visibility (and the likely effects on health) of organic and elemental carbon particles are quite different. Elemental carbon particles are very efficient light absorbers and, therefore, contribute disproportionately to visibility degradation. Hence, the preferential abatement of elemental carbon or organic carbon particles might be selected as an objective of future fine particle control efforts. Chapter 5 shows how preferential control of elemental carbon levels can be achieved.

It is concluded that the air quality model developed during this study is useful for identifying the major sources responsible for high air pollutant concentrations in an urban air basin. This modeling approach could be applied to the problem of designing control strategies for other pollutants and could be applied in other geographic areas. Opportunities for future research and model application are given in Chapter 6.

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CHAPTER 2

CHARACTERISTICS OF ATMOSPHERIC ORGANIC AND ELEMENTAL CARBON PARTICLE CONCENTRATIONS IN LOS ANGELES

2.1 Introduction

Fine carbonaceous particulate matter is emitted from most combustion processes (Siegla and Smith 1981, Wagner 1978, Muhlbaier and Williams 1982, Cass et al. 1982). These primary carbon particles consist of organic compounds accompanied by black non-volatile soot components that have a chemical structure similar to impure graphite (Rosen et al. 1978). The black portion of these particulate emissions, commonly referred to as elemental carbon, is a major contributor to visibility reduction in urban areas (Rosen et al. 1982, Waggoner and Charlson 1977, Pierson and Russell 1979, Conklin et al. 1981, Groblicki et al. 1981, Wolff et al. 1982), and some investigators recently have suggested that light absorption by elemental carbon plays an important role in the earth's radiation budget (Shaw and Stamnes 1980, Rosen et al. 1981, Patterson et al. 1982, Porch and MacCracken 1982, Cess 1983). Organic aerosol components present in vehicular emissions (Pierson et al. 1983) and in ambient samples (Pitts 1983) have been found to be mutagenic in the Ames test, and soots have been shown to be carcinogenic in experimental animal studies (IARC Working Group 1980). As a result, there is considerable interest in the behavior of primary carbon particle concentrations in the atmosphere, and in how those concentrations might be controlled.

Primary emissions of carbonaceous aerosols are not regulated separately from the remainder of the urban aerosol complex. Routine monitoring programs in the United States do not provide data on aerosol carbon concentrations in the atmosphere, and data on the emissions of carbonaceous aerosols are sparse. As a result, information sufficient to support engineering studies of methods for controlling fine carbon particle concentrations is lacking. This control strategy development problem is further complicated by the fact that several studies suggest that a large fraction of the organic aerosol is secondary in origin (i.e., formed in the atmosphere from the low vapor pressure products of reactions involving gaseous hydrocarbon precursors) (Grosjean and Friedlander 1975, Schuetzle et al. 1975, Cronn et al. 1977, Grosjean 1977, Appel et al. 1979). If the overwhelming majority of aerosol carbon was formed in the atmosphere as a secondary product of photochemical reactions, then controls on direct emissions of carbon particles from sources might have little effect on urban air quality.

The present chapter is the first of a series designed to describe methods for achieving deliberate control of urban fine carbon particle concentrations. In this work, the approach used to acquire an air quality model verification data set for organic and elemental carbon concentrations will be described. This method will be demonstrated in Los Angeles, and key characteristics of Los Angeles carbonaceous aerosol air quality will be defined. The spatial and temporal distribution of aerosol carbon concentrations over an entire annual cycle will be described. The geographic areas that experience the highest aerosol carbon concentrations will be identified and related to source density and pollutant transport patterns. The ratio of total carbon to elemental carbon in the atmosphere will be examined as an indicator of the extent of secondary organic carbon aerosol formation. In subsequent chapters, air quality models will be tested against this data set. The importance of major source types to observed aerosol carbon air quality will be quantified through that modeling effort. Mathematical programming methods for defining the most attractive approaches to aerosol carbon control then will be illustrated, using the results of the air quality modeling study.

2.2 Experimental Design

Throughout the year 1982, a fine particle air monitoring network was operated in the Los Angeles area at the locations shown in Figure 2.1. The ten stations marked with solid circles in Figure 2.1 are located in the South Coast Air Basin within the ring of mountains that surrounds Los Angeles. Samples also were collected from March through December at a remote off-shore site, San Nicolas Island, in order to define pollutant concentrations in the marine environment upwind of Los Angeles. Twenty-four hour average fine particle filter

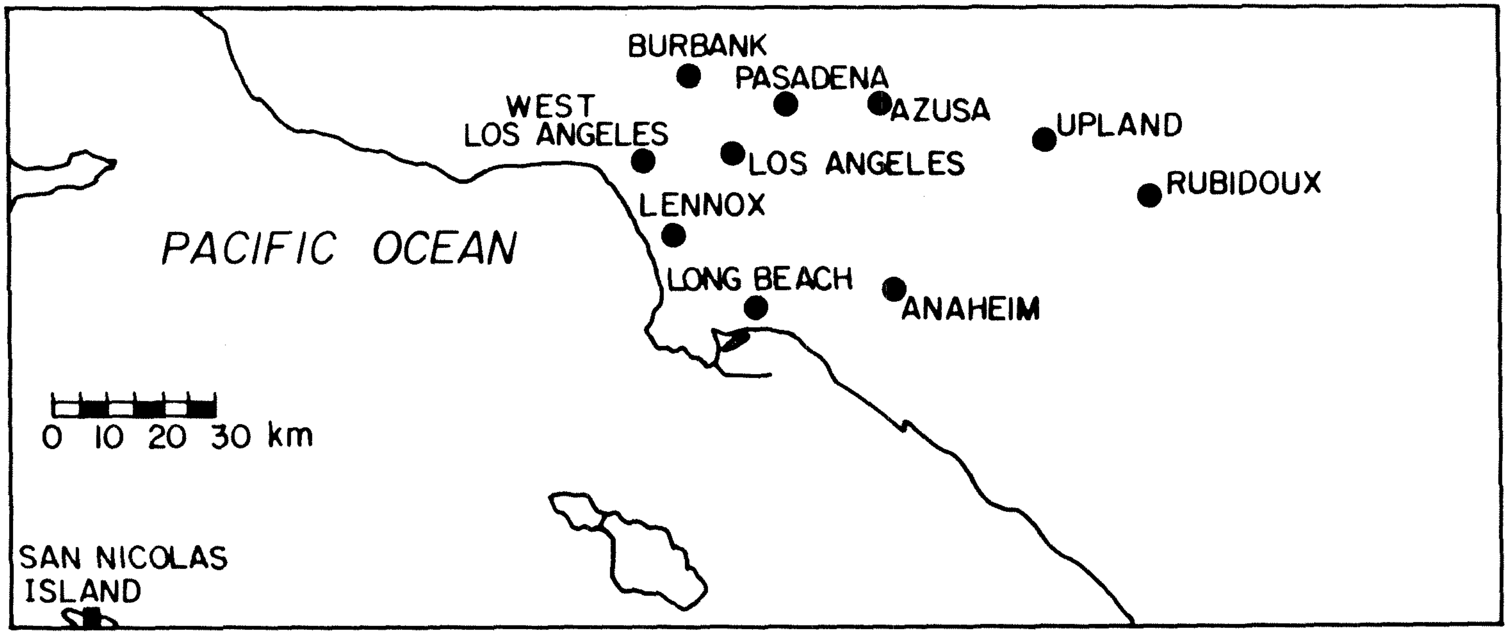


Figure 2.1 Fine particle air monitoring network.

samples were taken simultaneously throughout the network every sixth day during 1982 on a schedule coordinated with the National Air Surveillance Network (NASN) high volume sampling schedule.

The ambient sampling equipment constructed for use in this study is illustrated in Figure 2.2, and was designed to obtain a near mass balance on the chemically identifiable portion of the atmospheric fine particle loading. Ambient air at a flow rate of 25.9 lpm was drawn through an AIHL cyclone designed to remove particles with aerodynamic diameter larger than 2.1 μm (John and Reischl 1980). The air flow containing the fine particle fraction then was divided between four parallel filter assemblies. Each filter substrate was chosen for compatibility with a particular chemical or physical analysis procedure.

Samples taken for organic and elemental carbon determination were collected on 47 mm diameter quartz fiber filters (Pallflex Tissuquartz 2500 QAO) that had been heat treated to 600°C in air for more than 2 hours to lower their carbon blank. Filter samples were collected at a flow rate of 10 lpm, and all filters were refrigerated between collection and analysis to minimize losses due to volatilization and evaporation.

Organic and elemental carbon concentrations on these filters were measured by the method of Huntzicker et al. (1982) and Johnson et al. (1981). Four quartz fiber filter disks (0.25 cm^2 each) cut from a 47 mm filter are inserted into the combustion zone of a temperature programmed oven. Volatilization of organic carbon occurs

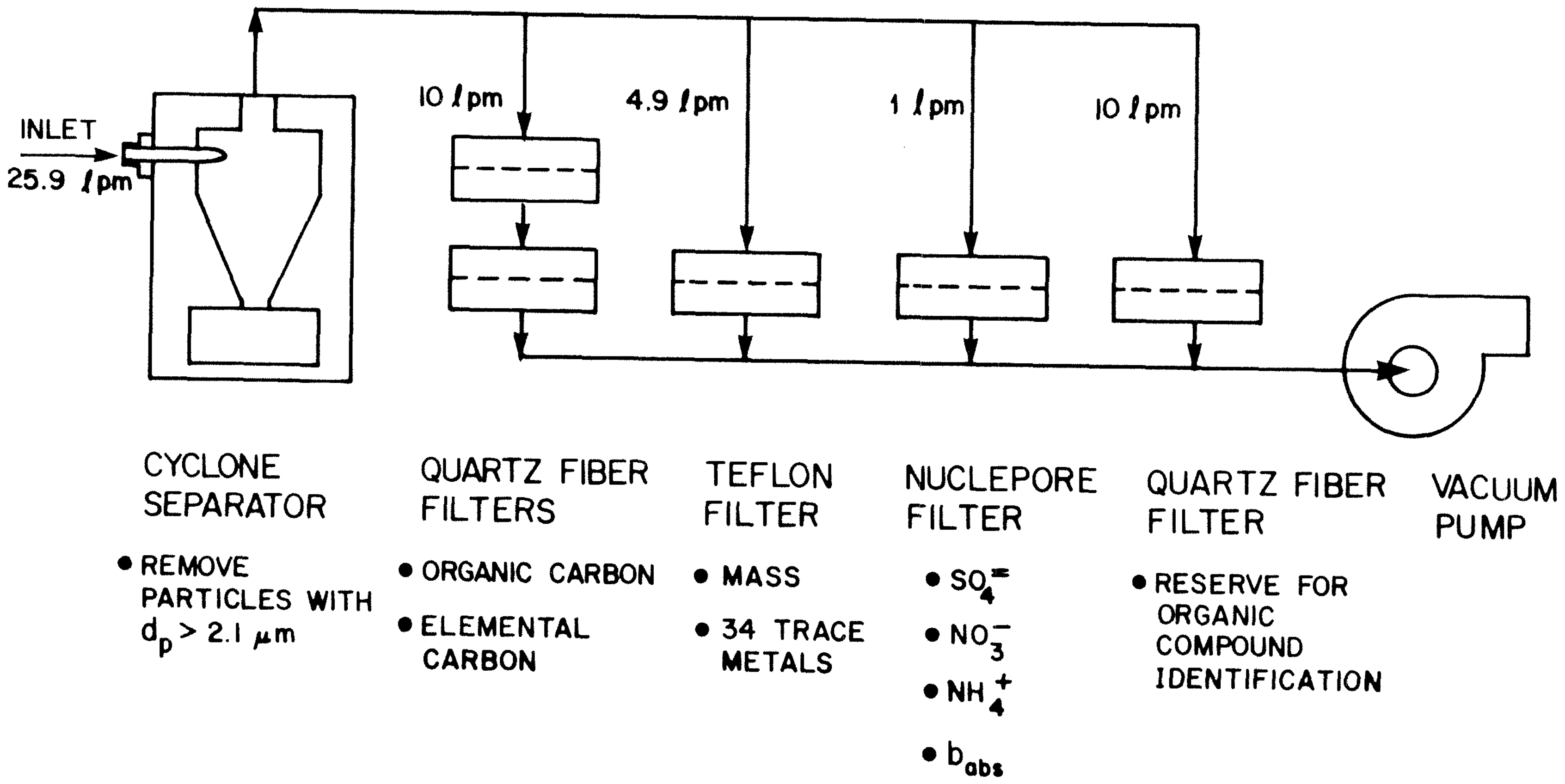


Figure 2.2 Ambient sampling protocol.

in two steps: at 400°C in flowing helium and at 600°C in He. The volatilized carbon is oxidized to CO_2 over an MnO_2 catalyst at 1000°C, reduced to CH_4, and measured by a flame ionization detector. Elemental carbon is measured by combusting the residual carbon on the filter disks to CO_2 in an O_2(2%)-He(98%) mixture at 400°C, 500°C and at 750°C, followed by methanation and detection as described above. A calibration is performed at the end of each analysis by injecting a known amount of CH_4 into the oven and measuring the response. The reflectance of the filter sample is monitored continuously by a He-Ne laser during the volatilization and combustion process to detect any pyrolytic conversion of organic carbon to elemental carbon. Correction for pyrolytic conversion of organic carbon to elemental carbon is accomplished by measuring the amount of elemental carbon combustion required to return the filter reflectance to the value that it had prior to pyrolysis.

Replicate analysis of 53 filters taken from the present field experiment was used to determine the precision of the carbon analysis procedure. Analysis of variance showed the following analytical precisions (± 1 standard deviation): organic carbon (OC), ± 0.54 $\mu g\ m^{-3}$; elemental carbon (EC), ± 0.31 $\mu g\ m^{-3}$; total carbon (TC), ± 0.64 $\mu g\ m^{-3}$. The analytical precision of a single determination of the ratio of various carbon species concentrations was found to be (± 1 standard deviation): OC/TC, ± 0.025; OC/EC, ± 0.20; TC/EC, ± 0.20. The analytical accuracy of each single total carbon determination during this experimental program is estimated to be ± 9.8% and includes the effects of uncertainties in carbon analyzer sample loop volume, calibration gas, area of the punches cut from each filter, temperature and pressure variations during analysis, filter surface area, and air volume sampled. The accuracy of total carbon measurements made by depositing known amounts of sucrose on filter disks and then analyzing the disks also was assessed. The average ratio of measured carbon to expected carbon was 1.01 ± 0.04 (95% confidence interval).

The filter intended for elemental and organic carbon aerosol collection was followed by a quartz fiber backup filter. This backup filter was included to permit assessment of the amount of organic carbon that can become attached to a clean filter due to adsorption of gas phase hydrocarbons or due to revaporization of organic material originally collected by the upstream aerosol filter. The extent of collection of aerosol and gas phase organics by aerosol sampling systems is dependent on the sample flow rate, temperature, and collection media used (Van Vaeck et al. 1979, Cadle et al. 1983, Appel et al. 1983, Grosjean 1983). Recent atmospheric sampling experiments conducted in Warren, Michigan, using dual filter units with quartz fiber filters showed that adsorption of organic compounds on backup filters as a result of sampling artifacts plus any contamination during handling accounted for at least 15% of the organic carbon collected on the upstream aerosol filter (Cadle et al. 1983). Analysis of three months of backup filters from the present set of Los Angeles area experiments showed that the backup filters adsorbed organic carbon during sampling and handling equal to 17 ± 11% of the organic carbon found on the preceding aerosol filters, a value similar to results obtained during the Warren, Michigan, experiments (Cadle et al. 1983).

The second filter holder line shown in Figure 2.2 contained a 47 mm Teflon membrane filter (Membrana 0.5 µm pore size) operated at a flow rate of 4.9 lpm. Fine particulate matter collected on this filter was analyzed for the concentration of 34 trace elements by X-ray fluorescence. The Teflon filters were equilibrated at low relative humidity before and after sampling, then weighed repeatedly to obtain fine particle mass concentrations.

Samples collected on Nuclepore filters (47 mm diameter, 0.4 µm pore size) were intended for aerosol light absorption coefficient determination by the integrating plate technique (Lin et al. 1973). As a result, those filters must be lightly loaded, and a 1 lpm flow rate was chosen. A portion of each of these filters was analyzed for sulfates and nitrates by ion chromatography (Mueller et al. 1978), and for ammonium ion content by the phenolhypochlorite method (Solorzano 1967).

The remaining quartz fiber filter shown in Figure 2.2 was intended for determination of the detailed organic species present by gas chromatography/mass spectrometry. These filters were heat treated prior to use in the same manner as the other quartz fiber filters previously described in order to reduce their carbon blank. Results of the analysis of these filters will be reported elsewhere.

2.3 Fine Particle Concentration and Composition

Fine particle mass concentration during the year 1982 averaged between 23 μg m^{-3} and 42 μg m^{-3} within the metropolitan Los Angeles area, falling to 7 μg m^{-3} at San Nicolas Island (see Figure 2.3a). Most of the fine particle air monitoring sites were co-located with a National Air Surveillance Network (NASN) or South Coast Air Quality Management District high volume sampler that operated on the same six-day schedule, and thus the average total suspended particulate matter concentration at these sites is known and is shown in Figure 2.3b. As a consistency check on the fine particle monitoring data, the fraction of the total aerosol mass found in particle sizes below 2.1 μm diameter was computed and found to constitute between 31% and 39% of the total particulate mass, as shown in Figure 2.3c. This result is in good agreement with South Coast Air Quality Management District special studies that show that 31% of TSP mass at El Monte in the Los Angeles area is present in particle sizes below 2.5 μm diameter (Witz 1982).

A mass balance was constructed at each air monitoring site by summing the chemically identified portions of the fine particulate matter samples. Trace metals were converted to their oxides, and organic carbon concentrations were multiplied by a factor of 1.2 to convert them to an estimate of organic species concentration. Table 2.1 summarizes these results and shows that the material balance closed to within ± 10% of gravimetrically determined fine particle mass at all but one of the on-land monitoring stations. Individual

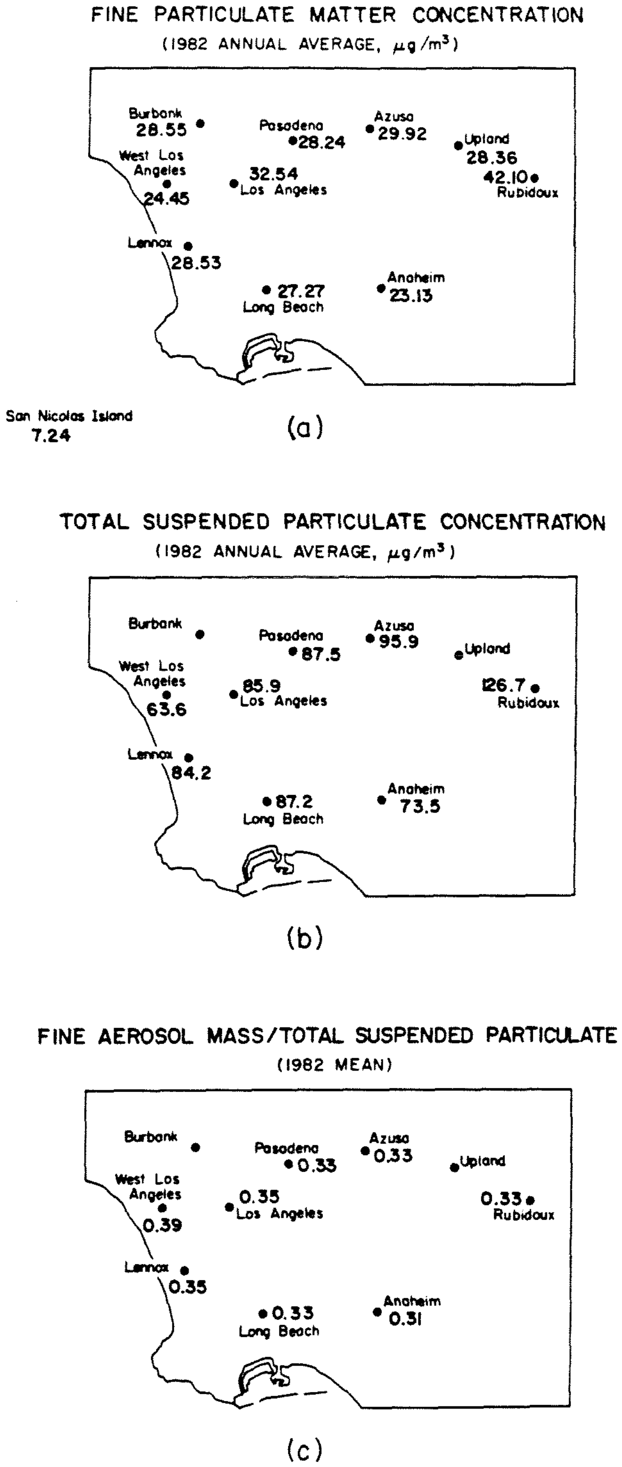


Figure 2.3 Comparison of fine particulate matter concentration to total suspended particulate matter concentration.

Table 2.1

Material Balance on the Chemical Composition of Fine Particulate Matter Concentrations--Los Angeles Area (1982 Annual Mean)

STATION	NUMBER OF SAMPLES (a)	FINE PARTICULATE MASS CONCENTRATION ($\mu g/m^3$)(b)	SUM OF IDENTIFIED CHEMICAL COMPONENTS ($\mu g/m^3$)	FRACTION IDENTIFIED (%)
Azusa	58	29.6	27.1	91.6
Burbank	58	28.6	30.0	105.6
Long Beach	58	27.5	25.9	94.2
Lennox	60	28.5	25.8	90.6
Pasadena	59	28.5	27.6	96.9
West Los Angeles	57	24.8	24.0	96.7
Los Angeles	60	32.7	30.4	92.8
Upland	55	27.7	25.4	91.5
Rubidoux	55	42.1	34.6	82.3
Anaheim	57	23.1	23.8	102.8
San Nicolas Island	43(c)	6.8	8.3	121.7

(a) Only those samples for which all scheduled chemical analyses are available. Averages thus differ slightly from those shown in Figure 2.3

(b) Determined gravimetrically.

(c) March-December 1982.

chemical species concentrations thus are consistent with a mass balance on the fine aerosol, and the major contributors to the fine aerosol loading have been identified.

Aerosol carbon species account for approximately 40% of the fine mass loading at most monitoring sites, as shown in Figure 2.4. At downtown Los Angeles, for example, the aerosol consists of 26.7% organics, 14.9% elemental carbon, 9.4% nitrate ion, 22.2% sulfate ion, 9.4% ammonium ion, 10.3% trace metal compounds, and 7.2% unidentified material (probably sea salt plus water retained on the filter despite desiccation). Results at the remaining stations are very similar except for Rubidoux and San Nicolas Island. The Rubidoux samples appear much lower in relative carbon content only because total fine particle mass concentration is higher there. This is due to addition of much more aerosol nitrate at Rubidoux than is found elsewhere, plus an added contribution from soil-like minerals when compared with other sites. The aerosol at San Nicolas Island is quite different from that found over the on-land portion of the air basin, being very low in elemental carbon content.

2.4 Characteristics of Elemental and Organic Carbon Concentrations

Fine total carbon concentrations are highest in heavily trafficked areas of the basin such as downtown Los Angeles and Burbank (see Figure 2.5a). Fine total carbon concentrations at those two sites averaged 12.2 and 13.7 $\mu g\ m^{-3}$, respectively, during 1982. Aerosol carbon concentrations decline with distance inland (the prevailing downwind direction), falling to 8.2 $\mu g\ m^{-3}$ for air masses

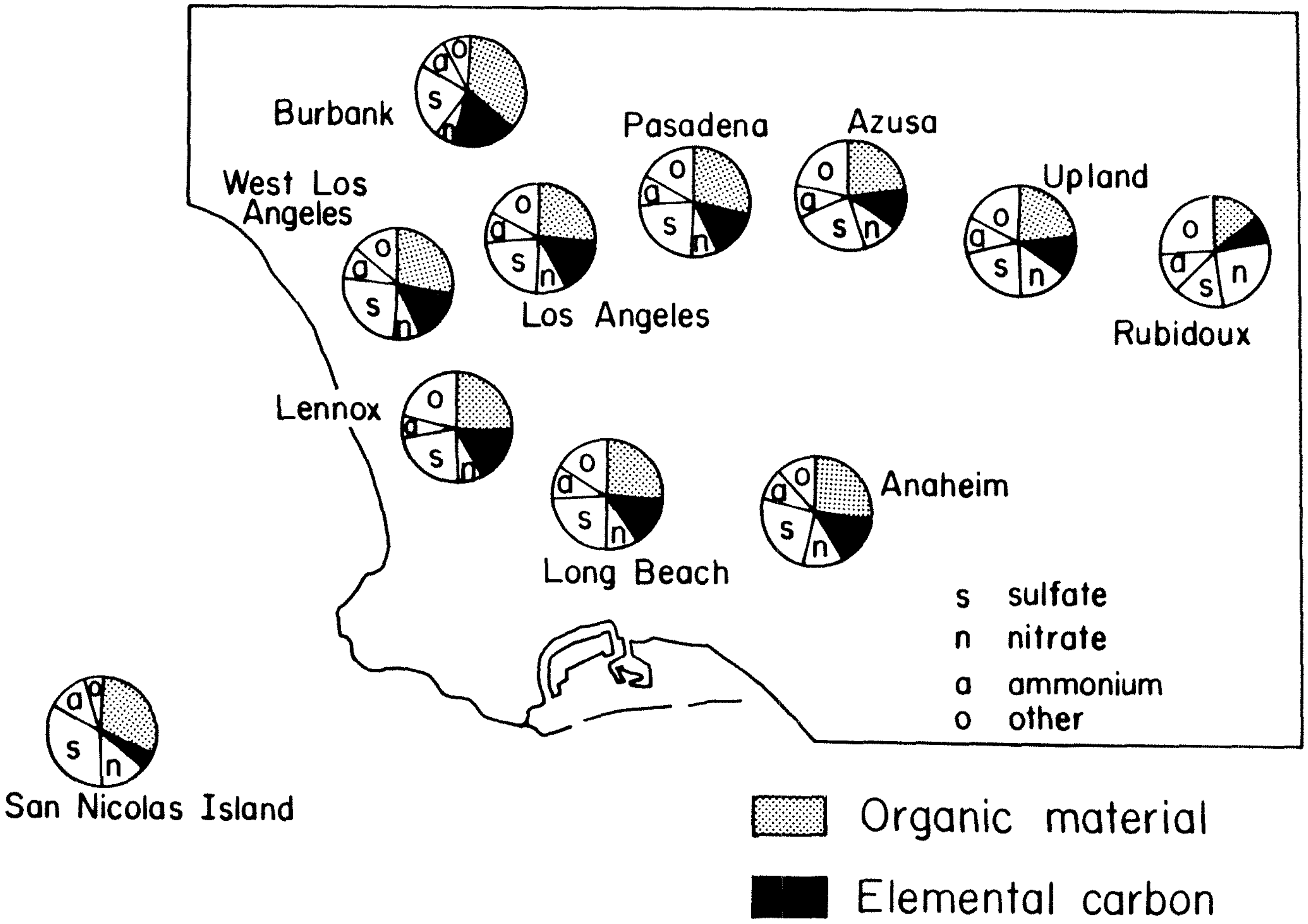
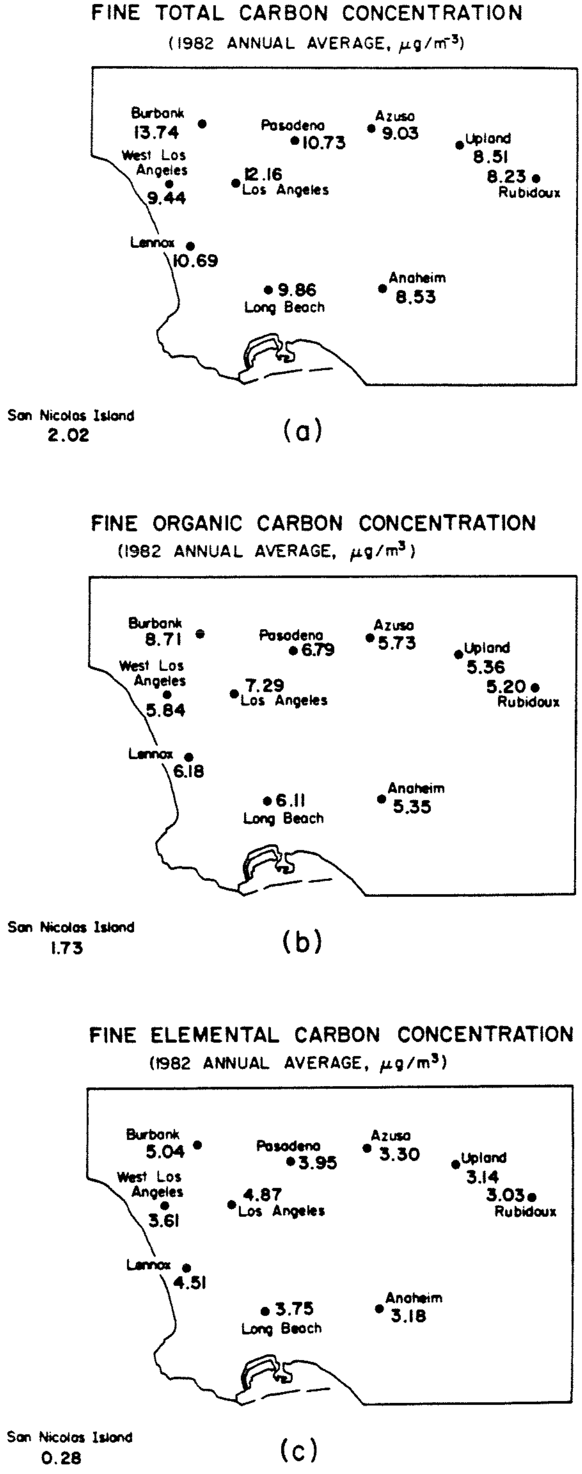


Figure 2.4 Material balance on the chemical composition of annual mean fine particle concentrations in the Los Angeles area--1982.



FINE TOTAL CARBON CONCENTRATION
(1982 ANNUAL AVERAGE, $\mu g/m^3$)

FINE ORGANIC CARBON CONCENTRATION
(1982 ANNUAL AVERAGE, $\mu g/m^3$)

FINE ELEMENTAL CARBON CONCENTRATION
(1982 ANNUAL AVERAGE, $\mu g/m^3$)

Figure 2.5 Fine carbonaceous particulate matter concentrations in the Los Angeles area.

TABLE 2.2

Statistical Description of Aerosol Carbon Data
Los Angeles Area - 1982

STATION	NUMBER OF CARBON SAMPLES	OC SAMPLE POPULATION		EC SAMPLE POPULATION		TC SAMPLE POPULATION		TC/EC POPULATION	
		Mean ($\mu g\ m^{-3}$)	Standard Deviation ($\mu g\ m^{-3}$)	Mean ($\mu g\ m^{-3}$)	Standard Deviation ($\mu g\ m^{-3}$)	Mean ($\mu g\ m^{-3}$)	Standard Deviation ($\mu g\ m^{-3}$)	Mean	Standard Deviation
Azusa	60	5.73	2.45	3.30	1.87	9.03	4.16	2.97	0.65
Burbank	58	8.71	4.50	5.04	3.20	13.74	7.56	2.89	0.46
Long Beach	59	6.11	4.65	3.75	3.00	9.86	7.57	2.77	0.46
Lennox	61	6.18	4.39	4.51	3.16	10.69	7.48	2.43	0.37
Pasadena	60	6.79	3.38	3.95	2.07	10.73	5.35	2.79	0.36
West Los Angeles	58	5.84	3.84	3.61	2.78	9.44	6.55	2.86	0.56
Los Angeles	61	7.29	4.30	4.87	3.24	12.16	7.44	2.59	0.35
Upland	56	5.36	1.99	3.14	1.34	8.51	3.07	2.83	0.63
Rubidoux	55	5.20	2.15	3.03	1.64	8.23	3.65	2.92	0.69
Anaheim	57	5.35	2.73	3.18	2.31	8.53	4.91	2.88	0.53
San Nicolas Is.	46	1.73	0.93	0.28	0.22	2.02	1.12	*	*

* Not computed because EC concentration approaches zero on a number of occasions.

passing Rubidoux in the Riverside area. A similar pattern is observed for both organic carbon (Figure 2.5b) and elemental carbon concentrations (Figure 2.5c). Note in Figure 2.5c that the elemental carbon concentration in marine air at San Nicolas Island is very low, about 0.3 $\mu g\ m^{-3}$ on the average. A statistical description of the aerosol carbon data set is provided in Table 2.2.

Aerosol carbon data at individual monitoring sites can be viewed on a seasonal basis. Figure 2.6a shows the time series of individual 24-hour average organic carbon samples at Lennox, a near-coastal site adjacent to a busy freeway. In Figure 2.6b, the time series of organic carbon concentrations has been smoothed by computing monthly average values. It is seen that the highest organic carbon values are observed in winter months, falling to a minimum in the summer. The same behavior is observed for elemental carbon at that site, as seen in Figures 2.6c and 2.6d. This pattern with high winter values and low summer concentrations is typical of primary automotive pollutants like CO and lead at that location (Hoggan et al. 1980).

Moving in the prevailing downwind direction from Lennox toward Los Angeles, a similar pattern of high winter values and a summer minimum in aerosol carbon levels is observed in 1982 (Figure 2.7ab). At Pasadena, a June minimum in fine carbon concentrations still is observed on average, but individual days during the late summer show total fine carbon concentrations that are as high as the winter values (Figure 2.7cd). Proceeding further downwind to Upland (Figure 2.7ef) and Rubidoux (Figure 2.7gh), the pronounced summer minimum in fine

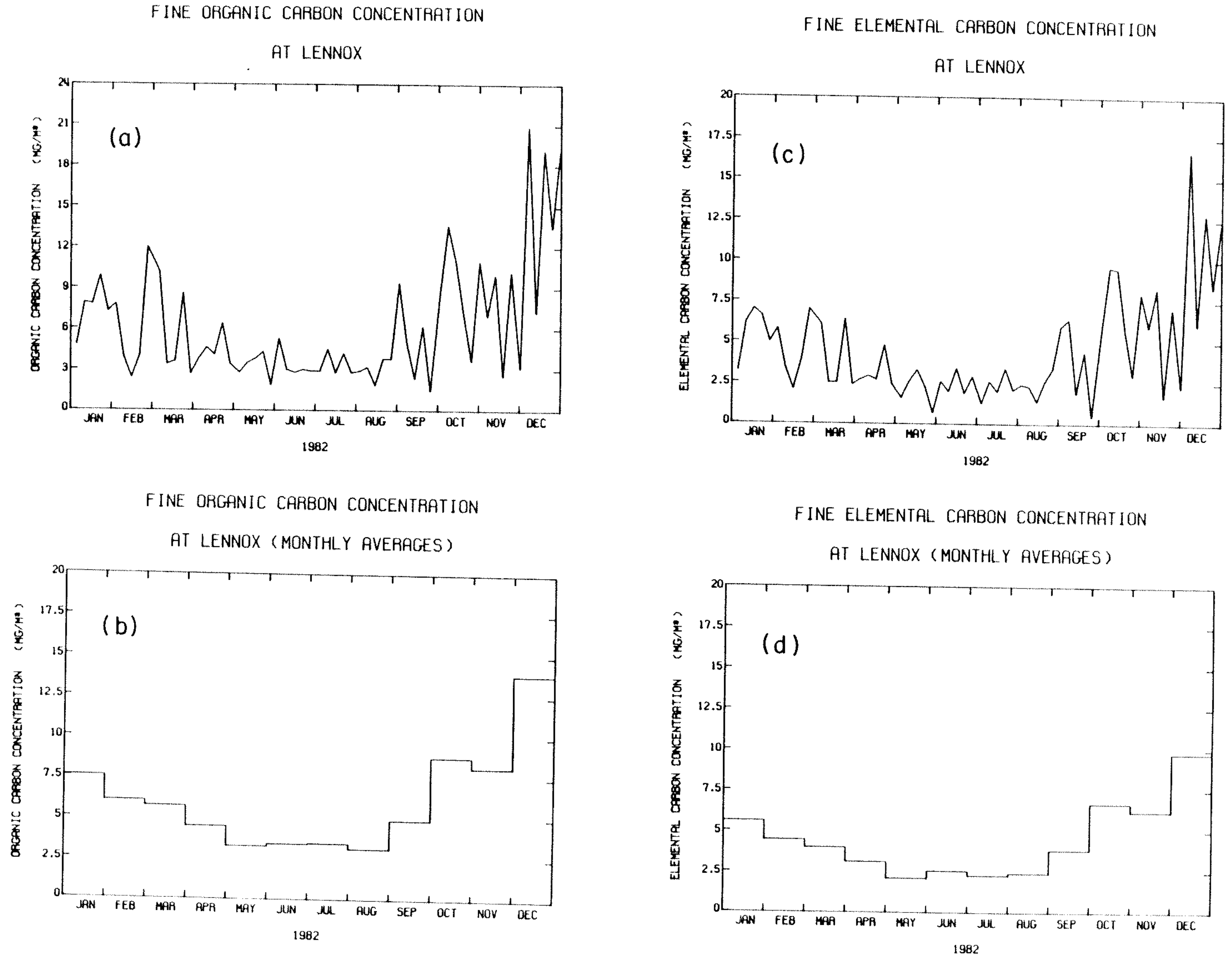
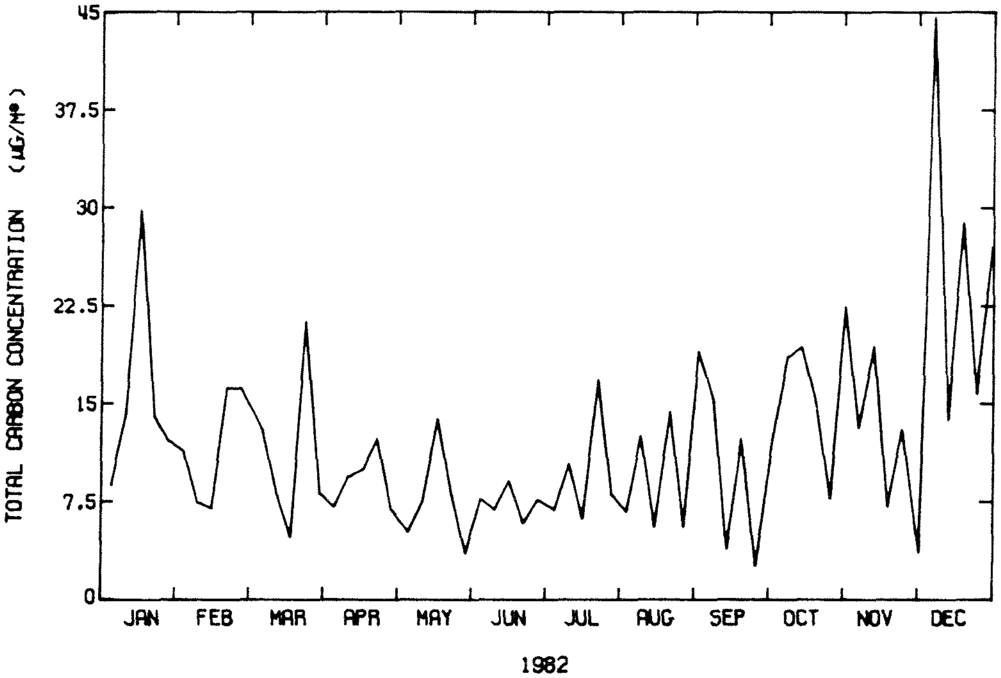


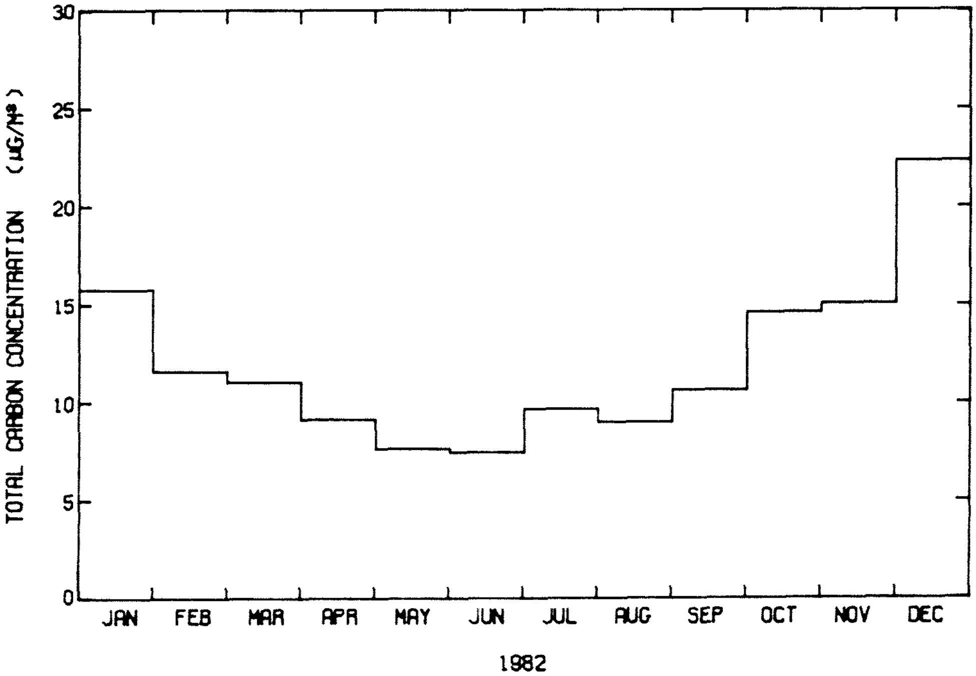
Figure 2.6 Daily and monthly average carbonaceous aerosol concentrations at Lennox, CA.



FINE TOTAL CARBON CONCENTRATION

AT LOS ANGELES

Figure 2.7a



FINE TOTAL CARBON CONCENTRATION

AT LOS ANGELES (MONTHLY AVERAGES)

Figure 2.7b

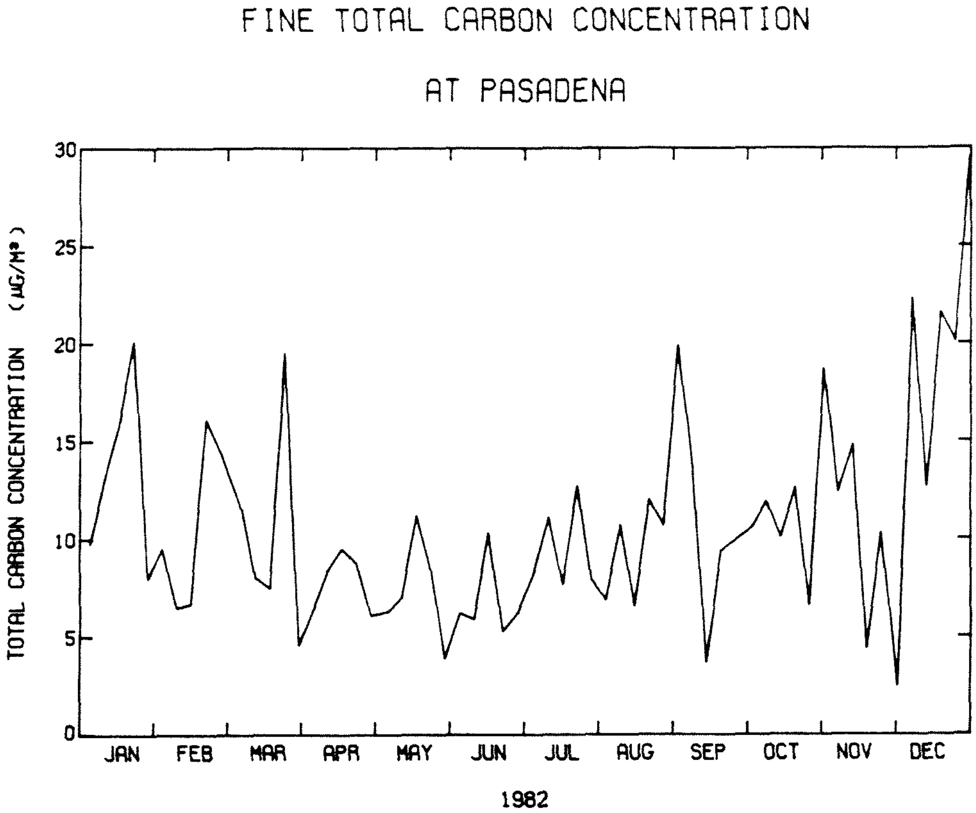


Figure 2.7c

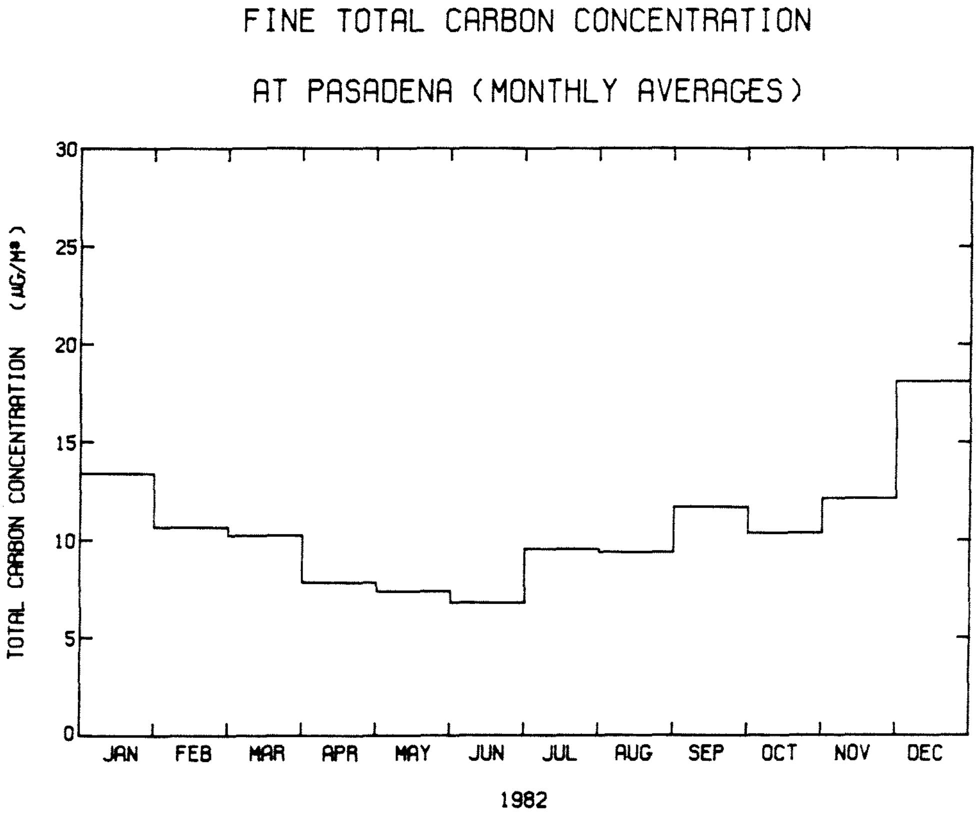


Figure 2.7d

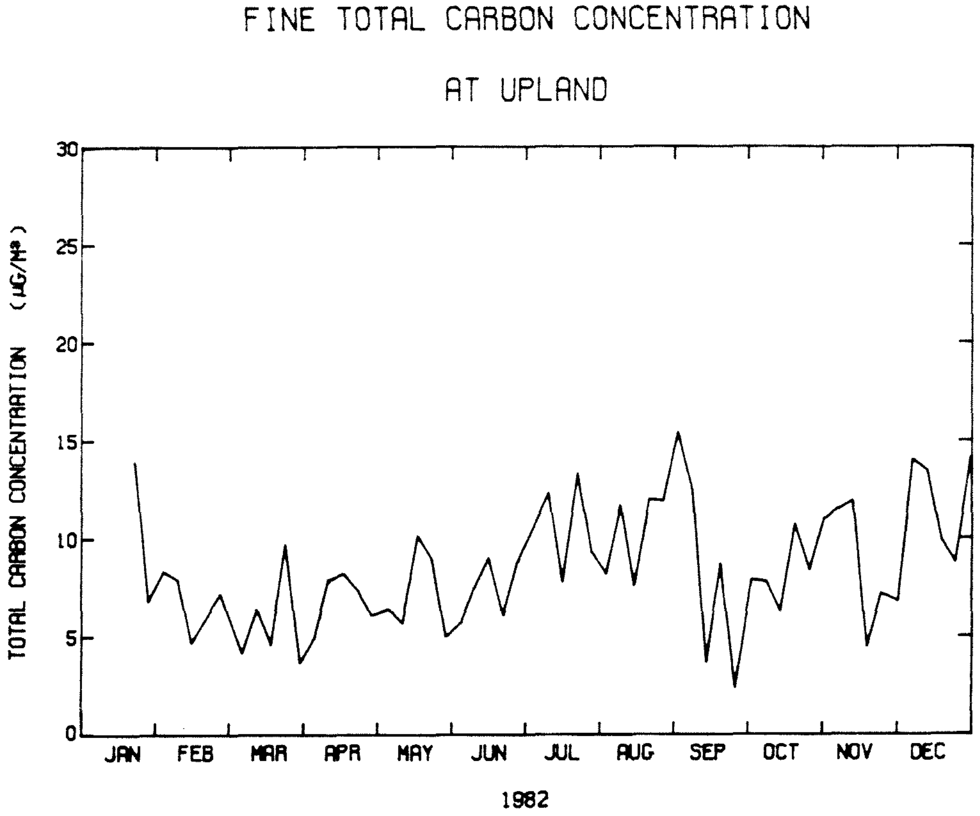


Figure 2.7e

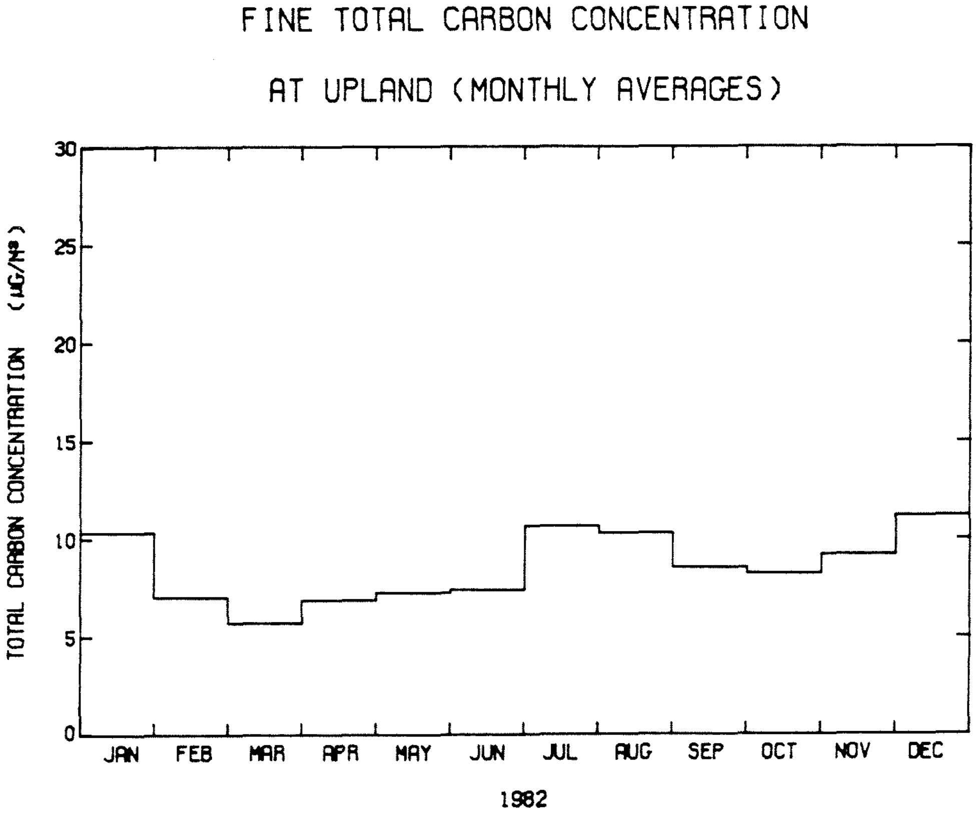


Figure 2.7f

FINE TOTAL CARBON CONCENTRATION

AT RUBIDOUX

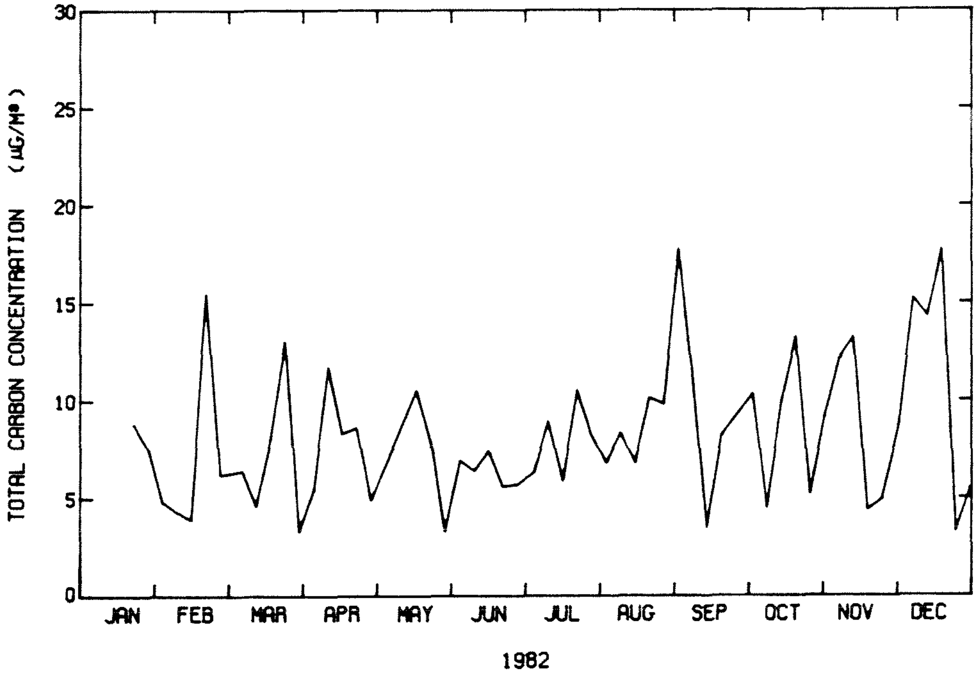


Figure 2.7g

FINE TOTAL CARBON CONCENTRATION

AT RUBIDOUX (MONTHLY AVERAGES)

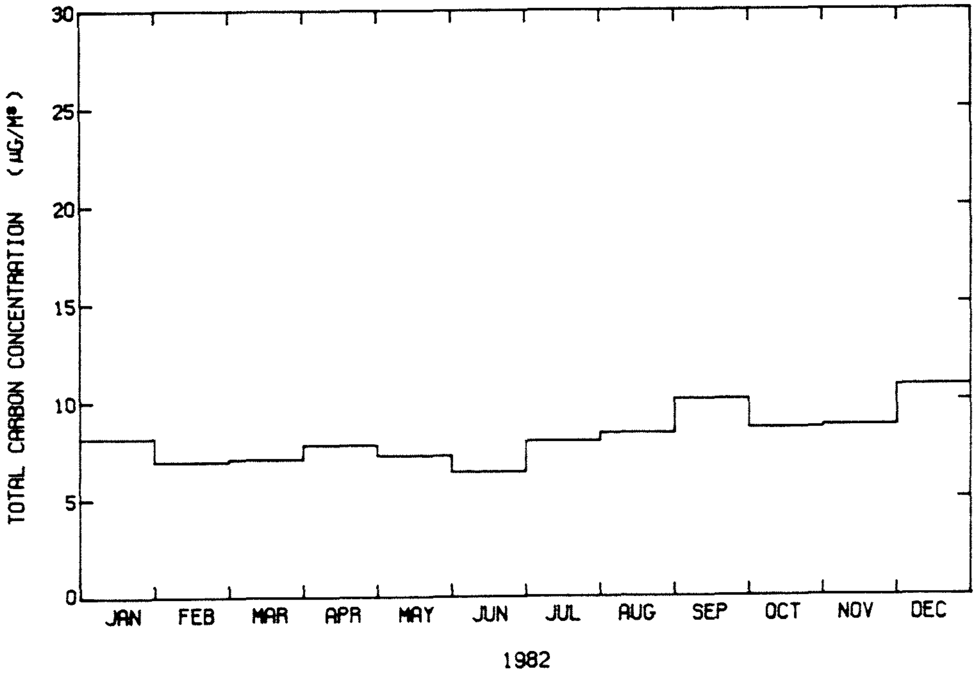


Figure 2.7h

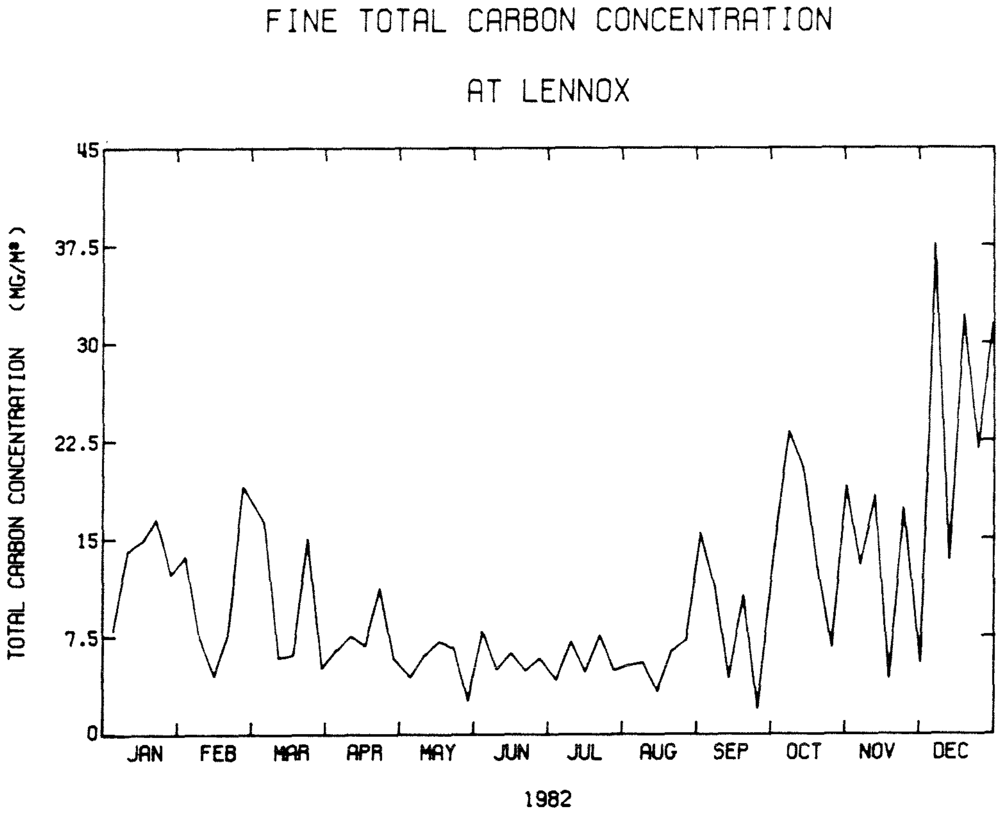


Figure 2.7i

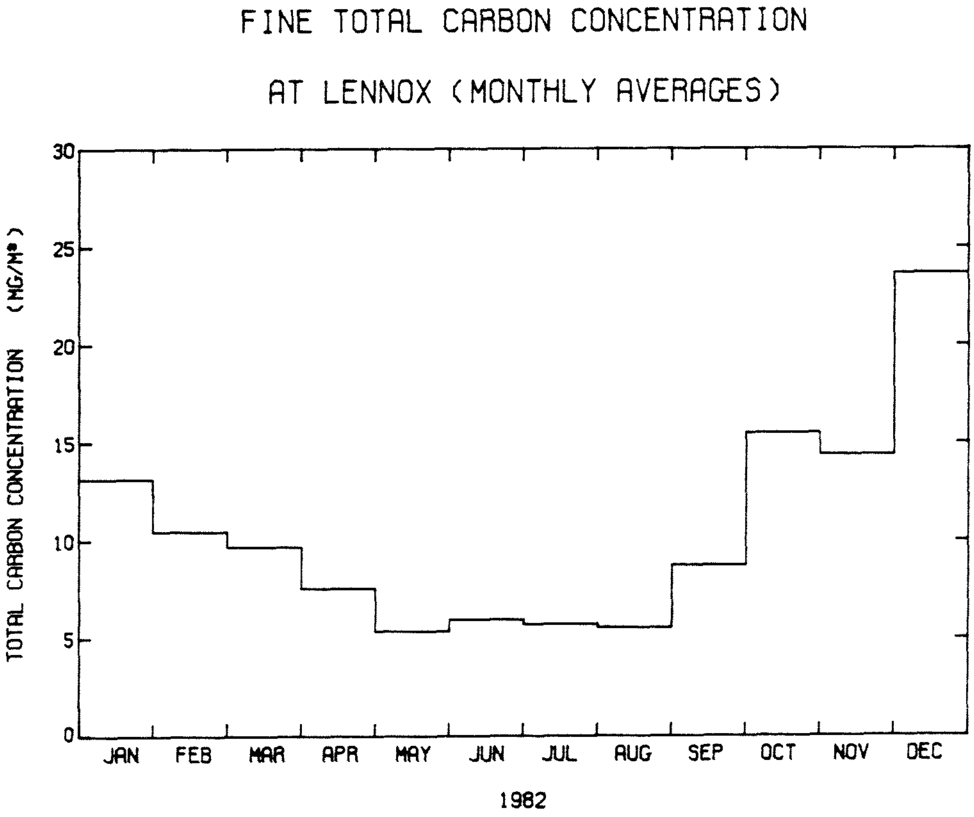


Figure 2.7j

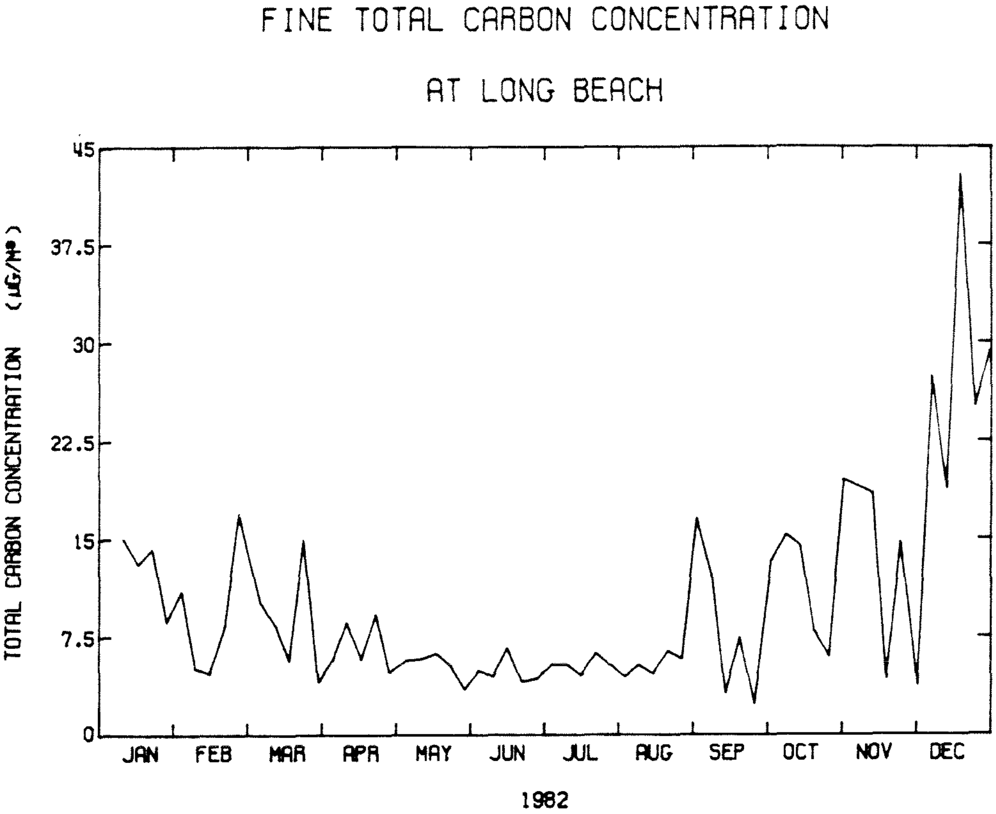


Figure 2.7k

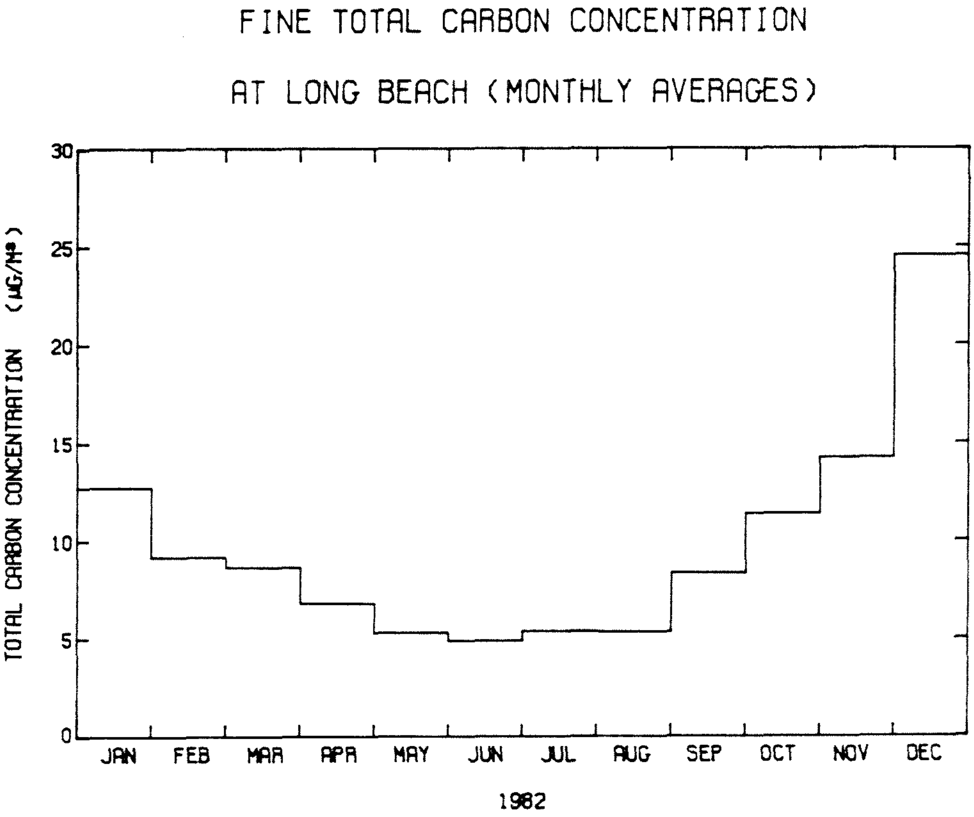
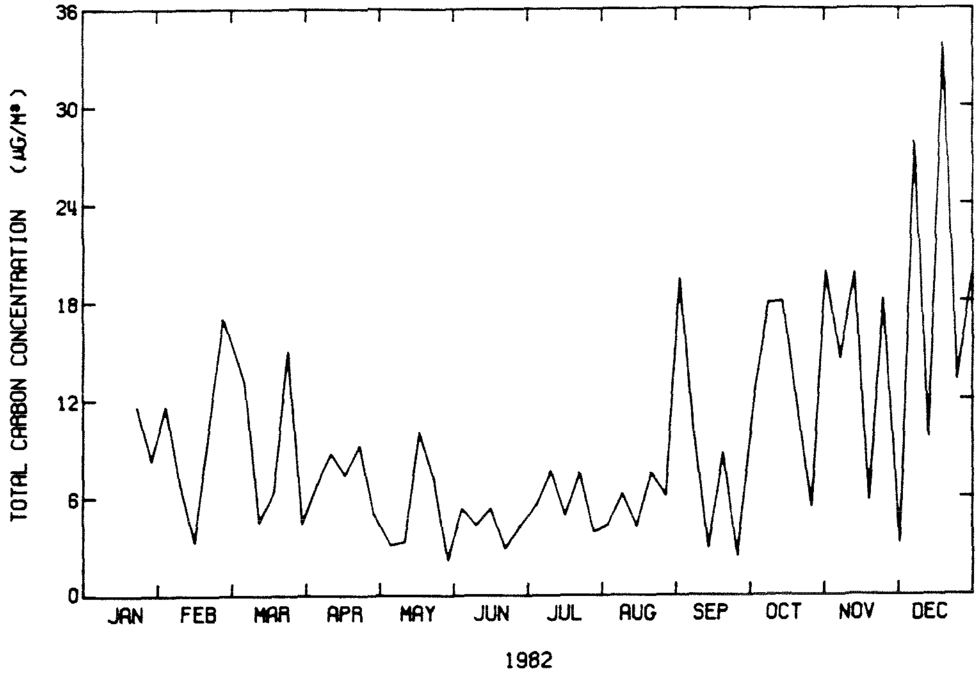


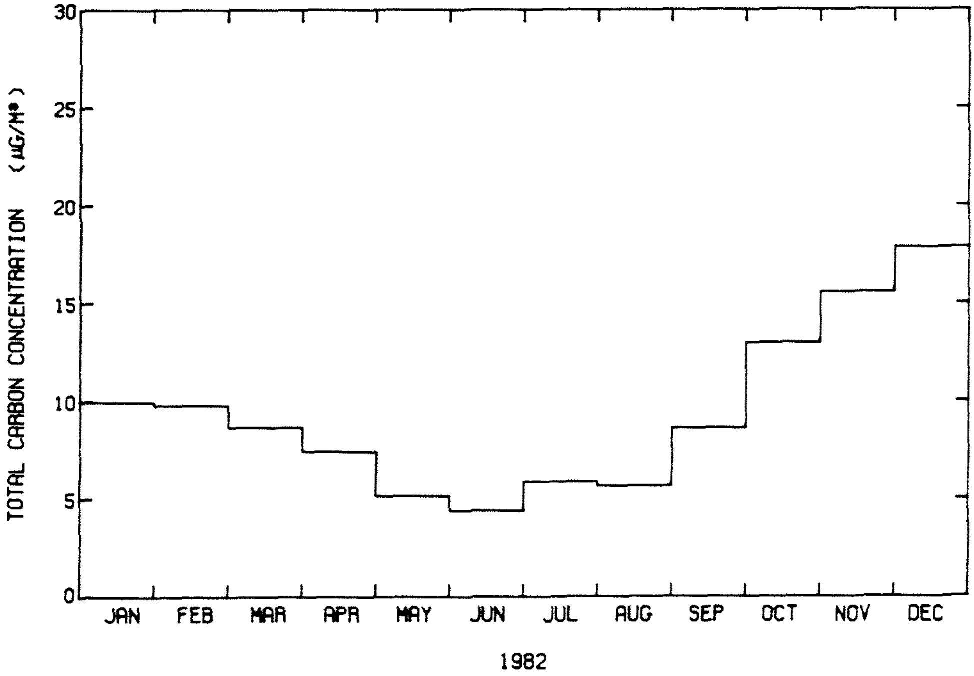
Figure 2.7l



FINE TOTAL CARBON CONCENTRATION

AT WEST LOS ANGELES

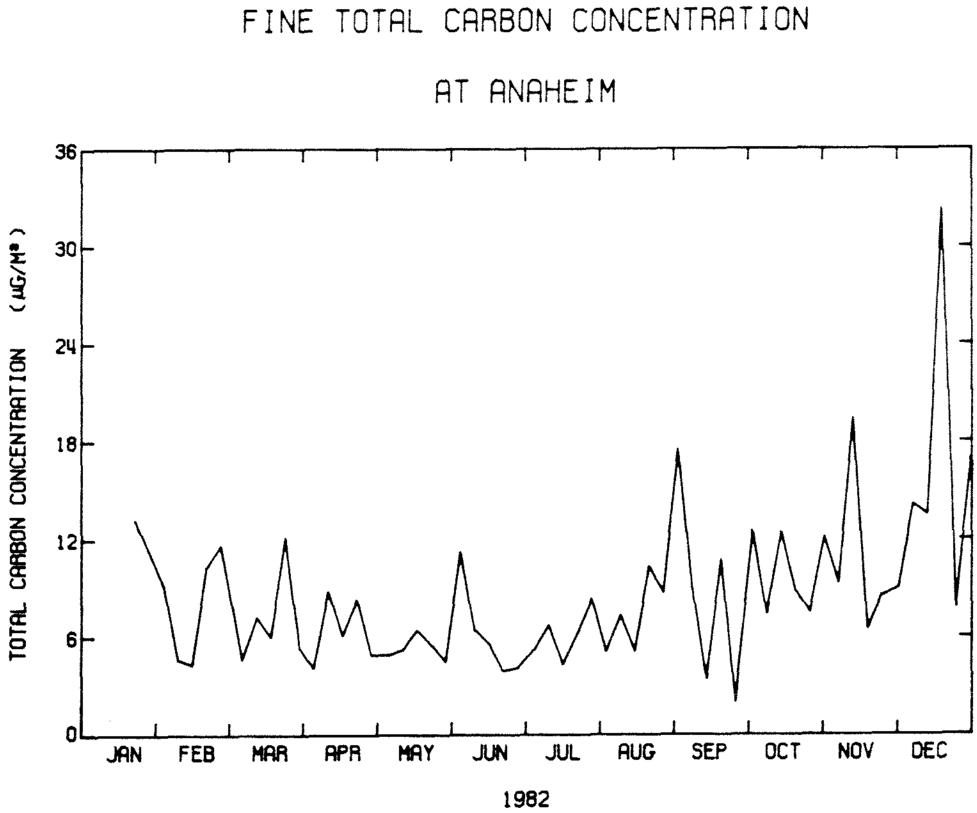
Figure 2.7m



FINE TOTAL CARBON CONCENTRATION

AT WEST LOS ANGELES (MONTHLY AVERAGES)

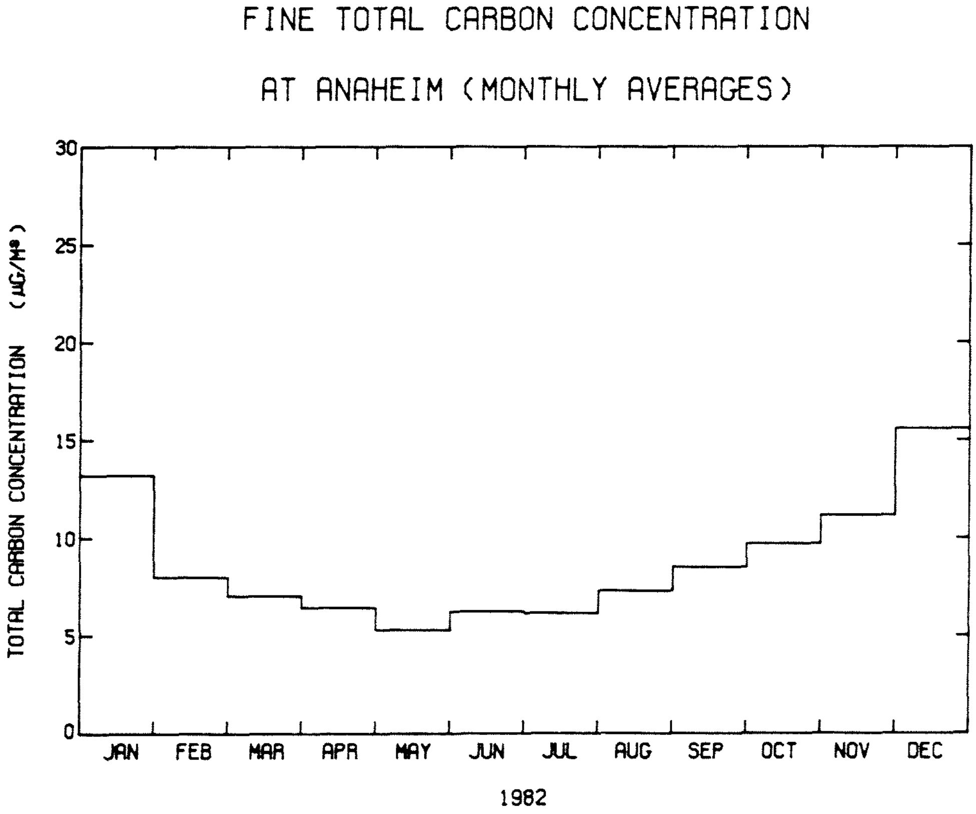
Figure 2.7n



FINE TOTAL CARBON CONCENTRATION

AT ANAHEIM

Figure 2.7o



FINE TOTAL CARBON CONCENTRATION

AT ANAHEIM (MONTHLY AVERAGES)

Figure 2.7p

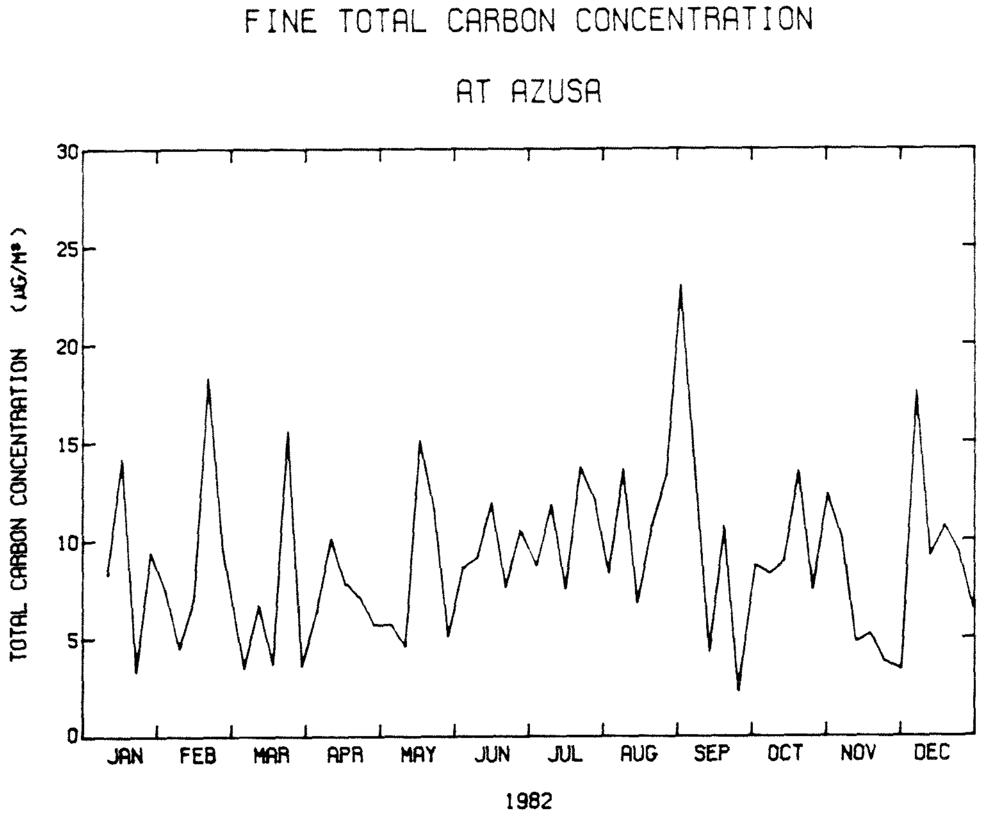


Figure 2.7q

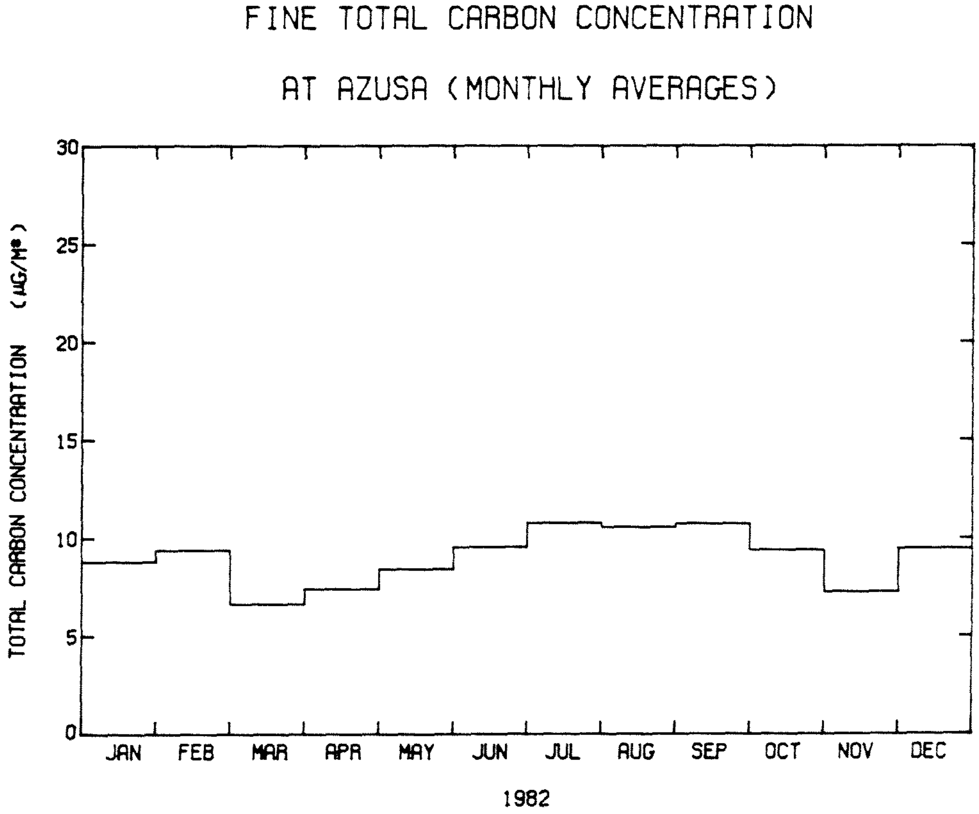


Figure 2.7r

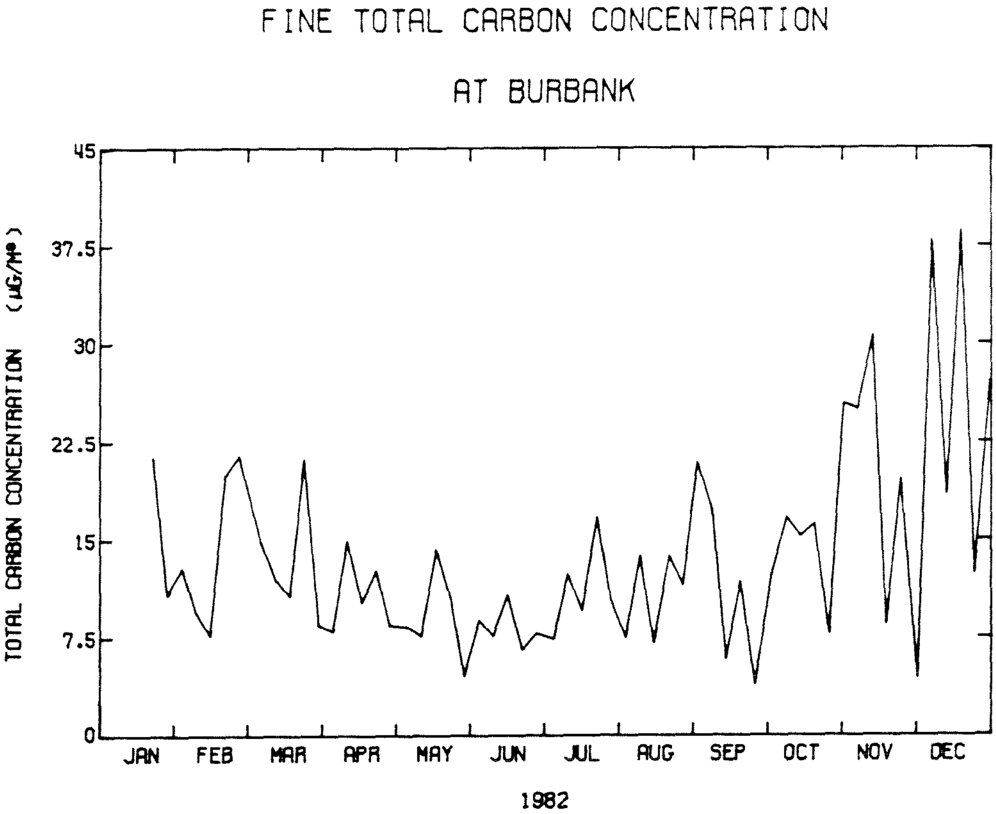


Figure 2.7s

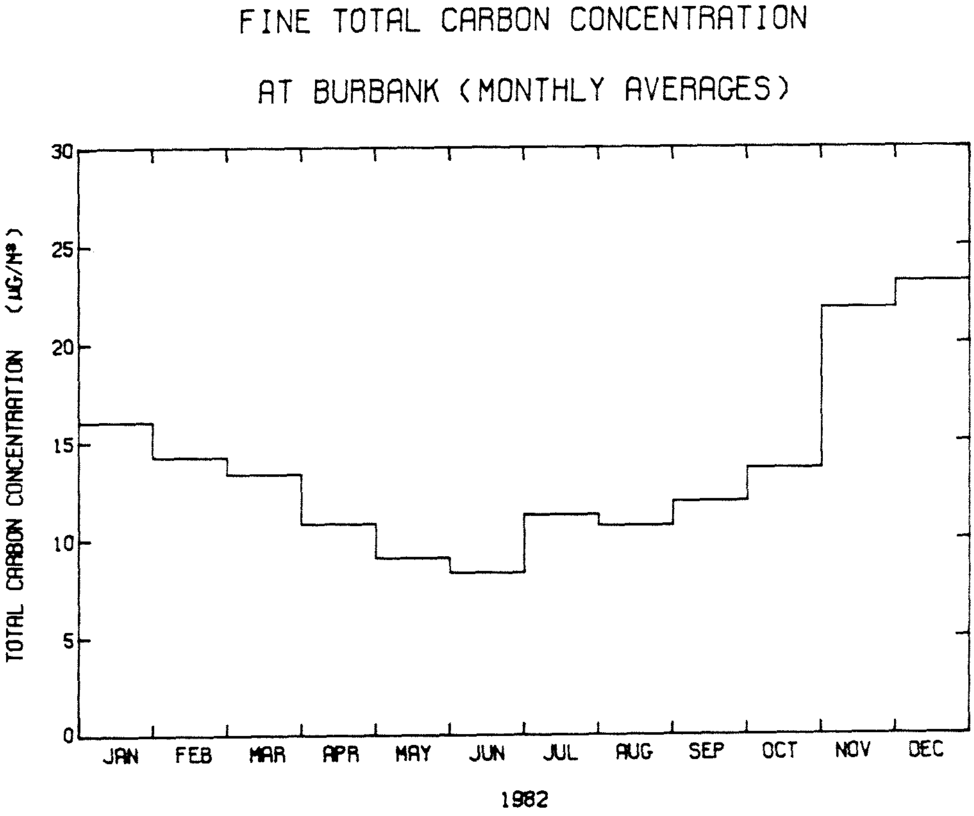
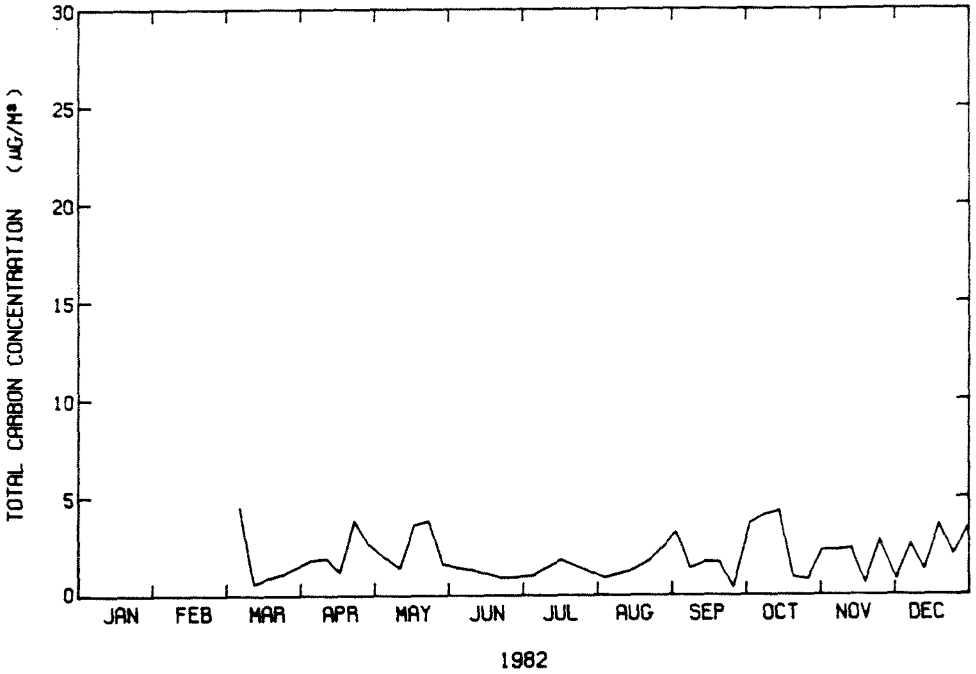


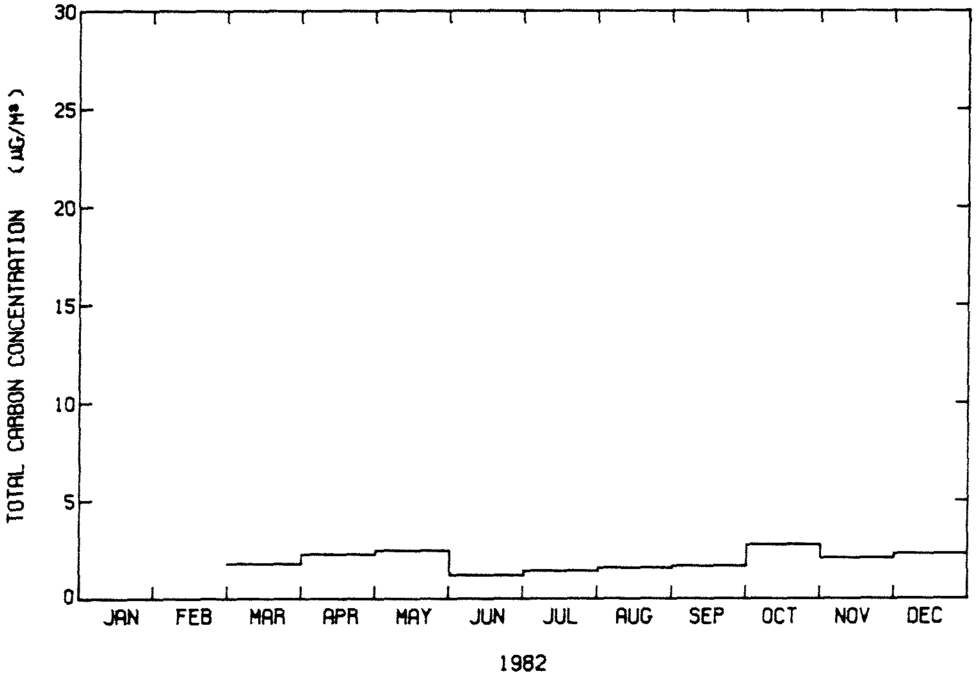
Figure 2.7t



FINE TOTAL CARBON CONCENTRATION

AT SAN NICOLAS ISLAND

Figure 2.7u



FINE TOTAL CARBON CONCENTRATION

AT SAN NICOLAS ISLAND (MONTHLY AVERAGES)

Figure 2.7v

aerosol carbon levels is absent; there even may be a relative peak in aerosol carbon concentrations in the summer at Upland. Total carbon concentration data at the remaining monitoring sites are given in Figures 2.7i through 2.7v

2.5 Comparison to Emission Data

An inventory of organic and elemental carbon particle emissions to the Los Angeles area atmosphere was developed for the year 1980 by Cass et al. (1982) and is summarized in Figure 2.8. Aerosol carbon emissions in particle sizes less than 10 μm were estimated to total about 46 tons per day. One quarter of that total came from gasoline powered vehicle exhaust, one fourth from diesel engine exhaust, and the remainder from a large variety of stationary fuel burning, industrial and fugitive sources. In contrast, the black elemental carbon particle emissions were dominated by diesel exhaust aerosol. The ratio of total carbon to elemental carbon in primary aerosol emissions was estimated to be about 3.2:1 averaged over all sources in the area in 1980. A weighted average highway traffic emission profile of gasoline fueled vehicle exhaust, diesel exhaust, tire dust and brake dust likewise indicated a total carbon to elemental carbon ratio of about 3.2:1. These total carbon to elemental carbon ratios obtained from the 1980 emissions survey may be slightly higher than would be obtained from a 1982 emission inventory for Los Angeles. One reason for this is that the relatively high organic carbon emissions from old non-catalyst automobiles are declining over time as catalyst-

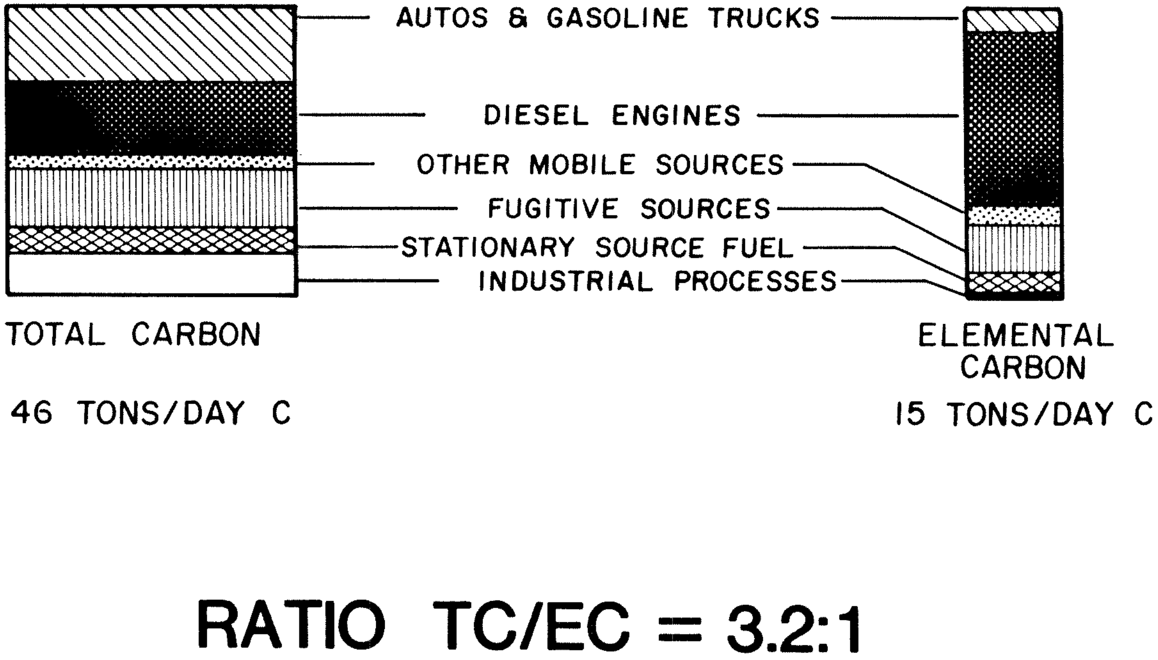


Figure 2.8 Aerosol carbon emissions in the greater Los Angeles area in particle sizes $\leq$ 10 μm diameter, winter 1980 (from Cass, Boone, and Macias 1982).

equipped new cars take their place in the vehicle fleet.

The ratio of total carbon to elemental carbon in source emissions when compared to the same ratio in atmospheric samples should be useful in detecting the presence of any large enrichment in organic aerosol in the atmosphere due to secondary aerosol formation. Fine elemental carbon aerosol is formed during combustion processes. This atmospheric elemental carbon is non-volatile, inert and is not formed in the atmosphere by reactions involving gaseous hydrocarbon precursors. Therefore, the entire concentration of elemental carbon observed in the atmosphere is from primary emission sources. Organic carbon may be emitted as primary aerosol directly from sources, but secondary organics also can be formed in the atmosphere from the low vapor pressure products of atmospheric chemical reactions (Grosjean 1977). If a large fraction of the atmospheric fine carbon particle burden in the Los Angeles area is contributed by secondary organics, three features might be expected. First, the ratio of total carbon to elemental carbon in atmospheric aerosol samples should exceed that found in primary source emissions. Second, a higher ratio of total carbon to elemental carbon might be expected during the summer peak photochemical smog season. Third, the ratio of total carbon to elemental carbon might be expected to increase as one moves inland along the prevailing downwind transport direction, in a manner similar to other secondary photochemical pollutants, like ozone.

The atmospheric fine carbon particle data were examined to note whether or not these likely indicators of high secondary aerosol levels were present during the year 1982. The discussion will begin at the upwind edge of the air basin near Lennox. Fine elemental and organic carbon concentrations at Lennox are shown in Figure 2.6ac. Elemental and organic aerosol concentrations are highly correlated. The daily ratio of total carbon (TC) to elemental carbon (EC) at Lennox is shown in Figure 2.9a. These values are fairly consistent from day to day, and are contained entirely within the range 4.0:1 to 1.8:1. In Figure 2.9b, the daily values of the TC to EC ratio are averaged over each month of the year 1982. It is seen that there is very little seasonal variation, with an annual average value of the daily TC to EC ratio of 2.4:1. An alternative statistic, the ratio of annual average TC to annual average EC, can be computed from Figures 2.5ac, with similar results. When compared to 1980 estimates of the TC to EC ratio in primary source emissions, the Lennox aerosol is not highly enriched in organic carbon relative to elemental carbon. This suggests that the carbonaceous aerosol at Lennox is dominated by primary source emissions on the average over long periods of time. This is not surprising since the Lennox site is located only about 100 m from a very large freeway, and shows the highest annual mean lead levels in the Los Angeles area (Davidson et al. 1979) (again an indicator of direct vehicle exhaust influence).

The situation at downtown Los Angeles is quite similar to that at Lennox (Figure 2.9cd). Peak TC to EC ratios of 4:1, little seasonal dependence, and an annual average value of the daily TC to EC ratio of 2.6:1, only slightly higher than at Lennox. Moving further

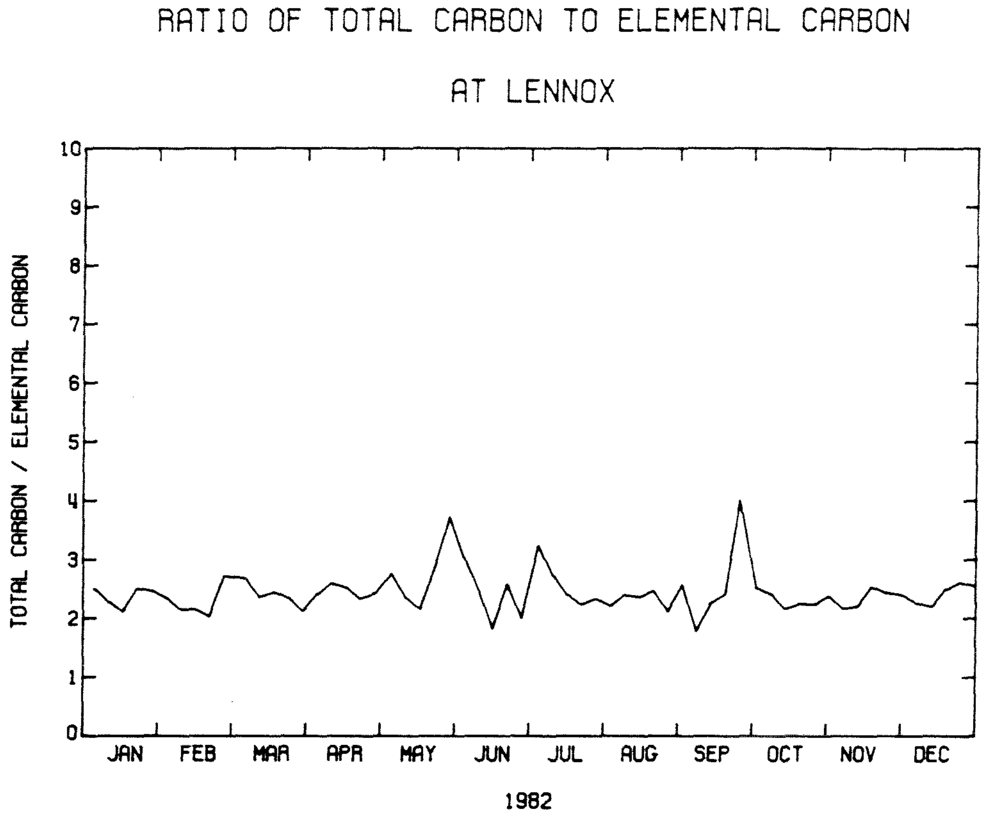


Figure 2.9a

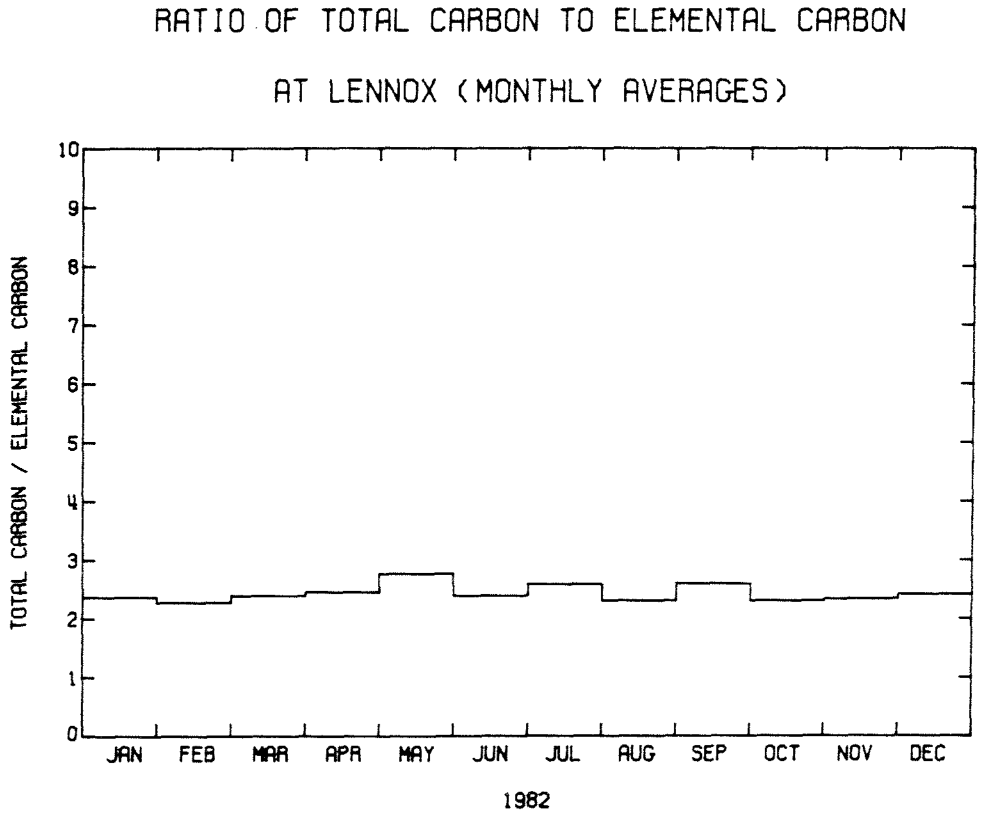


Figure 2.9b

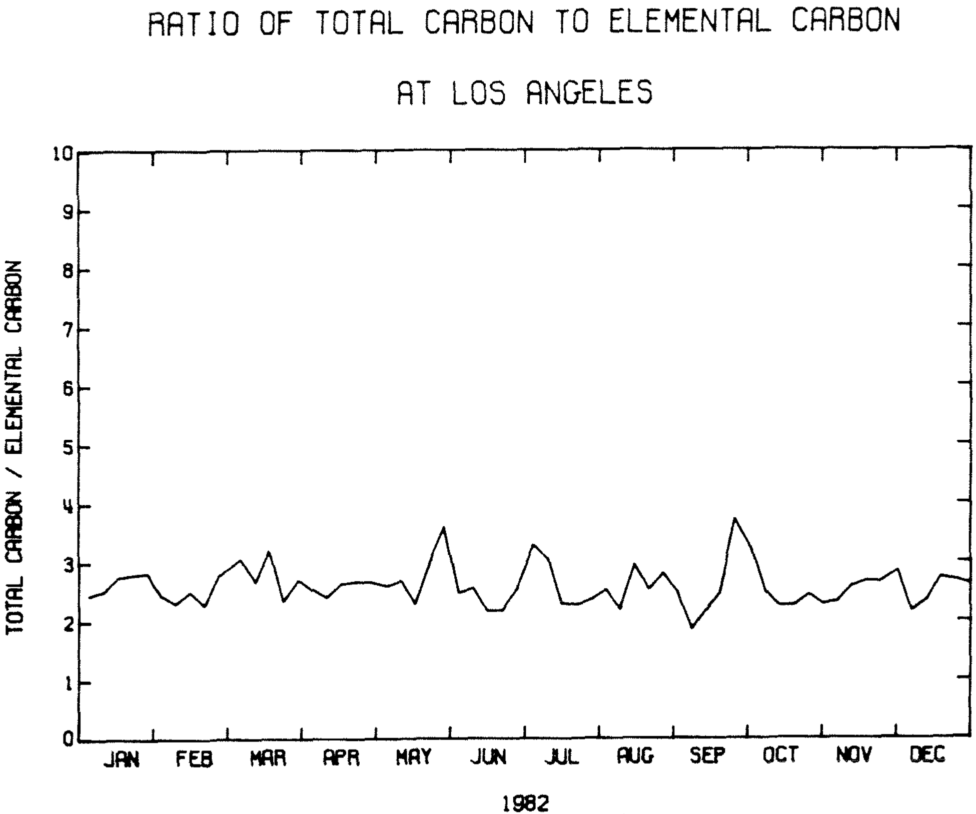


Figure 2.9c

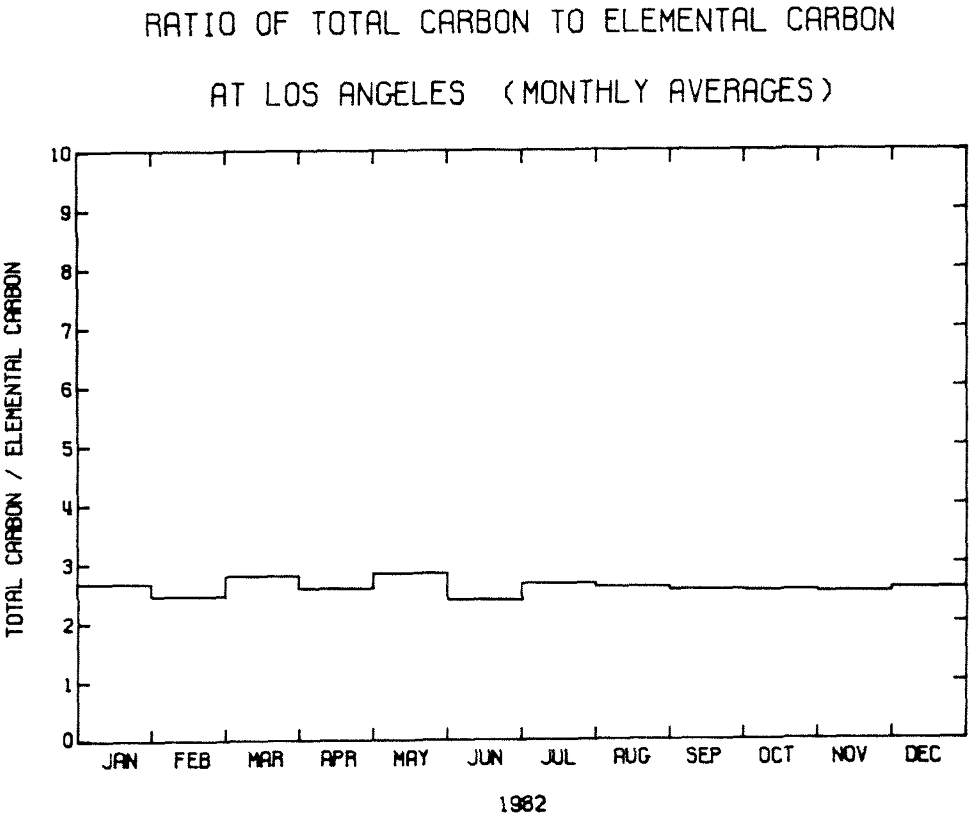


Figure 2.9d

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON

AT PASADENA

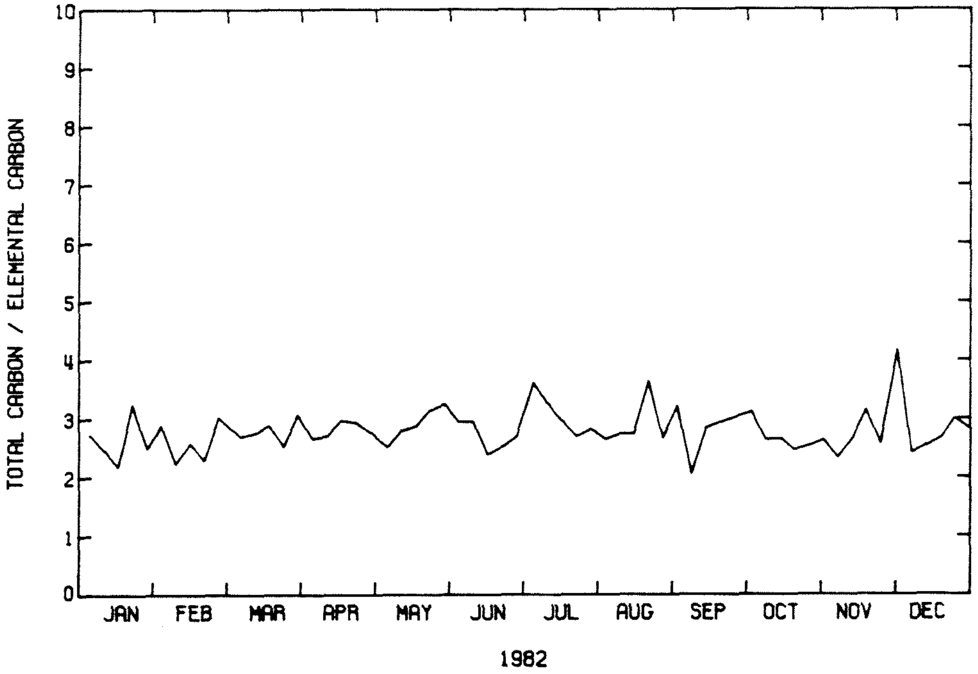


Figure 2.9e

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON

AT PASADENA (MONTHLY AVERAGES)

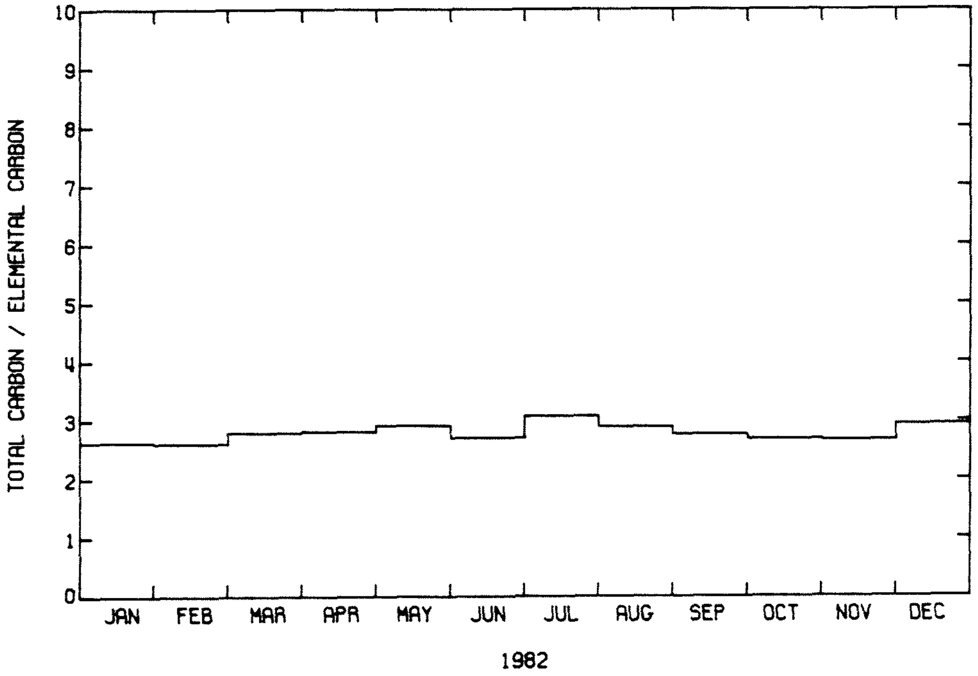


Figure 2.9f

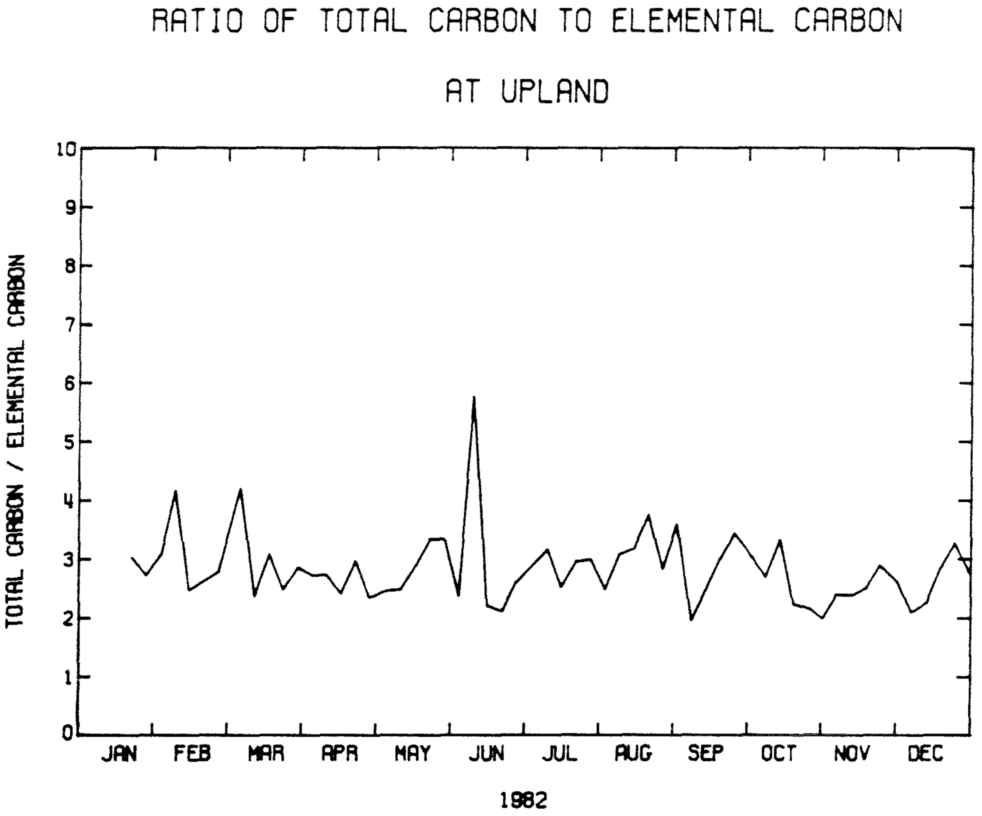

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON
AT UPLAND

Figure 2.9g

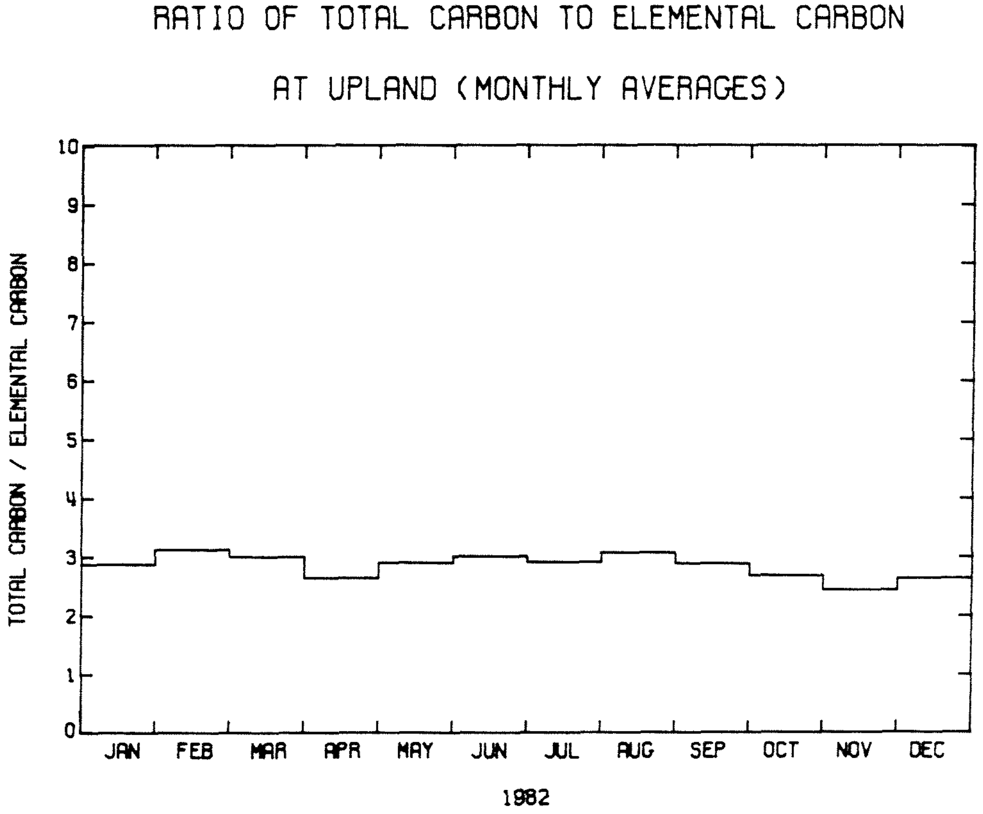

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON
AT UPLAND (MONTHLY AVERAGES)

Figure 2.9h

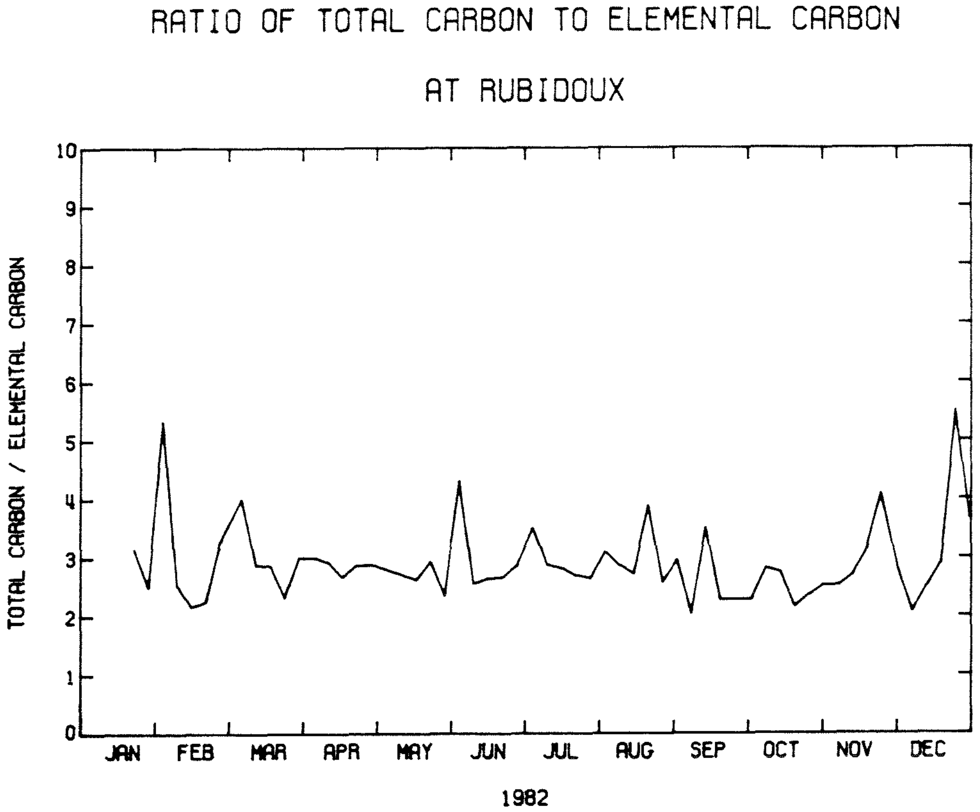


Figure 2.9i

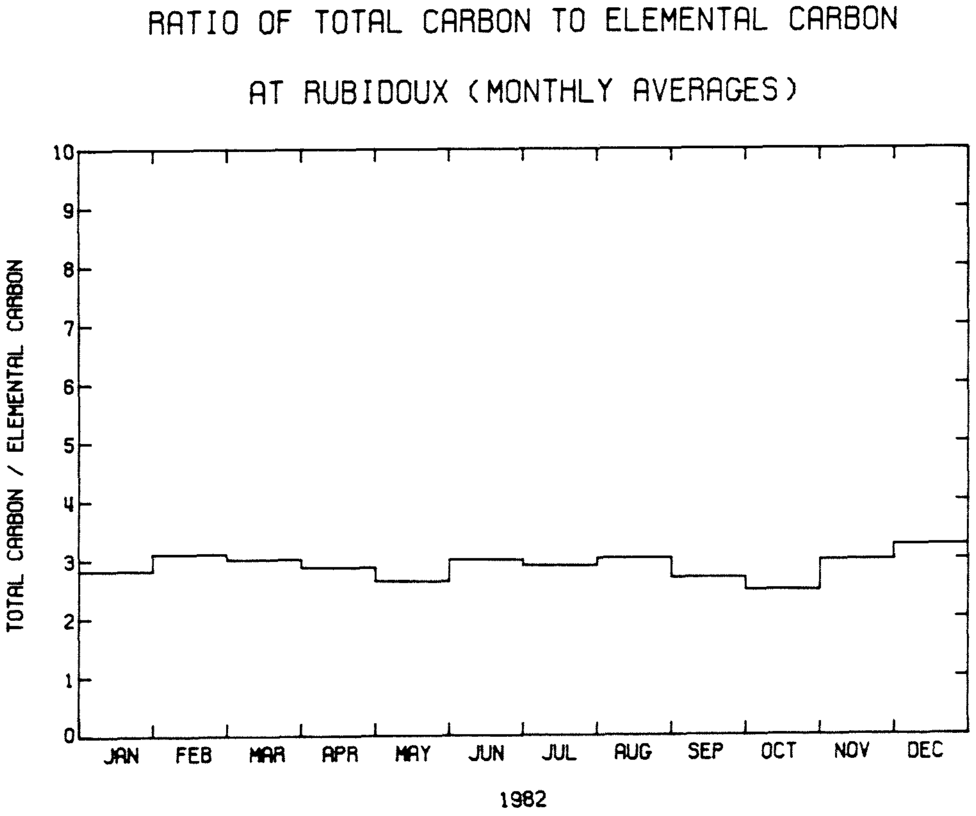


Figure 2.9j

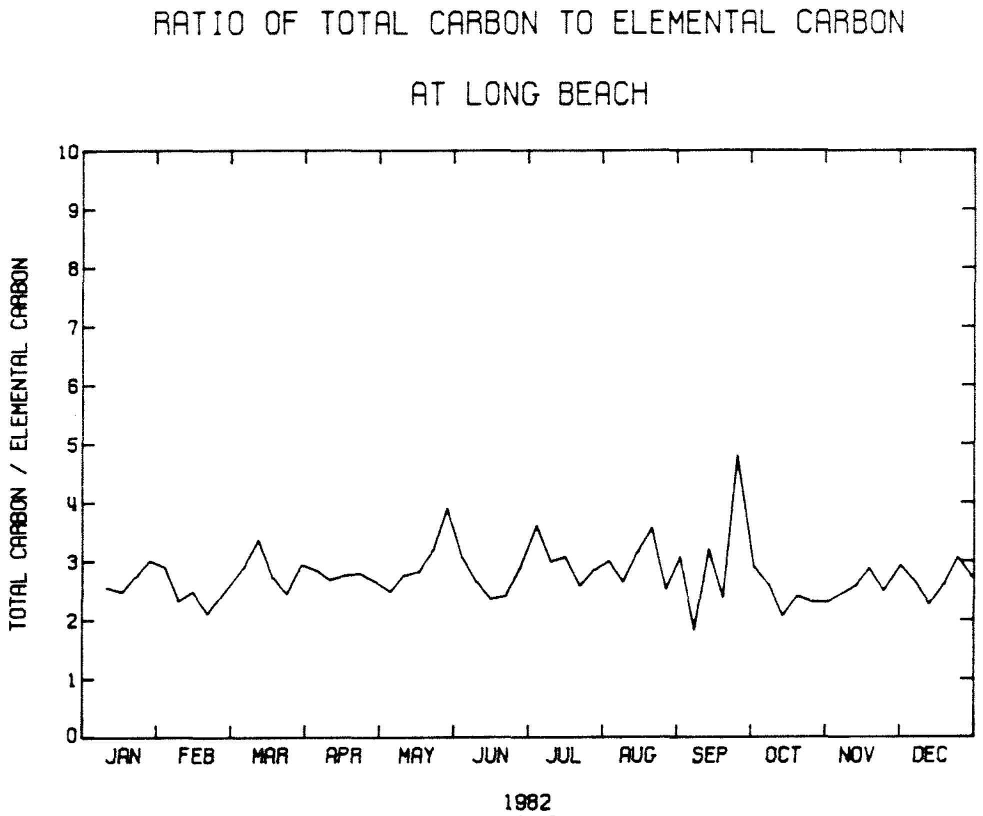


Figure 2.9k

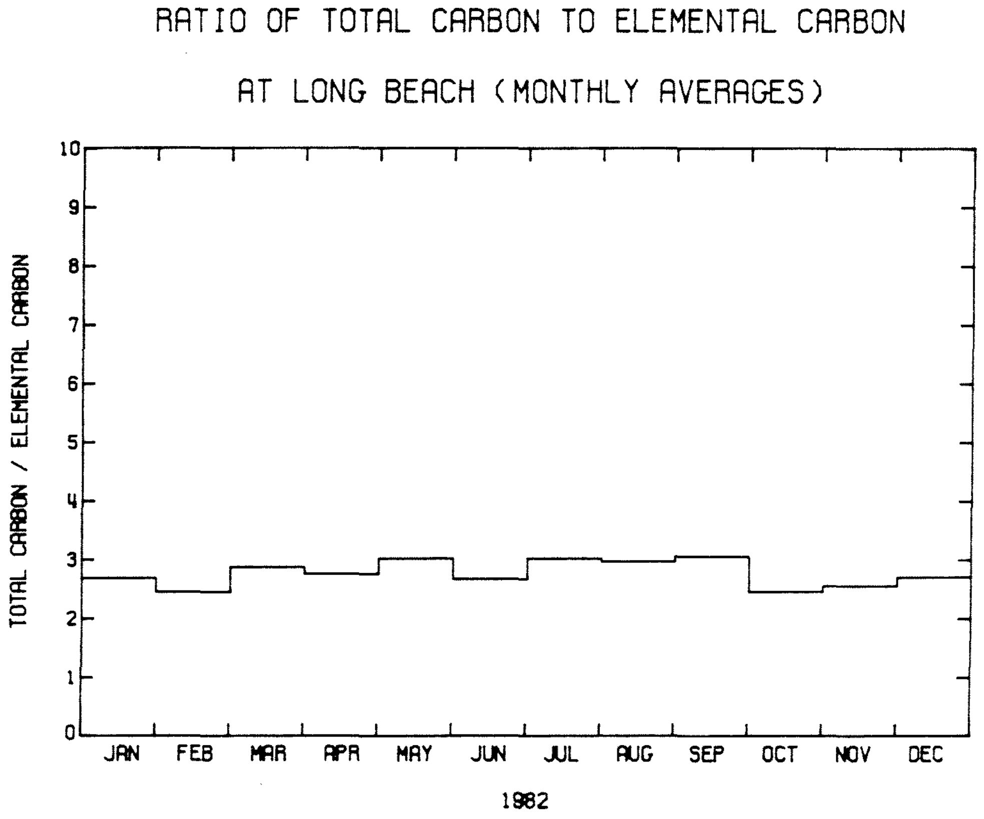


Figure 2.9l

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON

AT WEST LOS ANGELES

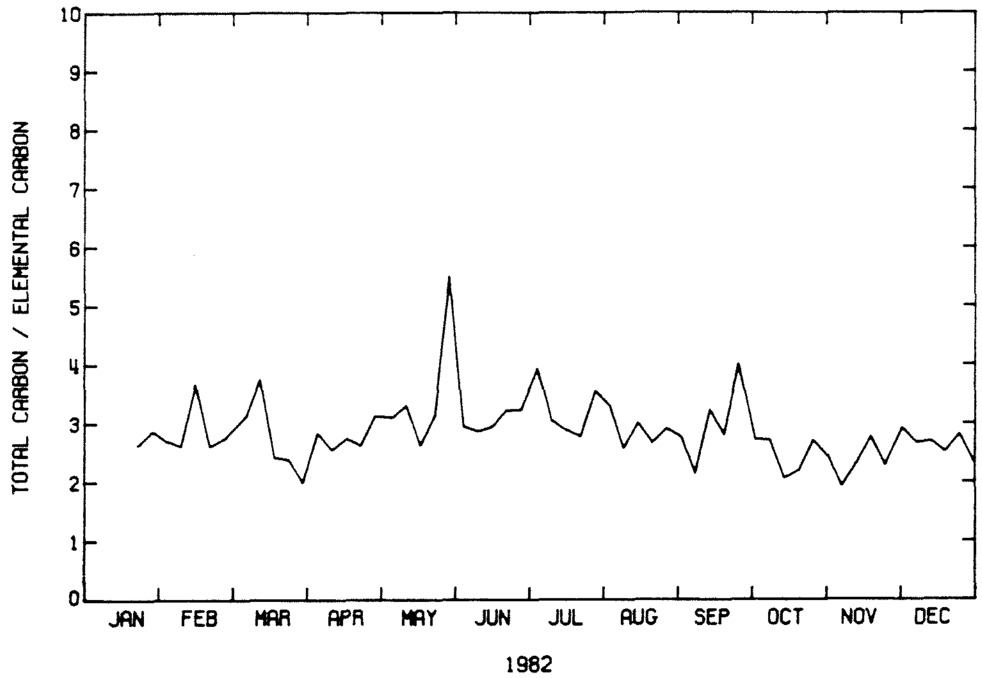


Figure 2.9m

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON

AT WEST LOS ANGELES (MONTHLY AVERAGES)

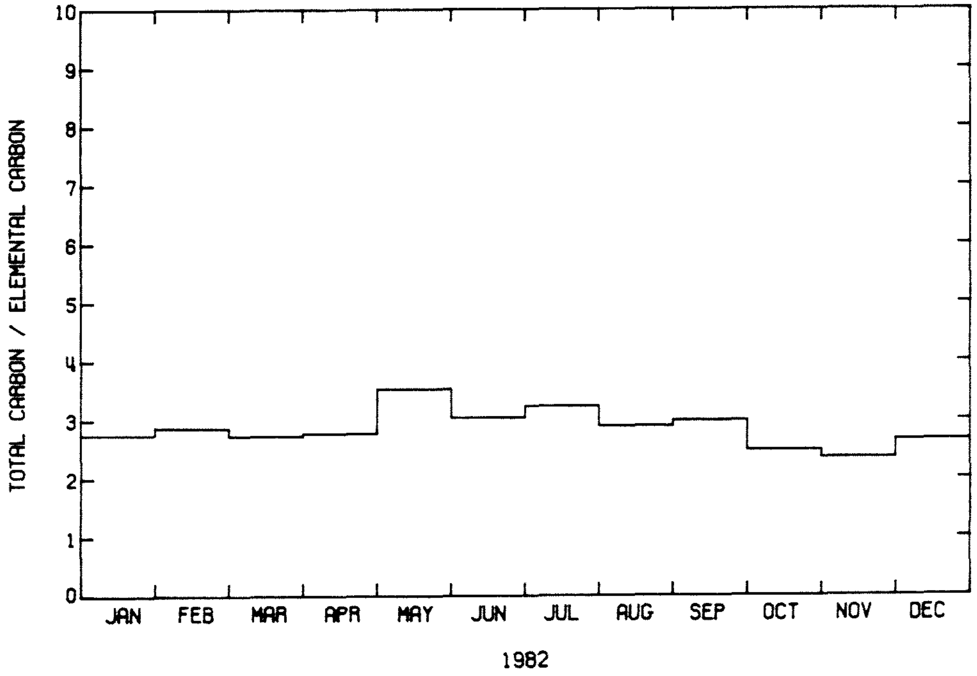


Figure 2.9n

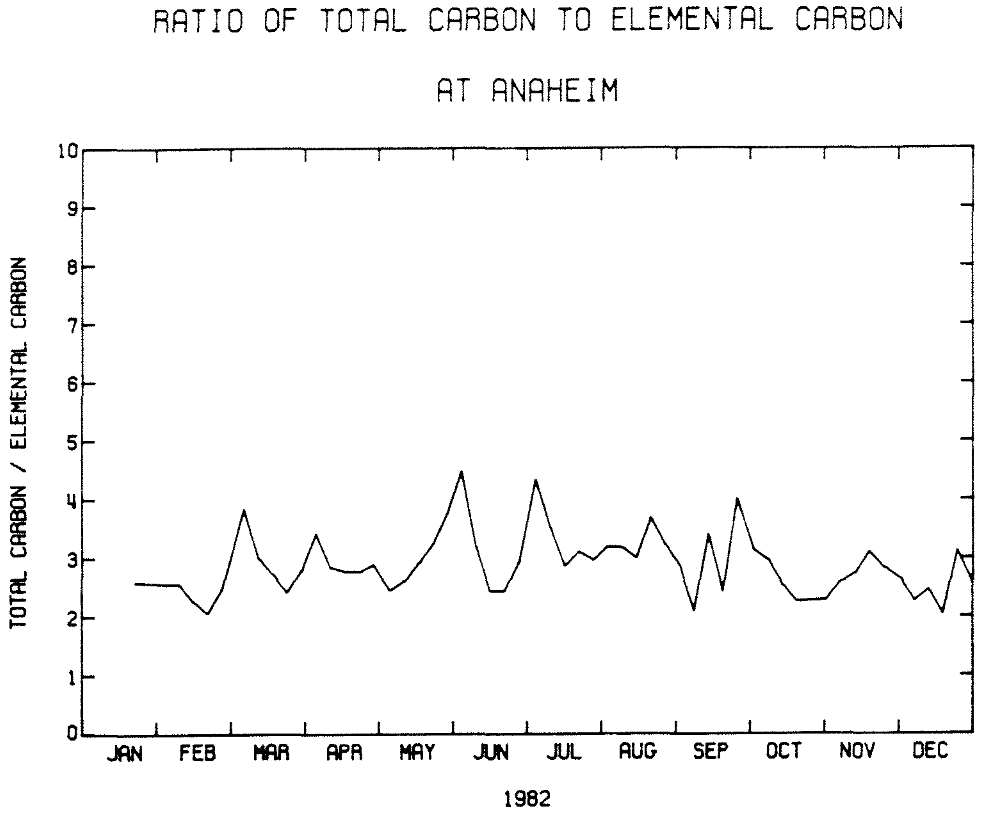


Figure 2.9o

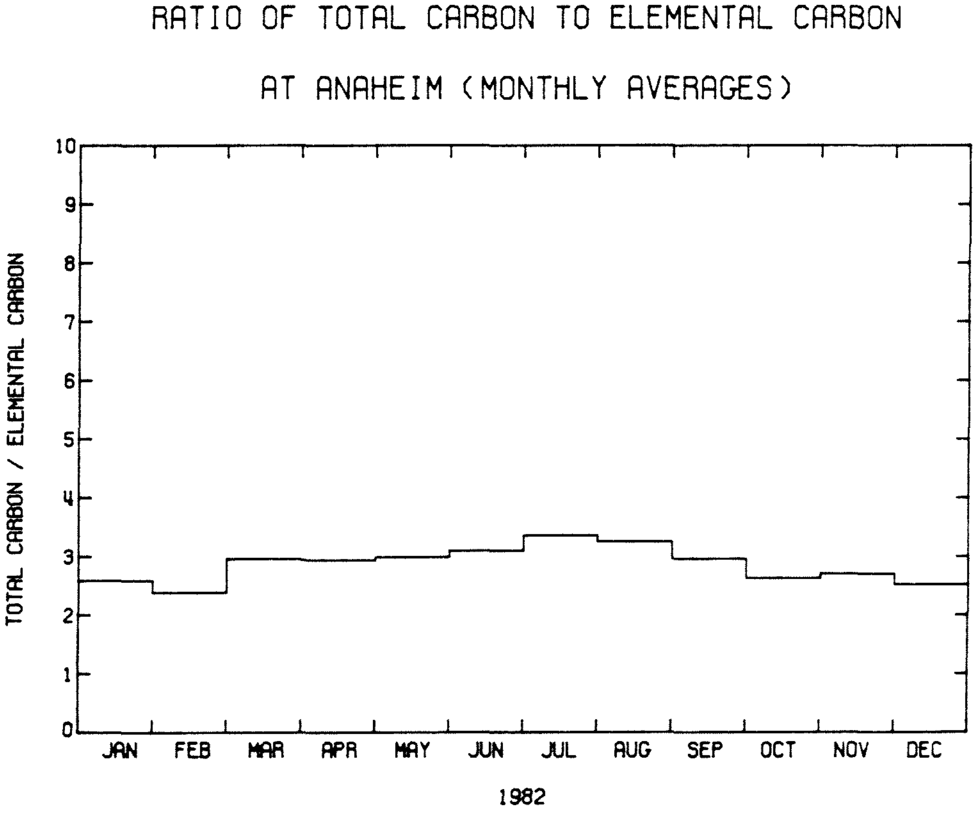


Figure 2.9p

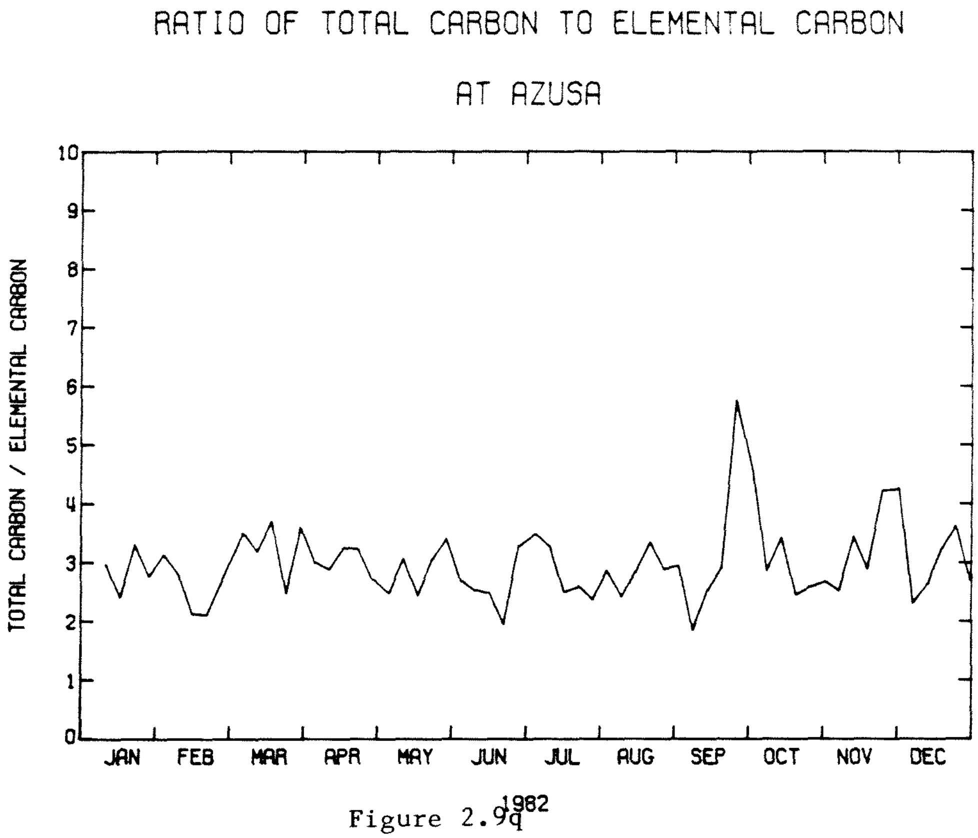

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON AT AZUSA

Figure 2.9q

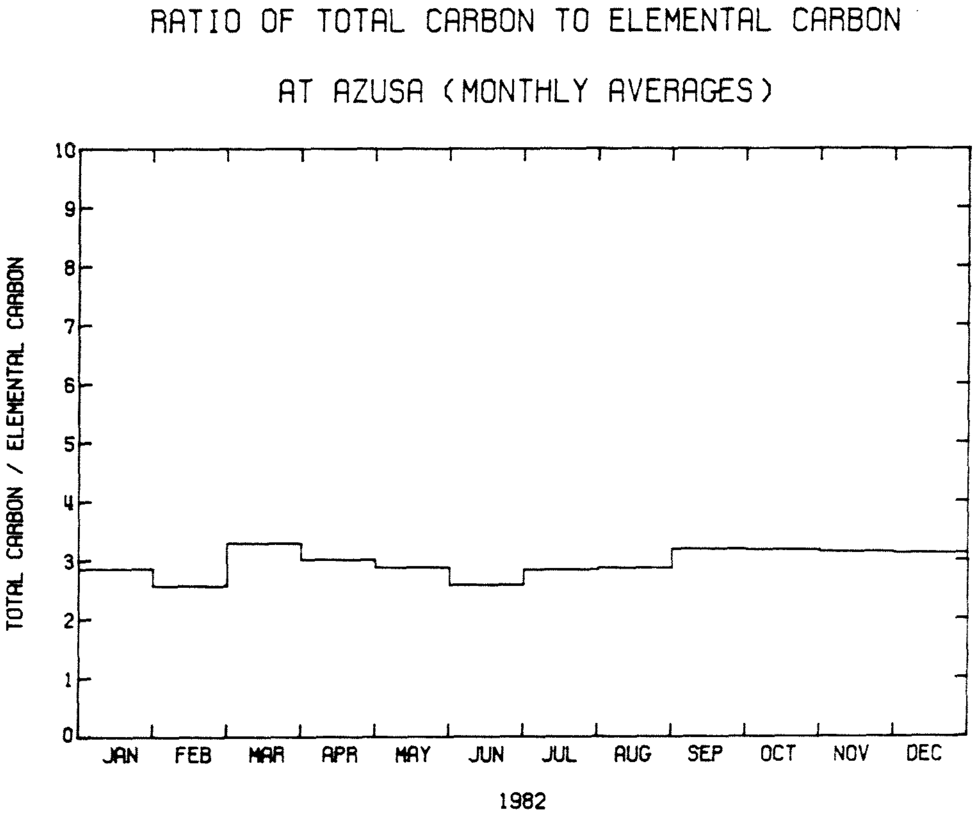

RATIO OF TOTAL CARBON TO ELEMENTAL CARBON AT AZUSA (MONTHLY AVERAGES)

Figure 2.9r

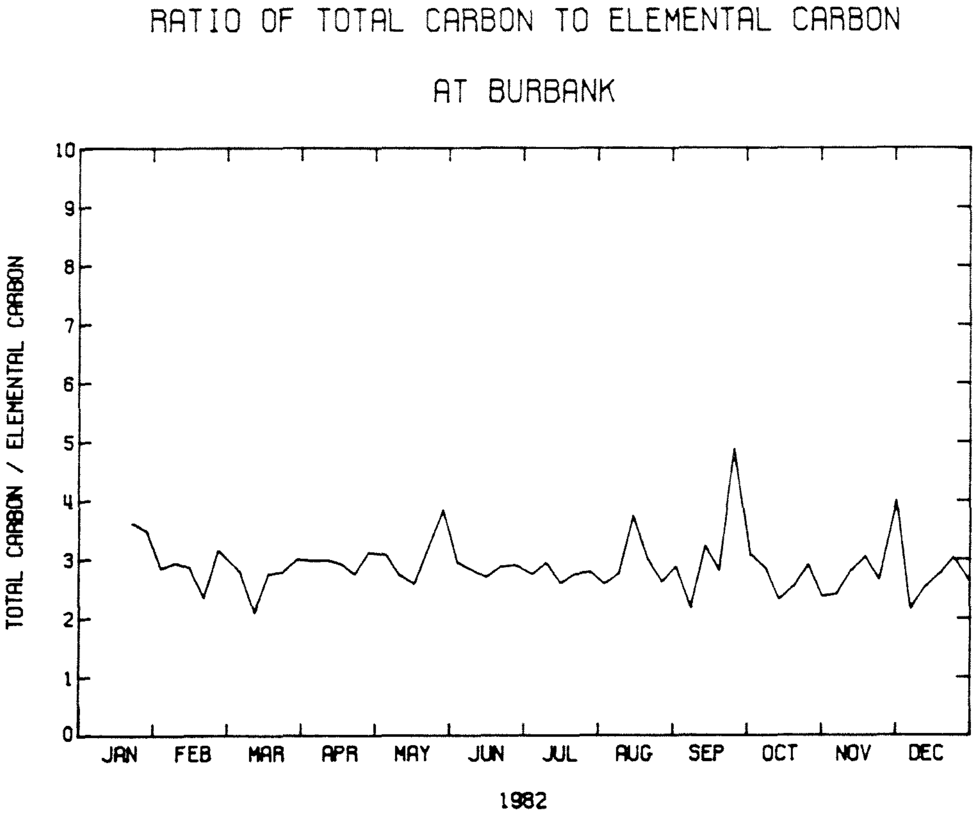


Figure 2.9s

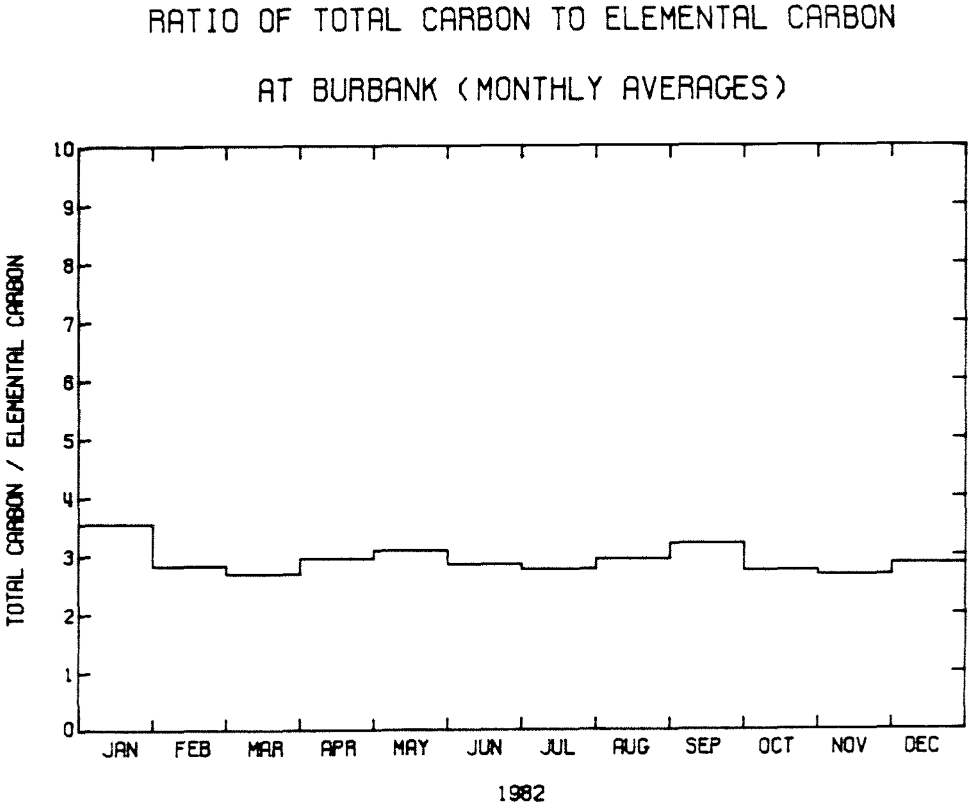


Figure 2.9t

inland to Pasadena, the annual average value of the daily TC to EC ratio rises to 2.8:1, again with little seasonal dependence (Figure 2.9ef). Air parcels reaching Upland on occasion are highly enriched in organics, with daily average TC to EC ratios often above 3:1, and on occasion approaching 6:1 (Figure 2.9gh). This may indicate periodic intrusion of heavy loadings of secondary organic aerosol at Upland. Nevertheless, Upland shows an annual average value of the daily TC to EC ratio of 2.8:1, not greatly different from Downtown Los Angeles. Aerosol behavior further downwind at Rubidoux near Riverside is similar to that at Upland (Figure 2.9ij). Occasional days with high TC to EC ratios are observed, but the monthly average value of the daily TC to EC ratio shows relatively little seasonal dependence. The annual average value of the daily TC to EC ratio at Rubidoux is 2.9:1, still not greatly different from the 1980 estimates of the TC to EC ratio in primary source emissions.

Daily values of the total carbon to elemental carbon ratios at each monitoring site have been averaged over the year 1982 and are shown in Figure 2.10. The lowest average TC to EC ratio is at Lennox adjacent to the San Diego Freeway on the western edge of the air basin, while the highest on-land values are at inland sites usually associated with heavy photochemical smog, like Azusa and Rubidoux. The TC to EC ratio of approximately 7:1 achieved at San Nicolas Island is due to the virtual absence of elemental carbon rather than to an anomalously high organic carbon loading.

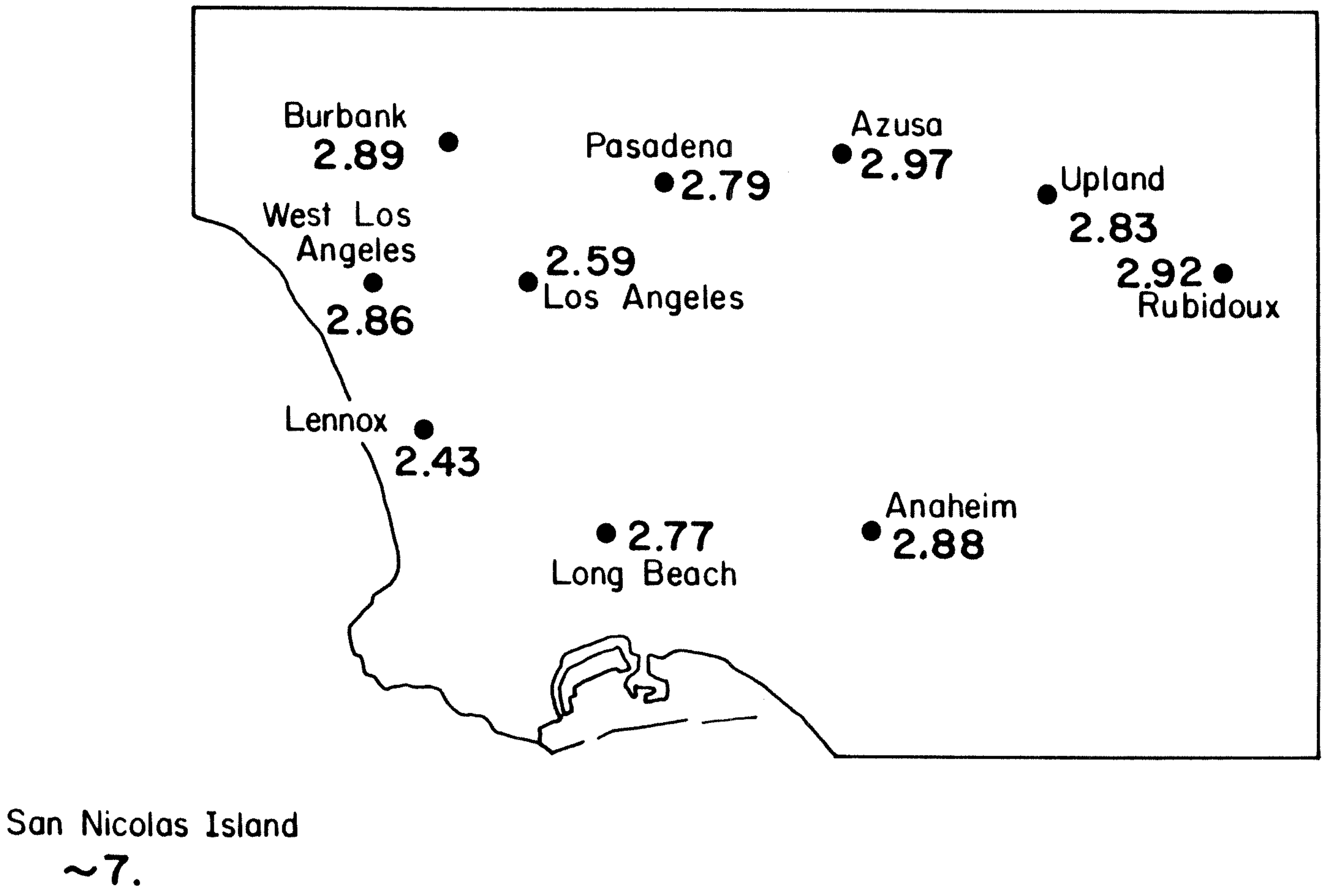


Figure 2.10 Annual average of the daily ratio of total carbon to elemental carbon in fine particles in the Los Angeles area--1982.

2.6 Summary and Discussion

An air quality monitoring protocol employing several parallel filter samples has been described that is capable of nearly closing a material balance on the chemical species contributing to atmospheric fine particle concentrations at all on-land sites other than Rubidoux. Application of this approach to the Los Angeles basin during 1982 shows that carbonaceous aerosols are the most abundant fine particle species present, accounting for roughly 40% of the average fine particle ($d_p < 2.1$ μm) loading at most air monitoring sites.

Fine organic and elemental carbon concentrations in the western Los Angeles basin peak in winter months, like CO and Pb concentrations at those sites. Less seasonal dependence is seen in the eastern basin near Upland and Rubidoux. When averaged over an annual cycle, fine organic and elemental carbon particle concentrations are highest in heavy traffic areas like Los Angeles, Lennox, and Burbank, and decline in downwind areas (Azusa, Upland, and Rubidoux). This spatial distribution and seasonal dependence is consistent with that expected of primary aerosol emissions from ground level sources in Los Angeles.

The comparison of the ratio of fine total carbon to fine elemental carbon in primary emissions versus ambient samples was explored as an indicator of the magnitude of secondary organic aerosol. Three characteristics might be expected if a large amount of secondary organics were present: (1) a ratio of TC to EC exceeding that in primary source emissions, (2) a summer seasonal peak in the ratio of TC to EC reflecting enhanced secondary organics production during the summer photochemical smog season, and (3) an increase in the ratio of TC to EC in the prevailing inland transport direction.

Results of the 1982 field experiment show little seasonal dependence in the ratio of TC to EC. This is true at all monitoring sites on the average over periods of many months, although individual days at inland monitoring sites do show large levels of organic carbon enrichment. Either secondary organic aerosol formation in summer months is a reasonably small fraction of long-term average total carbon concentrations, or alternatively secondary organic aerosol as a fraction of total aerosol carbon is roughly the same in both summer and winter months. The annual average of the daily ratio of fine total carbon to fine elemental carbon averaged from 2.4:1 to 3.0:1 throughout the Los Angeles area during 1982 versus about 3.2:1 in 1980 estimates of local primary source emissions. Again, little evidence of a large enrichment in organic aerosol due to secondary aerosol formation is seen on the average during 1982.

The best case that can be made for aerosol organic carbon enrichment of air parcels during transport in the prevailing inland wind direction is based on examination of differences in TC/EC and OC/EC ratios between stations. In the extreme, the annual average of the daily ratio of TC to EC rises from 2.43:1 at Lennox to 2.97:1 at Azusa and 2.92:1 at Rubidoux. These differences between Lennox and either Azusa or Rubidoux are statistically significant with greater than 95% confidence as can be seen by computing the standard error of the TC/EC sample mean from the TC/EC population standard deviation given in Table 2.2. This enrichment of up to 0.54 parts organic carbon added to the 2.43:1 ratio observed at Lennox represents a + 22% increase in total carbon relative to elemental carbon from one end of the air basin to the other. A + 16% enrichment in total carbon relative to elemental carbon would be found between Lennox and Azusa if the analysis is based on differences in the ratio of the annual mean TC and EC values (see Figure 2.5) rather than on differences in the mean of the daily TC/EC ratios. The organic carbon enrichment can be isolated from total carbon by examining the ratio of OC to EC. The OC enrichment relative to EC between Lennox and Azusa is + 38% based on the mean of the daily ratio of OC to EC, but only + 27% if based on the ratio of the annual mean OC to EC values (see Figure 2.5). One reason for the difference in these statistics is that the OC enrichment relative to EC is favored slightly during summer months when total carbon levels are lower than average. Summaries based on the average of the daily OC to EC ratio treat that ratio each day as equally important to the annual mean, while the ratio of annual means is most affected by the highest concentration events that occur in winter months. Over long averaging times, between 16% and 22% of the total carbon and between 27% and 38% of the organic carbon at an inland location like Azusa or Rubidoux might be due to secondary aerosol formation in excess of that found at Lennox, the range depending on the statistical measure used. By all of these measures, this enrichment contributes a minority of the total carbon and organic carbon present.

On the average over long periods of time, Los Angeles area fine aerosol carbon concentrations probably are dominated by primary source emissions. Secondary organic aerosols may be present, but they probably were not the overwhelming contributor to observed long term average fine carbon particle concentrations during 1982. This suggests that an emission control strategy that achieves a substantial reduction in primary aerosol carbon particle emissions could be expected to achieve a correspondingly large improvement in annual mean fine particle carbon concentrations in the atmosphere.

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CHAPTER 3

DEVELOPMENT OF A SIMULATION MODELING TECHNIQUE FOR LONG-TERM AVERAGE PRIMARY CARBON PARTICLE AIR QUALITY

3.1 Introduction

A procedure for computing the relationship between emissions of an inert pollutant, such as elemental carbon, and long-term average air quality is sought that can be applied in the Los Angeles area. If meteorological information on wind velocities were known with certainty at all locations at all times, then the path of an air parcel leaving an emission source could be tracked exactly. Of course, exact information concerning the transport of air parcels over an air basin is impossible to obtain due to the extremely small length scales for some of the motion which occurs in the atmosphere. However, by combining routine measurements on hourly average wind speed and direction, for which some information is available, and applying a probabilistic approach to the smaller scales of motion, a mathematical description of the transport of pollutants over an air basin may be developed which can be used to predict long-term average primary carbon particle concentrations in the Los Angeles area.

The model described in this chapter is designed to predict the long-term average concentration of elemental carbon in the Los Angeles area by simulating the transport of emissions by atmospheric processes such as advection, diffusion, and deposition. Los Angeles often is characterized by "unsteady" meteorology--light winds and shifting wind patterns over time scales shorter than that necessary to remove pollutants from the air basin. In this study, a Lagrangian marked particle modeling technique has been employed which simulates the motion and deposition of pollutants in an air basin that experiences unsteady meteorological conditions and a fluctuating temperature inversion aloft. In addition, the model is designed with special attention paid to the extent of vertical mixing of pollutants at locations near to their source.

In the following sections of this chapter, a short review of modeling techniques for predicting long-term average pollutant concentrations will be presented. The choice of a model for computing long-term average primary carbon particle concentrations in the Los Angeles area will be discussed, and the applicable mathematical equations will be formulated. In the next chapter, the model will be used to predict fine primary aerosol carbon concentrations in the central portion of the air basin that surrounds Los Angeles. Model predictions will be verified against monthly average elemental carbon concentrations observed during 1982 at a number of locations in the air basin.

3.2 An Overview of Long-term Average Air Quality Models

Emissions to air quality models directly simulate atmospheric fluid transport processes. These models are classified as Eulerian or Lagrangian, depending on the coordinate system employed. Both types of model are based on the atmospheric diffusion equation that mathematically describes the system of atmospheric transport.

Eulerian models are constructed by examining a volume element, fixed in space, and then accounting for all sources and sinks of a pollutant species within that control volume and across its boundaries. This is described mathematically for an inert pollutant (no chemical reactions) by the following set of continuity equations:

$$\frac{\partial c(x,t)}{\partial t} + \frac{\partial u_i(x,t)c(x,t)}{\partial x_i} = D\,\frac{\partial^2 c(x,t)}{\partial x_i \partial x_i} + S(x,t) \qquad (3.1)$$

$$i = 1,2,3$$

where

$c(x,t)$ is pollutant concentration at location $x = (x_1,x_2,x_3)$ and time t,

$u_i(x,t)$ is fluid velocity in the i^{th} coordinate direction at location x and time t,

D is the molecular or Brownian diffusivity of the pollutant species in air,

$S(x,t)$ is the source strength of emissions at location x and time t.

To apply the above equation to an air basin, one would need to know the fluid velocities at all locations. Because wind velocity fluctuates over length scales smaller than those that can be resolved by conventional wind monitors, the mass balance approach used in equation (3.1) cannot be applied as written. An approximate relationship for the ensemble mean concentration of a pollutant can be developed from equation (3.1), however, by separating the fluid transport into an advection term describing the mean wind motion and an eddy diffusion term that accounts for small scale features of atmospheric turbulence with periods less than about one-half hour (see Lamb and Seinfeld 1973):

$$\frac{\partial\langle c(x,t)\rangle}{\partial t} + \frac{\partial}{\partial x_i}\left(\bar{u}_i(x,t)\langle c(x,t)\rangle \right) = \frac{\partial}{\partial x_i}\left(\bar{K}_{ij} \frac{\partial\langle c(x,t)\rangle}{\partial x_j} \right) + S(x,t) \tag{3.2}$$

$$i = 1,2,3 \quad j = 1,2,3$$

where

$\langle c(x,t)\rangle$ is the ensemble mean pollutant concentration at location x and time t,

$\bar{u}_i(x,t)$ is average wind velocity in the i^{th} coordinate direction at location x and time t,

$\bar{K}_{ij}$ is the atmospheric eddy diffusivity tensor (usually it is assumed that $\bar{K}_{ij} = 0$ for $i \neq j$).

In the Lagrangian approach to air quality modeling, air parcels are represented by hypothetical mass points, the trajectories of which are computed from a stochastic solution to the atmospheric diffusion equation. Pollutant concentrations are determined by the probability that an air parcel (representing some pollutant mass) exists at location x and time t, given that it was present at a known location x', at an earlier time t'.

The ensemble mean pollutant concentration at location x and time t is found by integrating initial pollutant concentrations and continuing source emissions over all possible starting locations, weighted by the probability densities of displacement to x, for all times leading up to t:

$$\langle c(x,t)\rangle = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Q(x,t|x_o,t_o)\ \langle c(x_o,t_o)\rangle dx_o$$

$$+\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{t_o}^{t} Q(x,t|x',t')\ S(x',t')dt'dx' \qquad (3.3)$$

where

$\langle c(x,t)\rangle$ is the ensemble mean pollutant concentration at location x and time t,

$Q(x,t|x',t')$ is the transition probability density that a fluid particle existing at location x′ and time t′ will undergo a displacement to location x at time t,

$S(x',t')$ is the spatial and temporal distribution of emissions, evaluated at location x′ at time t′,

x_o and t_o are the initial conditions for location and time.

Equation (3.3) is the general Lagrangian expression developed for use in air quality modeling by Lamb for the case of a nonreactive pollutant (see Lamb 1971, Lamb and Neiburger 1971). The interested reader will find a discussion of the theoretical relationship between the Eulerian modeling approach of equation (3.2) and the Lagrangian solution of equation (3.3) in Lamb and Seinfeld (1973).

3.3 A Simulation Model for Long-term Average Primary Carbon Particle Air Quality under Unsteady Meteorological Conditions

To compute a time-averaged pollutant concentration, equation (3.2) or equation (3.3) could be solved for a large number of nearly instantaneous time increments, and then the results could be averaged. However, if a simulation model is to be run over a period of months, the computing resources required by that approach will become very large if the simulation used to compute the transition probability densities is at all realistic. Therefore, a method for directly computing long-term average concentrations can be developed. The long-term average pollutant concentration at x, over a time interval of duration T (typically one month), starting at time t_s, is defined as:

$$\overline{\langle c(x;T,t_s)\rangle} = \frac{1}{T}\int_{t_s}^{t_s+T} \langle c(x,t)\rangle dt \qquad (3.4)$$

Inserting equation (3.3) into equation (3.4) for the case of $\langle c(x_o,t_o)\rangle = 0$ (this can be accomplished by setting $t_o = -\infty$) gives equation (3.5):

$$\overline{\langle c(x;T,t_s)\rangle} = \frac{1}{T}\int_{t_s}^{t_s+T} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{t} Q(x,t|x',t')\ S(x',t')dt'dx'dt \qquad (3.5)$$

Changing the order of integration between dt and dx' and introducing a change of variable, $t' = t - \tau$ gives:

$$\overline{\langle c(x;T,t_s)\rangle} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{T}\int_{t_s}^{t_s+T}\int_{0}^{\infty} Q(x,t|x',t-\tau)S(x',t-\tau)d\tau dt dx' \tag{3.6}$$

For the case where the diurnal variation of emission source strength for a given source class is independent of location, then $S(x',t-\tau)$ may be written as $\overline{S}(x')\omega(t-\tau)$, where $\overline{S}(x')$ is the time-averaged source strength at location x' and $\omega(t')$ is the normalized diurnal fluctuation for this source class; note that $\omega(t') = \omega(t' + 24 \text{ hours})$. Then equation (3.6) becomes:

$$\overline{\langle c(x;T,t_s)\rangle} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left[\frac{1}{T}\int_{t_s}^{t_s+T}\int_{0}^{\infty} Q(x,t|x',t-\tau)\omega(t-\tau)d\tau dt\right]\overline{S}(x')dx' \tag{3.7}$$

The term in brackets in equation (3.7) may be defined as the time-averaged source-to-receptor transport probability density function:

$$\overline{Q}(x|x';T,t_s) = \frac{1}{T}\int_{t_s}^{t_s+T}\int_{0}^{\infty} Q(x,t|x',t-\tau)\omega(t-\tau)d\tau dt \tag{3.8}$$

Then equation (3.7) may be rewritten as:

$$\overline{\langle c(x;T,t_s)\rangle} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\overline{Q}(x|x';T,t_s)\overline{S}(x')dx' \tag{3.9}$$

The meteorology in Los Angeles would be characterized as unsteady. A daily land breeze/sea breeze wind reversal occurs regularly due to differential solar heating of the land and sea. During the morning and early evening hours, the winds often are stagnant, with no predominant direction during typical short averaging times of one hour. In addition, there is a strong diurnal variation in the height of the base of the temperature inversion. Low overnight inversions rise during the day due to solar heating of the land. In the evening, the inversion base descends again because of a sinking motion induced by the Pacific Anticyclone. The volume of air below the inversion base is often vertically well mixed, so that quick changes in the inversion base height may drastically alter pollutant dilution in the vertical direction. Because of this unsteady behavior in the meteorology, an analytical solution for $\overline{Q}(x|x';\ T,t_s)$ using pseudo-steady state parameterization cannot be obtained.

Lamb and Seinfeld (1973) suggest that the only feasible method of predicting source-to-receptor transport probabilities, $\overline{Q}(x|x';\ T,t_s)$, for an arbitrary sequence of unsteady meteorological events is by means of a simulation model. One straightforward way to estimate $\overline{Q}$ is to launch hypothetical mass points into a numerical simulation of atmospheric fluid flow, and observe their positions over time. The number of particles falling within each volume element of a geographical grid system can be counted to determine by inspection the probability, $P(x,t|x',t-\tau)$, that a particle released at location x' at time $t-\tau$ will be in the grid cell volume element Δx_1, Δx_2, Δx_3 that surrounds location x at time t. Then

$$\overline{Q}(x|x';T,t_s) = \frac{1}{T\Delta x_1\Delta x_2\Delta x_3} \int_{t_s}^{t_s+T} \int_{o}^{\tau_c} P(x,t|x',t-\tau)\omega(t-\tau)d\tau dt \qquad (3.10)$$

In practice, evaluation of equation (3.10) does not require integration of air parcel starting times over all past history. Integration over τ from $\tau = 0$ to $\tau = \tau_c$ is sufficient, where τ_c is the longest retention time for an air parcel within the airshed of interest.

In the following sections, a simulation model will be formulated which will follow the trajectory of statistical "marked" particles. A Lagrangian particle-in-cell air quality model, previously developed by Cass (1977, 1981), will be improved to handle near-source dispersion from ground level sources. Each particle, which represents an air parcel containing a known mass of pollutant, is numerically transported in accordance with a time sequence of meteorological events. First, a set of rules will be written that governs the motion of a single particle over time after it has been released from an air pollutant source of interest. The source-to-receptor probability calculation is broken down into components, each representing a stochastic process in a chain of meteorological events. From the simulation of many such particles representing emissions from a number of urban source types, the probabilities concerning the existence of pollutant mass at given locations can be computed and, hence, may be used to evaluate long-term average pollutant concentrations.

In each of the following sections, the numerical simulation procedure will be given that describes how individual physical processes affect a single particle. Probabilities of transition will be derived based on an idealized meteorological situation representing Los Angeles air basin conditions. Finally, an algorithm will be constructed for computing the overall source-to-receptor transition probabilities, $P(x,t|x',t-\tau)$ (from equation [3.10]), due to all physical processes for each source type in the air basin. Then $\bar{Q}$ can be evaluated from equation (3.10) for each separate source type. When combined with data on the spatial distribution of emission source strength as in equation (3.9), a multiple source urban air quality model results. Numerical solution of equation (3.9) is achieved by replacing the integrals with summations over discrete spatial intervals in the horizontal plane, (x_1,x_2). Concentrations are computed at a single height, x_3, near ground level. Contributions from all sources are added to an estimate of regional background air quality to arrive at the predicted long-term average pollutant concentration.

3.3.1 Single Particle Transport in the Horizontal Plane

The horizontal trajectory of an air parcel may be computed by integrating wind vectors instantaneously along the path of the air parcel. This calculation is impossible given data available in an actual urban air basin, however, since wind measurements are made only at a limited number of locations and generally are time-averaged over one-hour periods. Large scales of motion in an air basin are resolvable with such wind data, but there exist many smaller scale motions with periods of less than about one-half hour that are not measured directly. The cumulative effect of these small scale features of atmospheric turbulence is known as eddy diffusion and can be modeled as a random fluctuation in air parcel location about the path computed from hourly averaged wind data. It should be pointed out that the separation of horizontal transport into advection and diffusion merely reflects the observer's frame of reference. An air parcel experiences motion due to all scales of atmospheric turbulence acting together.

Mean air parcel trajectories in the horizontal plane will be computed by head-to-tail progressive addition of observed wind vectors. Eddy diffusion will be simulated by adding small random displacements to the air parcel location computed from hourly averaged wind data. A very sophisticated wind field generation scheme based on interpolation of all available hourly averaged wind measurements could be used to determine the mean wind components. However, the data entry effort and computer time necessary to construct highly accurate wind fields hourly over the period of a year can become extremely costly. Therefore, an approximation is sought that will simplify the computation of trajectories for an air basin such as Los Angeles.

Cass (1977) showed that a uniform parallel flow approximation at any single hour adequately represents transport over the flat portion of the Los Angeles coastal plain when used in this type of long-term average air quality modeling calculation. Under the parallel flow approximation, a single centrally located wind station is used to represent flow over the coastal plain. During near-stagnant conditions this approximation will not yield great accuracy, but during periods of higher wind speeds, flow becomes quite organized. Over long averaging times, experience shows that the approximation yields reasonable results.

Given that approximation, the trajectory computation for a single particle proceeds as follows. The reported hourly mean wind direction measurements are resolved only to within the 22.5° of arc which make up sectors of the 16-point compass reading. Therefore, a random direction is chosen from a uniform distribution of those possible directions within the sector of interest to be used as the mean direction for each hour. The two-dimensional random variable representing mean hourly horizontal wind speed, $\underset{\sim}{V}$, may be broken down into its two orthogonal components, V_1 and V_2, which are computed from the following equations:

$$V_1(t) = w(t) \cos (\theta(t)) \tag{3.11}$$

$$V_2(t) = w(t) \sin (\theta(t)) \tag{3.12}$$

where

$V_1(t)$ and $V_2(t)$	are the components of wind speed for hour t in the x_1 and x_2 directions, respectively,
ws(t)	is the reported hourly averaged wind speed during hour t,

and

$$\theta(t) = d(t) + 22.5\ U\,[-0.5, 0.5] \tag{3.13}$$

where

$\theta(t)$	is the randomized mean wind direction at hour t, in degrees,
$d(t)$	is the reported mean wind direction during hour t, in degrees measured counterclockwise from an axis pointing toward the east (direction x_1),
$U[a,b]$	is a uniform random variable with mean zero and range from a to b.

The randomized location due to the advective displacement from $\mathbf{x}' = (x'_1, x'_2)$ to $\mathbf{X}'' = (X''_1, X''_2)$ during the time from t_o to t is computed for a uniform parallel flow regime as:

$$X''_1\ (t\,|\,x'_1, t_o) = \int_{t_o}^{t} V_1(t')\,dt' + x'_1(t_o) \tag{3.14}$$

$$X''_2\ (t\,|\,x'_2, t_o) = \int_{t_o}^{t} V_2(t')\,dt' + x'_2(t_o) \tag{3.15}$$

Since the wind measurements are recorded as hourly averages, the integrals in equations (3.14) and (3.15) may be replaced by summations, with $\Delta t = 1$ hour:

$$X''_1\ (t\,|\,x'_1, t_o) = \sum_{n=0}^{N-1} V_1(t_o + n\Delta t)\Delta t + x'_1(t_o) \tag{3.16}$$

$$X''_2\ (t\,|\,x'_2, t_o) = \sum_{n=0}^{N-1} V_2(t_o + n\Delta t)\Delta t + x'_2(t_o) \tag{3.17}$$

where $N = \dfrac{(t - t_o)}{\Delta t}$.

In addition to the mean displacement due to advective transport, small scale turbulent fluctuations occur that randomize an air parcel's location about its mean trajectory. This process of eddy diffusion is simulated as a two-dimensional Gaussian random variable with mean zero and standard deviation $(\sigma_1(\tau), \sigma_2(\tau))$. Mean trajectory end points X''_1, X''_2 are perturbed at each hour by adding small distance increments $\delta X''_1$ and $\delta X''_2$ drawn at random from the family of displacements having a Gaussian distribution $(\sigma_1(\tau), \sigma_2(\tau))$.

Now, consider the probability distribution, $P_a(\underset{\sim}{x}'',t|\underset{\sim}{x}',t - \tau)$, for the displacement <u>by advection</u> (and eddy diffusion) of a single particle from starting point $\underset{\sim}{x}'$ to ending point $\underset{\sim}{x}''$ during the time interval from $t_o = (t - \tau)$ to t. A single particle can be only in one place. Therefore, for the case of P_a estimated from a single trajectory calculation with spatial location defined over a grid system based on discrete spatial intervals:

$$P_a(\underset{\sim}{x}'',t|x',t - \tau) = \lambda(x^* - \underset{\sim}{X}'') \qquad (3.18)$$

where $\lambda\ (\underset{\sim}{x}^* - \underset{\sim}{X}'')$ is a proximity function defined as

$$\lambda\ (\underset{\sim}{x}^* - \underset{\sim}{X}'') = \begin{cases} 1 \text{ if } |(x_i^* - X''_i)| < \dfrac{\Delta x_i}{2} \text{ for } i = 1,2 \\ 0 \text{ otherwise} \end{cases} \qquad (3.19)$$

and $\underset{\sim}{x}^*$ is the center of the grid cell in the horizontal plane of the modeling region that contains location $\underset{\sim}{x}''$. $P_a(x'',t|x',t - \tau)$ could be computed repeatedly for many single particle trajectories and then averaged to obtain an accurate spatially distributed probability density function $\langle P_a(x'',t|x',t-\tau)\rangle$ describing the fate of pollutants released at location x' at time $t-\tau$.

The instantaneous parallel flow assumption allows for a great savings in computation time, since the probability of finding the particle in the area element surrounding $\underset{\sim}{x}''$ at time t, given that it was at location $\underset{\sim}{x}'$ at time t_o, is only a function of the displacement $(\underset{\sim}{x}''-\underset{\sim}{x}')$ and the specific time interval $(t_{o,}t)$. The probability of a particle's experiencing a displacement $(\underset{\sim}{x}''-\underset{\sim}{x}')$ in the horizontal plane is not a function of starting location. Therefore, trajectory calculations for hundreds of different source starting locations may be collapsed into one source-to-receptor probability distribution calculation that may be applied to any starting location, $\underset{\sim}{x}'$, by simply subtracting the change in starting location from all possible endpoints of interest. The result is that $P_a(\underset{\sim}{x}'',t|\underset{\sim}{x}',t-\tau)$ may be rewritten as $P_a(\underset{\sim}{x}''-\underset{\sim}{x}',t,t-\tau)$.

3.3.2 Exchange in the Vertical Direction

Up to this point, the motion of an air parcel has been described only in two dimensions. The probabilities of transport presented thus far have dealt with the frequency of occurrence of air parcel transport to particular horizontal locations. The air parcel's motion in the vertical direction also may be simulated.

The geographic region of interest is assumed to experience an idealized stable temperature inversion aloft at all times. The base of the inversion generally rises during the day and falls at night due to the radiative heating and cooling of the earth. An air parcel containing particulate matter may reside in the stable layer above the inversion base or in the unstable layer below the inversion base. In addition, dry deposition of particulate matter occurs at the ground. In this section, a set of rules that describes the exchange of particulate-laden air parcels between these two vertical layers in the atmosphere will be constructed, and ground level dry deposition will be considered. Mathematical expressions for the probabilities associated with finding a particular fluid particle in each vertical compartment in the model will be formulated. These probability calculations will be discussed in two regimes. First, the case of an air parcel that has been emitted into the stable temperature inversion aloft or that has resided below the inversion base long enough to become fully mixed from the ground to the inversion base will be considered. In that case, the air parcel, _if_ it is below the inversion base, will have equal probability of being found at any particular elevation within the mixed layer, and calculation of the air parcel's probability of affecting ground level air quality is particularly easy. The second case, where the air parcel has not yet had time to become fully mixed within the ground level layer of the model, occurs for fresh emissions from low-level sources and on occasion from elevated sources when the inversion base is at a high elevation. That case of non-uniform vertical mixing will be treated later in Section 3.3.3.

The following set of rules, developed by Cass (1977), is adopted by which the probability may be computed that an air parcel containing particulate matter resides in one of three compartments in the model. At the time of emission, an air parcel is placed either into the mixed layer below the inversion base or into the inversion layer above, depending on the effective stack height of the source. Then a procedure is outlined that computes the probability that that air parcel resides above or below the inversion base at the end of each time step, or that it has undergone dry deposition at the earth's surface prior to the end of that time step. This probability depends upon the conditions at the beginning of the time step and upon inversion base motion that causes air parcels to be transferred between the mixed layer below the inversion and the stable layer within the inversion.

The following definitions are made:

$P_b(t|t - \tau)$ is the probability that an air parcel is <u>below</u> the inversion base at time t, given that it was emitted at time $t_o = t - \tau$,

$P_i(t|t - \tau)$ is the probability that an air parcel is in the <u>inversion</u> layer above the inversion base at time t, given that it was emitted at time $t_o = t - \tau$,

$P_g(t|t - \tau)$ is the probability that an air parcel has been deposited at the <u>ground</u> sometime between the time of emission, $t_o = t - \tau$, and time t,

$h(t)$ is the height of the inversion base separating the inversion layer above from the mixed layer below,

$h_m(t, t - \tau)$ is the maximum inversion base height, $h(t)$, over the time interval from $t_o = t - \tau$ to t,

$H(t_o)$ is the effective stack height of emissions.

At the time of release, an air parcel is assumed to reside below the inversion base if the effective stack height of the source is below the inversion base. Otherwise, the air parcel's initial location is assumed to be stratified at the effective stack height within the stable inversion layer. This is shown schematically in Figure 3.1. The initial conditions for the probability of finding the particle in a given compartment of the model are as follows:

$$P_b(t_o) = \begin{cases} 1 & H(t_o) \leq h(t) \\ 0 & h(t) < H(t_o) \end{cases} \tag{3.20}$$

$$P_i(t_o) = 1 - P_b(t_o) \tag{3.21}$$

$$P_g(t_o) = 0 \tag{3.22}$$

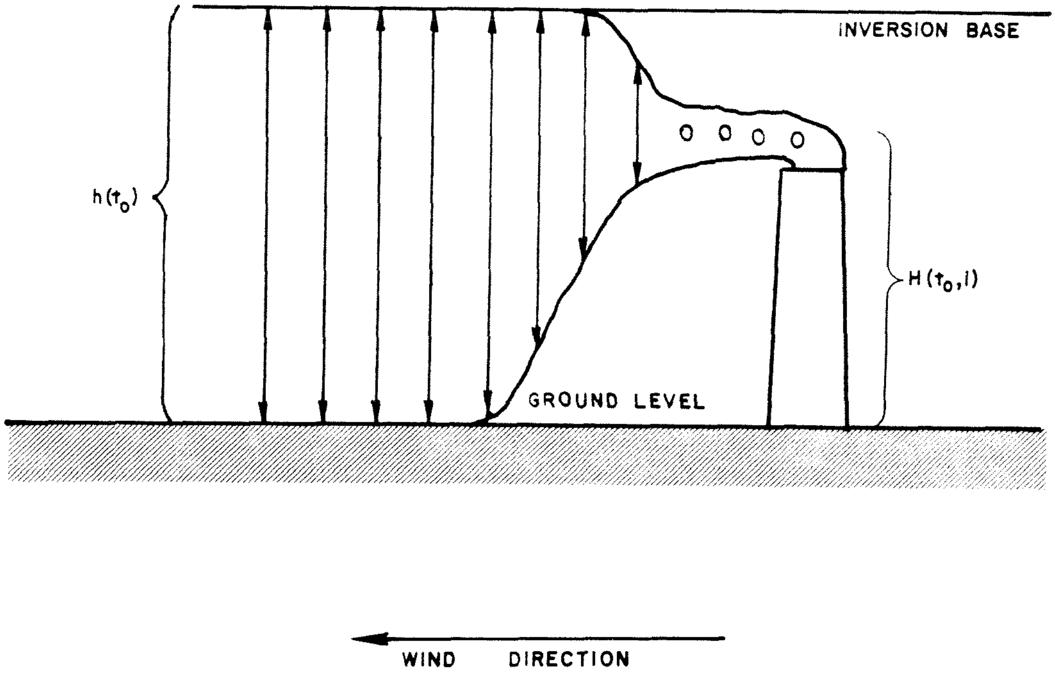
and

$$h_m(t_o) = h(t_o) \tag{3.23}$$

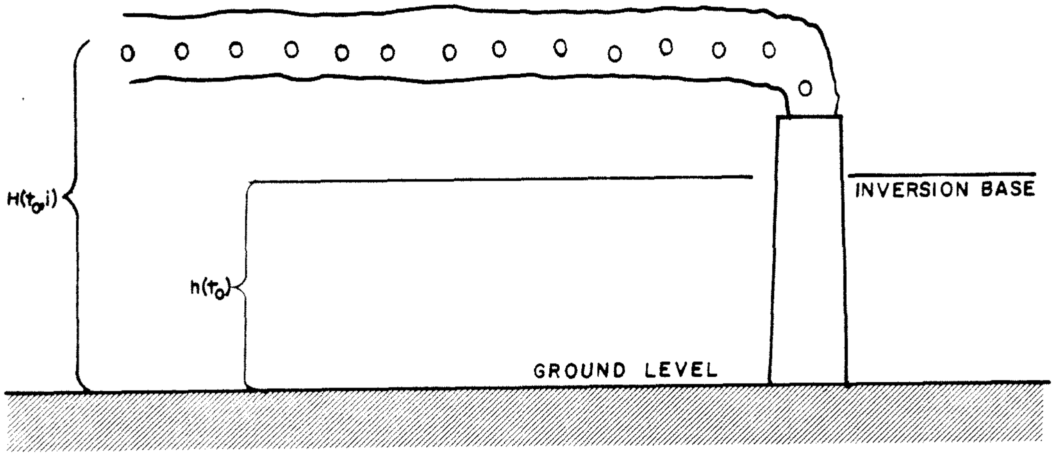
Dry deposition of particulate matter from the mixed layer to the ground may be represented as a first order process. The rate of removal from the mixed layer due to dry deposition alone is:

Figure 3.1 Air parcel insertion into the atmosphere (from Cass 1977).

CASE 1



CASE 2



$$\frac{dP_b(t)}{dt} = -\frac{V_g}{h(t)} P_b(t) \qquad (3.24)$$

where V_g is the effective deposition velocity for particles of a given size range. (This is not actually a settling velocity, but rather the ratio between pollutant flux to the ground and atmospheric concentration.)

Solving equation (3.24) for a short interval time, Δt, where $h(t + \Delta t) \simeq h(t) \simeq h$:

$$P_b(t + \Delta t) = P_b(t) \exp\left[\frac{-V_g}{h} \Delta t\right] \qquad (3.25)$$

This is the probability that an air parcel residing in the mixed layer below the inversion at time t remains in the mixed layer after Δt, i.e., it is not deposited at the ground. Therefore, the probability that an air parcel has been deposited by time $t + \Delta t$ is:

$$P_g(t + \Delta t) = P_g(t) + P_b(t) \left\{1 - \exp\left[\frac{-V_g}{h} \Delta t\right]\right\} \qquad (3.26)$$

The probability of transfer of an air parcel from the mixed layer to the ground represented in equations (3.25) and (3.26) now must be coupled with the process by which an air parcel may move between the mixed layer and the inversion layer. The mixed layer has a depth, changing with time, equal to the current inversion base height. The inversion base height above ground level, and hence the mixing depth, will be taken as independent of horizontal location at any single time. Justification for this approximation over the western portion of the Los Angeles basin is provided by Cass (1977). This approximation when combined with previous assumptions about horizontal transport allows for calculation of vertical motions independently of horizontal location in the air basin.

Consider the fate of an air parcel emitted from an elevated source at night into the stable inversion aloft. That air parcel will remain at the effective height of emission until such time as the inversion base rises to intercept the air parcel, transferring it to the layer below the inversion base. Once below the inversion base, that air parcel has equal probability of being found at any elevation (i.e., pollutants fumigated down from high elevation become fully mixed between the inversion base and the ground). If the inversion base descends over time, an air parcel located below the inversion base within the mixed layer has some probability of becoming trapped within the inversion layer. Assuming that pollutant-laden air parcels are well mixed below the inversion base, then the probability that a particular air parcel remains in the mixed layer and is not transferred to the inversion layer is equal to the ratio of the inversion base heights before and after the descent of the inversion base. Inversion base descent through a polluted mixed layer results in stabilization of a thick polluted air mass within the inversion itself. The depth of this thick pollutant layer within the inversion is equal to the distance between the previous maximum mixing depth and the current lower inversion base height. If the inversion base subsequently rises into this thick polluted layer aloft, the probability that an air parcel is transferred from the inversion layer back into the mixed layer is taken in proportion to the change in

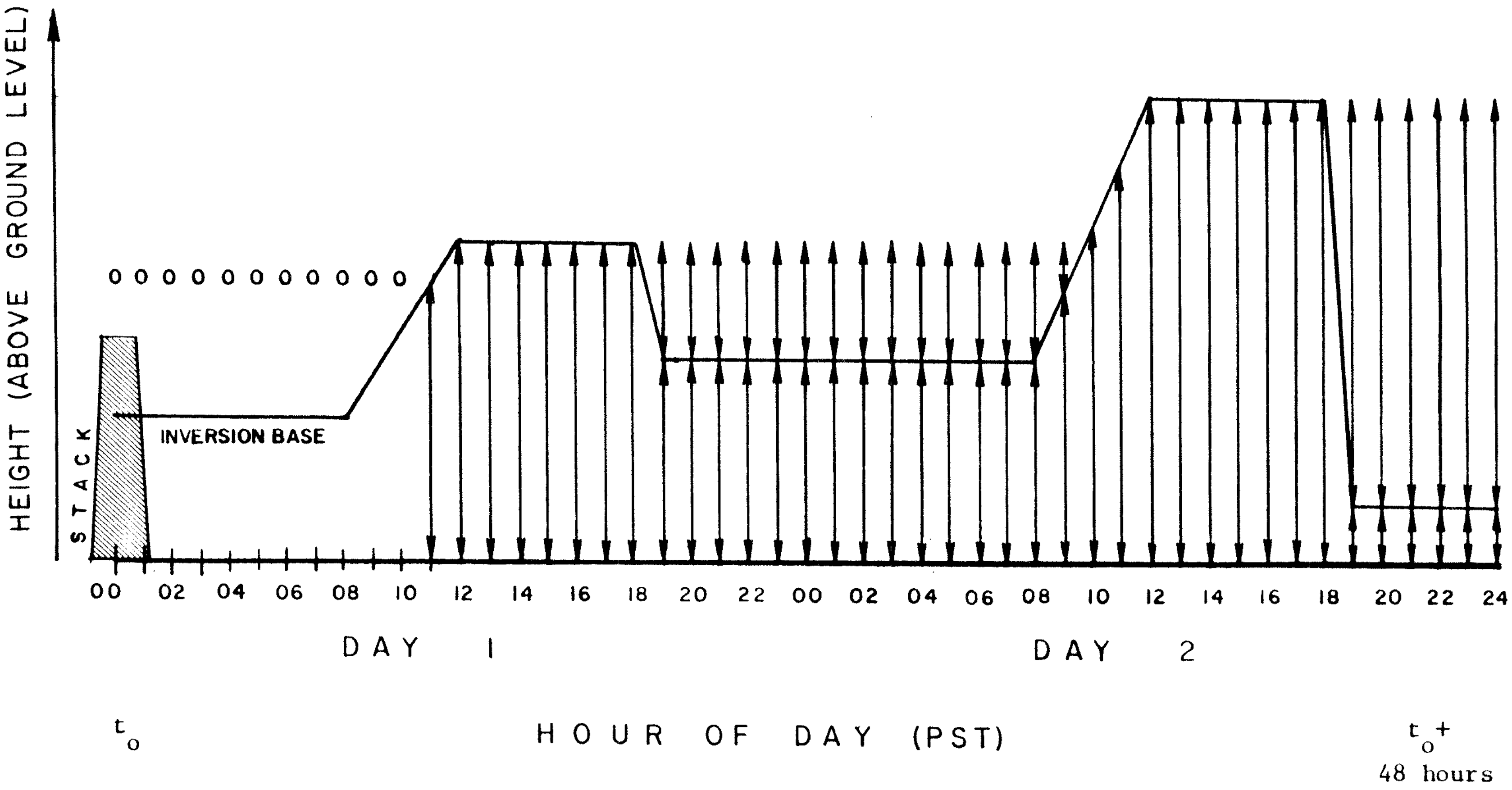


Figure 3.2 Hypothetical time history of interaction between the inversion base and a fluid particle released at time t_o (from Cass 1977).

inversion base height relative to the previously established maximum mixing depth. This process is described graphically in Figure 3.2.

The initial conditions in equations (3.20) through (3.23), when combined with the following stepwise procedure for computing probabilities of transfer of air parcels between each vertical layer over a time interval, Δt, can be used to propagate the probabilities that an air parcel resides in each layer of the model during the history of the air parcel's trajectory. For each time interval $(t, t + \Delta t)$ perform the following steps:

1. Compute f_d, the probability that an air parcel in the mixed layer has deposited at the ground during this time interval:

$$f_d = 1 - \exp\left[\frac{-V_g \Delta t}{h(t + \Delta t)}\right] \tag{3.27}$$

2. If $h(t + \Delta t) > h_m(t)$, then set maximum inversion height $h_m(t + \Delta t)$, to new maximum $h(t + \Delta t)$, else $h_m(t + \Delta t) = h_m(t)$.
3. Determine the parameter f_s which is related to the air mass that is exchanged between the inversion layer and the mixed layer when the inversion base moves. If the inversion base is rising, f_s will be negative.

For effective stack height, $H(t_o) > h_m(t + \Delta t)$:

$$f_s = 0 \tag{3.28}$$

For $H(t_o) \lesssim h_m(t + \Delta t)$:

$$f_s = \begin{cases} & \text{inversion base} & \\ P_b(t) \left[\dfrac{h(t) - h(t + \Delta t)}{h(t)}\right] & \text{falling:} & h(t + \Delta t) < h(t) \\ 0 & \text{steady:} & h(t + \Delta t) = h(t) \\ P_i(t) \left[\dfrac{h(t) - h(t + \Delta t)}{h_m(t) - h(t)}\right] & \text{rising:} & h(t) < h(t + \Delta t) < h_m(t) \\ -P_i(t) & \text{rising:} & h(t) \lesssim h_m(t) < h(t + \Delta t) \end{cases} \tag{3.29}$$

4. Compute new probabilities at end of time increment $t + \Delta t$:

$$P_i(t + \Delta t) = P_i(t) + f_s \tag{3.30}$$

$$P_b(t + \Delta t) = (P_b(t) - f_s)\ (1 - f_d) \tag{3.31}$$

$$P_g(t + \Delta t) = P_g(t) + \left[P_b(t) - f_s\right] f_d \tag{3.32}$$

If this procedure is executed repeatedly for time steps from $t_o = t - \tau$ to t, then the result will be the three probabilities, $P_i(t|t - \tau)$, $P_b(t|t - \tau)$, and $P_g(t|t - \tau)$ that the air parcel is within the stable inversion, or below the inversion base within the mixed layer, or has deposited at the ground by time t, given that it was emitted at time $t - \tau$. Note that the summation of equations (3.30), (3.31), and (3.32) results in:

$$P_i(t + \Delta t) + P_b(t + \Delta t) + P_g(t + \Delta t) = P_i(t) + P_b(t) + P_g(t) \qquad (3.33)$$

The sum of these probabilities always will be 1.0 since $P_i(t_o) + P_b(t_o) + P_g(t_o) = 1.0$ (see equations [3.20] through [3.22]). Therefore, mass is conserved during this process.

3.3.3 Vertical Profile below Inversion Base

Particulate matter residing below the inversion base may not always be completely mixed in the vertical direction. Although the ground level computational cell in the model is called the "mixed layer," there are times when the probabilities of finding a polluted air parcel at different heights within that cell are unequal. If the pollutant were assumed to be fully mixed below the inversion base, then the probability of finding an air parcel at any height (or, more specifically, within Δx_3 of any height) below the inversion base would be inversely proportional to inversion base height, h(t). This assumption becomes unreasonable when polluted air parcels are near their sources and the pollutant has not had sufficient time to become fully mixed.

In order to accurately predict particulate concentrations near ground level in the vicinity of ground level sources, a model must include the effect of short travel times on vertical mixing. In this section, the probability of finding a polluted air parcel at a particular elevation within the mixed layer is computed for the first few time steps after release from a source with effective stack height below the inversion base.

A vertical profile of probable air parcel location is formulated assuming a Gaussian distribution of plume spread from an effective source height, H. Three regimes are possible, depending on the degree of dispersion and the height of the inversion base: (1) when the inversion base height, h, is very high (or the air parcel's travel time is very short), there is no effect of the inversion base on the vertical dispersion of the plume; (2) as the air parcel moves away from its source, the vertical dispersion increases until the stable layer aloft begins to trap the air parcel below the inversion base; (3) when the plume has traveled sufficiently far, it becomes fully mixed between the ground and the inversion base. It is necessary that each of these three regimes be considered and that the transitions between the regimes be smooth. This is accomplished by utilizing basic analytical procedures for estimating dispersion as outlined by Turner (1969).

Assume that the probable location of a pollutant-laden air parcel has a Gaussian distribution, centered along the mean horizontal wind trajectory, in both the crosswind and vertical directions. Further assume that there is a total reflection of the plume at the earth's surface (deposition is accounted for elsewhere; see Section 3.3.2). Then the normalized concentration at location x = (x_1,x_2,x_3) due to a continuous unit source located at $x_1 = x_2 = 0$ with effective stack height H, for the case of transport in the x_1 direction when the inversion base is high relative to the characteristic scale for vertical mixing (i.e., $\sigma_3 << h$), may be computed as follows (from Turner 1969):

$$C(x_1,x_2,x_3;H) = \frac{1}{2\pi\sigma_2\sigma_3 u} \exp\left[-½\left(\frac{x_2}{\sigma_2}\right)^2\right]$$

$$\left\{\exp\left[-½\left(\frac{x_3 - H}{\sigma_3}\right)^2\right] + \exp\left[-½\left(\frac{x_3 + H}{\sigma_3}\right)^2\right]\right\}$$

(3.34)

where σ_2 and σ_3 are the standard deviation of plume spread in the crosswind and vertical directions, respectively, u is wind speed, C is pollutant concentration (mass per unit volume of air) resulting from a source of one mass unit per unit time. Note that σ_2 and σ_3 are increasing functions of x_1, the distance along the centerline of the plume trajectory, and hence σ_2 and σ_3 depend on the travel time, τ, of the air parcel from its time of release until reaching location x, downwind. If a slice is taken across the plume at distance x_1 downwind and that slice is integrated in the crosswind direction, one determines the probability of finding a polluted air parcel at a specific height x_3 or, more specifically, within the small differential height element Δx_3 about x_3 at time t given that it was released at time $t - \tau$:

$$P_v(x_3,t\,|\,H,t-\tau) = \frac{\Delta x_3}{\sqrt{2\pi}\,\sigma_3}\left\{\exp\left[-\tfrac{1}{2}\left(\frac{x_3-H}{\sigma_3}\right)^2\right] + \exp\left[-\tfrac{1}{2}\left(\frac{x_3+H}{\sigma_3}\right)^2\right]\right\} \tag{3.35}$$

Equation (3.35) is used when a fresh air parcel is released below the inversion base while $\sigma_3 << h$. When the magnitude of σ_3 grows to approach the location of the inversion base, the presence of the inversion base begins to affect material in the upper tail of the Gaussian plume, and a correction to equation (3.35) is necessary. Bierly and Hewson (1962) have suggested the addition of numerous terms to equation (3.35) that account for the multiple reflections from both the ground and the stable layer:

$$\begin{aligned} P_v(x_3,t\,|\,H,t-\tau) = \frac{\Delta x_3}{\sqrt{2\pi}\,\sigma_3}\Bigg(&\exp\left[-\tfrac{1}{2}\left(\frac{x_3-H}{\sigma_3}\right)^2\right] + \exp\left[-\tfrac{1}{2}\left(\frac{x_3+H}{\sigma_3}\right)^2\right] \\ &+ \sum_{n=1}^{J}\Bigg\{\exp\left[-\tfrac{1}{2}\left(\frac{x_3-H-2nh(t)}{\sigma_3}\right)^2\right] + \exp\left[-\tfrac{1}{2}\left(\frac{x_3+H-2nh(t)}{\sigma_3}\right)^2\right] \\ &+ \exp\left[-\tfrac{1}{2}\left(\frac{x_3-H+2nh(t)}{\sigma_3}\right)^2\right] + \exp\left[-\tfrac{1}{2}\left(\frac{x_3+H+2nh(t)}{\sigma_3}\right)^2\right]\Bigg\}\Bigg) \end{aligned} \tag{3.36}$$

where J = 4 is sufficient to include the important reflections.

Equation (3.36) may be used for all three regimes discussed above. When the inversion base is very high ($\sigma_3 << h$), the reflection terms are near zero so equation (3.36) becomes the same as equation (3.35). As the plume moves farther downwind, σ_3 continues to grow rapidly, until the plume becomes completely mixed between the ground and the base of the temperature inversion. At this point, $P_v(x_3,t|H,t - \tau)$ approaches $\Delta x_3/h(t)$, which means it is equiprobable that a polluted air parcel from this plume will be found at any elevation below the inversion base. Computation on equation (3.36) for the case of $\sigma_3 >> h$ gives the desired result (as h/σ_3 approaches zero, it is necessary to increase J for convergence):

$$P_v(x_3,t|H,t - \tau) \rightarrow \frac{\Delta x_3}{h(t)} \quad \text{as } \frac{h}{\sigma_3} \rightarrow 0 \qquad (3.37)$$

Since equation (3.36) collapses into equation (3.35) when the inversion base has no effect, and into equation (3.37) when complete mixing occurs, it can be used for the general case to compute the probability that an air parcel resides within a particular domain within the mixed layer during the first few time steps after its release below the inversion base.

In practice, Turner (1969) suggests using an equation like (3.35) for $\sigma_3 < h^* = 0.47$ h. At the time when σ_3 equals h^*, the error in $P_v(x_3,t|H,t - \tau)$ associated with not using the additional reflection terms found in equation (3.36) is only 0.02% (for $x_3 = H =$

0). Equation (3.36) is used when $\sigma_3 > h^*$. At some point, however, σ_3 will become large enough that the air parcels may be considered well mixed below the inversion base and $P_v(x_3,t|H,t-\tau)$ will approach $\Delta x_3/h(t)$ as in equation (3.37). It can be seen that when σ_3 increases to 2.5 h^*, the use of equation (3.37) instead of equation (3.36) results in an error in $P_v(x_3,t|H,t-\tau)$ of only 0.22% (for $x_3 = H = 0$). As time increases, σ_3 increases so that when σ_3 increases beyond 2.5 h^* and equation (3.37) has been chosen once, that portion of an air parcel that is located below the inversion base is considered fully mixed between the ground and inversion base for all subsequent time steps. It should be understood that the imposition of the vertical profile in this section will be operative only for the first few time steps of an air parcel's travel from its source. The vertical profile approximation constructed in this section, therefore, is employed as a correction for close-to-source, pollutant-laden air parcels during periods when σ_3 is small relative to the inversion base height.

3.3.4 Computational Procedure for Air Quality Model Simulation

The methods described in the previous sections for calculating probable air parcel motion over time due to individual physical processes may be combined to compute the overall source-to-receptor transport relationship in three-dimensional space. Let $P(x,t|x',t-\tau)$ be the probability of finding an air parcel within the air volume $x_i - \frac{\Delta x_i}{2} \leq x_i < x_i + \frac{\Delta x_i}{2}$, $i = 1,2,3$ surrounding near-ground level location x given that it was released at location x′ at time $t - \tau$. That probability density function can be constructed by multiplying the separate probabilities that the air parcel is (1) in the horizontal domain $x_i - \frac{\Delta x_i}{2} \leq x_i < x_i + \frac{\Delta x_i}{2}$, $i = 1,2$, and (2) resides below the inversion base, and (3) that the particle is at elevation $x_3 - \frac{\Delta x_3}{2} \leq x_3 < x_3 + \frac{\Delta x_3}{2}$ given that it is below the inversion base:

$$P(x,t|x',t - \tau) = P_a(\mathbf{x} - \mathbf{x}',t,t - \tau)\ P_b(t|t - \tau)\ P_v(x_3,t|x'_3,t - \tau) \tag{3.38}$$

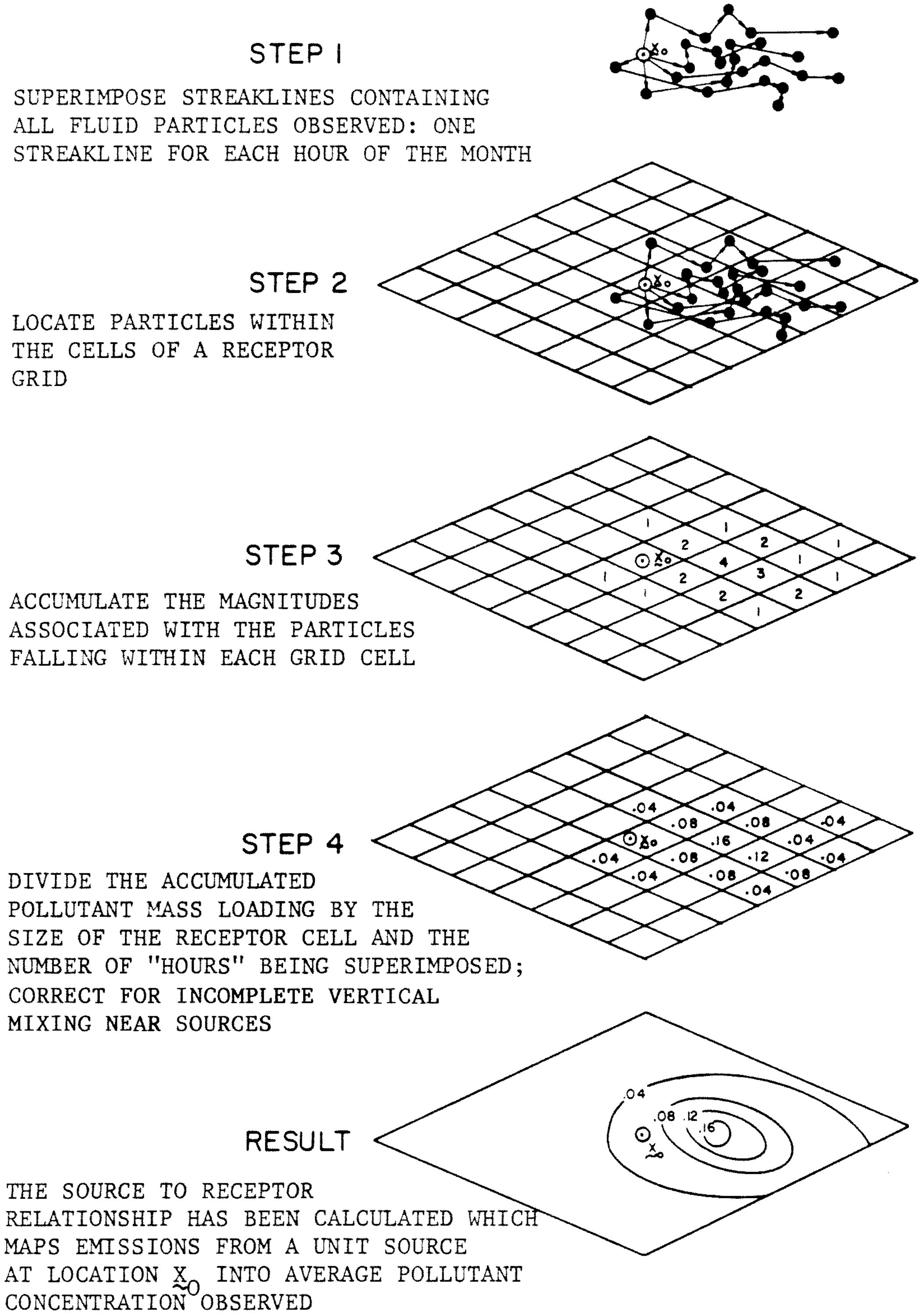
By integrating equation (3.10) over time for many particle trajectories defined by equation (3.38) and then over many source locations using equation (3.9), long-term average pollutant concentration estimates are obtained. The computer program written to perform this integration works on the basis of a numerical simulation. Hypothetical mass points are released successively at small time intervals, Δt, from source location x′ at the effective stack height of the source of interest. The pollutant mass associated with each particle is weighted by the diurnal source strength function appropriate to that source. Then for each time increment, the horizontal displacement of each of the many particles released is computed as a random variable in accordance with the probabilities of transition due to advection and horizontal diffusion as detailed in

Section 3.3.1. This is followed by the simulation of vertical exchange during the time increment, with probabilities computed as in Section 3.3.2. Finally, the probability that each mathematical particle is near the specified height, x_3, is computed for this time increment from equations in Section 3.3.3. At each time increment, Δt, of interest during the averaging time interval $(t_s, t_s + T)$, a grid system is laid down over the air basin. The number of particles falling within each grid cell and the pollutant mass associated with each particle are summed. The pollutant mass is divided by the volume of the cell in order to obtain pollutant concentration in mass/unit volume of air. This procedure is described graphically in Figure 3.3 for the case of $\Delta t = 1$ hour and $T = 1$ month.

Results for the same time of day on each day during $(t_s, t_s + T)$ are superimposed and then averaged in order to obtain the average diurnal variation of predicted pollutant concentration. Results at all times during the period $(t_s, t_s + T)$ are superimposed and averaged in order to compute the long-term average pollutant concentration as a function of grid cell location in the air basin.

This simulation procedure is executed separately for each source class (e.g., automobiles, jet aircraft, power plants, etc.), resulting in a separate estimate of the contribution to pollutant concentration due to each source class. The incremental impacts from all source classes are added to form a total air quality impact at each horizontal grid cell location and height x_3 due to local pollution sources. Finally, an estimate of background pollutant

Figure 3.3



STEP 1

SUPERIMPOSE STREAKLINES CONTAINING ALL FLUID PARTICLES OBSERVED: ONE STREAKLINE FOR EACH HOUR OF THE MONTH

STEP 2

LOCATE PARTICLES WITHIN THE CELLS OF A RECEPTOR GRID

STEP 3

ACCUMULATE THE MAGNITUDES ASSOCIATED WITH THE PARTICLES FALLING WITHIN EACH GRID CELL

STEP 4

DIVIDE THE ACCUMULATED POLLUTANT MASS LOADING BY THE SIZE OF THE RECEPTOR CELL AND THE NUMBER OF "HOURS" BEING SUPERIMPOSED; CORRECT FOR INCOMPLETE VERTICAL MIXING NEAR SOURCES

RESULT

THE SOURCE TO RECEPTOR RELATIONSHIP HAS BEEN CALCULATED WHICH MAPS EMISSIONS FROM A UNIT SOURCE AT LOCATION $\underset{\sim}{X}_0$ INTO AVERAGE POLLUTANT CONCENTRATION OBSERVED concentration is added to the computed pollutant concentration from all local pollution sources to arrive at a predicted long-term average pollutant concentration.

In practice, the order of integration in the above description may be changed. Simulations may be carried out such that all trajectories ending (not starting) at a specific time are computed together. This enables one to readily examine long-term average diurnal concentration patterns. Also, computation time is saved because trajectories may be constructed by integrating backwards in time such that one mathematical trajectory represents the current locations of $\tau_c/\Delta t$ air parcels which were released from a single location during the preceding $\tau_c/\Delta t$ time increments. This one trajectory calculation replaces $\tau_c/\Delta t$ separate trajectory calculations to arrive at the same information (see Cass 1977).

3.4 Summary

In this chapter, a mathematical model has been stated that is suited to the computation of long-term average primary carbon particle air quality in an urban air basin. A Lagrangian simulation model has been constructed that tracks a large number of statistical air parcels, representing the transport of air pollutants under unsteady meteorological conditions. Each physical transport process is modeled as an independent stochastic process. Pollutant transport is simulated between the mixed layer adjacent to the ground and the atmosphere within a stable temperature inversion aloft. The model also imposes a vertical (crosswind integrated) Gaussian concentration profile to compute the impact of emissions close to their sources.

A procedure was outlined for computing the long-term average concentrations of a primary (inert) pollutant that is released from a number of sources. In addition to predicting total pollutant concentrations, the model separates the individual source class contributions to air quality. In Chapter 4, this procedure will be applied to the prediction of monthly averaged concentrations of fine carbonaceous particulate matter from a variety of sources in the Los Angeles area.

3.5 References for Chapter 3

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CHAPTER 4

APPLICATION OF THE SIMULATION MODEL TO LOS ANGELES FINE PRIMARY CARBON PARTICULATE AIR QUALITY

4.1 Introduction

In this chapter, the air quality model developed in Chapter 3 will be used to predict monthly averaged fine primary carbonaceous particulate matter concentrations for each month of 1982 in the central portion of the South Coast Air Basin. First, the data requirements of the simulation model will be outlined and satisfied. Then the air quality model results will be examined and verified based on comparisons between predicted concentrations and those observed during the 1982 field experiments described in Chapter 2.

4.2 Data Requirements for Model Application

In order to apply the air quality model to the task of simulating the emission and transport of fine primary carbonaceous particulate matter in the Los Angeles area, information is needed regarding the sources of emissions, meteorology, atmospheric dispersion parameters, deposition rates, and aerosol carbon background concentrations. In addition, the receptor grid system must be defined and the cell size chosen. The time step, Δt, used for numerical integration of the transport equations must be identified. Finally, the 1982 air quality observations must be organized for comparison to model predictions.

4.2.1 Emission Source Related Data

A spatially resolved inventory of fine carbon particle emissions during 1982 was compiled for over 70 types of mobile and stationary sources. Emission estimates made within the 80X80-km (50X50-mile) grid system of Figure 4.1 are summarized in Tables 4.1 through 4.4. Details of the emissions estimation procedure are given in Appendix A (Tables A.1–A.4). A tabulation of emissions within the entire South Coast Air Basin (four counties) is presented in Appendix C. By comparing these sets of tables, it is seen that the majority of the aerosol carbon emissions in the South Coast Air Basin arise from sources located within the grid system. A summary of emissions in the 50X50-mile grid, organized by major source category, is shown in Figure 4.2 and in Table 4.5.

Emissions from major stationary fuel burning sources were placed within 2-mile X 2-mile grid cells corresponding to the actual locations of those sources (South Coast Air Quality Managment District 1983a). Emissions from residential sources were distributed spatially in proportion to population density. Highway vehicle emissions were allocated to the grid system in proportion to traffic densities for surface streets and freeways (see procedure of Cass, 1977, updated to the year 1982). Emissions from other mobile sources (ships, railroads, airplanes) likewise were allocated to the grid system based

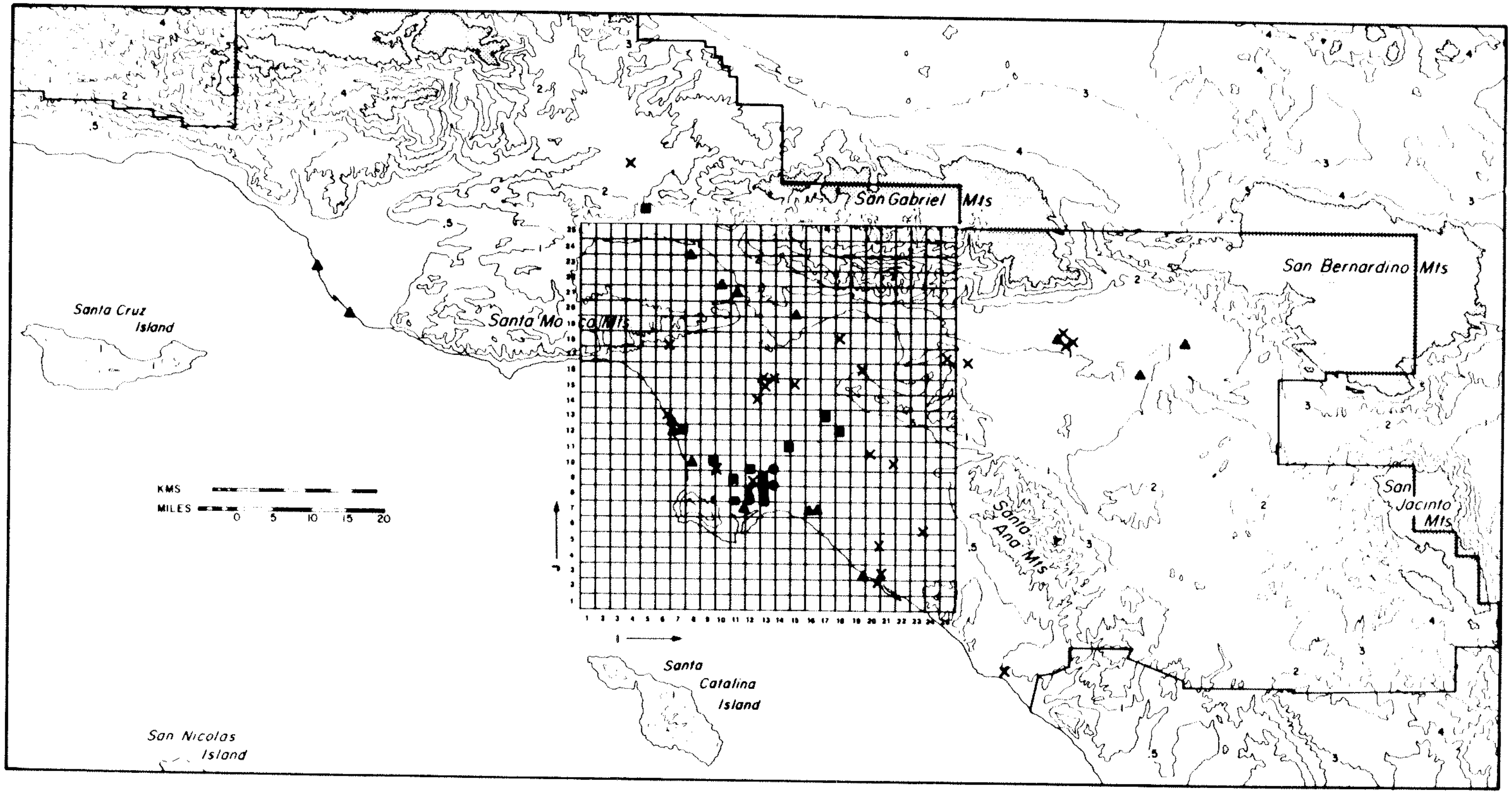


Figure 4.1 The central portion of the South Coast Air Basin showing the grid system used.

Table 4.1

Emissions Estimates for Mobile Sources
Within the 50X50-mile Grid 1982

	Source Class (a)	Fine(c) Total Carbon (kg/day)	Fine(c) Elemental Carbon (kg/day)
MOBILE SOURCES			
Highway Vehicles			
Catalyst Autos	1	466.9	210.1
Non-catalyst Autos	2	2971.0	632.8
Diesel Autos	3	931.9	713.8
Catalyst Light Trucks	1	87.7	39.5
Non-catalyst Light Trucks	2	558.0	118.8
Diesel Light Trucks	3	127.4	97.6
Catalyst Medium Trucks	4	55.3	24.9
Non-catalyst Medium Trucks	4	387.6	82.5
Gasoline Heavy Trucks	4	653.1	139.1
Diesel Heavy Trucks and Buses	5	6337.2	4854.3
Motorcycles	2	62.7	13.4
Civil Aviation			
Jet Aircraft	6,7,8 (b)	394.1	301.9
Aviation Gas	6	12.2	2.6
Commercial Shipping			
Residual Oil-fired Ships	9	82.8	16.6
Diesel Ships	10	179.9	137.8
Railroad			
Diesel Oil	11	899.4	689.0
Miscellaneous			
Off Highway Diesel Vehicles	12	1275.6	1206.9
Off Highway Gasoline Vehicles	13	82.1	17.5
TOTAL MOBILE SOURCES		15864.9	9299.1

(a) See Table D.38 for the definition of the 47 source classes used with the air quality model.

(b) Jet aircraft emissions supplied to the air quality model are divided into emissions located at three separate elevations.

(c) Fine particles below 2.1 µm.

Table 4.2

Emissions Estimates for Stationary Combustion Sources
Within the 50X50-mile Grid 1982

	Source Class (a)	Fine[(b)] Total Carbon (kg/day)	Fine[(b)] Elemental Carbon (kg/day)
<u>STATIONARY SOURCES</u>			
Fuel Combustion			
Electric Utilities			
Natural Gas (boilers)	14	39.8	small
Natural Gas (turbines)	14	14.8	small
Residual Oil	14	193.6	38.7
Distillate Oil (turbines)	14	0.9	0.5
Digester Gas	14	0.04	small
Refinery Fuel			
Natural Gas	15	57.8	small
Refinery Gas	15	194.9	small
Residual Oil	15	9.2	1.8
Non-refinery Industrial/Low Priority Commercial Fuel			
Natural Gas	16	149.6	small
LPG	16	2.0	small
Residual Oil	16	12.8	2.6
Distillate Oil	16	90.2	52.3
Digester Gas (IC engines)	17	24.2	5.6
Coke Oven Gas	16	0 (c)	0 (c)
Gasoline (IC engines)	17	21.1	2.1
Distillate Oil (IC engines)	17	22.2	22.2
Residential/High Priority Commercial Fuel			
Natural Gas	18	642.1	211.9
LPG	18	11.6	3.8
Residual Oil	18	41.2	8.2
Distillate Oil	18	53.5	31.0
Coal	18	96.7	21.3
TOTAL FUEL COMBUSTION		1678.2	402.0

(a) See Table D.38 for the definition of the 47 source classes used with the air quality model.

(b) Fine particles below 2.1 μm.

(c) Sources located outside the 50X50-mile grid.

Table 4.3

Emissions Estimates for Industrial Processes
Within the 50X50-mile Grid 1982

	Source Class (a)	Fine[(b)] Total Carbon (kg/day)	Fine[(b)] Elemental Carbon (kg/day)
<u>STATIONARY</u> <u>SOURCES</u>			
Industrial Process Point Sources			
Petroleum Industry			
Refining (FCCU)	19	32.7	8.2
Other	20	278.2	0
Organic Solvent Use			
Surface Coating	21	1432.9	0
Printing	21	12.9	0
Degreasing	22	5.1	0
Other	22	106.2	0
Chemical			
Organic	23	736.2	44.2
Inorganic	43	0	0
Metallurgical			
Primary	24	228.4	0
Secondary	25	166.8	0
Fabrication	44	0	0
Mineral	26	212.0	54.3
Waste Burning	27	67.2	47.0
Wood Processing	28	85.6	11.1
Food and Agriculture	32	5.0	0
Asphalt Roofing	29	84.2	3.4
Textile	32	1.8	0
Rubber and Plastics	30	35.7	0
Coke Calciner	31	239.2	239.2
Miscellaneous Industrial	32	423.9	30.5
TOTAL PROCESS POINT SOURCES		4154.0	437.9

(a) See Table D.38 for the definition of the 47 source classes used with the air quality model.

(b) Fine particles below 2.1 μm.

Table 4.4

Emissions Estimates for Fugitive Sources
Within the 50X50-mile Grid 1982

	Source Class (a)	Fine$^{(c)}$ Total Carbon (kg/day)	Fine$^{(c)}$ Elemental Carbon (kg/day)
<u>FUGITIVE</u> <u>SOURCES</u>			
Road and Building Construction	45	0	0
Agricultural Tilling	46	0	0
Livestock Feedlots	33	20.4	0
Unpaved Road Dust	47	0	0
Paved Road Dust	34	5288.1	174.5
Tire Attrition	35	1001.4	330.5
Brake Lining Attrition	36	1804.8	324.9
Forest Fires (seasonal)	(b)	933.1	56.0
Structural Fires	37	92.8	29.7
Fireplaces	38	1612.6	343.0
Cigarettes	39	1376.9	41.3
Charcoal Broilers	41	4456.1	66.8
Agricultural Burning	40	2.8	0.3
Sea Salt	(b)	0	0
Roofing Tar Pots	42	753.2	0.8
TOTAL FUGITIVE SOURCES		17342.2	1367.8

(a) See Table D.38 for the definition of the 47 source classes used with the air quality model.

(b) Source class is not used with the air quality model.

(c) Fine particles below 2.1 μm.

Figure 4.2

FINE AEROSOL CARBON EMISSIONS
IN THE 50×50 MI. MODELING REGION, 1982

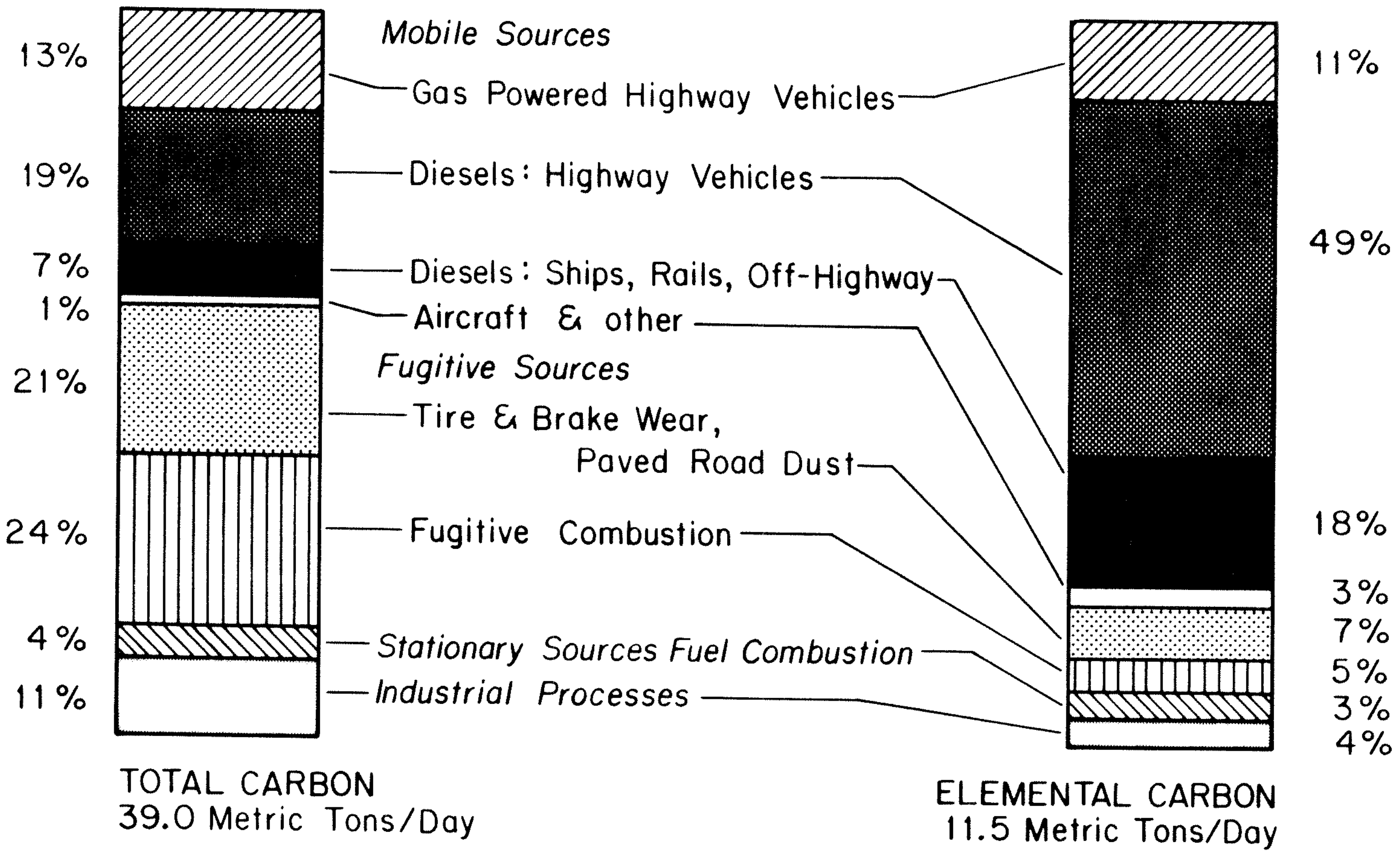
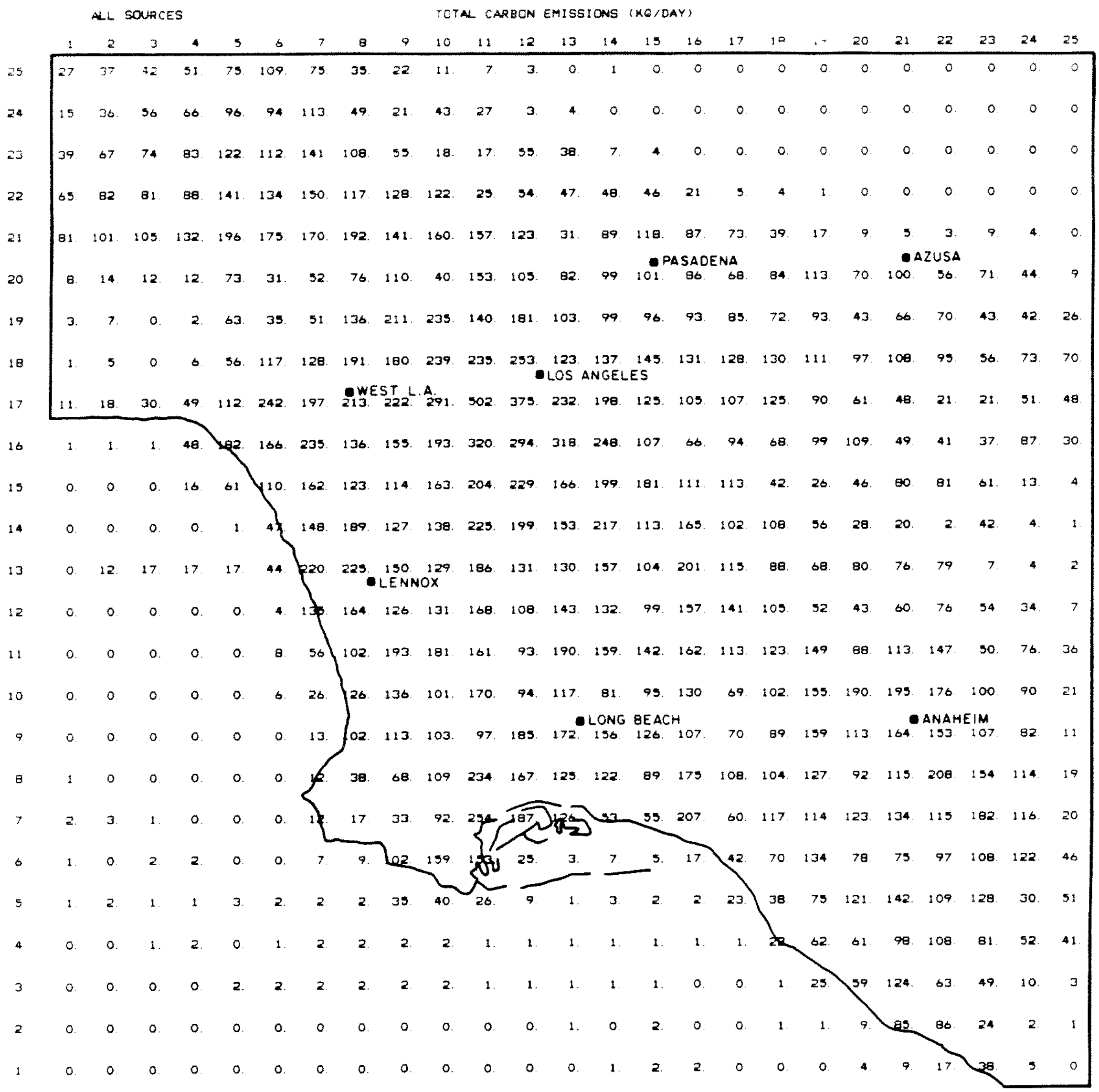


Table 4.5

1982 Annual Average Fine Particulate
Carbon Emissions Summary
Within the 50X50-mile grid

Major Source Category	Fine Total Carbon (kg/day) TC	Fine Elemental Carbon (kg/day) EC
Gasoline powered highway vehicles	5242.3	1261.1
Diesel: highway vehicles	7396.5	5665.7
Diesel: ships, rail, off-highway	2654.9	2033.7
Aircraft and other mobile	571.2	338.6
Highway fugitive (tire and brake wear; road dust)	8094.3	829.9
Other fugitive (fugitive combustion + livestock feedlots)	9247.9	537.9
Stationary source fuel combustion	1678.2	402.0
Industrial processes	4154.0	437.9
TOTAL	39039.3	11506.8

on travel patterns (see Cass 1977). Source location (by source class) was obtained for all other sources from a computerized emission inventory forecast provided by the California Air Resources Board (Ranzieri 1983). The spatial distribution of average daily emissions from all sources for December 1982 is illustrated in Figure 4.3 for total carbon emissions and in Figure 4.4 for elemental carbon



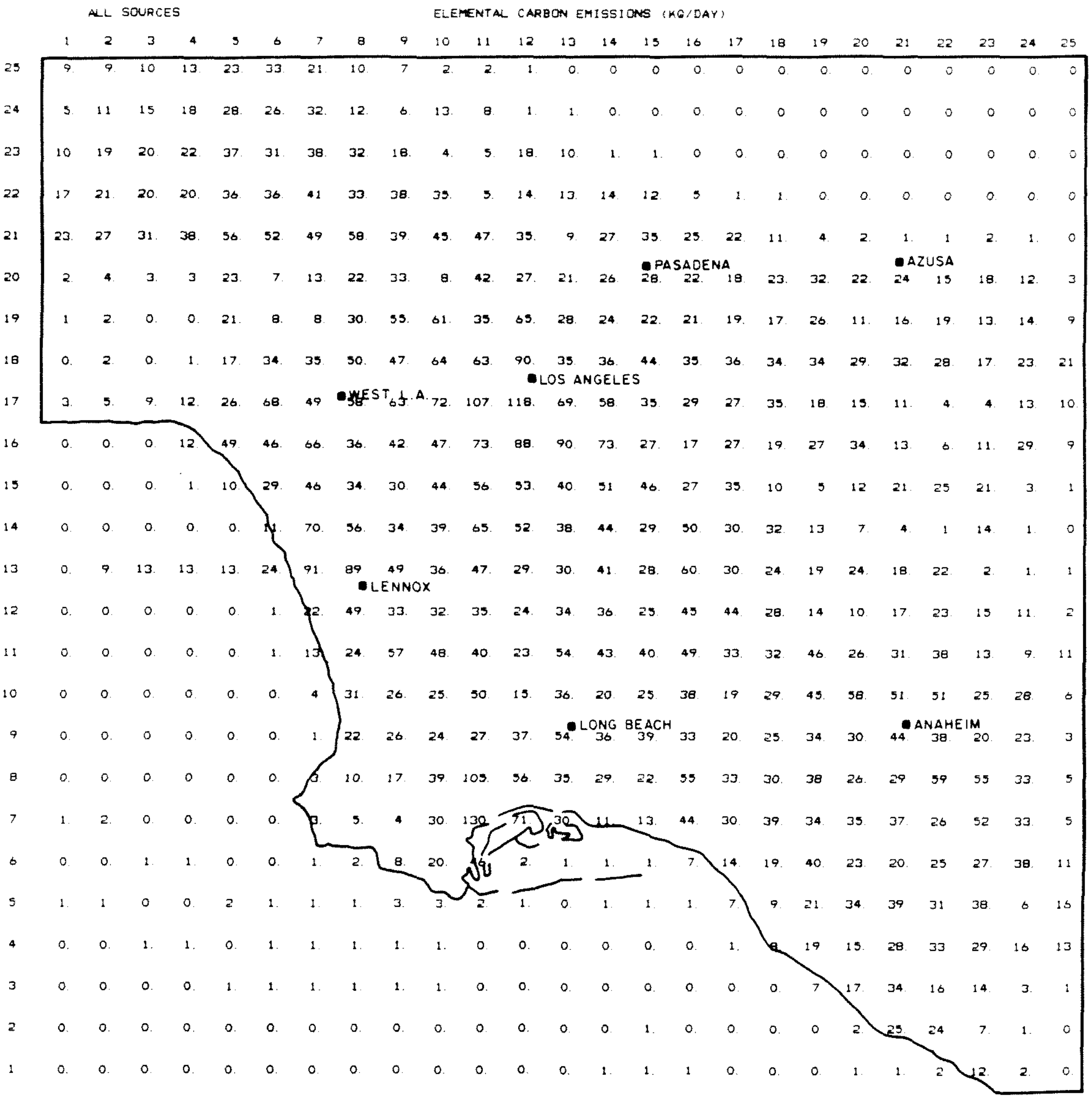
ALL SOURCES

TOTAL CARBON EMISSIONS (KG/DAY)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
25	27	37	42	51	75	109	75	35	22	11	7	3	0	1	0	0	0	0	0	0	0	0	0	0	0
24	15	36	56	66	96	94	113	49	21	43	27	3	4	0	0	0	0	0	0	0	0	0	0	0	0
23	39	67	74	83	122	112	141	108	55	18	17	55	38	7	4	0	0	0	0	0	0	0	0	0	0
22	65	82	81	88	141	134	150	117	128	122	25	54	47	48	46	21	5	4	1	0	0	0	0	0	0
21	81	101	105	132	196	175	170	192	141	160	157	123	31	89	118	87	73	39	17	9	5	3	9	4	0
20	8	14	12	12	73	31	52	76	110	40	153	105	82	99	101	86	68	84	113	70	100	56	71	44	9
19	3	7	0	2	63	35	51	136	211	235	140	181	103	99	96	93	85	72	93	43	66	70	43	42	26
18	1	5	0	6	56	117	128	191	180	239	235	253	123	137	145	131	128	130	111	97	108	95	56	73	70
17	11	18	30	49	112	242	197	213	222	291	502	375	232	198	125	105	107	125	90	61	48	21	21	51	48
16	1	1	1	48	182	166	235	136	155	193	320	294	318	248	107	66	94	68	99	109	49	41	37	87	30
15	0	0	0	16	61	110	162	123	114	163	204	229	166	199	181	111	113	42	26	46	80	81	61	13	4
14	0	0	0	0	1	47	148	189	127	138	225	199	153	217	113	165	102	108	56	28	20	2	42	4	1
13	0	12	17	17	17	44	220	225	150	129	186	131	130	157	104	201	115	88	68	80	76	79	7	4	2
12	0	0	0	0	0	4	135	164	126	131	168	108	143	132	99	157	141	105	52	43	60	76	54	34	7
11	0	0	0	0	0	8	56	102	193	181	161	93	190	159	142	162	113	123	149	88	113	147	50	76	36
10	0	0	0	0	0	6	26	126	136	101	170	94	117	81	95	130	69	102	155	190	195	176	100	90	21
9	0	0	0	0	0	0	13	102	113	103	97	185	172	156	126	107	70	89	159	113	164	153	107	82	11
8	1	0	0	0	0	0	12	38	68	109	234	167	125	122	89	175	108	104	127	92	115	208	154	114	19
7	2	3	1	0	0	0	12	17	33	92	254	187	126	53	55	207	60	117	114	123	134	115	182	116	20
6	1	0	2	2	0	0	7	9	102	159	153	25	3	7	5	17	42	70	134	78	75	97	108	122	46
5	1	2	1	1	3	2	2	2	35	40	26	9	1	3	2	2	23	38	75	121	142	109	128	30	51
4	0	0	1	2	0	1	2	2	2	2	1	1	1	1	1	1	1	28	62	61	98	108	81	52	41
3	0	0	0	0	2	2	2	2	2	2	1	1	1	1	1	0	0	1	25	59	124	63	49	10	3
2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0	1	1	9	85	86	24	2	1
1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	2	0	0	0	4	9	17	38	5	0

TOTAL = 41419.11 KG/DAY

Figure 4.3 Fine total carbon emissions within the 50X50-mile grid during December 1982.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
25	9	9	10	13	23	33	21	10	7	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
24	5	11	15	18	28	26	32	12	6	13	8	1	1	0	0	0	0	0	0	0	0	0	0	0	0
23	10	19	20	22	37	31	38	32	18	4	5	18	10	1	1	0	0	0	0	0	0	0	0	0	0
22	17	21	20	20	36	36	41	33	38	35	5	14	13	14	12	5	1	1	0	0	0	0	0	0	0
21	23	27	31	38	56	52	49	58	39	45	47	35	9	27	35	25	22	11	4	2	1	1	2	1	0
20	2	4	3	3	23	7	13	22	33	8	42	27	21	26	28	22	18	23	32	22	24	15	18	12	3
19	1	2	0	0	21	8	8	30	55	61	35	65	28	24	22	21	19	17	26	11	16	19	13	14	9
18	0	2	0	1	17	34	35	50	47	64	63	90	35	36	44	35	36	34	34	29	32	28	17	23	21
17	3	5	9	12	26	68	49	58	63	72	107	118	69	58	35	29	27	35	18	15	11	4	4	13	10
16	0	0	0	12	49	46	66	36	42	47	73	88	90	73	27	17	27	19	27	34	13	6	11	29	9
15	0	0	0	1	10	29	46	34	30	44	56	53	40	51	46	27	35	10	5	12	21	25	21	3	1
14	0	0	0	0	0	11	70	56	34	39	65	52	38	44	29	50	30	32	13	7	4	1	14	1	0
13	0	9	13	13	13	24	91	89	49	36	47	29	30	41	28	60	30	24	19	24	18	22	2	1	1
12	0	0	0	0	0	1	22	49	33	32	35	24	34	36	25	45	44	28	14	10	17	23	15	11	2
11	0	0	0	0	0	1	13	24	57	48	40	23	54	43	40	49	33	32	46	26	31	38	13	9	11
10	0	0	0	0	0	0	4	31	26	25	50	15	36	20	25	38	19	29	45	58	51	51	25	28	6
9	0	0	0	0	0	0	1	22	26	24	27	37	54	36	39	33	20	25	34	30	44	38	20	23	3
8	0	0	0	0	0	0	3	10	17	39	105	56	35	29	22	55	33	30	38	26	29	59	55	33	5
7	1	2	0	0	0	0	3	5	4	30	130	71	30	11	13	44	30	39	34	35	37	26	52	33	5
6	0	0	1	1	0	0	1	2	8	20	[illegible]	2	1	1	1	7	14	19	40	23	20	25	27	38	11
5	1	1	0	0	2	1	1	1	3	3	2	1	0	1	1	1	7	9	21	34	39	31	38	6	16
4	0	0	1	1	0	1	1	1	1	1	0	0	0	0	0	0	1	8	19	15	28	33	29	16	13
3	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	7	17	34	16	14	3	1
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	25	24	7	1	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	2	12	2	0

TOTAL = 11480.39 KG/DAY

Figure 4.4 Fine elemental carbon emissions within the 50X50-mile grid during December 1982.

emissions. These gridded emissions maps were obtained by overlaying many similar maps, one developed for each source class. (Note that total carbon emissions in December slightly exceed the annual average value given in Table 4.5.)

Monthly fuel consumption data were used to determine seasonal trends in emissions for stationary fuel burning sources. The seasonal variation in emissions from fireplace combustion of wood is documented in Appendix A, Table A.9, note (b). All other source classes are assumed to operate without a pronounced seasonal variation.

The typical diurnal variation of emissions from vehicular traffic, airport operations, and electric utilities was specified based on the past studies of those sources (see Cass 1977). Local charcoal broiler establishments were surveyed to determine their level of operation at various times of day in order to approximate a typical diurnal pattern for emissions from this source class. The remaining source types were divided into two categories: (1) those that were assumed to operate at a uniform rate 24 hours per day and (2) those that were assumed to operate only during daylight hours. The latter group includes agricultural tilling, roofing tar pots, and off-road vehicles.

An effective stack height was specified for each source class which varies in accordance with hourly meteorological conditions. The Briggs plume rise formula (Briggs 1971) was used to compute plume rise as a function of wind speed for each source class. Plume rise was computed during each time step of the model's execution, depending on the wind speed at that time step. Then computed plume rise was added to the physical stack height of the source to arrive at the effective stack height of emissions (see Cass 1977; Appendix A4).

All emissions from a given source class residing within a single grid cell are aggregated to form a single virtual source. To approximate an area source of particulate matter being released throughout the cell, the location of the virtual source is selected at random at each time step from a uniform distribution of possible horizontal locations within the grid cell.

Since the model performs a separate transport calculation for each source class, computation time may be shortened by combining several similar source types into a single source class. The sources must be similar, however, since all sources within a source class will have the same effective stack height and will experience an identical diurnal modulation of emissions strength within the model. Also, if too many source types are combined to form a single source class, information regarding the incremental contribution to air pollutant concentrations from individual source types will be lost. This information on source class contribution to downwind air quality is needed for control strategy analysis. The 74 separate source types listed in Tables 4.1 through 4.4 were grouped into 47 source classes, each of which will be handled separately during air quality modeling calculations. The members of each of these 47 source classes are indicated in the second column of Tables 4.1 through 4.4.

Although reasonable estimates of the chemical composition of paved road dust may be made, it is difficult to assess the emission rate and the fraction of street dust that becomes airborne. For this source class only, a receptor modeling calculation was performed which will replace the transport model as the method chosen to account for the paved road dust contribution to aerosol carbon levels. Fine particle road dust samples were taken that were analyzed chemically to determine their elemental composition, including the percentage of Al, Si, TC and EC in the road dust (Gray, Cass, and Turpin 1985). The ambient measurements of Al and Si taken at each monitoring site during 1982 each were used independently to estimate the maximum aerosol carbon concentrations that could be present due to paved road dust at the seven monitoring sites. Then the two estimates based on Al and Si were averaged. This calculation was performed separately for each month of the year at each monitoring site. (For an example of the receptor modeling technique applied to source apportionment in Los Angeles, see Cass and McRae [1983].) The ratio between receptor-modeled monthly average total carbon (or elemental carbon) and transport-modeled monthly average total carbon (using estimates of emissions of paved road dust from Table A.4) ranged from 0.12 to 0.53, with an average of 0.276. This indicates that the fine carbon particulate emissions from paved road dust presented in Table 4.4 that are based on present government estimates of road dust emissions may have been overestimated by as much as a factor of 8 but, more likely, closer to a factor of about 3 or 4.

4.2.2 Meteorological Data

It is necessary to construct a time history of wind speed, wind direction, and inversion base motion for use with the air quality model presented in Chapter 3. It is also necessary to estimate the maximum retention time of air parcels within the grid system, τ_c.

After careful consideration of the available wind monitoring locations, the wind station operated by the South Coast Air Quality Management District at their central Los Angeles site was chosen (see Cass 1977, p. 157) to supply hourly averaged wind speeds and directions for use with the model (South Coast Air Quality Management District 1983b). A more detailed treatment would be needed in order to track the turning of the wind field around the Santa Monica Mountains as air parcels enter the San Fernando Valley. In order to avoid that problem, the model calculation will be restricted to predicting the concentration of carbonaceous particulate mater over the central flatlands of the Los Angeles basin and the adjoining San Gabriel Valley.

Inversion base motion above ground level is represented by a stylized diurnal cycle that passes through two daily measures of inversion base height. Early morning inversion base height is measured daily at the University of California at Los Angeles (UCLA), and maximum afternoon mixing depth over downtown Los Angeles is calculated based on the morning sounding combined with data on the maximum ground level temperature reached at downtown Los Angeles. These two estimates of overnight and afternoon mixing depth were obtained from the South Coast Air Quality Management District (1983c) for each day during 1982, and then the mixing depth data were interpolated to form a diurnal cycle of the form shown in Figure 3.2 (from Cass 1977). Fresh emissions contribute to model-computed concentrations in inverse proportion to inversion base height. Examination of the monthly averaged diurnal cycle of model-computed elemental carbon concentrations shows early morning peaks and afternoon/evening lows in ratios similar to those found in observed concentrations of elemental carbon as inferred from km tape sampler data (Phadke et al. 1975, Cass et al. 1984). The use of this approximate diurnal cycle appears to adequately represent the mixing depth during computation of pollutant concentrations.

A selection of trajectory integration time, τ_c, must be made in order to determine how long each air parcel must be tracked. Cass (1981) observed that over 95% of the air parcels originating at major source locations within the 50X50-mile grid system will be outside the gridded area after 48 hours (using trajectories based on hourly averaged wind data from the years 1972 through 1974). Therefore, τ_c, is set to 48 hours for this model application.

4.2.3 Estimation of Atmospheric Diffusive Dispersion Parameters

Atmospheric turbulence causes small scale air parcel motions that are not resolvable from trajectory calculations based on mean wind speed and direction alone. The degree of air parcel dispersion in the i^{th} coordinate direction may be measured in terms of the standard deviation $\sigma_i(t)$ of the concentration distribution in that direction. Estimates of $\sigma_1(t)$ and $\sigma_2(t)$ are necessary for the simulation of horizontal eddy diffusion as described in Chapter 3, Section 3.3.1. Evaluation of a vertical dispersion parameter, $\sigma_z(t)$, is also required in order to account for incomplete vertical mixing of plumes at locations close to their source (see Chapter 3, Section 3.3.3).

4.2.3.1 Horizontal Dispersion Parameter In Chapter 3, Section 3.3.1, the assumption was made that the process of horizontal diffusion could be modeled by drawing displacements at random from a two-dimensional Gaussian distribution with mean zero and standard deviation $(\sigma_1(t),\sigma_2(t))$. If it is assumed that an expanding puff in the atmosphere remains symmetric with equal standard deviations in the downwind and crosswind directions, then $\sigma_1(t) = \sigma_2(t) = \sigma_y(t)$.

The most commonly employed estimates of atmospheric dispersion rates have been assembled based on observation of air parcels traveling over open countryside (see Pasquill 1961, Gifford 1961, Turner 1969). In urban areas, however, larger surface roughness and heat island effects result in a greater degree of dispersion than is expected over open terrain. Cass (1977) summarized experimental observations on the rate of air parcel dispersion for long distance transport over the Los Angeles urban area, based on experiments by Drivas and Shair (1975) and Shair (1977), and for shorter distances in St. Louis by McElroy and Pooler (1968). The resulting equation for σ_y

in meters and travel time in seconds, as graphed in Figure 4.5, is

$$\sigma_y(t) = 1.73\ t^{0.80} \tag{4.1}$$

4.2.3.2 Vertical Dispersion Parameter McElroy and Pooler (1968), as part of their study of dispersion in St. Louis, collected data on the vertical dispersion parameter, σ_z, in terms of Pasquill-Turner stability class. From Figure 4.5, it can be observed that data on σ_y, collected in the Los Angeles basin, are in general agreement with similar estimates for St. Louis. Estimates of vertical dispersion rates based on experiments conducted in Los Angeles are not available. In the absence of any other experimental data for mixing over urban areas, the estimates of σ_z presented by McElroy and Pooler for the St. Louis urban area will be used to represent the rate of vertical dispersion over the Los Angeles urban area.

The standard deviation of plume concentration in the vertical direction is presented by McElroy and Pooler (1968) for St. Louis as either a function of travel time or downwind distance. Curves of σ_z versus downwind distance are plotted in Figure 4.6 from McElroy and Pooler (1968) for the Pasquill-Turner stability classes B through F. An estimate of σ_z may be obtained at given downwind distance once the Pasquill-Turner stability class has been determined. This stability class, in turn, is a function of surface wind speed and solar radiation or cloud cover. The stability categories are grouped into six classes. Class A is the most unstable, class F the most stable.

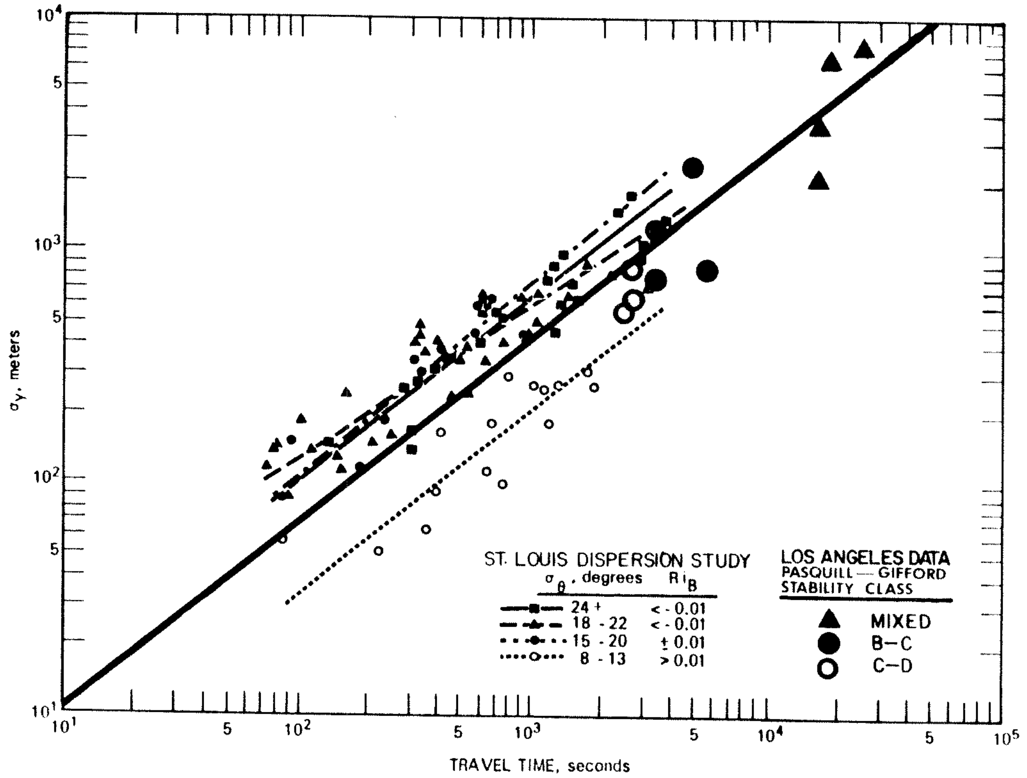


Figure 4.5 Cross-wind standard deviation of plume spread as a function of travel time. St. Louis data from McElroy and Pooler (1968). Los Angeles data from Drivas and Shair (1975) and Shair (1977). Heavy solid line represents function for $\sigma_y(t)$ fit to the Los Angeles data, from Cass (1977).

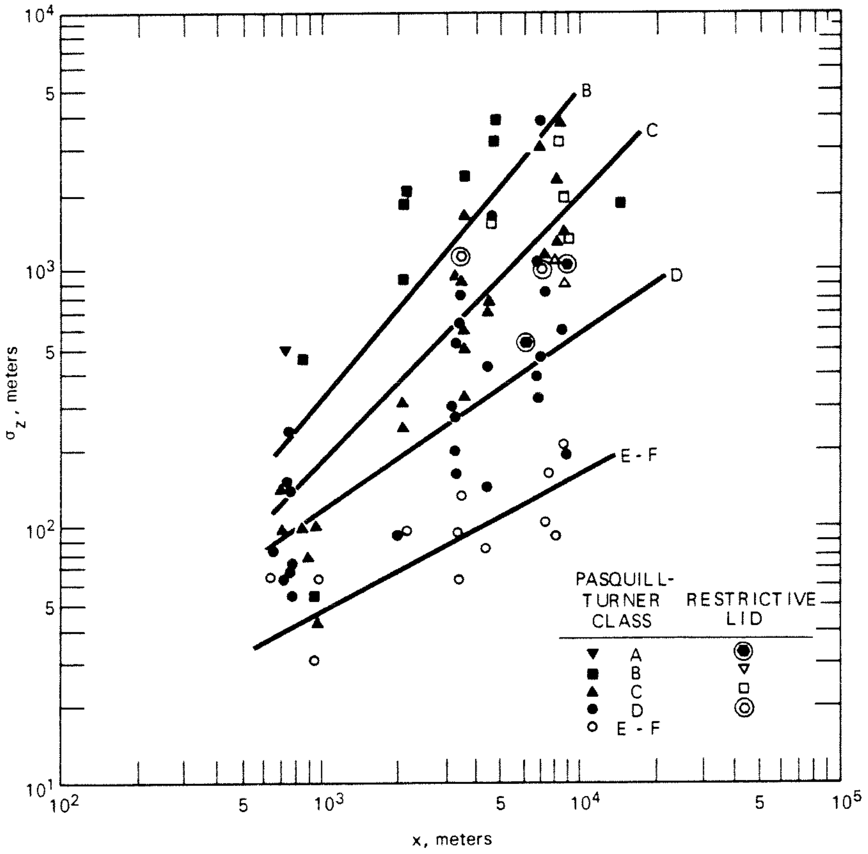


Figure 4.6 Effective vertical standard deviation of plume spread as a function of downwind distance in terms of Pasquill-Turner stability classes (from McElroy and Pooler, 1968).

A guide to the selection of stability categories is given in Table 4.6 (from Turner 1969).

Table 4.6

Key to Stability Categories (from Turner 1969)

Surface Wind Speed (m/sec)	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or	
	Strong	Moderate	Slight	$\geq$ 4/8 Low Cloud	$\leq$ 3/8 Low Cloud
< 2	A	A–B	B	–	–
2–3	A–B	B	C	E	F
3–5	B	B–C	C	D	E
5–6	C	C–D	D	D	D
> 6	C	D	D	D	D

Selection of stablility classes for use during model calculations is accomplished by computing solar radiation intensity at every hour of the year from a solar simulator (McRae 1981) and then combining that information with hourly wind speed observations. For the current model application, only stability classes B, C, and D are used. Class A is not often encountered: McElroy and Pooler (1968) only recorded one example of class A conditions out of over 80 experimental data points. It was also assumed that due to heat island effects and the large effective surface roughness in urban areas, there would always exist sufficient vertical mixing near the surface such that class D would reasonably represent the minimum level of atmospheric mixing for a given downwind distance.

In general, the power law for σ_z as a function of downwind distance, x, may be expressed as:

$$\sigma_z = ax^b \tag{4.2}$$

where both σ_z and x are in meters. Estimation of the coefficients a and b are summarized for the data of McElroy and Pooler (1968) in Table 4.7.

Table 4.7

Coefficients of $\sigma_z = ax^b$ by Stability Class, Fit to the Data of McElroy and Pooler (1968)

Stability Class	a	b
B	0.066	1.22
C	0.142	1.03
D	0.95	0.70
E-F	1.17	0.54

4.2.4 Estimation of Particulate Dry Deposition Velocity

Cass (1977) used a value for particulate sulfate dry deposition velocity of 0.03 cm/sec. This is within the range of experimental data collected by Davidson (1977), which indicated that sulfate deposition velocities in Los Angeles are in the range 0.01 to 0.1 cm/sec.

The deposition rate of atmospheric aerosols is dependent upon the size distribution of particulate matter in the surface layer near the ground. Both carbonaceous particulate matter and sulfates in the atmosphere are found predominantly in the fine particle fraction, so their dry deposition velocities would be expected to be similar. Therefore, a deposition velocity of 0.03 cm/sec will be used for this model application. That value implies a time scale for removal of particulate from the mixed layer by dry deposition ranging from about a day to several weeks, depending on the depth of the mixed layer.

4.2.5 Background Concentrations of Fine Atmospheric Carbonaceous Particulate Matter

The prevailing wind direction in the South Coast Air Basin surrounding Los Angeles is from the southwest which means that most new air masses entering the air basin are of marine origin. Therefore, air pollutant concentrations measured at San Nicolas Island, a remote offshore island, should serve as satisfactory estimates of background air quality.

As reported in Chapter 2, fine aerosol concentrations (24-hour averages) were measured at San Nicolas Island for 47 days from March to December 1982. Monthly averaged fine total carbon and fine elemental carbon background concentrations based on the San Nicolas Island data are given in Table 4.8.

4.2.6 Selection of Time Step and Receptor Grid Cell Size

The selection of a time step and horizontal grid cell dimensions should be made simultaneously. One would like to keep the time step as large as possible to reduce the number of computations required to represent a one-year period. On the other hand, the time

Table 4.8

Fine Particulate Carbon
Background Concentrations (a)

	Fine Total Carbon ($\mu g/m^3$)	Fine Elemental Carbon ($\mu g/m^3$)
Jan (b)	2.30	0.35
Feb (b)	2.08	0.34
Mar	1.78	0.28
Apr	2.26	0.34
May	2.46	0.30
Jun	1.20	0.20
Jul	1.43	0.13
Aug	1.58	0.20
Sep	1.68	0.16
Oct	2.76	0.42
Nov	2.08	0.34
Dec	2.30	0.35

Notes:

(a) Monthly average concentrations from samples taken during 1982 at San Nicolas Island, a remote offshore island.

(b) No data were taken during January and February 1982. Concentrations are assumed to be equal to December and November 1982, respectively.

step must be kept small enough for enough statistical particles to be released to adequately estimate the probabilities of transition and, hence, pollutant concentrations. It is desirable to keep the grid cells small in order to attain a high level of spatial resolution in the computed pollutant concentrations. However, if the time step is very large and the grid cells are too small, an insufficient number of particles will reside within each cell. The result will be manifested by computed voids in some grid cells located within zones of significant pollutant concentration. This is because the grid cells are too small and, hence, too numerous to have accumulated a statistically significant number of pollutant particles.

A time step of one hour is the largest time step possible without discarding useful meteorological information (wind speeds and directions are reported as hourly averages; see Section 4.2.2). Use of a grid cell size with the same dimensions as the 2 mile X 2 mile squares which make up the emissions grid (see Figure 4.1) was investigated by Cass (1977). It was determined that a one-hour time step coupled with $\tau_c = 48$ hours (see Section 4.2.2) and a grid cell size of 2 miles X 2 miles would result in a smooth contour of monthly averaged concentrations from any single source location. Tests of the model simulation under typical 1982 conditions for a single source resulted in concentration distributions free of voids. Therefore, a time step, Δt, of one hour and horizontal grid cell dimensions $(\Delta x_1, \Delta x_2)$ of 2 miles X 2 miles should result in concentration predictions which are smooth and accurate.

It may be noted that specification of a vertical cell dimension, Δx_3, is unnecessary. Examination of equations (3.10) and (3.35) through (3.38) reveals that Δx_3 cancels out.

4.2.7 Model Validation Data

During 1982, ambient elemental carbon concentrations were measured at a number of locations in the South Coast Air Basin, as reported in Chapter 2. Seven of these sites are located within the receptor area that will appear later in Figure 4.23. These observations of monthly averaged elemental carbon air quality may be used to validate the model's prediction of monthly averaged fine elemental carbon concentrations. Verification of the model's performance may be found in the following section of this chapter.

4.3 Air Quality Model Results

4.3.1 Predicted versus Observed Fine Elemental Carbon Particle Concentrations

Elemental carbon is virtually inert in the atmosphere and is released only from primary emission sources. In order to avoid any ambiguity due to the presence of secondary organic aerosols, the accuracy of the predictions of the present air quality model can best be assessed by comparison of observed and predicted elemental carbon levels. Figures 4.7a through 4.13a present the results of the air quality simulation model for fine elemental carbon concentrations at each of the seven monitoring sites located within the receptor grid. The solid horizontal lines represent the monthly averaged concentrations predicted by the model. The small circles represent the arithmetical mean of concentrations observed at the monitoring sites during each month. The error bounds shown denote approximate 95% confidence intervals about each measured monthly mean value (see Cass [1977], Appendix B4, for standard error estimation procedure).

MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT LENNOX

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

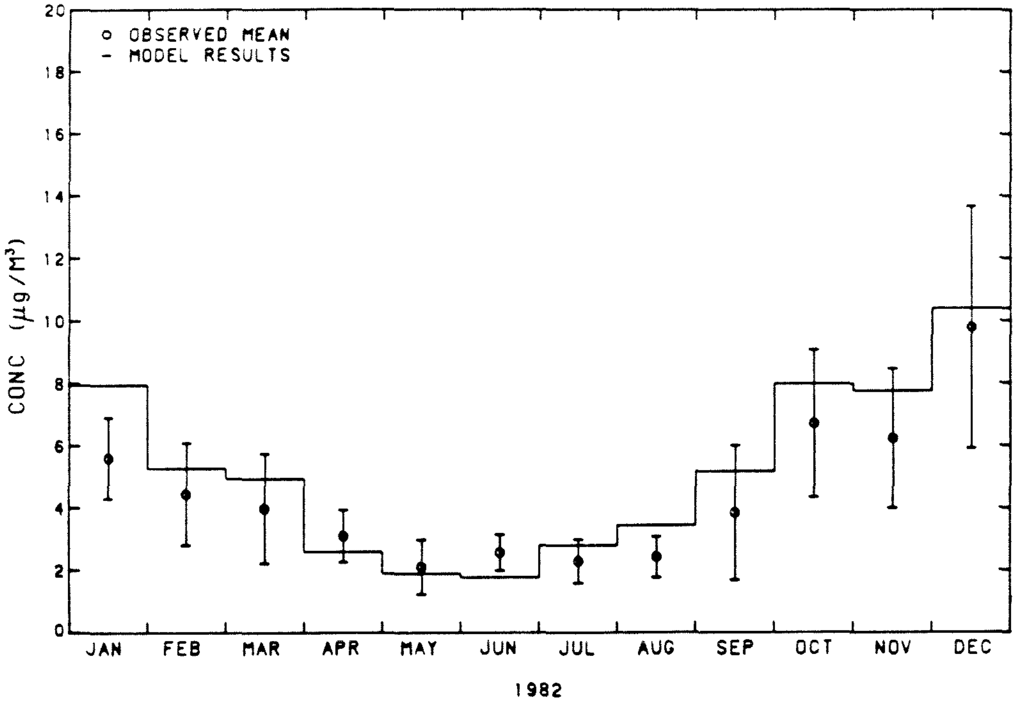


Figure 4.7a

SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT LENNOX

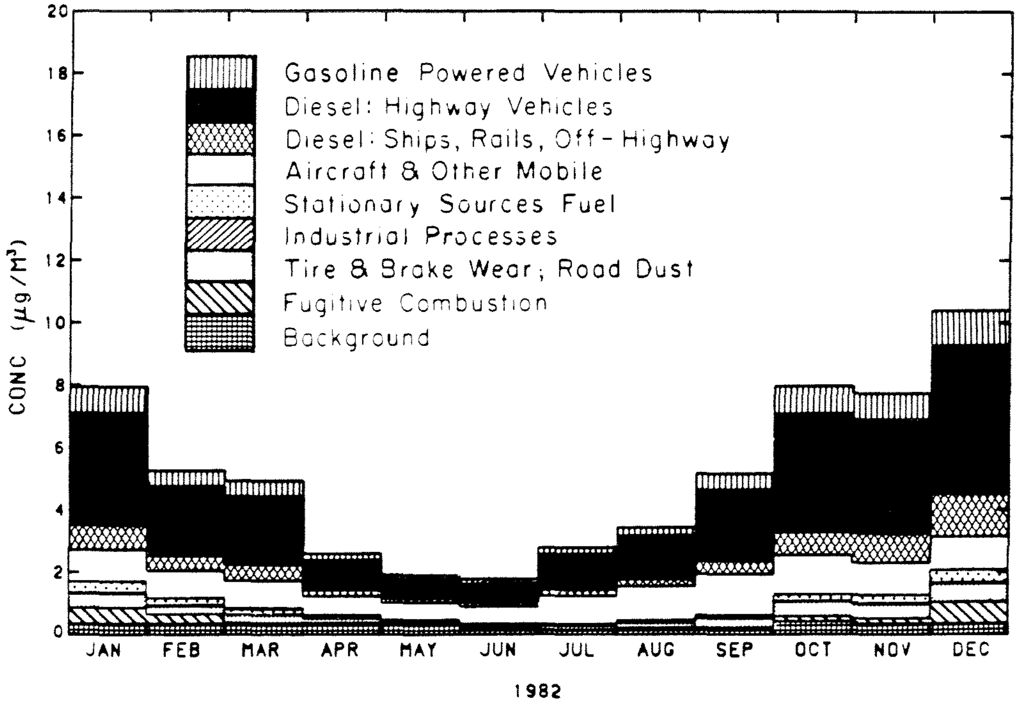


Figure 4.7b

MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT LONG BEACH

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

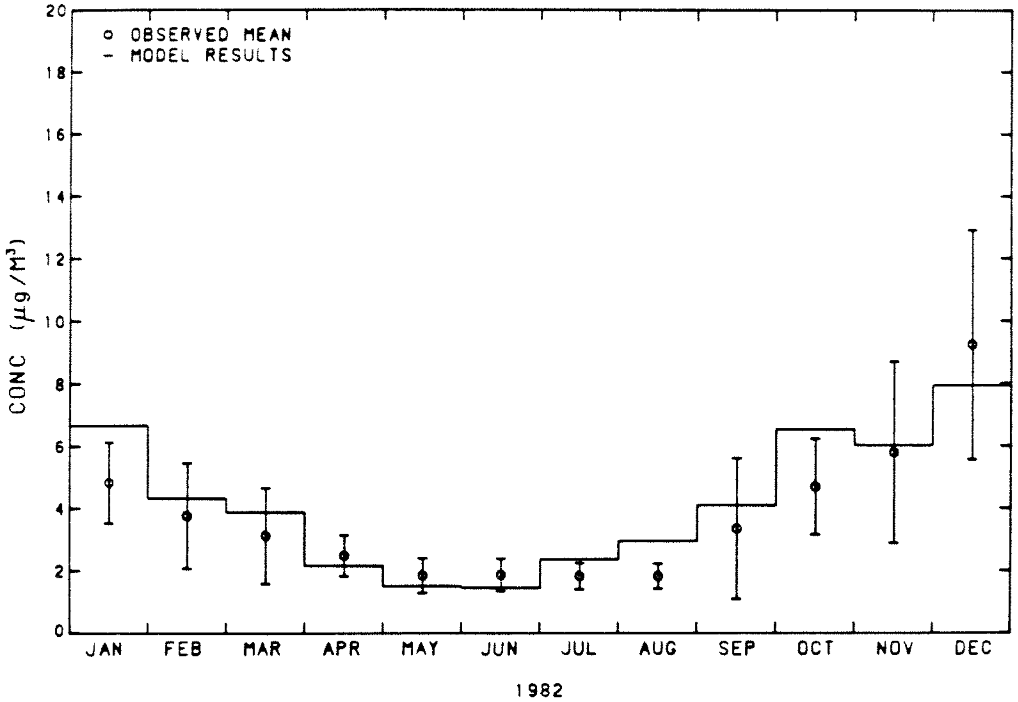


Figure 4.8a

SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT LONG BEACH

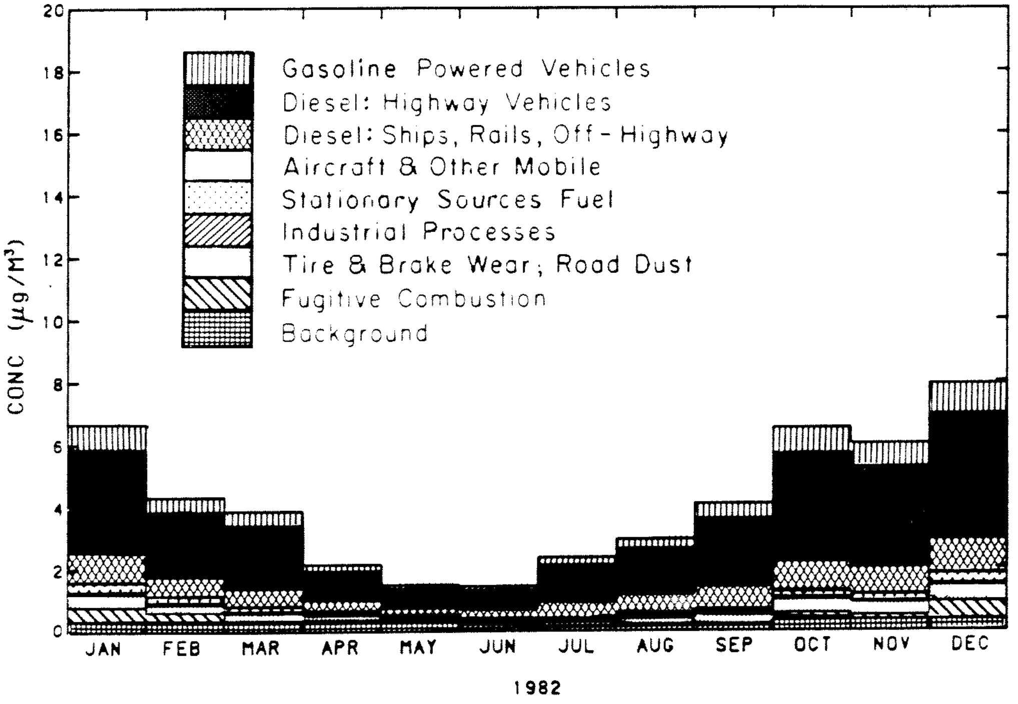


Figure 4.8b

MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT WEST LOS ANGELES

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

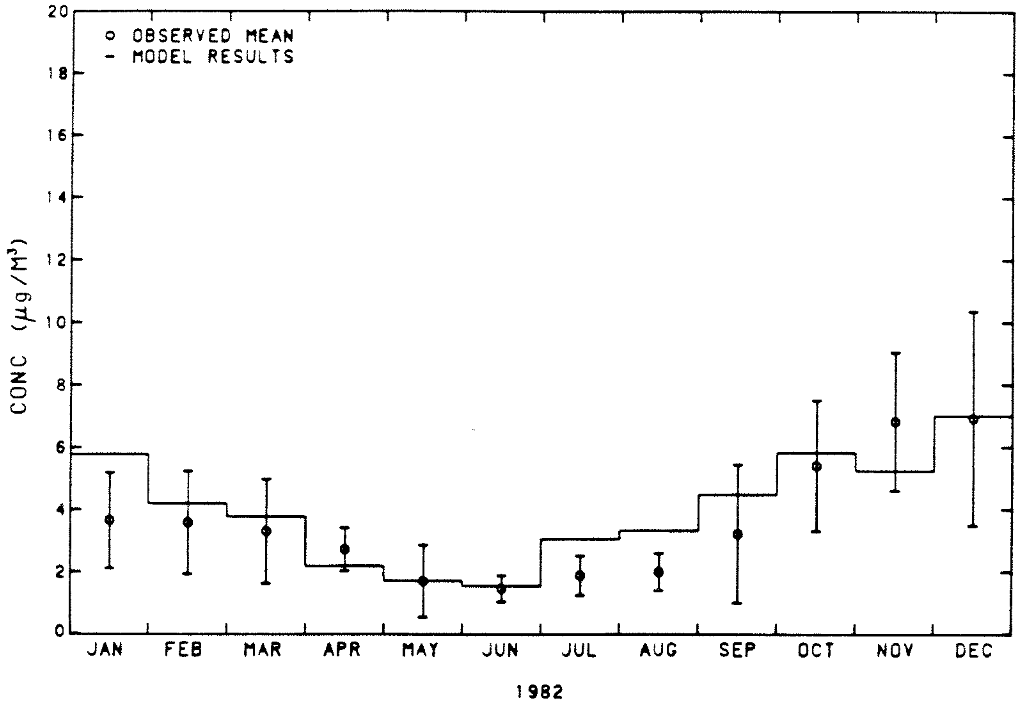


Figure 4.9a

SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT WEST LOS ANGELES

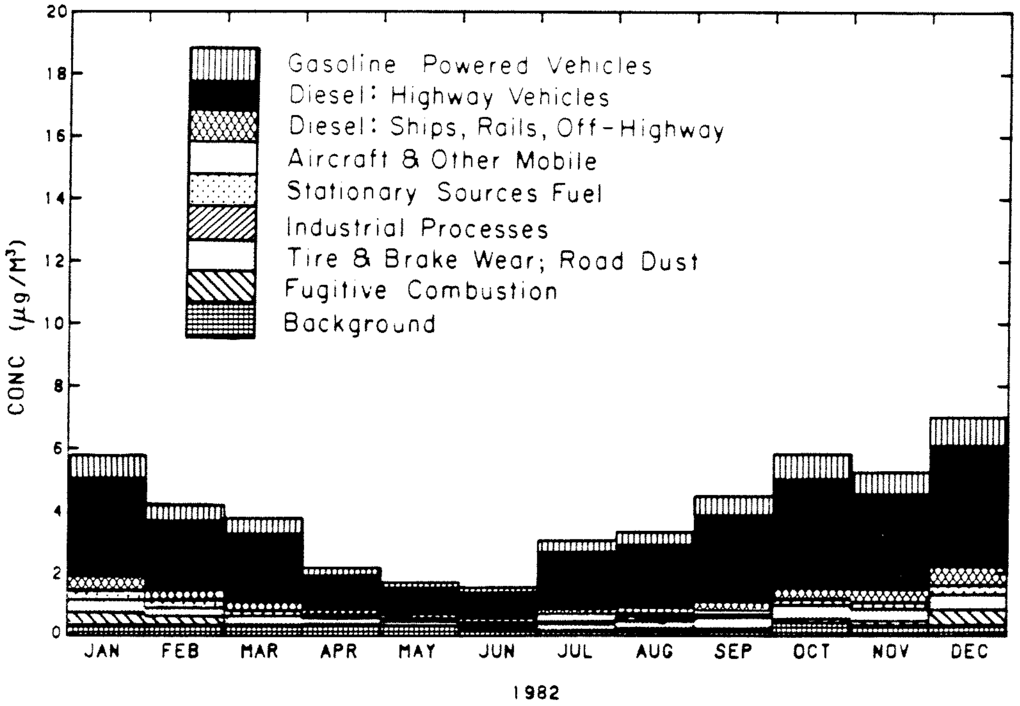
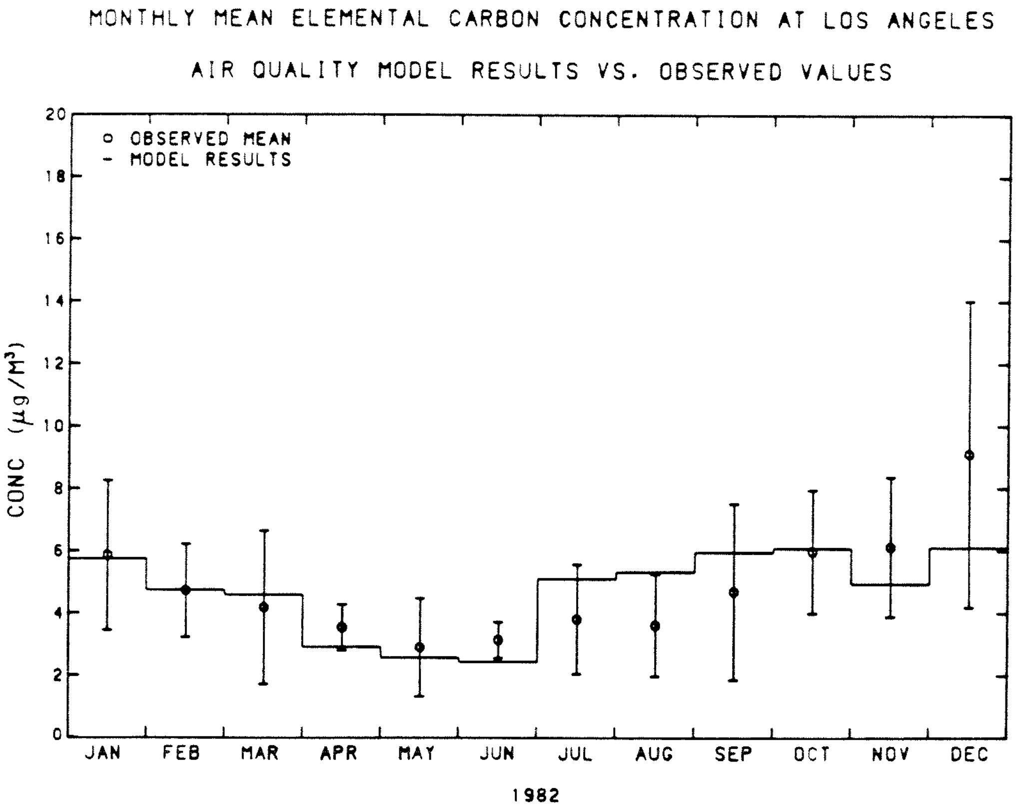
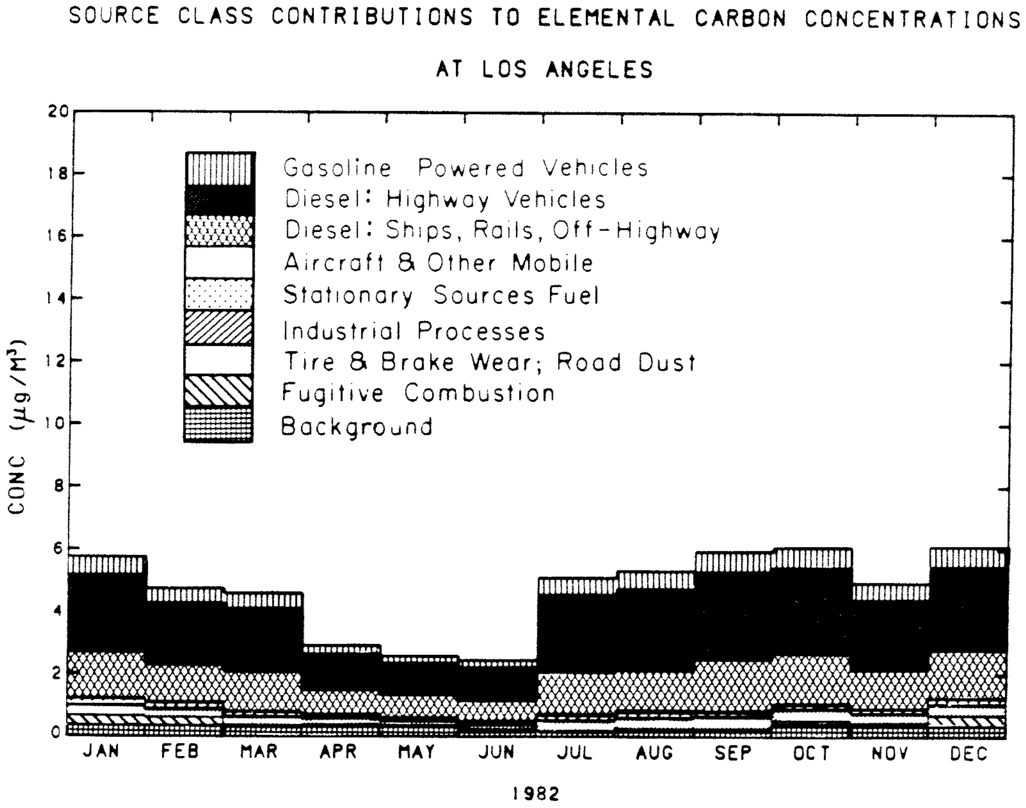


Figure 4.9b


MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT LOS ANGELES

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.10a


SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT LOS ANGELES

Figure 4.10b

MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT ANAHEIM

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

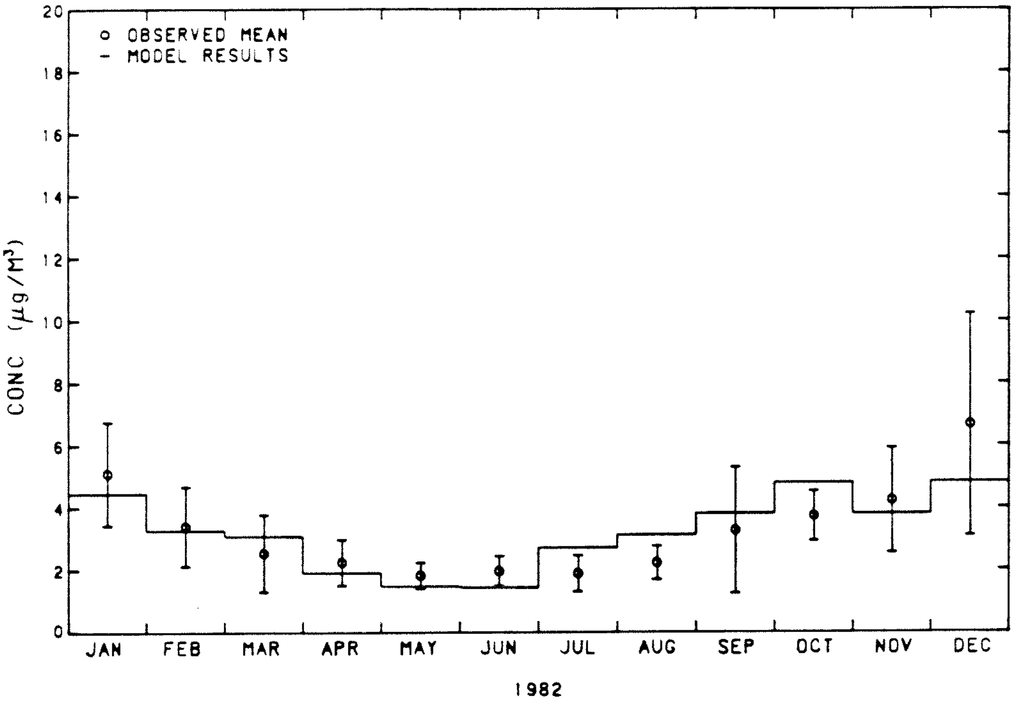


Figure 4.11a

SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT ANAHEIM

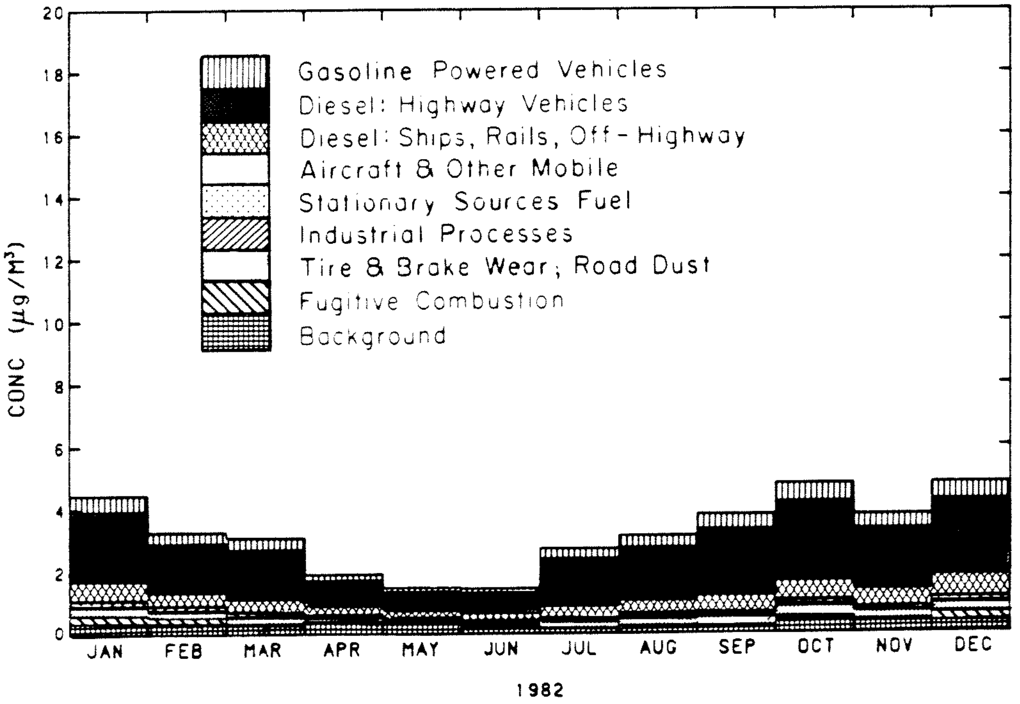
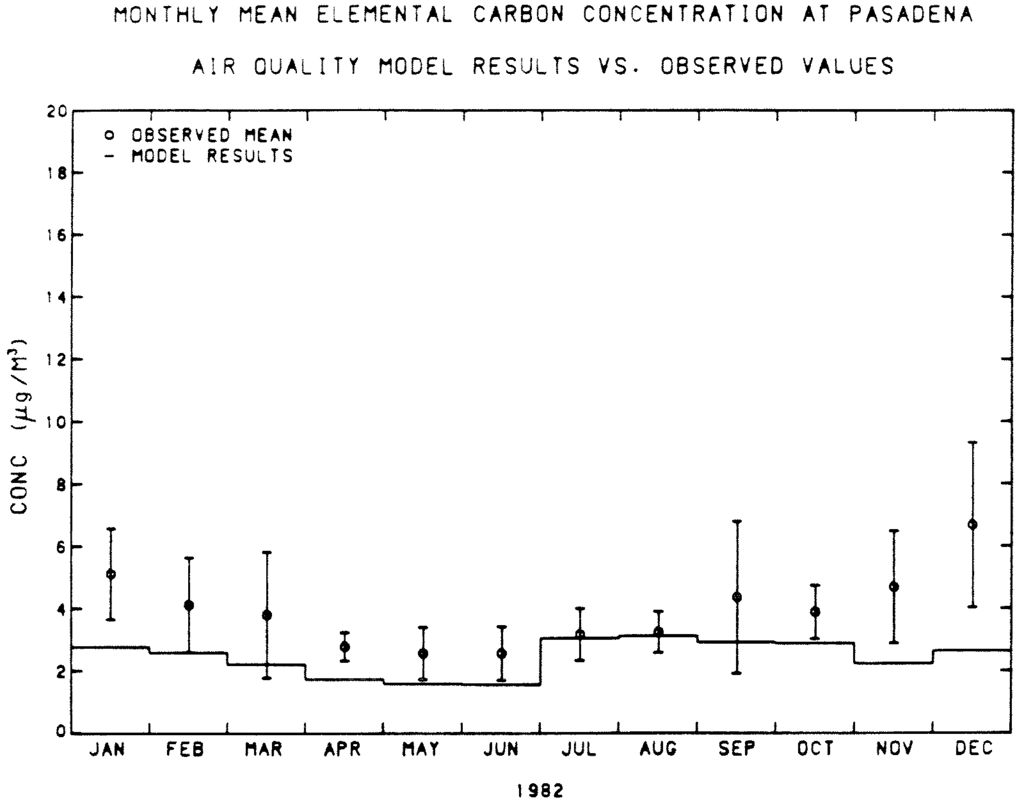


Figure 4.11b


MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT PASADENA

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.12a

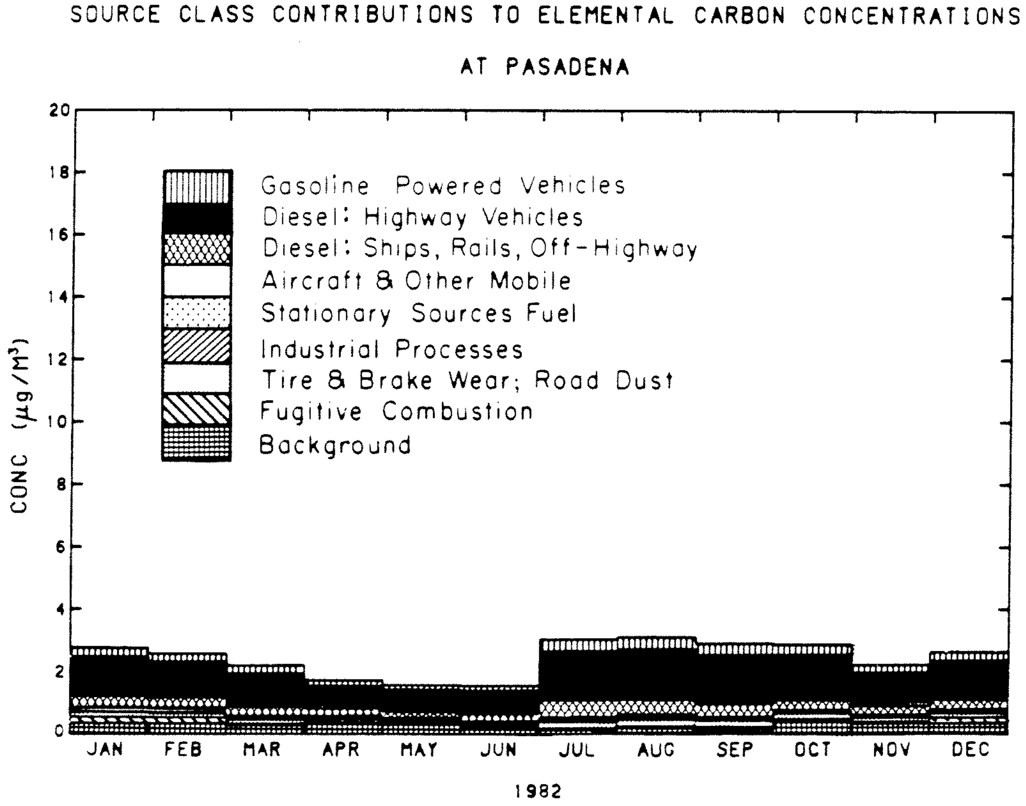
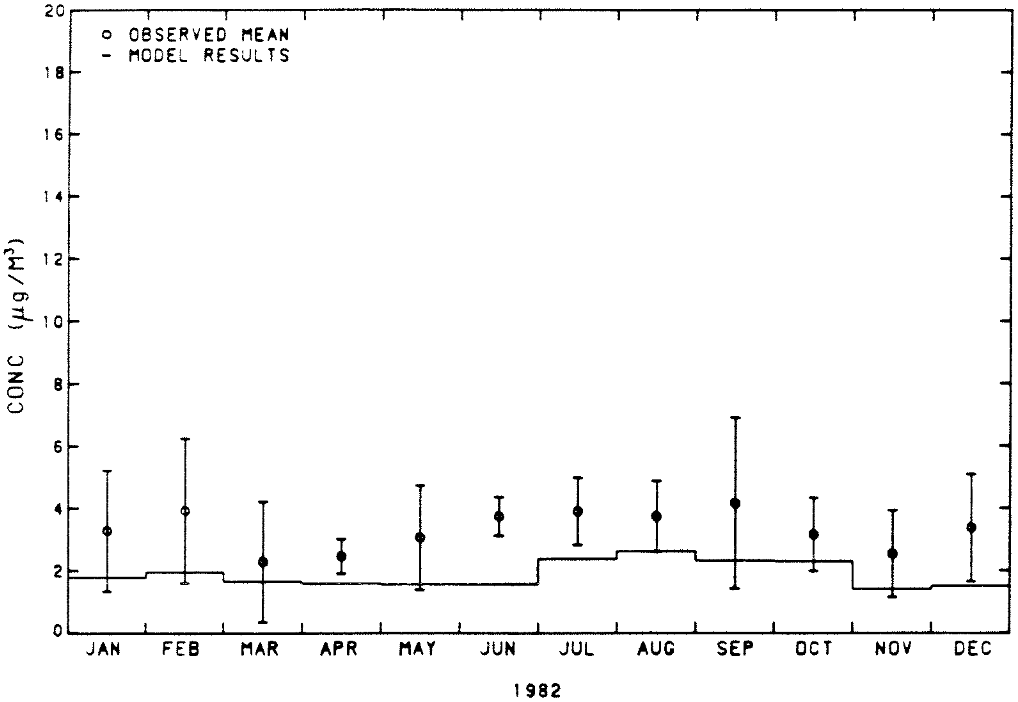

SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS AT PASADENA

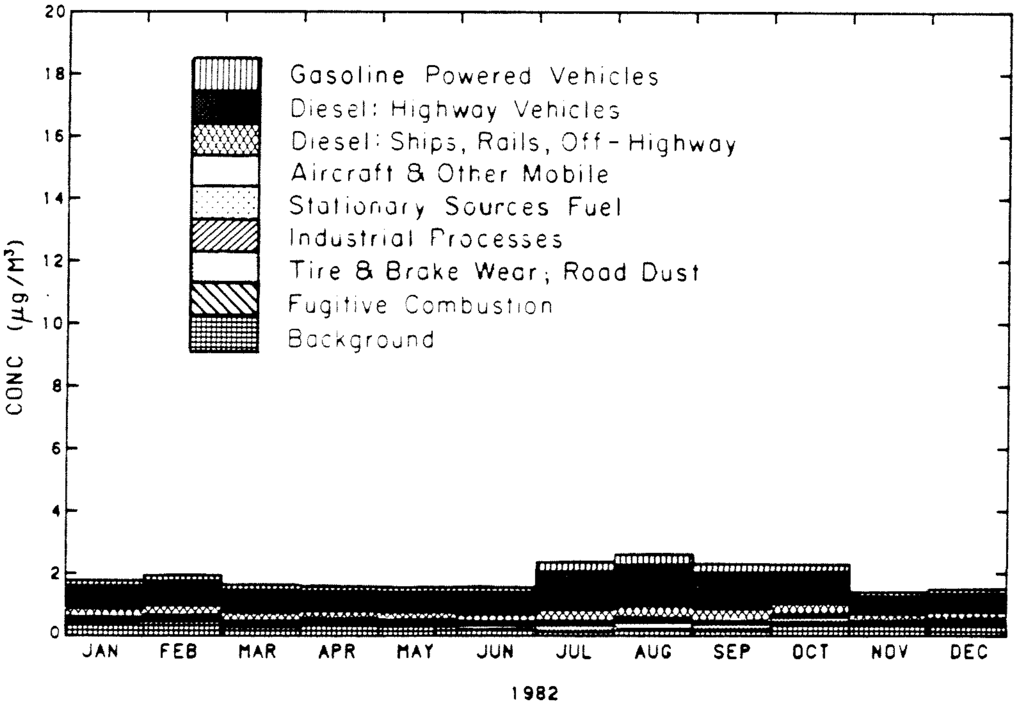
Figure 4.12b



MONTHLY MEAN ELEMENTAL CARBON CONCENTRATION AT AZUSA

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.13a



SOURCE CLASS CONTRIBUTIONS TO ELEMENTAL CARBON CONCENTRATIONS

AT AZUSA

Figure 4.13b

These uncertainties in observed monthly average concentrations are due almost entirely to the facts that atmospheric concentrations fluctuate from day to day and that not all days in each month were sampled. Therefore, the true mean may not have been observed. Any model-predicted monthly average concentration that is within those error bounds is statistically indistinguishable from the measured monthly mean concentration. Fine monthly average elemental carbon particle concentrations predicted by the model are within the error bounds of the observations approximately 68% of the time. Annual average elemental carbon concentration predictions are compared to observations in Table 4.9. At all monitoring sites except Pasadena and Azusa, the annual average prediction is within the 95% confidence interval for the corresponding observation. Examination of Figures 4.7a through 4.13a shows that the model captures the major seasonal features of observed elemental carbon levels. At coastal sites like Lennox, predictions and observations are characterized by high winter concentrations and much lower summer values. At inland sites like Azusa, predicted and observed elemental carbon concentrations remain at about the same level year-round.

4.3.2 Spatial-Temporal Correlation between Predicted and Observed Fine Elemental Carbon Particle Concentrations

Predicted monthly average fine elemental carbon particle concentrations are compared graphically to air quality observations in Figure 4.14. Each data point represents a predicted monthly average

Table 4.9

Observed versus Predicted 1982 Annual Average
Fine Elemental Carbon Concentrations
(concentrations in μg/m^3)

	Air Quality Observations					Model Results	
	Sample arithmetic mean $\bar{y}$	Sample arithmetic standard deviation σ	Number of 24-hr. samples	Lower confidence limit on $\bar{y}$ (2.5%ile)	Upper confidence limit on $\bar{y}$ (97.5%ile)	Arithmetic mean from air quality model	Prediction is within confidence interval of observations?
Azusa	3.30	1.87	60	2.86	3.74	1.88	No
Long Beach	3.75	3.00	59	3.05	4.46	4.16	Yes
Lennox	4.51	3.16	61	3.78	5.23	5.17	Yes
Pasadena	3.95	2.07	60	3.46	4.43	2.43	No
West Los Angeles	3.61	2.78	58	2.94	4.27	4.01	Yes
Los Angeles	4.87	3.24	61	4.12	5.62	4.71	Yes
Anaheim	3.18	2.31	57	2.62	3.74	3.22	Yes
7 locations	3.88	2.68	416	3.64	4.12	3.66	Yes

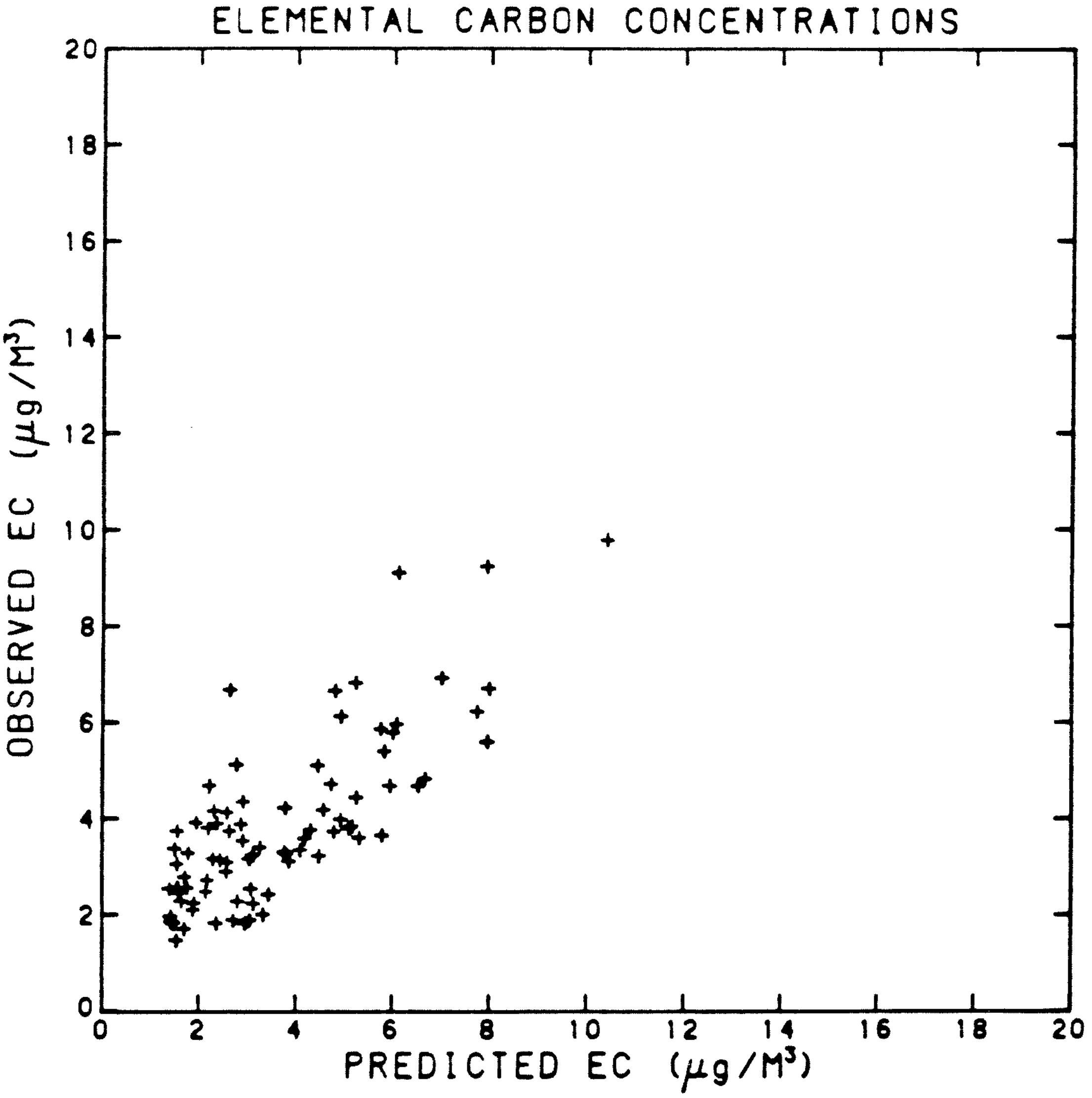


Figure 4.14 Monthly average fine elemental carbon particle concentrations at seven monitoring sites--observations vs. predictions.

concentration at one of the seven monitoring sites versus the corresponding monthly mean of measured concentrations. The correlation between observed and predicted elemental carbon concentrations is 0.78.

The model's ability to predict observed concentrations may be assessed by performing a goodness-of-fit test. The sum of squares of the difference between model predictions and observations, each square normalized by the observed concentration, approximately follows a chi-square distribution. The null hypothesis is that the model predicts elemental carbon concentrations accurately. This hypothesis will be rejected at the α level of significance only if the summation results in a value larger than χ^2_α (where the degrees of freedom equal the number of comparisons minus one); see Walpole and Myers (1978, p. 265) for a discussion of the goodness-of-fit test.

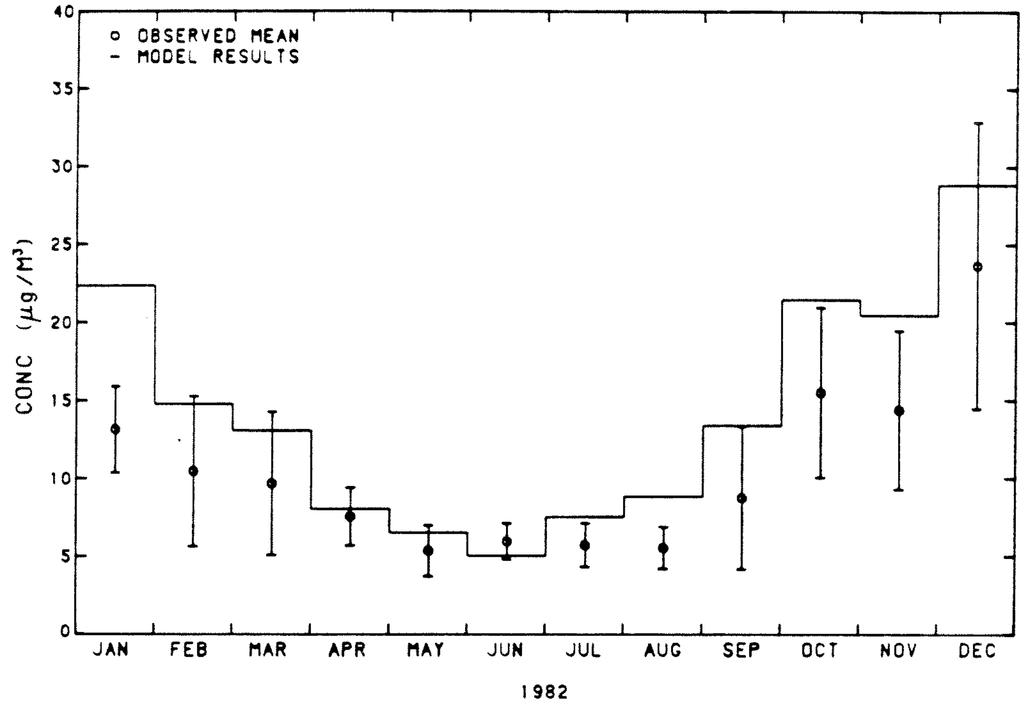
The comparison of predicted and observed <u>annual</u> average elemental carbon concentrations at the seven monitoring sites results in a goodness-of-fit statistic of 1.38. The value is well below $\chi^2_{.05} = 12.59$ (degrees of freedom = 6), so the null hypothesis may not be rejected at the 0.05 level of significance. This implies that the model is a good predictor of annual average elemental carbon concentrations.

A more severe test involves performing the goodness-of-fit test on predicted <u>monthly</u> averages. The result for monthly average elemental carbon concentrations produces a statistic of 31.55. The chi-square value, $\chi^2_{.05}$ (degrees of freedom = 83), is approximately

105.0 (approximation for χ^2 with large degrees of freedom from Benjamin and Cornell [1970]; Table A.2, note 3); hence, the null hypothesis cannot be rejected at the 0.05 level of significance. The conclusion is that the model provides a good fit to the observed data; therefore, the model may be considered a good predictor of monthly average elemental carbon particle concentrations.

4.3.3 Comparison of Primary Fine Total Carbon Concentration Predictions and Fine Total Carbon Air Quality Observations

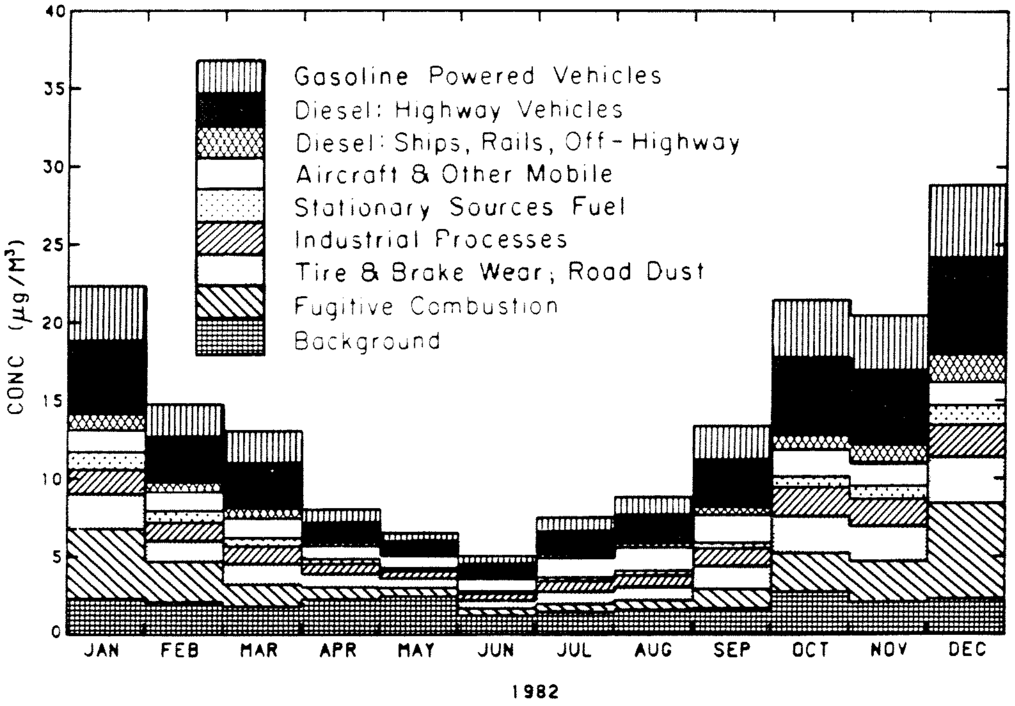
The air quality model employed in this study is capable of predicting the primary aerosol contribution to total carbon concentrations, given the inventory of primary aerosol carbon emissions presented in Section 4.2.1. A complete assessment of total aerosol carbon levels cannot be predicted by this model because no provision is made for secondary organic aerosol production due to chemical reaction of gas phase hydrocarbons present in the atmosphere. However, as noted in Chapter 2, ambient monitoring data show that the long-term average ratio of total carbon to elemental carbon in the Los Angeles atmosphere during the year 1982 did not show a summer peak that is characteristic of the presence of a great deal of secondary organic aerosol. Therefore, primary aerosol total carbon concentrations predicted by the air quality model should come close to explaining the origin of most of the total carbon levels observed over long averaging times in the atmosphere in that year.



MONTHLY MEAN TOTAL CARBON CONCENTRATION AT LENNOX

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

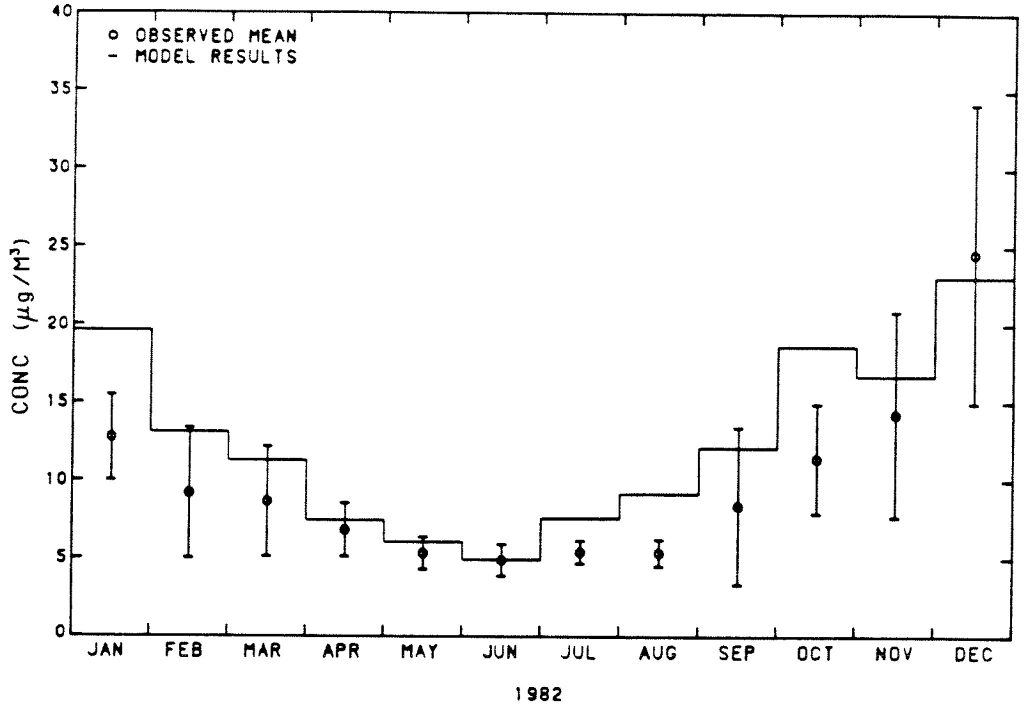
Figure 4.15a



SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS

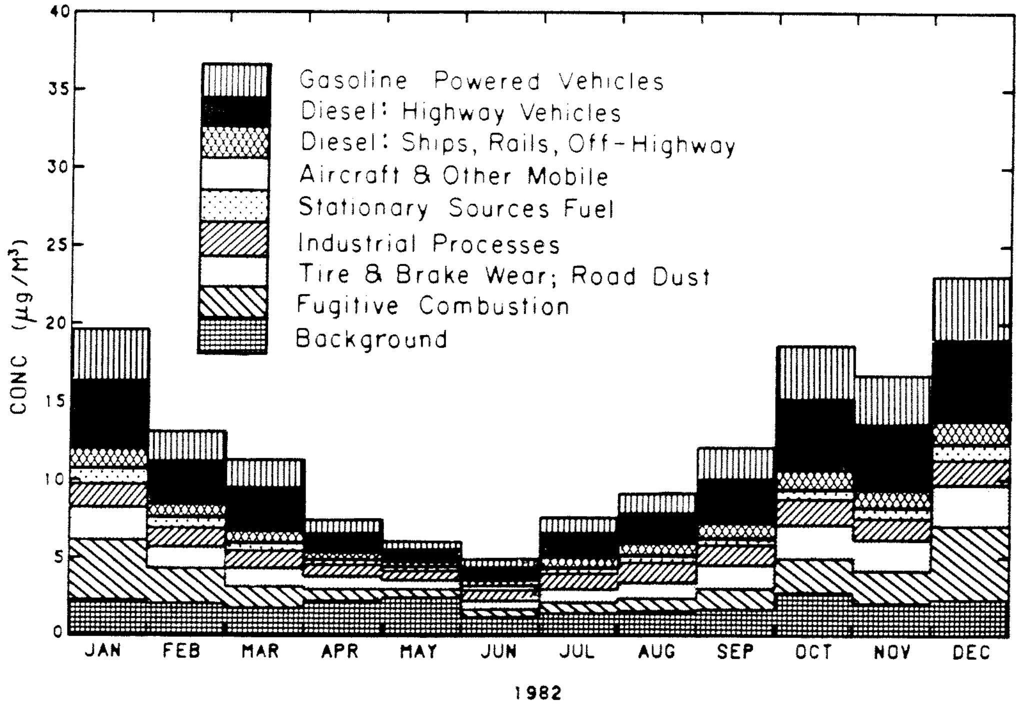
AT LENNOX

Figure 4.15b


MONTHLY MEAN TOTAL CARBON CONCENTRATION AT LONG BEACH

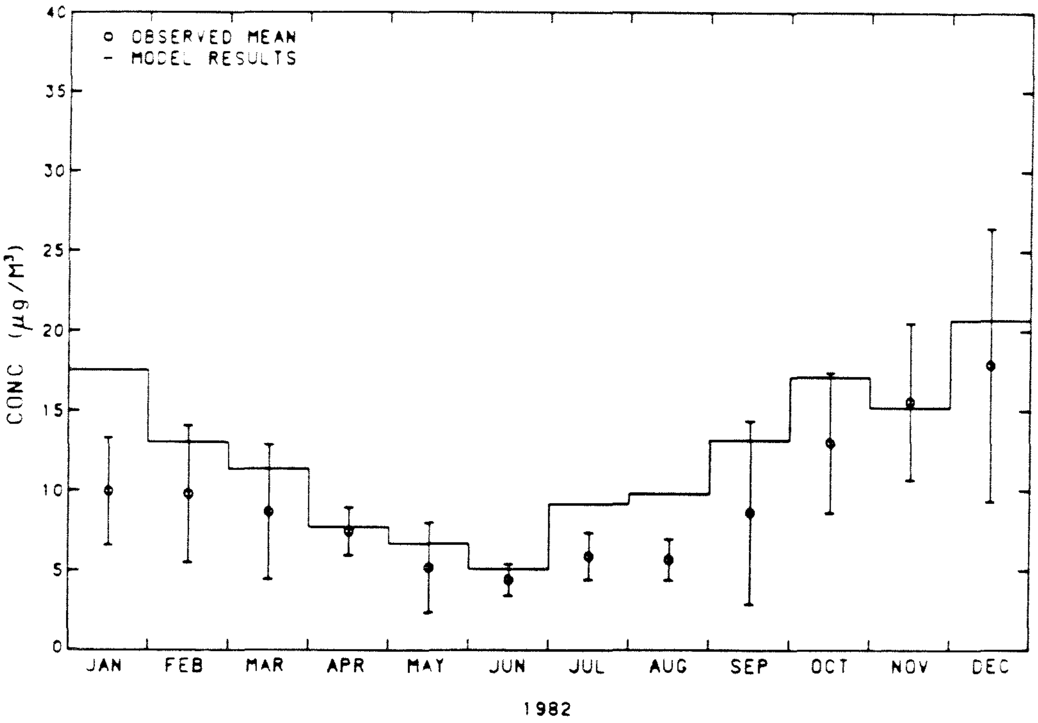
AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.16a


SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS

AT LONG BEACH

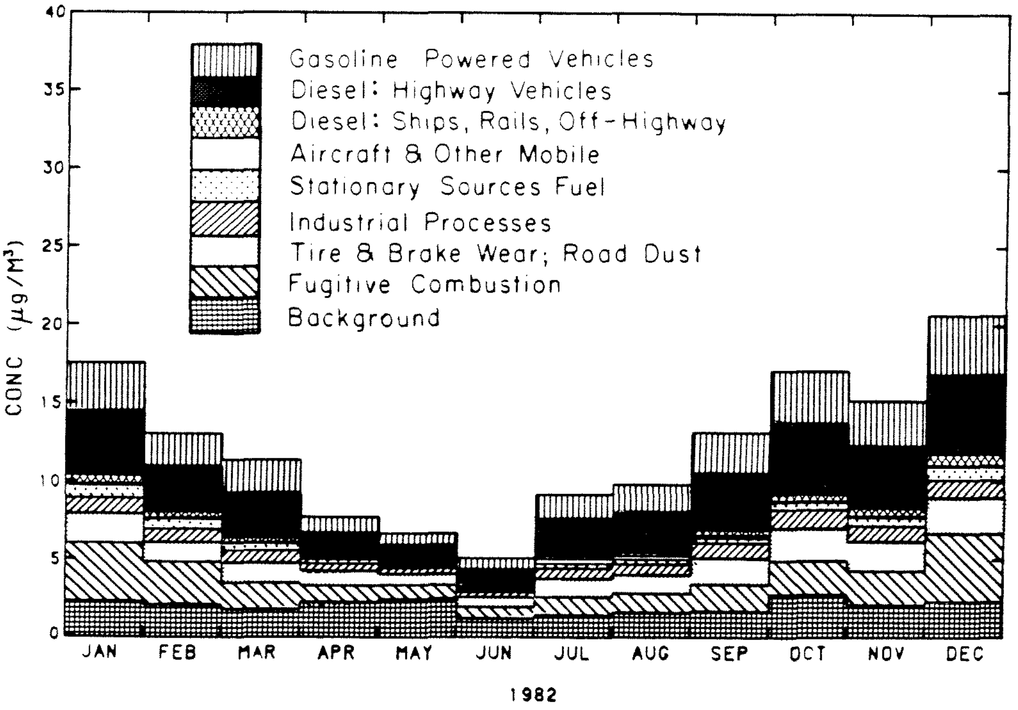
Figure 4.16b



MONTHLY MEAN TOTAL CARBON CONCENTRATION AT WEST LOS ANGELES

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.17a



SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS

AT WEST LOS ANGELES

Figure 4.17b

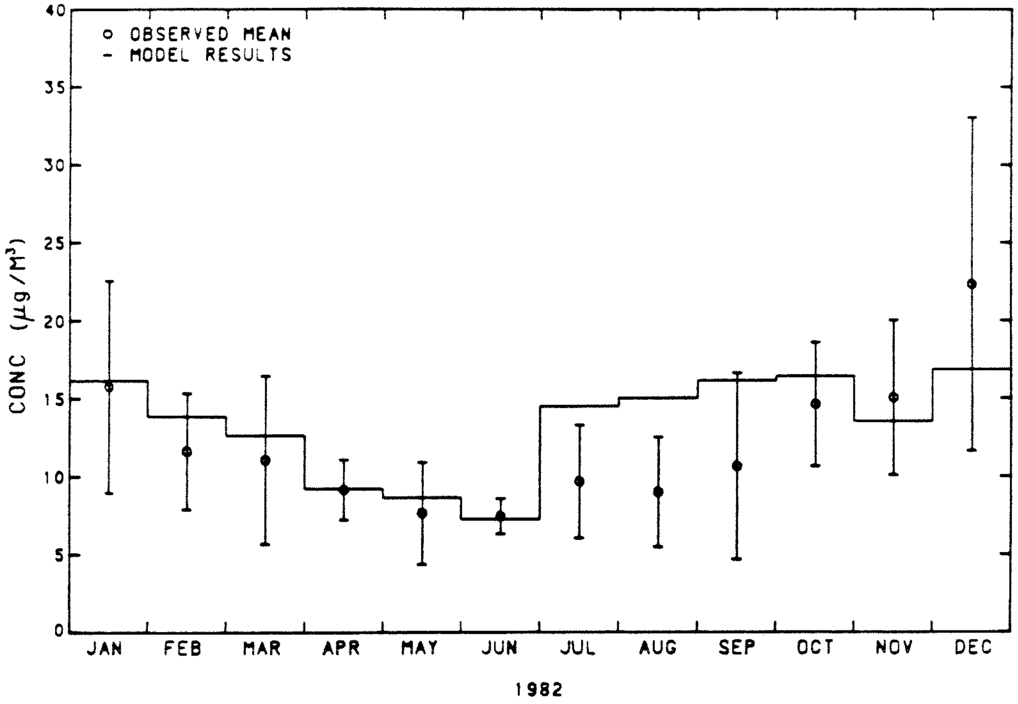


Figure 4.18a

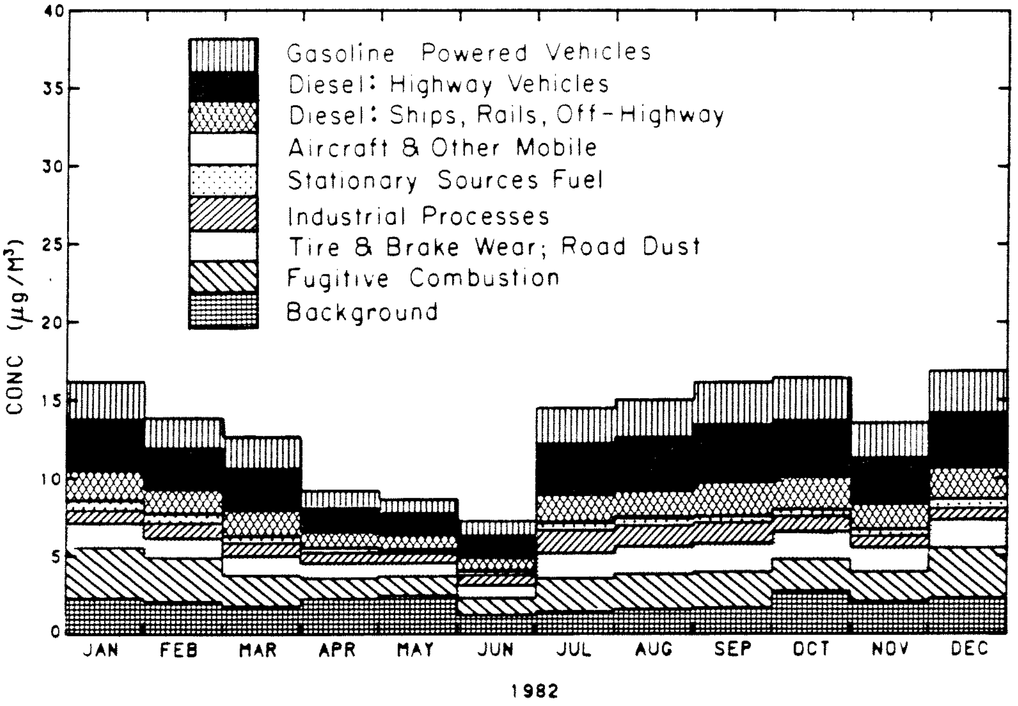
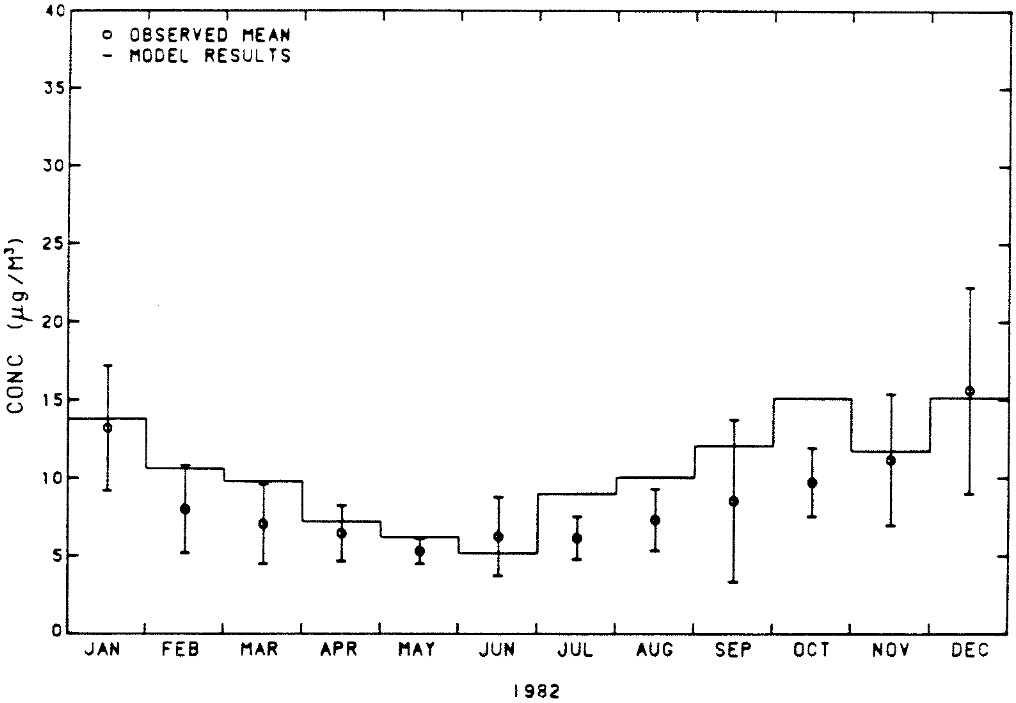


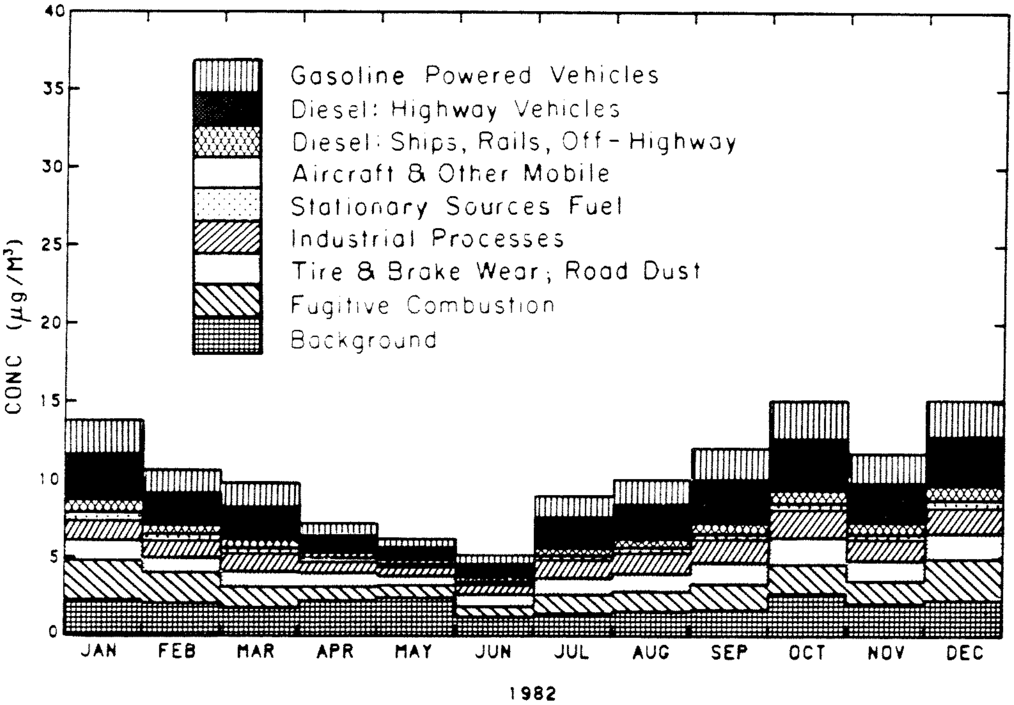
Figure 4.18b



MONTHLY MEAN TOTAL CARBON CONCENTRATION AT ANAHEIM

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

Figure 4.19a



SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS AT ANAHEIM

Figure 4.19b

MONTHLY MEAN TOTAL CARBON CONCENTRATION AT PASADENA

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

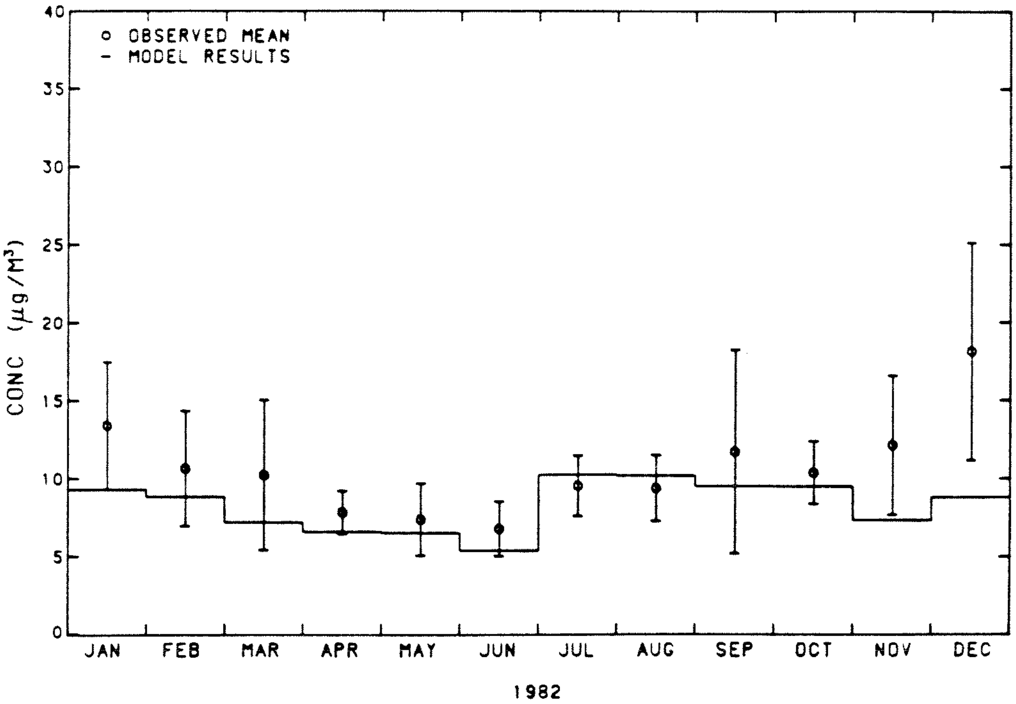


Figure 4.20a

SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS

AT PASADENA

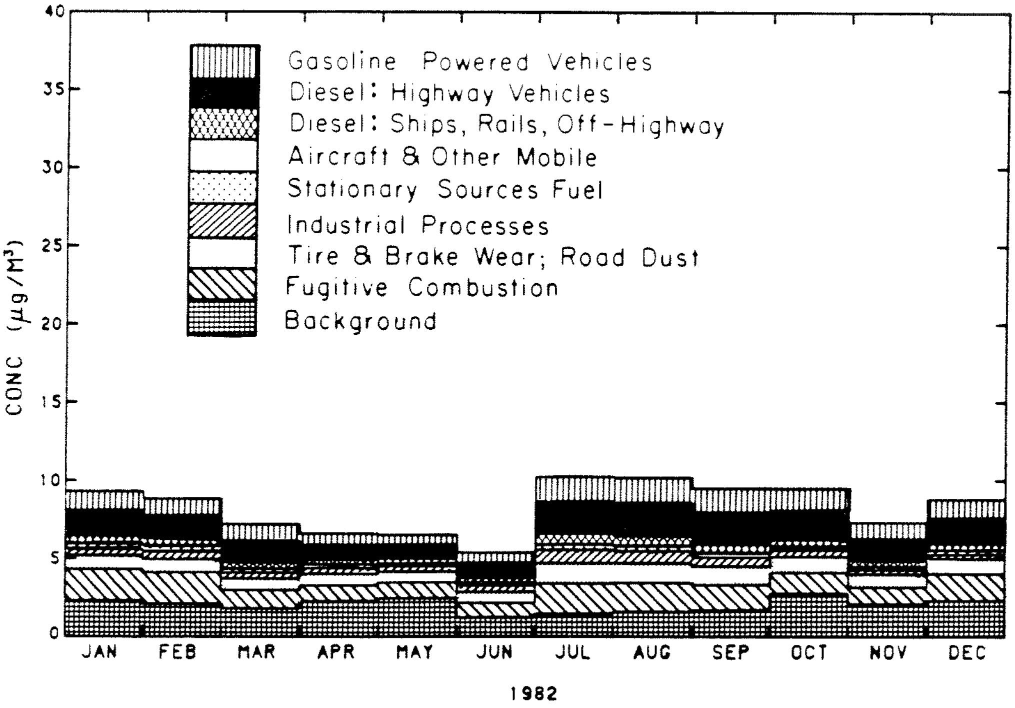


Figure 4.20b

MONTHLY MEAN TOTAL CARBON CONCENTRATION AT AZUSA

AIR QUALITY MODEL RESULTS VS. OBSERVED VALUES

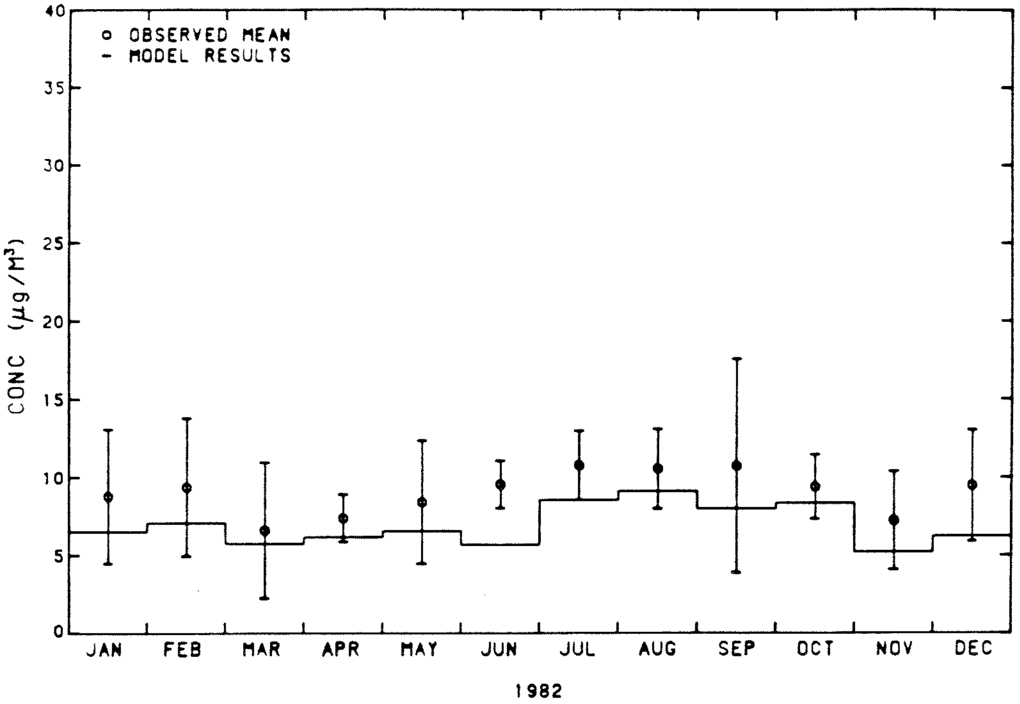


Figure 4.21a

SOURCE CLASS CONTRIBUTIONS TO TOTAL CARBON CONCENTRATIONS

AT AZUSA

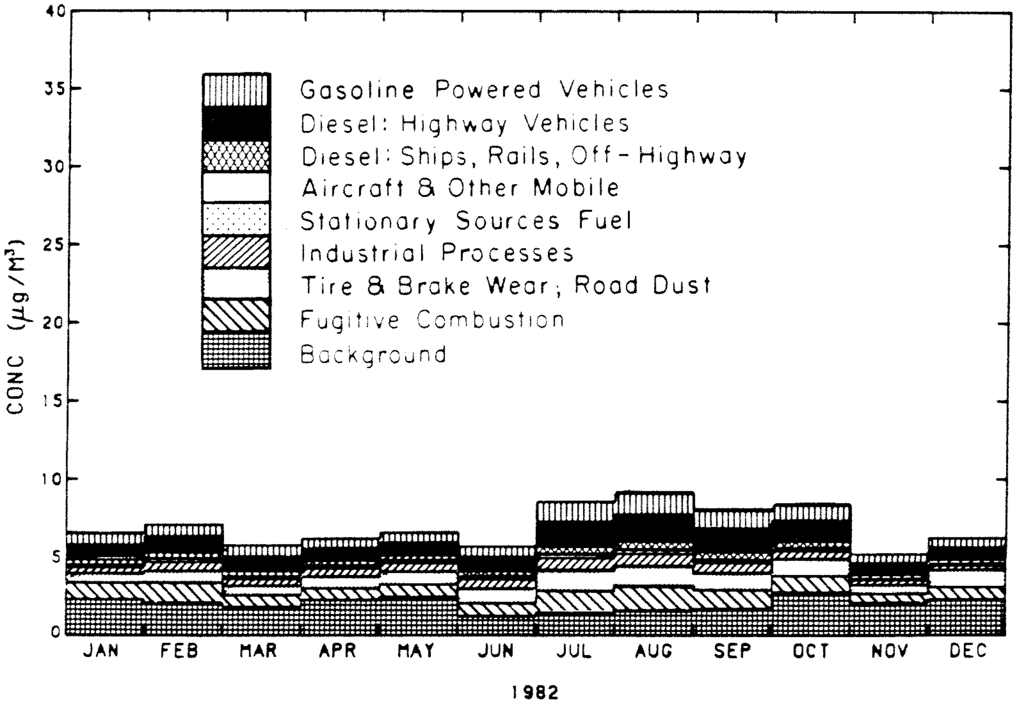


Figure 4.21b

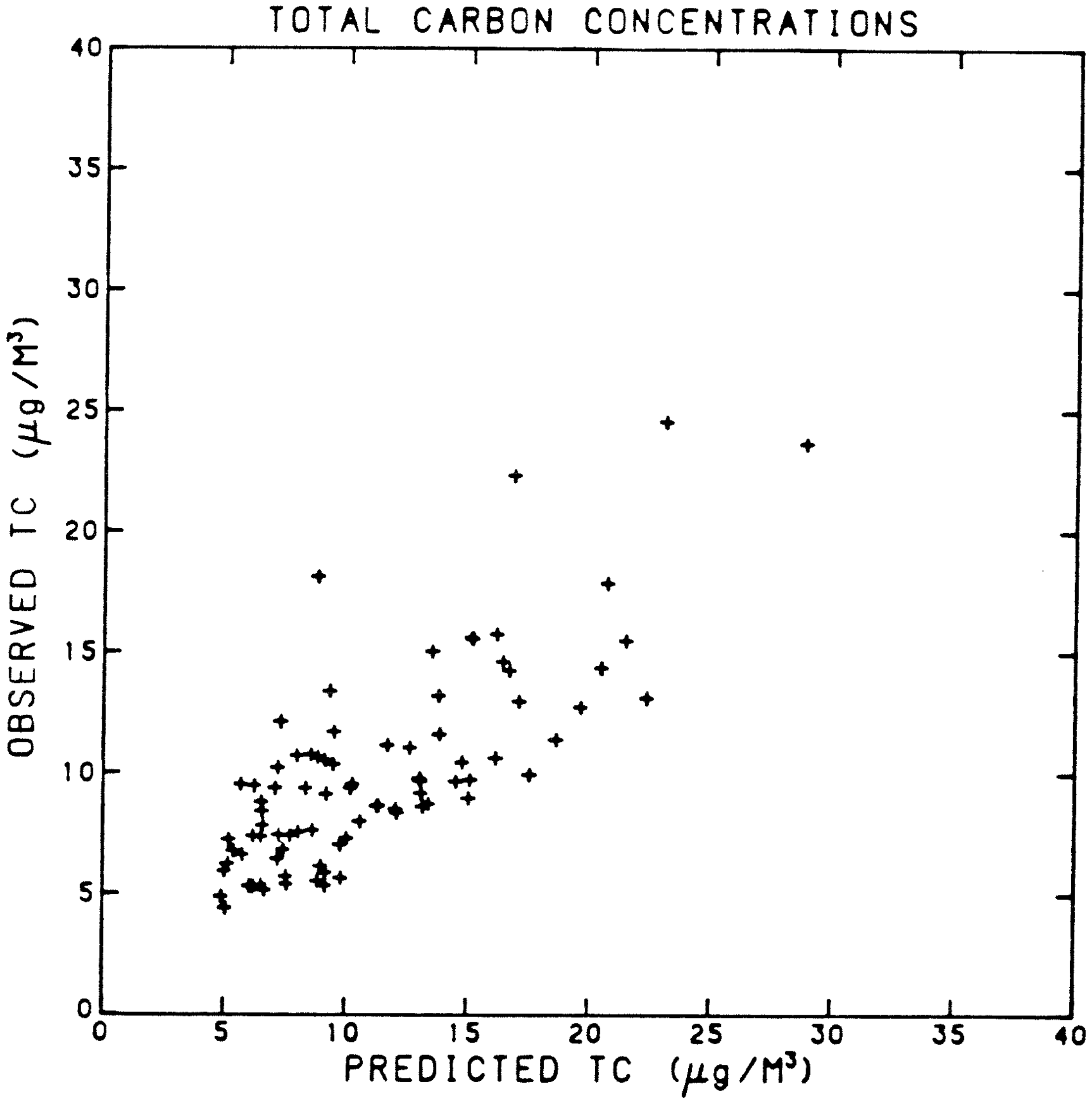


Figure 4.22 Observations of monthly average fine total carbon particle concentrations vs. predictions of fine primary total carbon particle concentrations at seven monitoring sites.

The primary total carbon emission inventory was matched to the air quality model, and primary total carbon concentrations were predicted for each month of the year 1982. Results at each of the seven monitoring sites are shown in Figures 4.15a through 4.21a. About 73% of the monthly average primary fine total carbon particle concentrations predicted by the model are within the error bounds of the observed monthly mean fine total carbon concentrations. It is seen that present estimates of primary total carbon emissions are sufficient to account for most of the observed concentrations and seasonal behavior of long-term average fine total carbon air quality during 1982.

The correlation between model-predicted primary fine total carbon concentrations and observed total carbon concentrations is shown in Figure 4.22. The predictions and observations of total carbon concentrations have a positive correlation coefficient of 0.76.

The goodness-of-fit test, which was performed on elemental carbon predictions in the previous section, also may be conducted to test the hypothesis that primary fine total carbon concentrations computed by the model may serve as accurate predictions of fine total carbon air quality. The comparison of predicted and observed <u>annual</u> average total carbon concentrations at the seven monitoring sites results in a goodness-of-fit statistic of 4.28, which is below $\chi^2_{.05} \simeq 105.0$ ($\nu = 83$). It may be concluded, therefore, that the model provides an accurate prediction of fine total carbon air quality.

4.3.4 Spatial Variations in Fine Carbon Particle Air Quality

Figures 4.23 and 4.24 show contour plots of the 1982 annual mean air quality predictions of fine primary total carbon and fine elemental carbon concentrations throughout the modeling region. The area surrounding the downtown Los Angeles central business district southwest of the central Los Angeles air monitoring site is subject to the highest annual mean concentrations of carbonaceous particulate matter.

Contour plots showing fine elemental carbon concentration predictions for each month of 1982 are presented in Figures 4.25 through 4.36. In January, winds from the northeast cause emissions to be pushed toward the southwestern portion of the modeling grid, with monthly averaged concentrations of elemental carbon reaching 6 $\mu g/m^3$ at the coastline. The direction of flow is similar in February and March; however, the magnitude of peak concentrations has decreased. As the weather warms, the net transport direction shifts and concentrations in the northeastern portion of the modeling region become as high as high as at the coast, as seen in April, May, and June. Overall concentration levels decrease drastically in the central portion of the air basin. In July, the peak elemental carbon concentrations increase, while the direction of flow is still predominantly from the west and southwest, causing higher concentrations in the eastern locations of the modeling grid. This trend continues through August and September. As the temperature cools, peak concentrations increase and the area most affected by

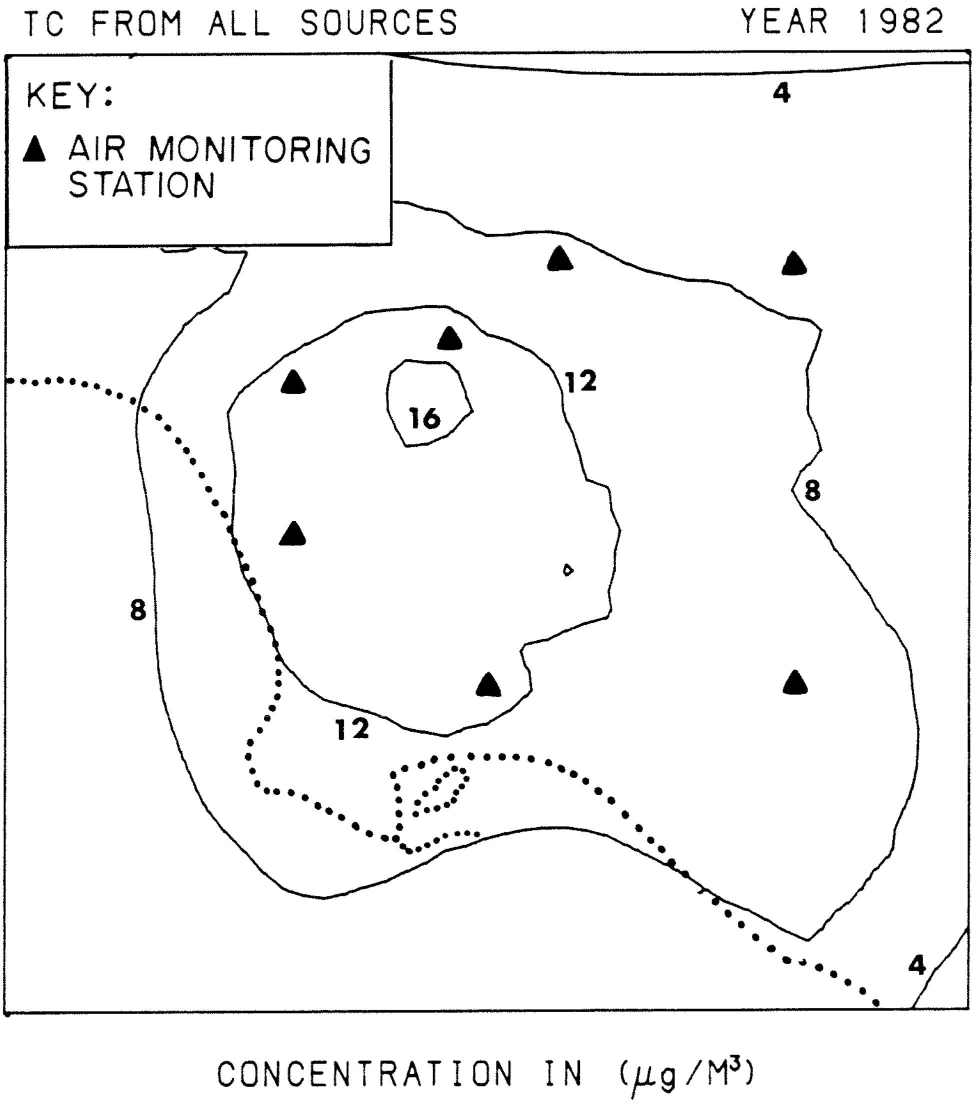


Figure 4.23 Annual mean fine primary total carbon concentration isopleths computed by the air quality model simulation.

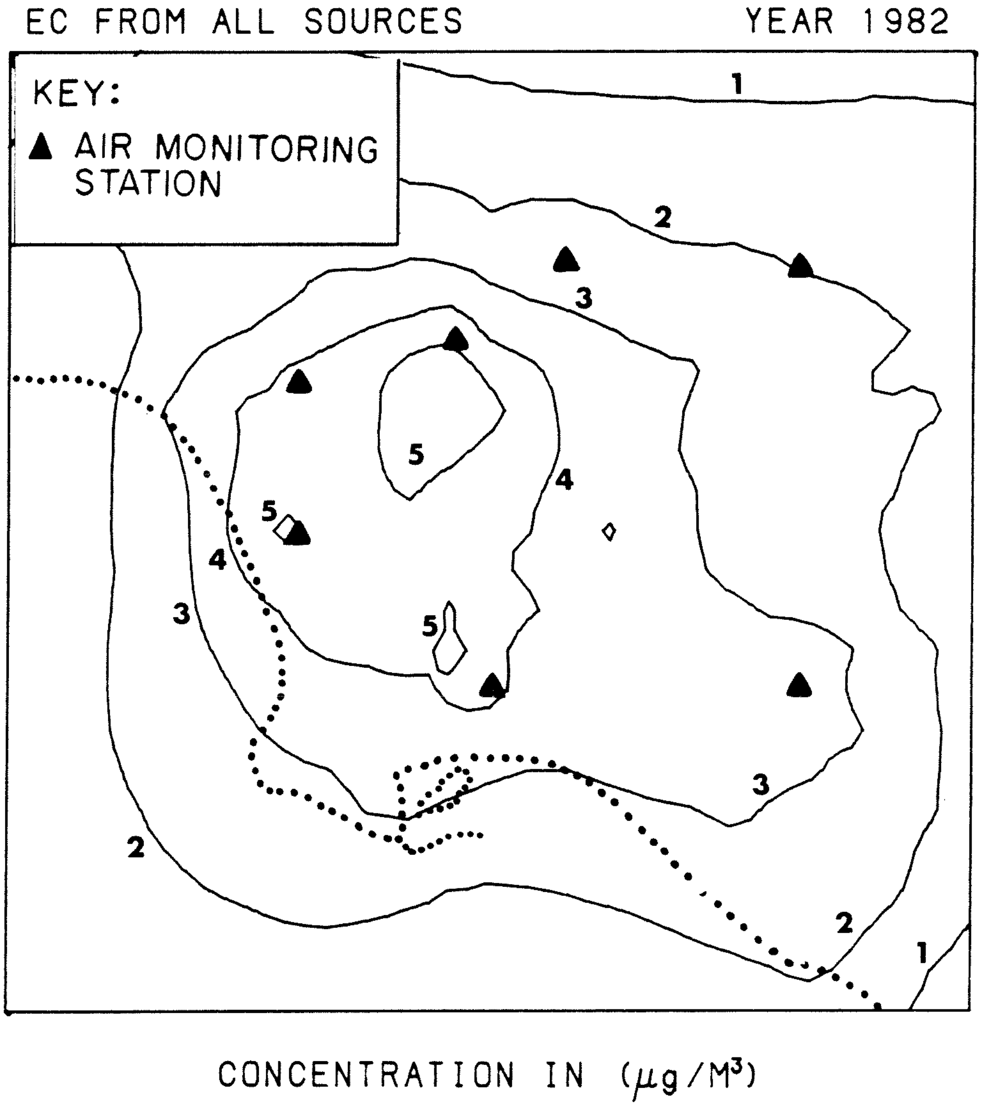


Figure 4.24 Annual mean fine elemental carbon concentration isopleths computed by the air quality model simulation.

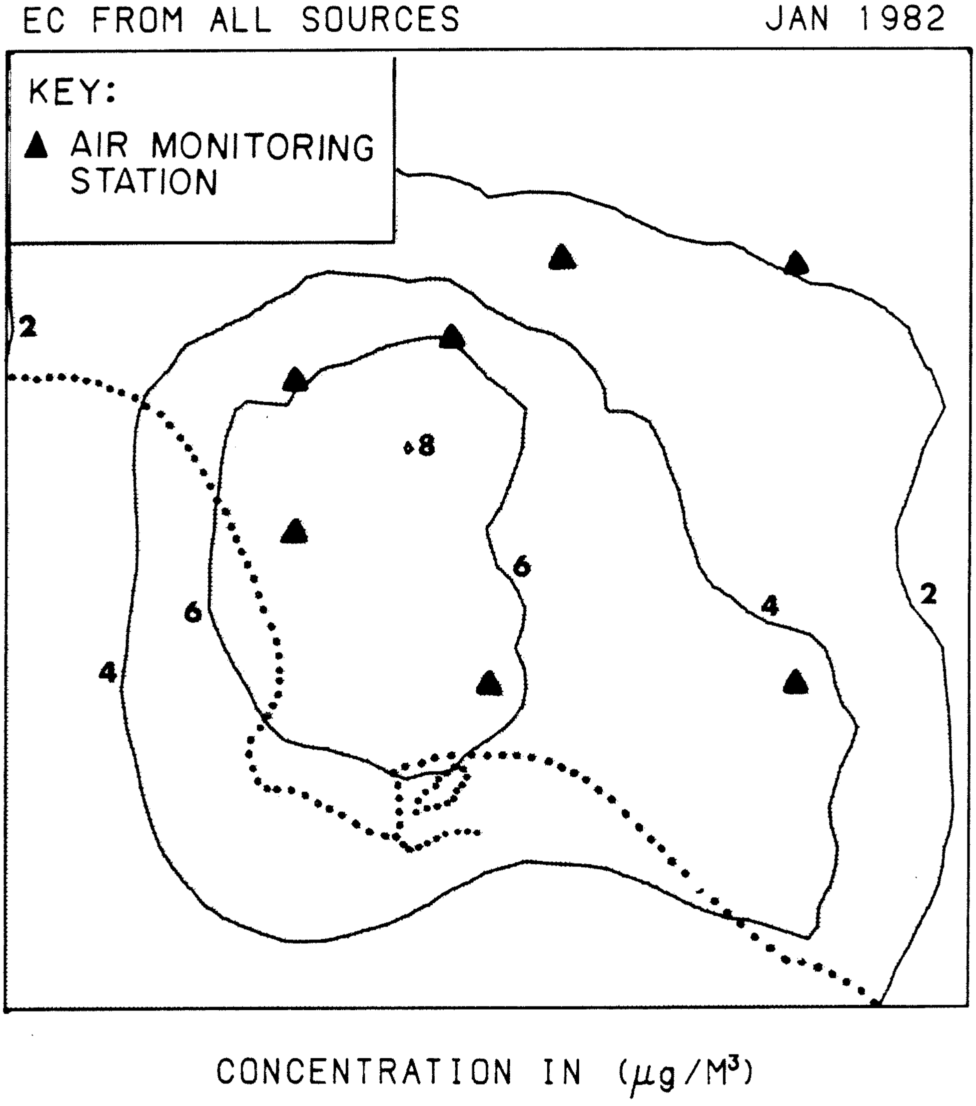


Figure 4.25 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--January 1982.

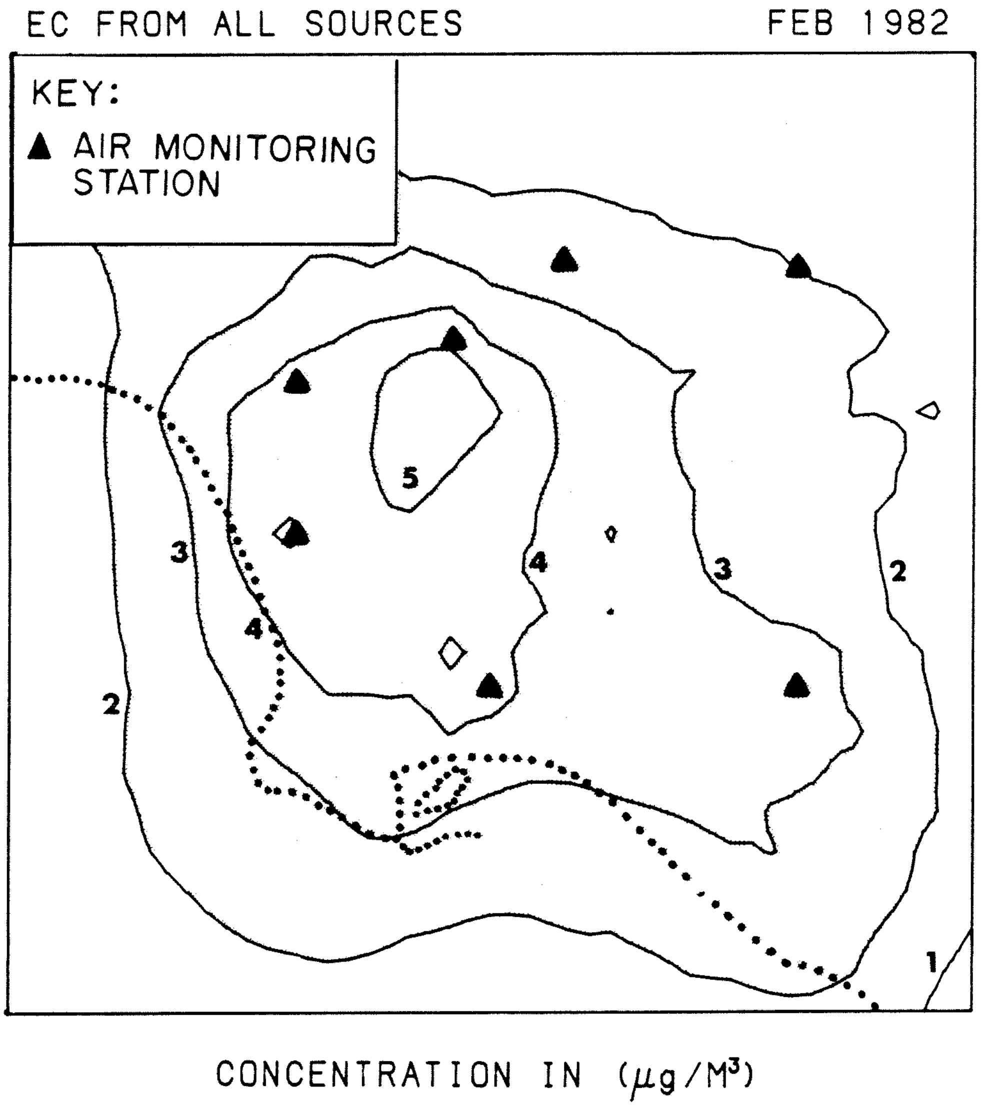


Figure 4.26 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--February 1982.

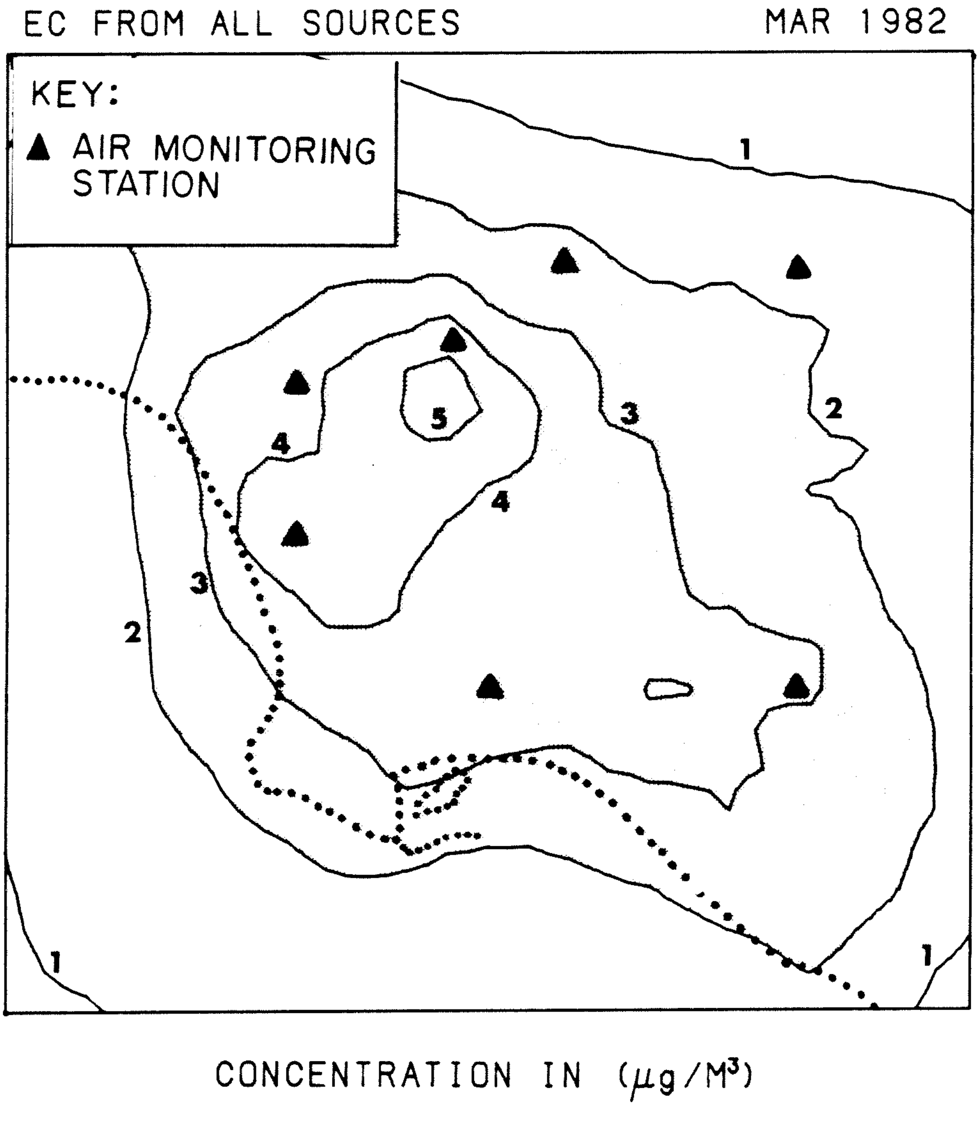


Figure 4.27 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation-- March 1982.

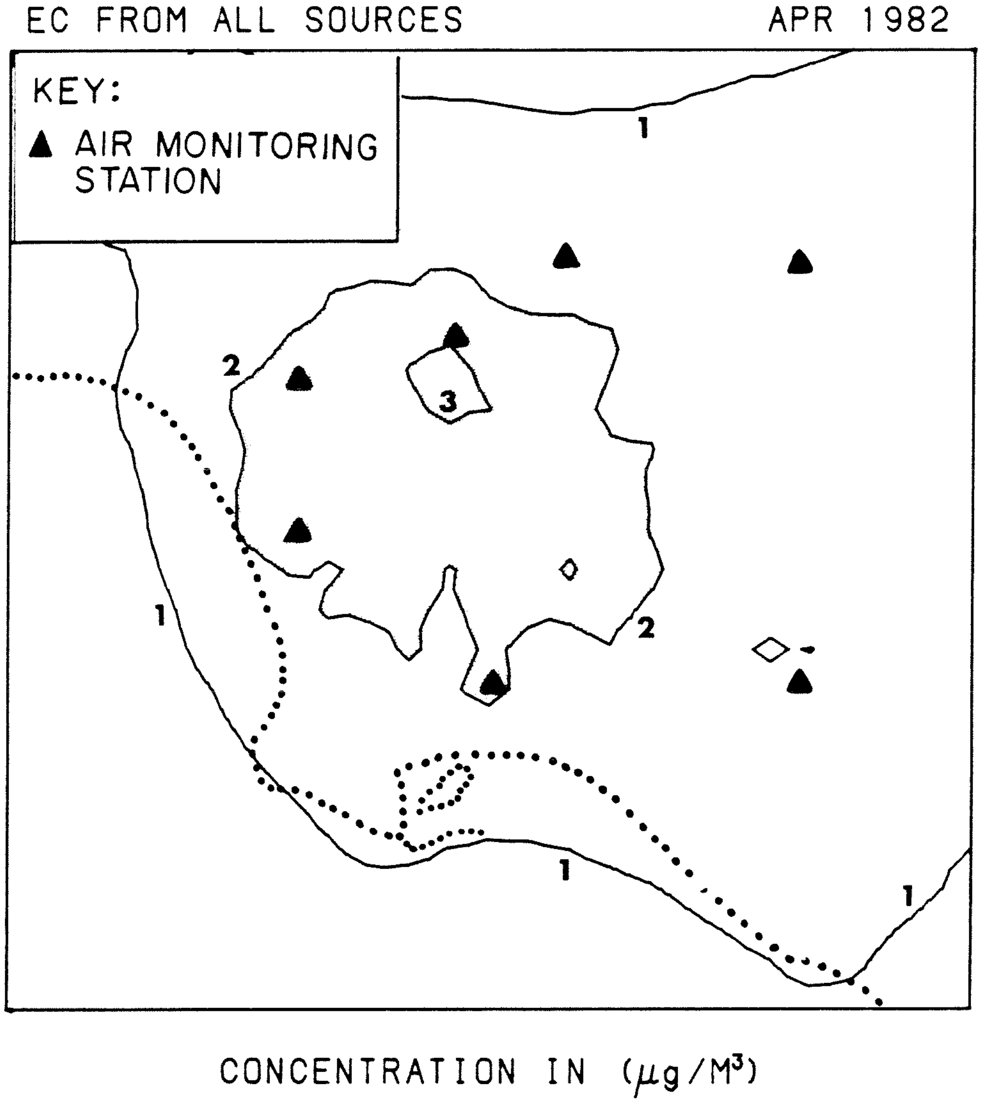


Figure 4.28 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--April 1982.

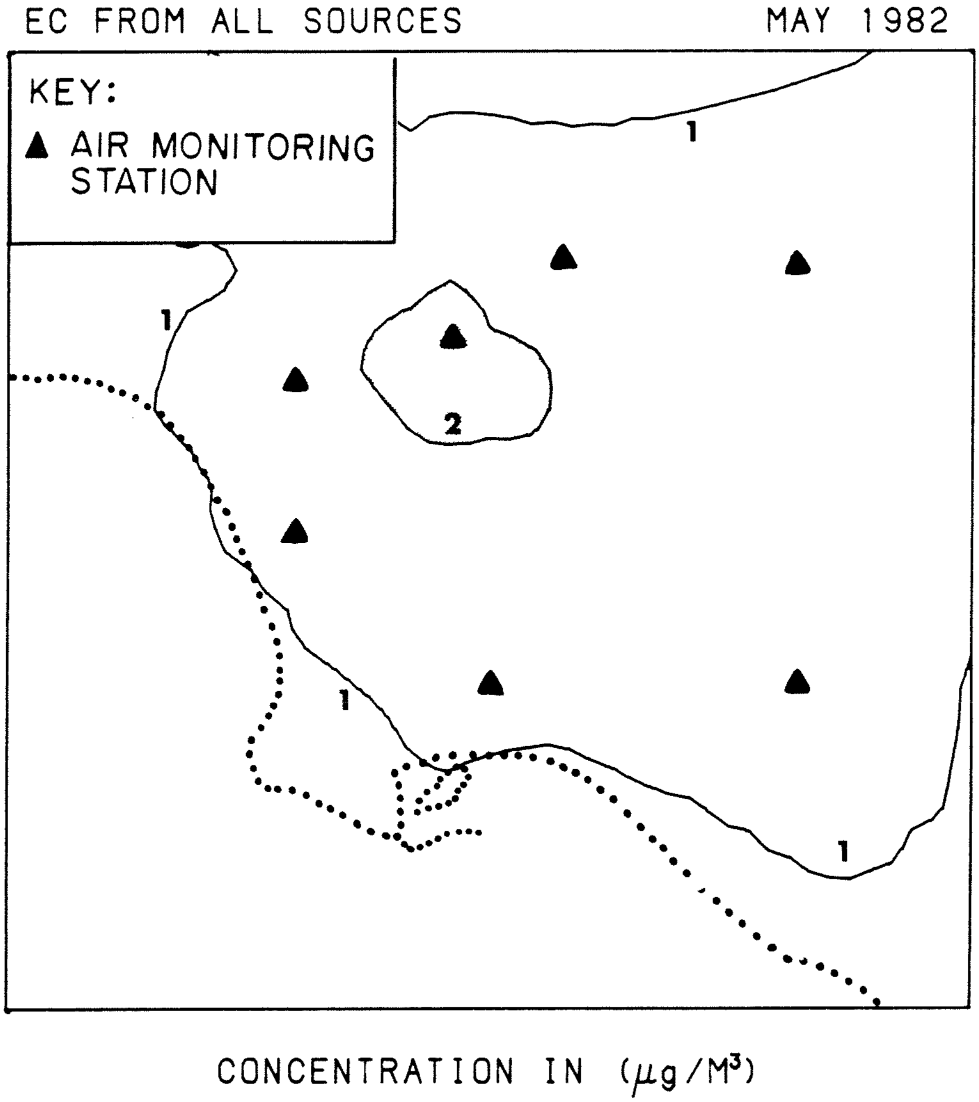


Figure 4.29 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--May 1982.

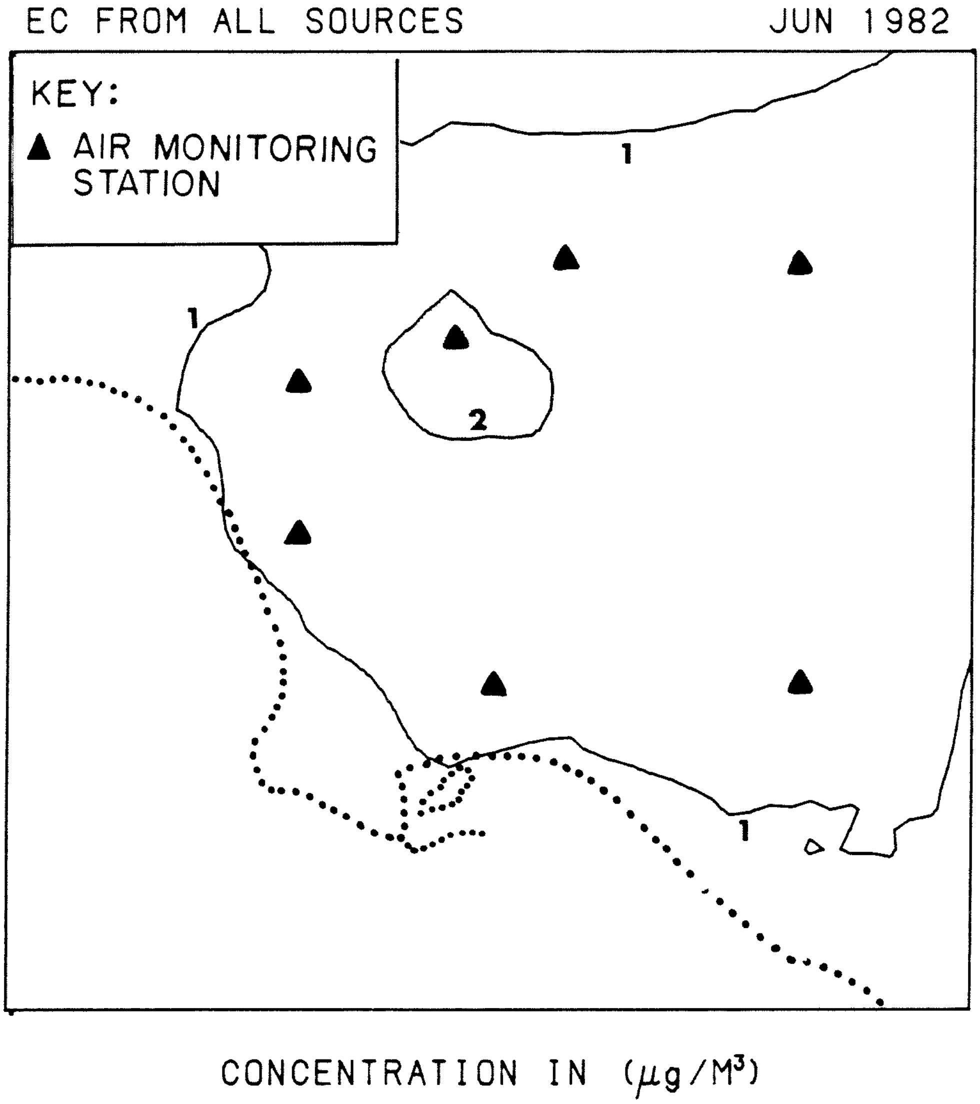


Figure 4.30 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--June 1982.

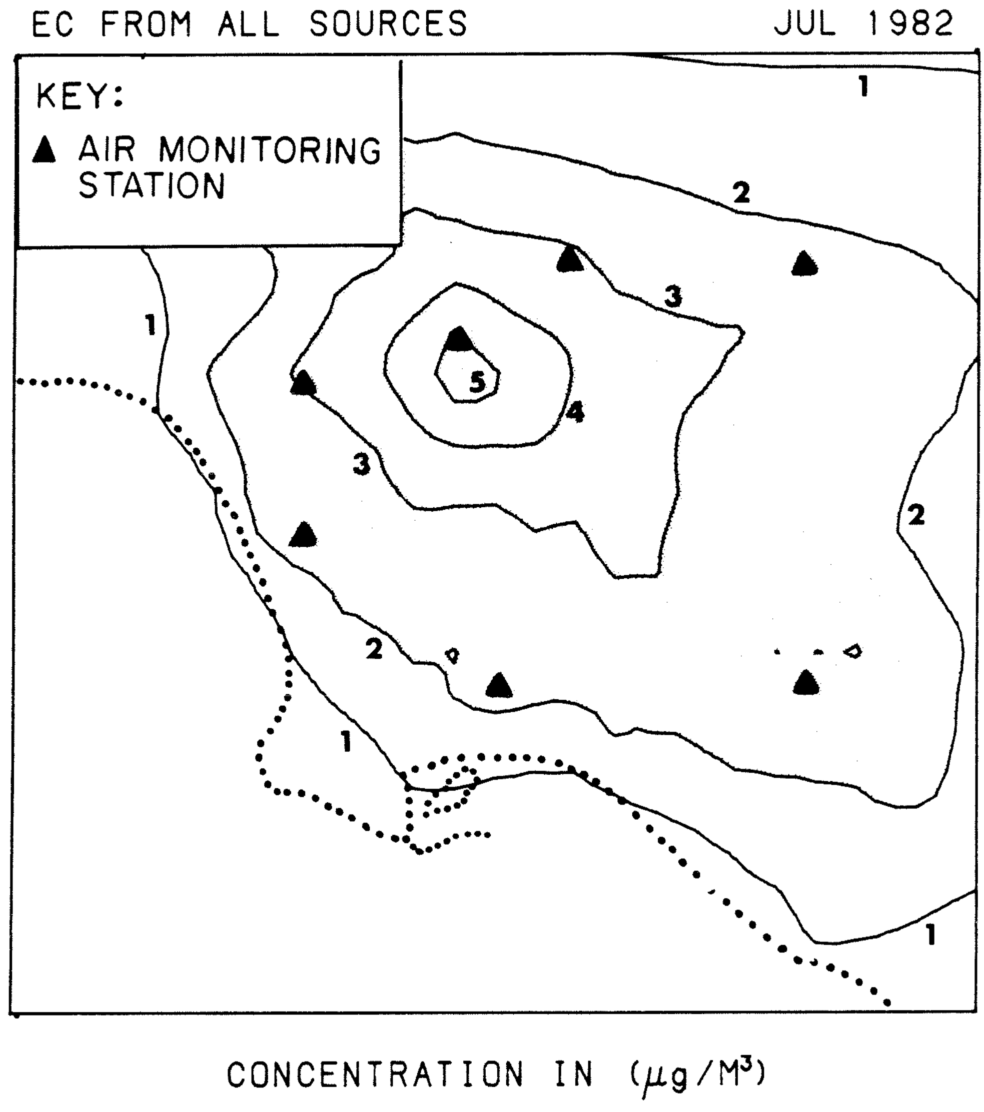


Figure 4.31 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation-- July 1982.

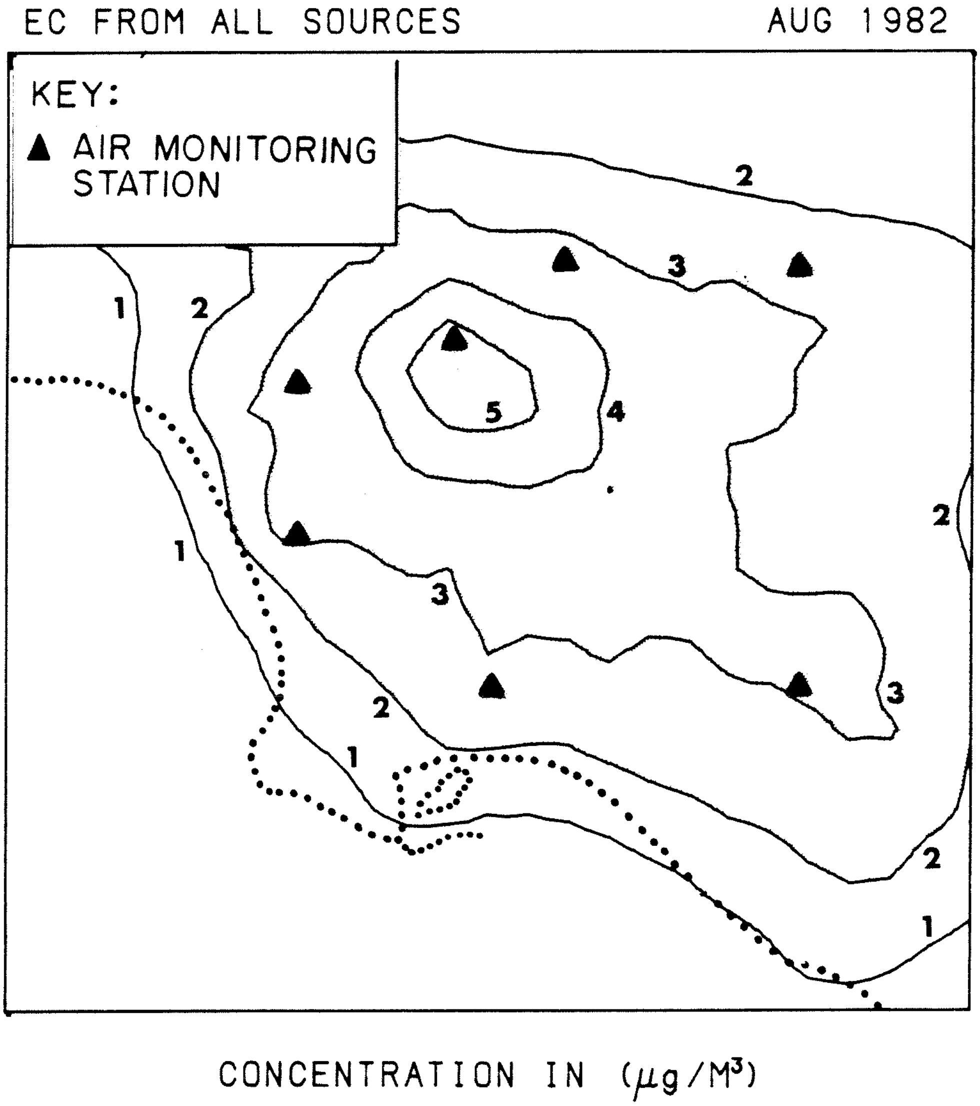


Figure 4.32 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--August 1982.

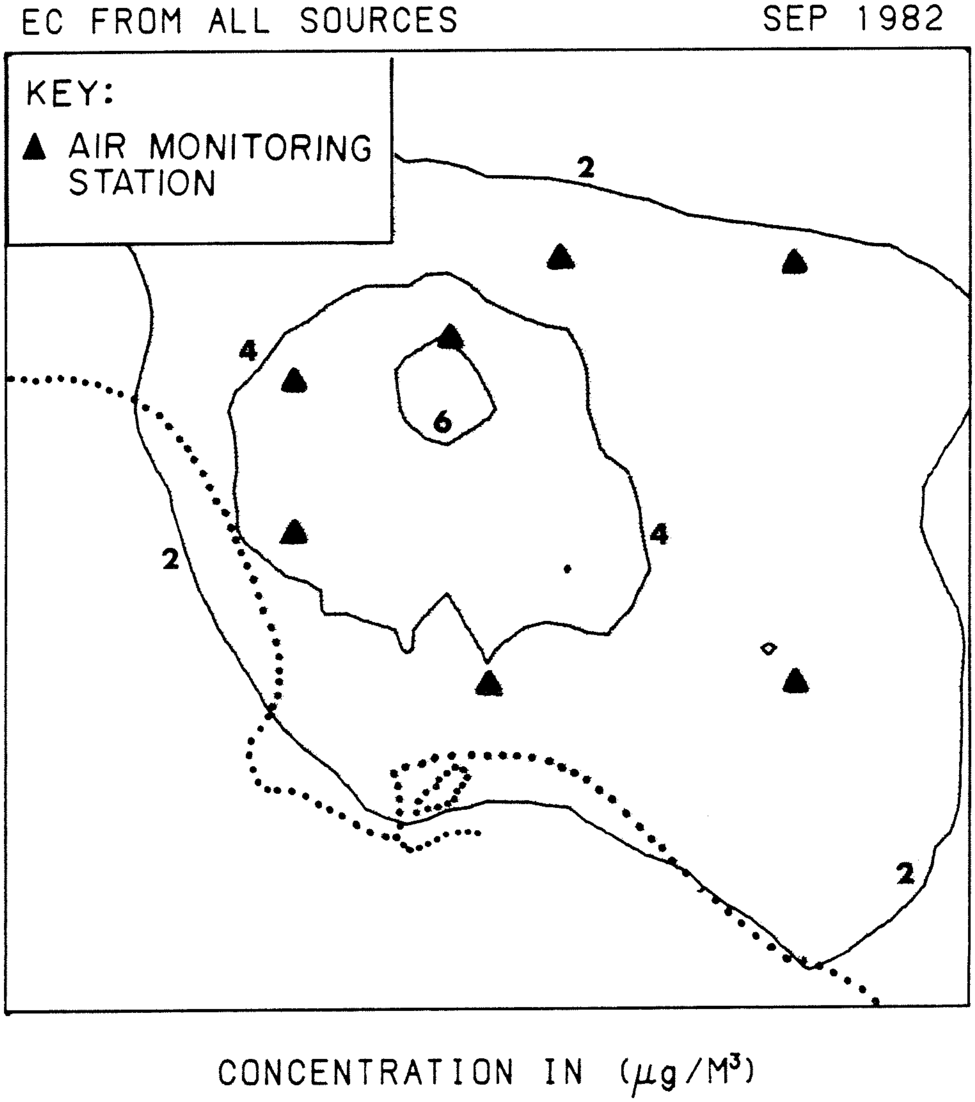


Figure 4.33 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--September 1982.

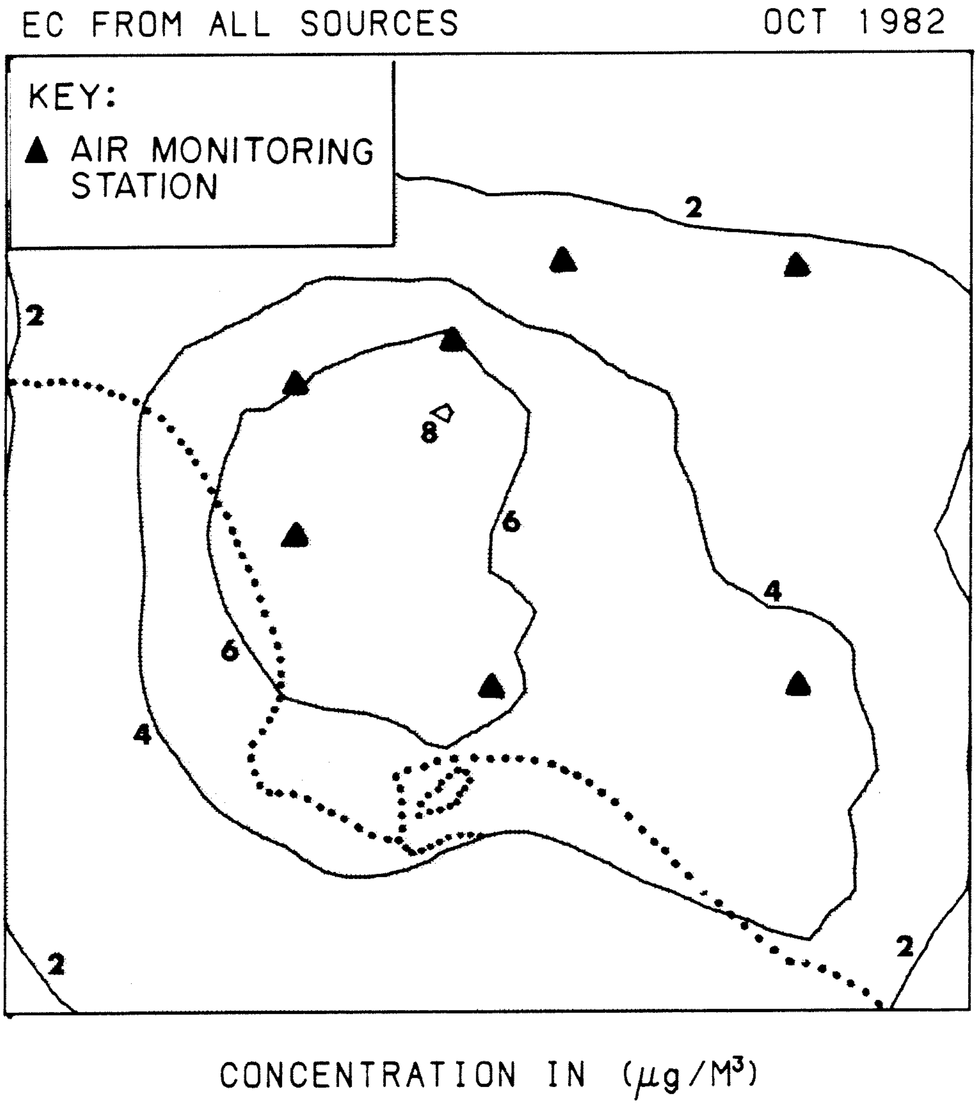


Figure 4.34 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--October 1982.

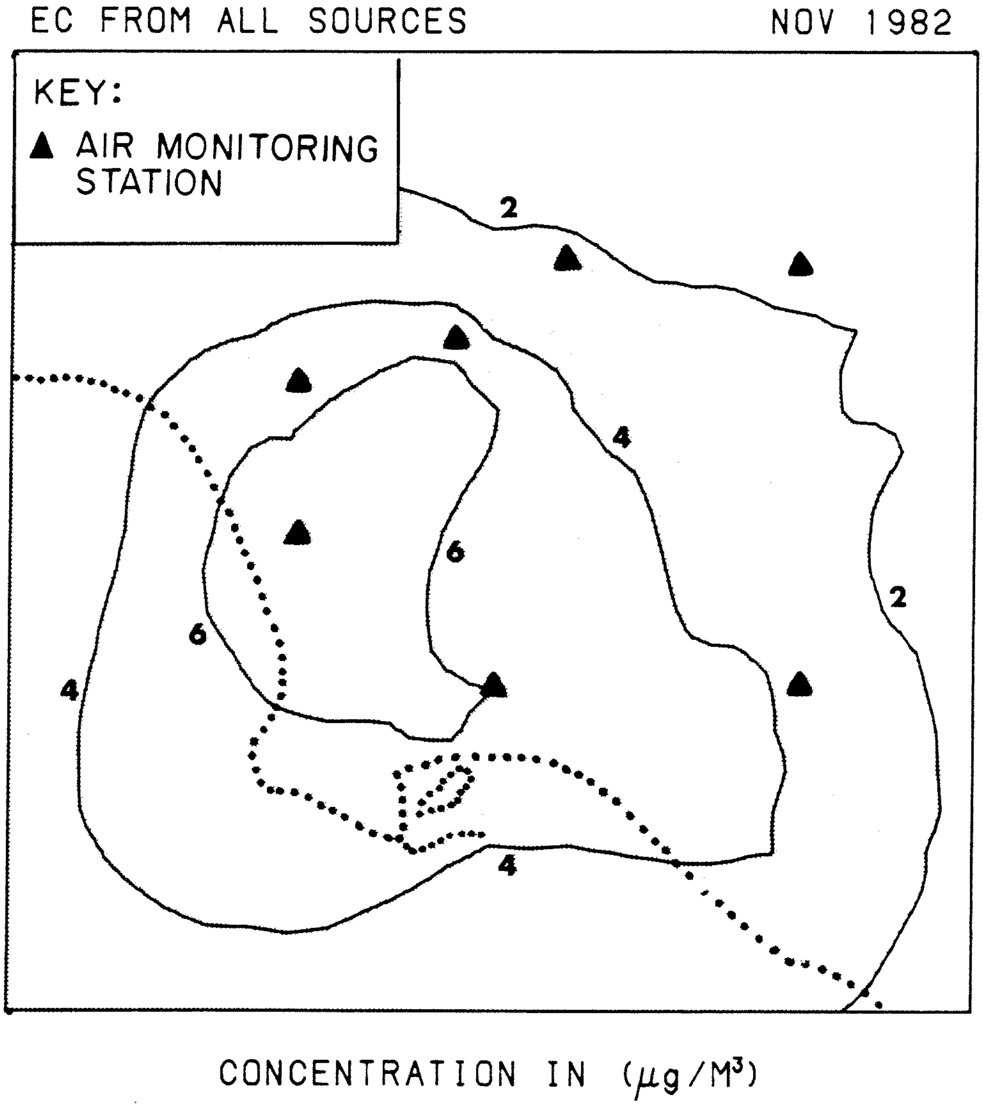


Figure 4.35 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--November 1982.

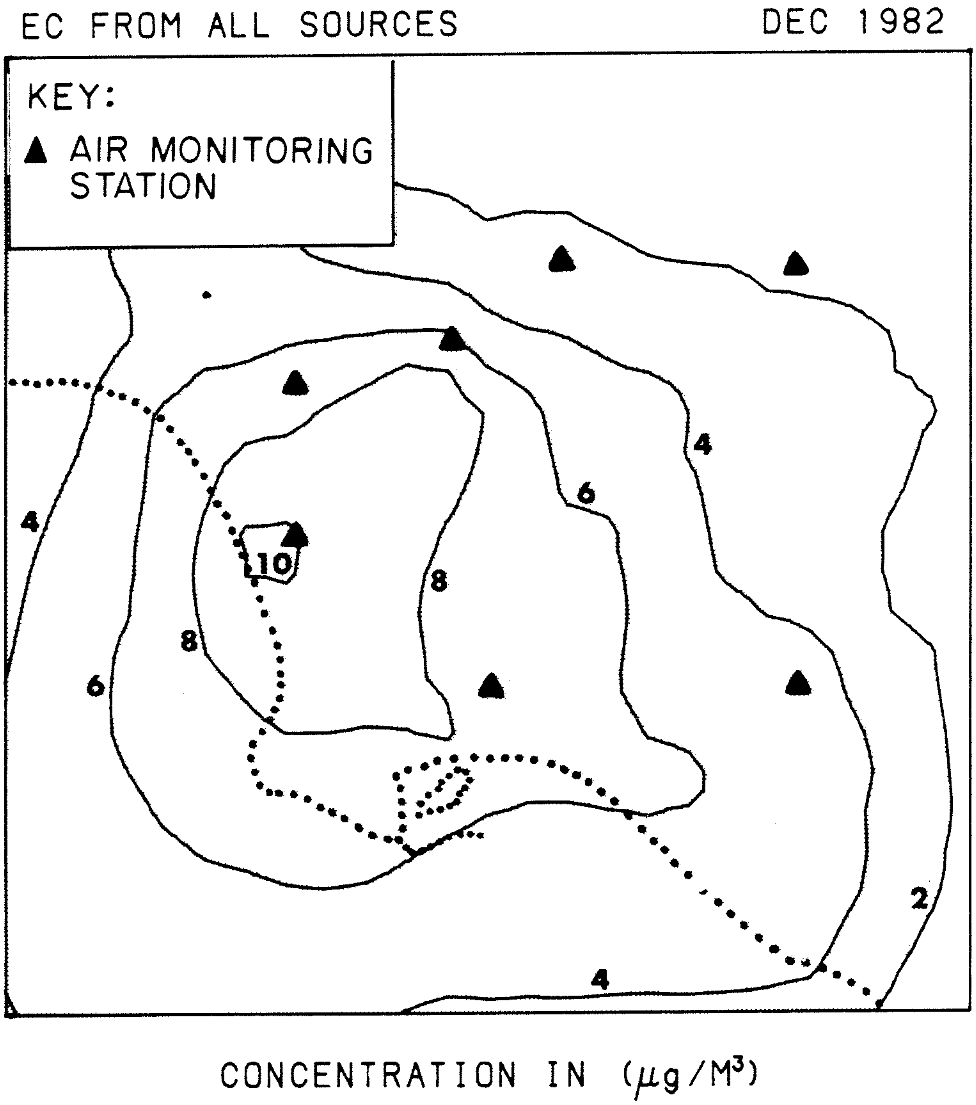


Figure 4.36 Monthly average fine elemental carbon concentration isopleths computed by the air quality model simulation--December 1982.

emissions shifts toward the southwest. By October, peak monthly averaged elemental carbon concentrations reach 8 $\mu g/m^3$ while seaward transport causes contours to extend off-grid to the southwest. This feature becomes more pronounced in November and December. In December, peak concentrations are predicted to be over 10 $\mu g/m^3$ in western Los Angeles County near the coast. The peak predicted and observed monthly average elemental carbon concentration value at any monitoring site occurs at Lennox in December 1982. Contours of high concentration extend out over the ocean.

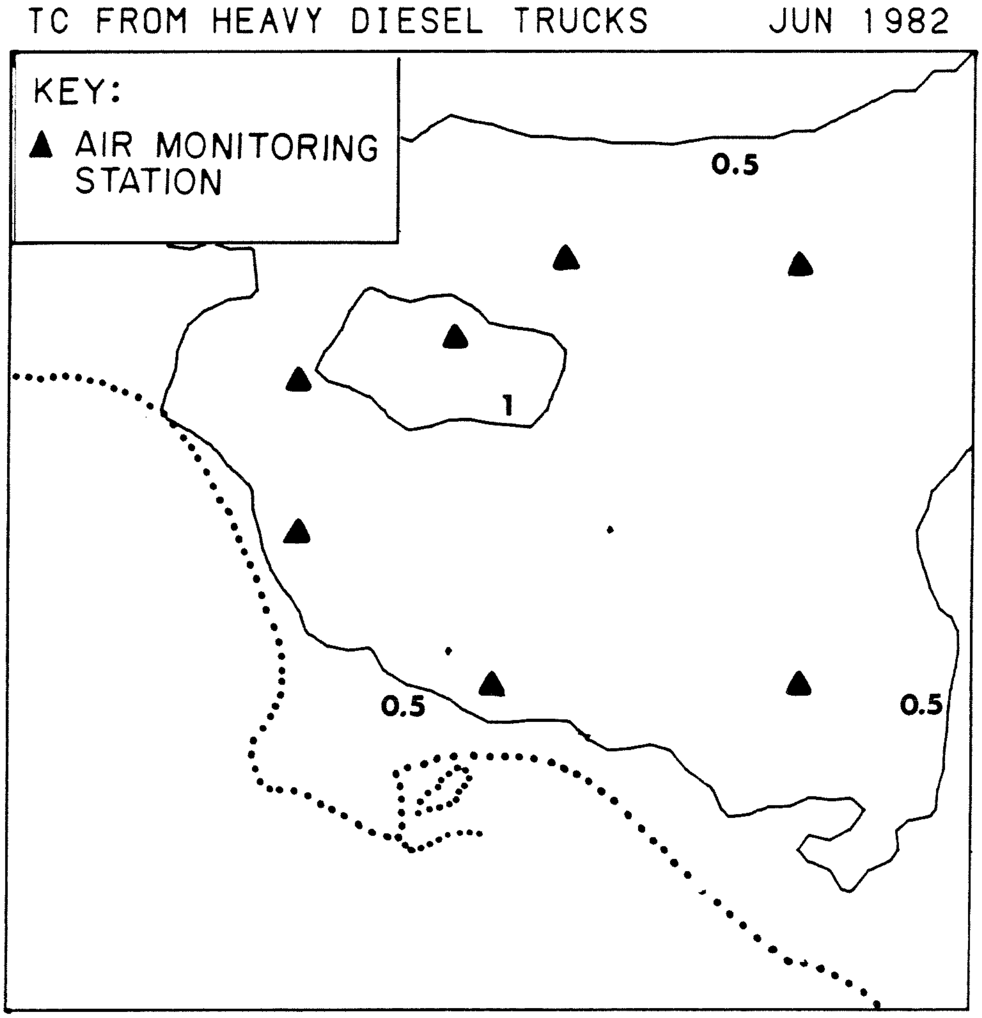
The geographic region affected by elemental carbon concentrations in excess of 2 $\mu g/m^3$ during each month is represented by the shaded area in Figures 4.25 through 4.36. This shaded area covers almost the entire 50X50-mile grid, with the exception of the northeast and east, during the months of October through January. In February, the turning of the general direction of transport has begun, and by April the shaded region has shrunk considerably. In June, minimum monthly average concentrations of elemental carbon are reached. The following months show a larger region being affected by elemental carbon concentrations greater than 2 $\mu g/m^3$; however, the region extends much farther inland than in winter months. By September, the shaded region appears to be turning toward the southwest and includes most of Orange County and the Los Angeles harbor area.

4.3.5 Source Class Contributions to Atmospheric Fine Carbon Particle Concentrations

The air quality model computes the contribution to pollutant loadings from each source type separately. Because the spatial distribution of emissions in the modeling region is different for each source type, the resulting contribution to air quality from each source type varies by location. Other characteristics of emission sources that vary between source types, such as effective stack height and diurnal cycle of release, also add to the disparity between source types with respect to the contribution to resulting air quality.

Contour plots of individual source class contributions to carbon particle air quality can be examined to further understand the impact on air quality from each source type. The increment to monthly average fine total carbon concentrations in June 1982 is shown in Figures 4.37 and 4.38 for diesel trucks and for petroleum refinery fuel burning. Contour plots showing the contribution to fine total carbon concentrations in December 1982 from these same two source types are displayed in Figures 4.39 and 4.40.

Emissions from heavy diesel trucks (air quality model source class no. 5; see Table D.38) are widespread throughout the Los Angeles air basin. All locations in the modeling region are affected to some extent by this large area source, emissions of which were assumed to be constant from month to month during 1982. In June, the effect is felt throughout the central and eastern portion of the modeling grid, with the peak contribution of 1.25 $\mu g/m^3$ near downtown Los Angeles.



CONCENTRATION IN ($\mu g/M^3$)

Figure 4.37 Fine primary total carbon air quality increment due to heavy diesel trucks--June 1982.

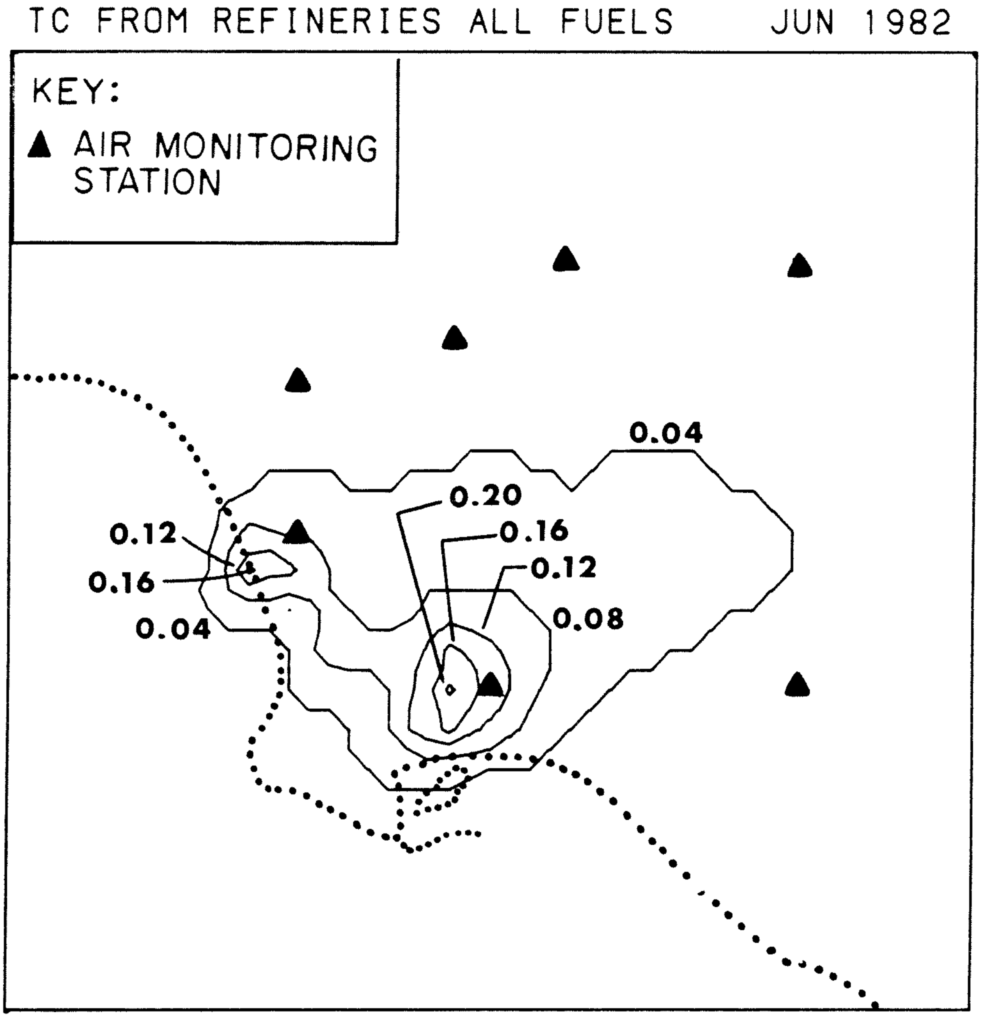


Figure 4.38 Fine primary total carbon air quality increment due to petroleum refinery fuel combustion--June 1982.

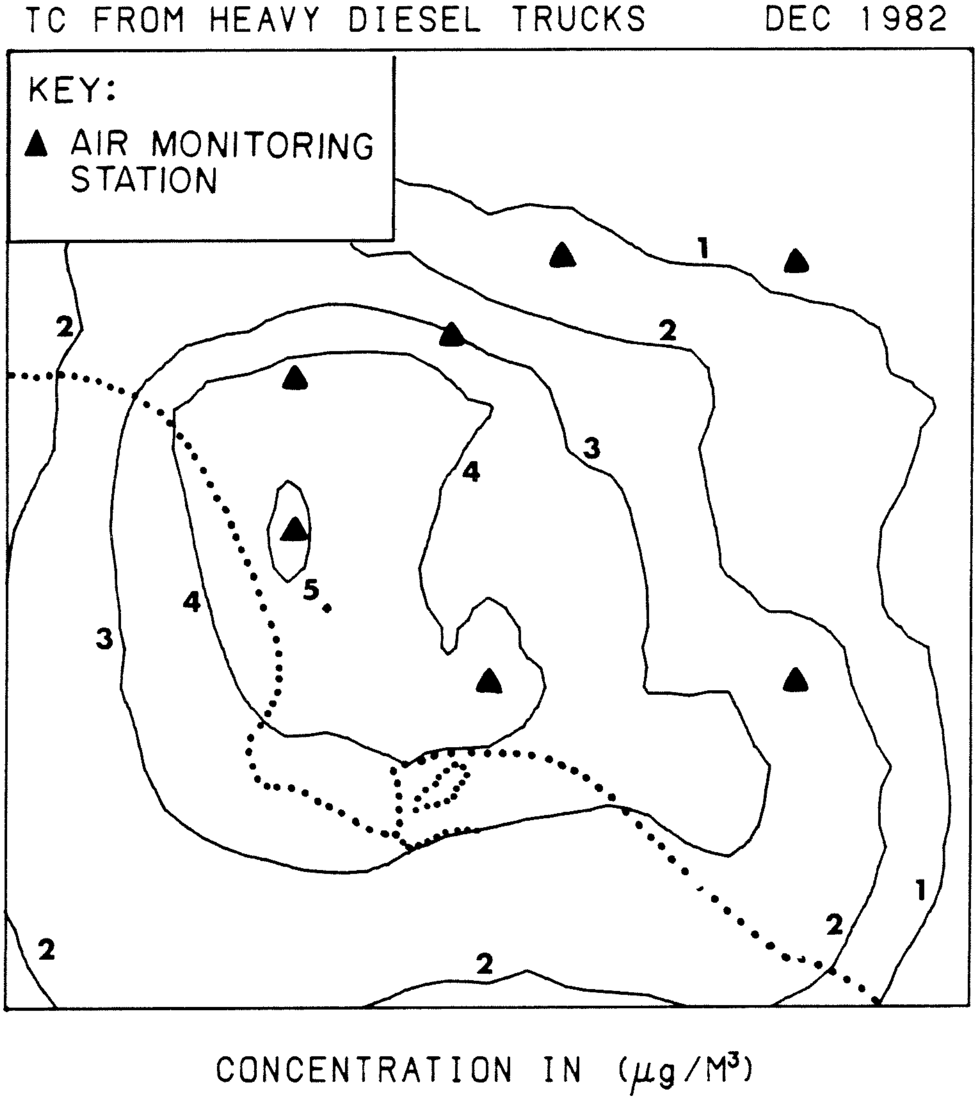


Figure 4.39 Fine primary total carbon air quality increment due to heavy diesel trucks--December 1982.

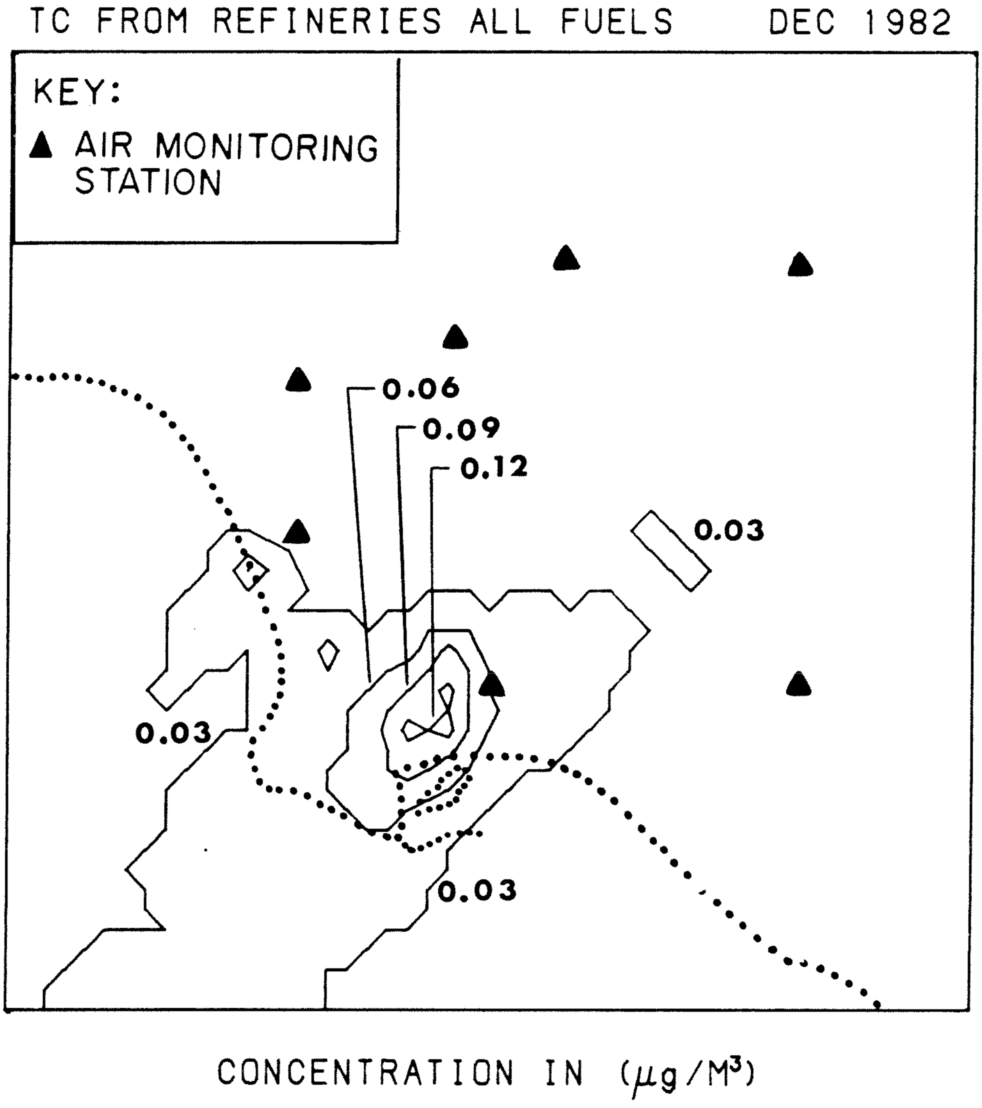


Figure 4.40 Fine primary total carbon air quality increment due to petroleum refinery fuel combustion--December 1982.

In December, the magnitude of total carbon concentrations due to heavy diesel trucks is much greater, with a peak increment of 5.23 $\mu g/m^3$ near Lennox. In winter months, predominant winds are from the northeast, thereby causing the areas of greatest impact to be the western portion of Los Angeles County and northern Orange County. Since this source type is the largest single source of total carbon emissions in the air basin, pollutant concentrations are largely affected by contributions from heavy diesel trucks. The contour plots for monthly averaged total carbon particulate concentrations from all sources in Figures 4.41 and 4.42 strongly resemble the contour plots representing the contribution to total carbon concentrations from heavy diesel trucks shown in Figure 4.37 and 4.39.

Figures 4.38 and 4.40 show the contribution to total carbon concentrations from fuel burning at refineries in June and December, respectively. Note that the magnitude of the contribution is very low, even in December. Refinery operations are located in the southwest of Los Angeles County, mostly near Long Beach, with other refineries located in Torrance and at El Segundo near Lennox. Overall transport of emissions from fuel combustion at refineries is offshore, towards the southwest, in December (Figure 4.40) and inland, towards the northeast, in June (Figure 4.38).

In Figures 4.7b through 4.13b and 4.15b through 4.21b, model-computed concentrations are divided into contributions from eight major source groups plus background concentrations at each of the monitoring locations. The spatial distribution of emissions is

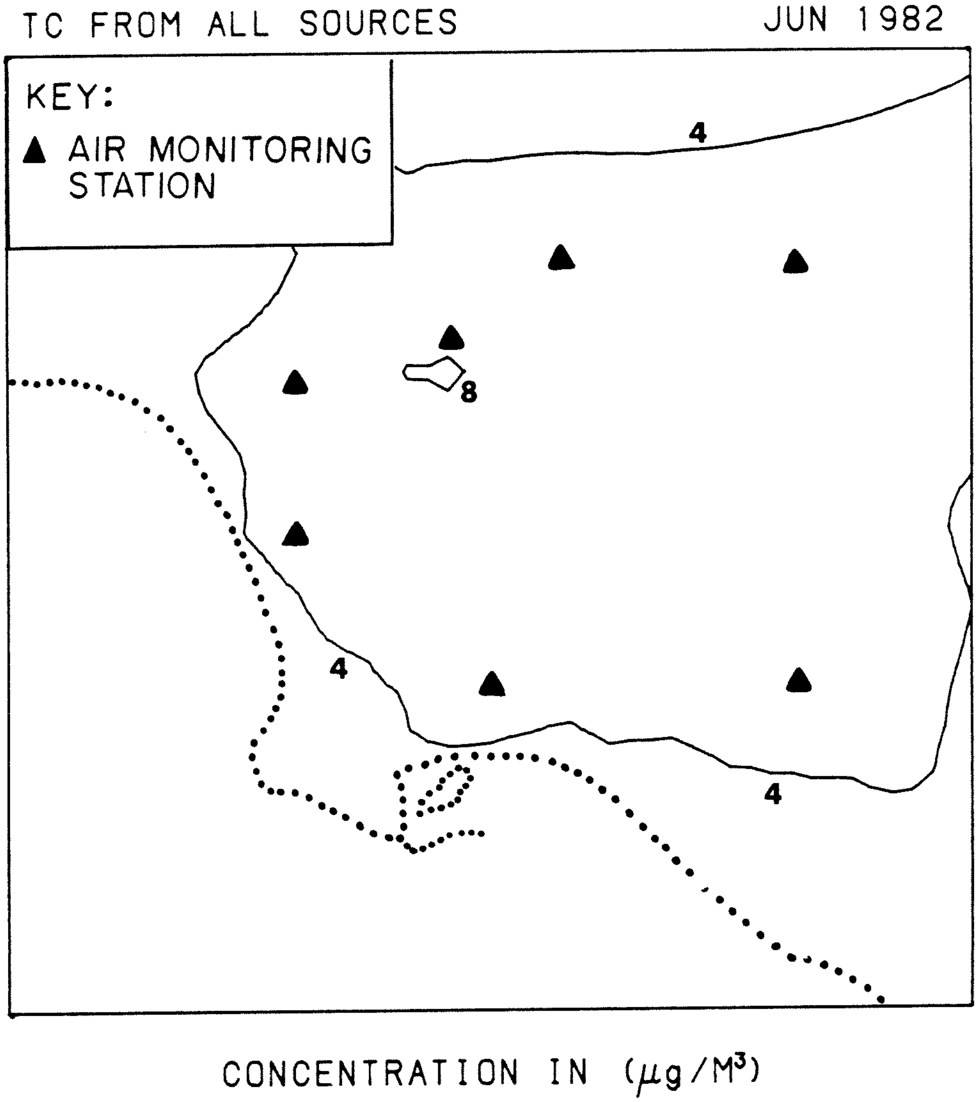


Figure 4.41 Monthly average fine primary total carbon concentration isopleths computed by the air quality model simulation--June 1982.

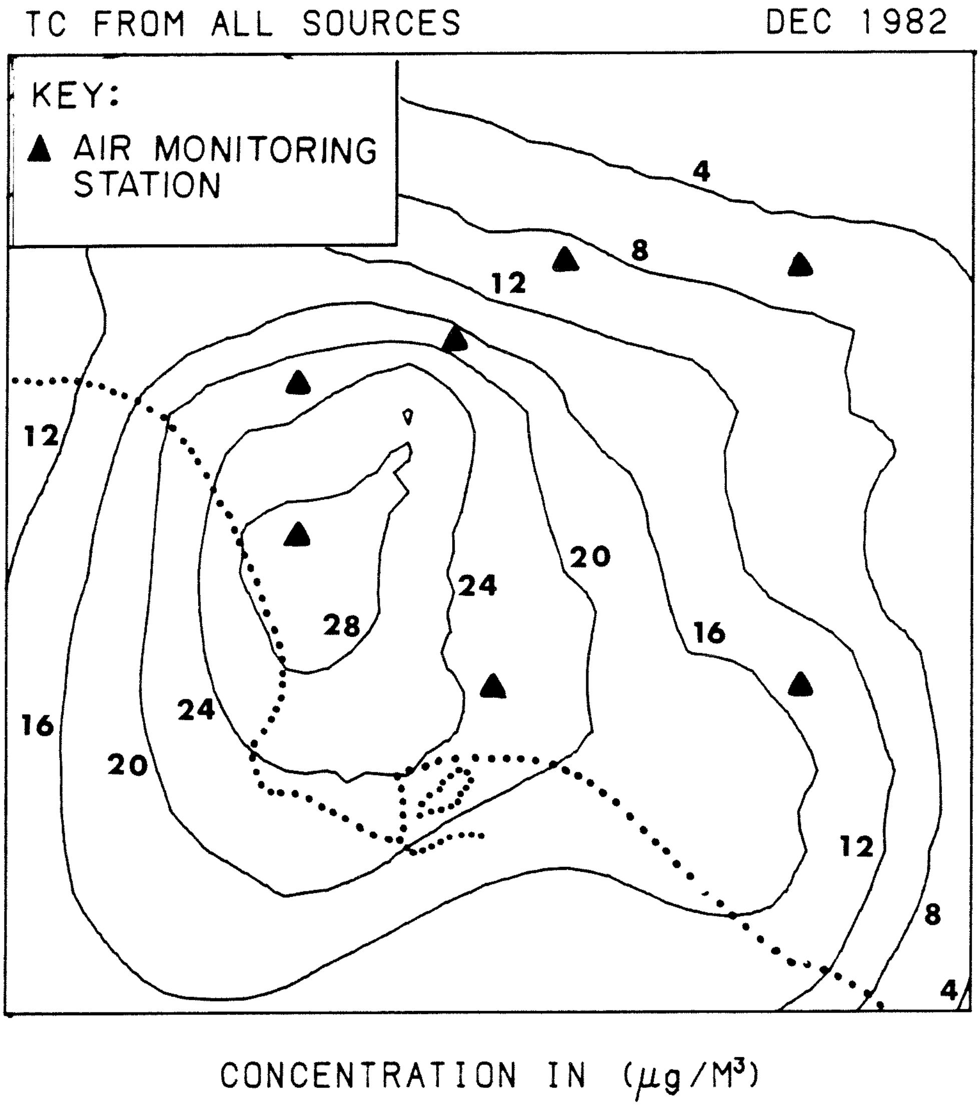


Figure 4.42 Monthly average fine primary total carbon concentration isopleths computed by the air quality model simulation--December 1982.

different for each source group. Hence, the relative importance of each source class varies by location.

As an extreme example, one may examine the contribution of aircraft emissions to atmospheric carbon particle concentrations. There is very little contribution at all sites except Lennox, which is near the Los Angeles International Airport. At Lennox, aircraft emissions are an important contributor, especially to elemental carbon concentrations (see Figure 4.7b).

At all stations, the largest single contribution to elemental carbon concentrations is due to emissions from diesel highway vehicles. This source class is responsible for between 40% to 50% of the elemental carbon concentrations in most months at most stations. At West Los Angeles, the contribution from highway diesels is near 60% for the later months of 1982. Other sources of elemental carbon emissions that contributed to a lesser extent were gasoline-powered vehicles and non-highway diesel fuel applications. These three mobile source classes were responsible for the overwhelming majority of elemental carbon concentrations at all sites.

On the other hand, total carbon concentrations are made up from contributions from a large number of varied source classes. The mobile sources, which were responsible for the majority of elemental carbon concentrations, are large contributors to fine total carbon particulate concentrations as well. However, there are other source classes, such as charcoal broilers (within the fugitive combustion source category), which do not emit much elemental carbon but do emit particulate organic carbon and, therefore, contribute to the total carbon burden.

The sources responsible for pollutant concentrations have a direct bearing on the choice of an effective strategy for pollution control. If control of total carbon mass concentration is desired, then measures aimed at reducing emissions from many different sources must be considered. Diesel vehicle exhaust alone contributes the majority of the elemental carbon concentrations in Los Angeles. Therefore, if an effective control strategy for elemental carbon concentrations is sought, it must necessarily include measures which reduce particulate emissions from combustion of diesel fuel.

4.4 Summary

The Lagrangian air quality model, developed in Chapter 3, was applied to the task of predicting 1982 monthly average carbonaceous particulate concentrations in the Los Angeles air basin. An extensive fine particulate emissions inventory was assembled for the Los Angeles air basin. Other data requirements (e.g., meteorological) were outlined and satisfied. The model was employed to predict monthly average fine primary total carbon and fine elemental carbon concentrations at seven receptor locations that were monitored during 1982.

Concentration predictions were compared with observations of concentrations from the air monitoring network described in Chapter 2. The model appears to be a very good predictor of monthly average fine elemental carbon and total carbon particle concentrations. The model predicted seasonal trends that were very similar to those observed at most locations, and the correlation between predicted and observed monthly average concentrations was very high.

The model is accurate at predicting the magnitude and location of peak concentrations, which were generally at Los Angeles and Lennox. Concentration predictions may be improved in areas far from downtown Los Angeles (e.g., Azusa) by utilizing a more sophisticated wind field in the horizontal transport calculation.

The model, after having been validated, was used to determine source class contributions to both fine primary total carbon and fine elemental carbon concentrations at the seven receptor locations. These source-to-receptor transfer relationships may be used to predict the long-term average pollutant concentrations that would result from a different set of emission source strengths. Changes in emission strength can occur as a result of control measures being applied to a number of the source classes. Therefore, the model results may be used to determine the effect of strategies for control of fine carbonaceous particulate concentrations. This useful application of the modeling exercise is demonstrated in Chapter 5.

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CHAPTER 5

OPTIMAL STRATEGIES FOR THE CONTROL OF FINE PRIMARY PARTICULATE CARBON AIR QUALITY

5.1 Introduction

In the previous chapter, a Lagrangian air quality model was applied to the task of predicting monthly average fine primary particulate carbon concentrations in the Los Angeles area. Results from the model calculation may be combined with information on emission control measures and their costs in order to determine the optimal strategy for attaining any desired level of improved aerosol carbon air quality. The air quality model predicts the contribution to pollutant concentrations at seven monitoring sites from many different source types. The model's calculation scheme is linear in pollutant emissions. In other words, the model-computed contribution from any single source type is proportional to the basin-wide level of emissions from that source type. Therefore, a linear programming algorithm may be applied to determine the least costly combination of control measures that would achieve a given air quality goal simultaneously at the seven monitoring sites.

A linear program consists of an objective to be optimized, in the form of a function to be minimized or maximized, and a set of constraints, which take the form of a set of linear inequalities. The objective in this application is to minimize the cost of applying a set of emission control measures. The most important constraint is that the air quality must improve. It is required that the annual average pollutant concentration be held at below a stated limit at each of the seven monitoring sites. To achieve this air quality goal, a trial set of emission control measures is selected. Results of the air quality model then are used to compute a hypothetical prediction of the 1982 annual average pollutant concentration at each site that would result from the pollutant emissions that remain after the given set of controls has been put in place. If the combination of control measures produces air quality which satisfies the constraints, then the strategy is feasible. The optimal control strategy is the feasible strategy that has the lowest cost.

Linear programming techniques often are used alongside air quality models to determine the least costly air pollution control strategy. Kohn (1970) minimized the cost of reducing basin-wide emissions in St. Louis using a linear rollback emissions to air quality model. Spatially resolved Gaussian plume models that attempt to account for atmospheric transport processes have been employed by researchers, in conjunction with linear programming techniques, to choose the least costly combination of control measures that will result in a required level of air quality improvement (Atkinson and Lewis 1974, Kohn 1974, Teller 1967). Burton and Sanjour (1970) combined a Gaussian plume air quality model with integer programming techniques (that guard against the choice of fractions of a control measure) to select strategies for control of particulate matter and sulfur oxides in Washington, D.C., and Kansas City. Integer programming and linear programming techniques were compared by Gipson, Freas, and Meyer (1975) in case studies of three urban areas. Trijonis et al. (1975) used linear programming techniques to select least costly strategies for particulate matter control based on a non-linear emissions to air quality model that takes into account the secondary formation of particulate matter. Atkinson and Lewis (1974) and many others have indicated that the use of sophisticated air quality models to predict pollutant contributions from sources will result in a large cost savings when addressing the question of air quality control. A review of air quality modeling techniques that have been matched to optimization techniques may be found in Cass and McRae (1981).

In this chapter, a linear programming technique is stated that optimizes the choice of a strategy for regional air pollution control. The technique is applied to the control of fine primary carbonaceous particulate concentrations in the Los Angeles area. Since air quality standards do not exist at present for aerosol carbon species, no single air quality constraint can be considered at this point. Instead, the linear programming exercise can be run repeatedly for a variety of possible air quality objectives. By organizing those results, one can depict the least costly path toward air quality improvement, that is, the sequence in which the control measures are to be applied as air quality constraints are tightened. Optimal strategies for control of fine primary total aerosol carbon concentrations are compared to optimal strategies aimed at controlling fine elemental carbon concentrations. The distinction between these two possible objectives is important. Total carbon control would be favored if reduction in aerosol mass loading is sought, while preferential control of elemental carbon would be favored as part of a strategy aimed at visibility improvement.

5.2 Formulation of the Linear Programming Technique

The control strategy which satisfies a regional air quality goal at the lowest cost can be identified by solving the following minimization problem:

Choose $x_1, x_2, \ldots, x_K$ to minimize:

$$C = \sum_{k=1}^{K} c_k x_k \tag{5.1}$$

Subject to:

$$\sum_{k=1}^{K} \sum_{j=1}^{J} t_{ij}\, r_{jk}\, x_k \geq q_i \qquad i = 1,\ldots,I \tag{5.2}$$

$$\sum_{k=1}^{K} d_{mk}\, x_k \leq s_m \qquad m = 1,\ldots,M \tag{5.3}$$

$$\sum_{k=1}^{K} b_{nk}\, x_k \leq 1 \qquad n = 1,\ldots,N \tag{5.4}$$

$$0 \leq x_k \leq 1 \qquad k = 1,\ldots,K \tag{5.5}$$

where

C is the total annual cost of the emission control strategy (\$/year).

c_k is the cost of utilizing control measure k at all emission sources to which the control measure applies (\$/year).

x_k is the level of application of control measure k. If $x_k = 0$ then control k is not used. If $x_k = 1$ then control k is applied to the maximum possible extent.

t_{ij} is a transfer coefficient from the air quality model which indicates the predicted annual average pollutant concentration increment at monitoring site i contributed by a single source class j ($\mu g/m^3$) at uncontrolled emission levels.

r_{jk} is the fractional reduction in pollutant emissions at source class j resulting from the application of control measure k. It is assumed that the fractional reduction in emissions, if control k is applied, is the same for all sources within single source class j. (Local emission control regulations generally apply uniformly to all sources of the same type in an air basin.)

q_i is the required air quality improvement at site i ($\mu g/m^3$). Note that $q_i = p_i - g$ where p_i is the present pollutant concentration at site i and g is the regional air quality goal.

d_{mk} is the amount of scarce resource m which is required if control measure k is adopted as part of the control strategy.

s_m is the limited supply of scarce resource m which is available for control strategy use.

b_{nk} is a compatibility parameter. The purpose of inequalities (5.4) is to prevent the simultaneous application of two or more incompatible control measures. For example, if control measure α conflicts with control measure β, then the requirement $x_\alpha + x_\beta \leq 1$ would prevent the application of both control measures to the same source. Emission control measures that conflict with one another will be grouped. All control measures k falling in the same group of conflicting controls are assigned values $b_{nk} = 1$; otherwise, $b_{nk} = 0$.

I is the number of air monitoring sites at which the air quality goal must be satisfied.

J is the number of source classes.

K is the number of control measures.

M is the number of different scarce resources required by the set of K control measures.

N is the number of groups of conflicting control measures among the universe of K control measures.

It is desired to solve for the control strategy, $(x_1, x_2, \ldots, x_K)$ which will minimize the overall cost, as shown in equation (5.1), while meeting the required air quality goal as expressed in the inequalities of (5.2). Constraints (5.3) are used to limit the consumption of resources, each of which is needed by one or more of the control measures. The inequalities of (5.4) are used to prevent the simultaneous application of conflicting control measures and the inequalities of (5.5) require that each x_k lie in the interval between 0 and 1 (between zero use and 100% application).

The minimization problem stated in (5.1) through (5.5) may be rewritten using matrices and vectors as follows:

Minimize

$$C = \underset{\sim}{c}^T \underset{\sim}{x} \qquad (5.1')$$

subject to:

$$TR\underset{\sim}{x} \geq \underset{\sim}{q} \qquad (5.2')$$

$$D\underset{\sim}{x} \leq \underset{\sim}{s} \qquad (5.3')$$

$$B\underset{\sim}{x} \leq \underset{\sim}{e} \qquad (5.4')$$

$$\underset{\sim}{x} \geq \underset{\sim}{0} \qquad (5.5')$$

where

$\underset{\sim}{c}, \underset{\sim}{x}, \underset{\sim}{q}$, and $\underset{\sim}{s}$	are vectors whose elements are the values c_k, x_k, q_k, and s_m, respectively, as described in (5.1) through (5.5).
T, R, and D	are matrices whose elements are the values t_{ij}, r_{jk} and d_{mk}, respectively, as described in (5.1) through (5.5).
B	serves two purposes. As in (5.4), it requires that $x_\alpha + x_\beta + \ldots + x_\gamma \leq 1$ for controls α, β, . . ., γ which cannot be applied simultaneously. Since all $x_k \geq 0$, this is a stricter constraint than each of $x_\alpha \leq 1, x_\beta \leq 1, \ldots + x_\gamma \leq 1$ which are required by (5.5). Therefore, the constraints $x_k \leq 1$ of (5.5) may be incorporated into the matrix B in the following manner. B is constructed by starting with the identity matrix I (k X k), followed by adding a row for each conflict group n, such that $b_{nk} = 1$ if control k is in the group (0 otherwise), and then finally removing each row k of the original identity matrix if control k was specified in any conflict group. Therefore a 1 should appear at least once in each column of B.

$\underset{\sim}{e}$ is a vector whose elements, e_n, all equal 1, i.e., $e^T = (1,1,\ldots,1)$.

$\underset{\sim}{0}$ is a vector whose elements are all zero, i.e., $\underset{\sim}{0}^T = (0,0,\ldots,0)$.

The problem stated in (5.1) through (5.5) or in (5.1′) through (5.5′) may be solved directly by linear programming techniques. Linear programming is the study of systems of linear inequalities. In general, any equality, $x = a$, may be represented by two inequalities, $x \geq a$ and $x \leq a$. Therefore linear algebra, which is the study of systems of linear equalities, is merely a special case of linear programming. In 1902, Julius Farkas proved an important theoretical result concerning the existence of solutions to linear programming problems. However, not until the computer age began did efficient methods of finding solutions arrive. In 1951, George Dantzig's simplex method appeared (Dantzig 1951, Franklin 1980). The simplex method enables one to find the optimal feasible solution (if a feasible solution exists) to the following general problem (stated in canonical form):

$$A\underset{\sim}{x} = \underset{\sim}{b}, \quad \underset{\sim}{x} \geq \underset{\sim}{0}, \quad \underset{\sim}{c}^T\underset{\sim}{x} = \min \tag{5.6}$$

The simplex algorithm may be found in any introductory text on linear programming (e.g., Gale [1960] or Franklin [1980]).

It remains to convert the system of (5.1′) through (5.5′) into the form of the canonical minimization problem (5.6). An inequality

$x \leq a$ may be transformed into an equality by introducing a slack variable z. Then $x + z = a$ together with $z \geq 0$ implies $x \leq a$. Introducing slack variables to the set of inequalities (5.2′) through (5.5′) yields:

$$(-TR)\underset{\sim}{x} + \underset{\sim}{z}^{(1)} = -\underset{\sim}{q} \tag{5.7}$$

$$D\underset{\sim}{x} + \underset{\sim}{z}^{(2)} = \underset{\sim}{s} \tag{5.8}$$

$$B\underset{\sim}{x} + \underset{\sim}{z}^{(3)} = \underset{\sim}{e} \tag{5.9}$$

$$\underset{\sim}{x} \geq 0, \ \underset{\sim}{z} \geq 0 \tag{5.10}$$

The matrix equations (5.7) through (5.9) may be rewritten as one partitioned matrix equation:

$$\begin{bmatrix} -TR & \\ D & I \\ B & \end{bmatrix} \begin{pmatrix} \underset{\sim}{x} \\ \underset{\sim}{z} \end{pmatrix} = \begin{bmatrix} -\underset{\sim}{q} \\ \underset{\sim}{s} \\ \underset{\sim}{e} \end{bmatrix} \tag{5.11}$$

and (5.10) becomes:

$$\begin{pmatrix} \underset{\sim}{x} \\ \underset{\sim}{z} \end{pmatrix} \geq \begin{pmatrix} \underset{\sim}{0} \\ \underset{\sim}{0} \end{pmatrix} \tag{5.12}$$

where

$$\underset{\sim}{z}^{T} = (\underset{\sim}{z}^{(1)T}, \underset{\sim}{z}^{(2)T}, \underset{\sim}{z}^{(3)T})$$

If equation (5.1′) is restated to minimize

$$C = (\underset{\sim}{c}^T, \underset{\sim}{0}^T) \begin{pmatrix} \underset{\sim}{x} \\ \underset{\sim}{z} \end{pmatrix} \qquad (5.13)$$

then (5.11) through (5.13) are in the canonical form of (5.6) and are equivalent to the minimization problem presented in (5.1′) through (5.5′). It now requires only the application of the simplex method to determine if there exists a strategy $\underset{\sim}{x}$ which satisfies (5.11) and (5.12) (feasibility), and if there is, to compute the optimal control strategy, $\underset{\sim}{x}$.

5.3 Application of the Linear Programming Technique for Control of Fine Primary Carbonaceous Particulate Air Quality in the Los Angeles Area

5.3.1 Introduction

In this section, the linear programming technique discussed in Section 5.2 is applied to the task of computing the optimal strategy for controlling fine primary carbonaceous particulate air quality in the Los Angeles area. The calculation is performed using 1982 emissions data extracted from Chapter 4 of this work.

If a given set of emission control measures, which were not being used in 1982, had been in place during that year, then an improvement in air quality would have resulted. A prediction of what the 1982 air quality would have been, in the presence of an additional set of emission controls, may be made by using the source class contributions to 1982 fine primary carbonaceous particulate concentrations computed by the air quality model in Chapter 4. A feasible set of emission control measures is sought, which would have resulted in a desired level of air quality improvement at a minimum cost.

Solving the fine particulate air quality problem in Los Angeles is difficult. In the last few decades, control devices have been installed at almost all industrial process sources that emit particulate matter. Despite these efforts, fine particulate matter concentrations in ambient air remain high. At downtown Los Angeles the 1982 annual average fine particulate matter concentration was measured to be 32.5 $\mu g/m^3$ and the peak monthly averaged fine particulate concentration was 58.2 $\mu g/m^3$ during December 1982. About 40% of the fine particulate was observed to be carbonaceous (see Chapter 2). The regional Air Quality Management Plan for the Los Angeles area (South Coast Air Quality Management District, 1982) does not offer much hope for future particulate air quality improvement. It contains only a few control measures for particulate emissions, and the emissions reductions are small.

In order to solve an air pollution problem, those sources responsible for the problem must be identified. In Chapter 4, Section 4.3.5, it was discovered that highway-related emissions are responsible for the majority of the fine carbonaceous particulate matter concentrations in the Los Angeles area. Therefore, it is necessary to control these sources if a substantial improvement in fine carbonaceous particulate air quality is to be achieved.

5.3.2 Data Requirements

In order to solve the linear program of (5.11) through (5.13) to determine fine carbon particle control strategies, the matrices T, R, D and B and the corresponding requirement vectors $\underset{\sim}{q}$ and $\underset{\sim}{s}$ must be specified. Also the unit control cost vector, $\underset{\sim}{c}$, must be assembled.

The source to receptor transfer coefficient matrix, T, is constructed from the results of the air quality model calculation which was presented in Chapter 4. Each t_{ij} represents the predicted annual average pollutant concentration increment ($\mu g/m^3$) at site i due to emissions from source type j (at uncontrolled 1982 emission levels). Model concentration predictions made at seven air monitoring station sites resulting from emissions from 74 source types will be employed in the linear programming calculation (i.e. $I = 7$, $J = 74$). The increments to both fine primary total carbon and fine elemental carbon concentrations at each of these air monitoring sites from each source type are presented in Appendix F. Model results from all months of 1982 were averaged, weighted by the number of days in each month, to arrive at the predicted contributions to annual average fine primary total carbon and fine elemental carbon concentrations from each source.

Potential control measures for fine particulate carbon were inventoried, resulting in a list of 33 control measures (i.e., K =

33). Measures were sought which are technically feasible and the existence of which are reasonably certain. Generally, only control measures which involve some technological change were considered during this study, for example: control devices which are applied to emissions sources or the switching of grades of fuel. Control measures which require a political or social restructuring were not considered, for example: the changing of driving habits.

Detailed estimates of the costs and emission reduction capabilities of each of the 33 control measures appear in Appendix D. This information is summarized in Table 5.1. The costs are stated as an equivalent annual cost of operation plus allowance for amortization of capital investments in 1982 dollars per year. Estimation of the costs of control often is difficult. In recent years fuel prices have fluctuated greatly. The ultimate price of a new technology that has, to date, been demonstrated only at the prototype stage often is not known exactly. The price of a control device or resource may change drastically when demand is increased. It should be understood that the purpose of this exercise is to demonstrate the utility of the proposed linear programming calculation procedure, and that the calculations may be rerun when more reliable data on emission control measures and their costs become available.

The linear programming objective function, (5.13), assumes that the cost of a control is proportional to its application level, which may not always hold true. Some control cost functions may be non-linear. A non-linear cost function could be used to replace (5.13);

Table 5.1

Costs and Emissions Reductions of Control Measures Used in This Study

No.	Control Measure	Annual Cost (10^6\$/year)	Fine Carbon Emissions Reductions (T/day) Total Carbon	Fine Carbon Emissions Reductions (T/day) Elemental Carbon	Source Types Affected (a)	Conflicts
D.2	Catalysts on Non-catalyst Autos and Light Trucks	236.352	3.7387	0.7053	non-cat light duty vehicles(3,4)	
D.3	#1 Diesel Fuel Use by Light-duty Diesel Vehicles	4.317	0.2475	0.1896	light duty diesel vehicles(6,7)	D.4,D.5
D.4	Particle Traps on Light-duty Diesel Vehicles	8.148	0.9900	0.7583	light duty diesel vehicles(6,7)	D.3,D.5
D.5	Particle Traps & #1 Diesel Fuel Use for Lt-duty Diesel Vehicles	12.465	1.0395	0.7962	light duty diesel vehicles(6,7)	D.3,D.4
D.7	Catalysts on Non-Catalyst Medium & Heavy Gas Vehicles	66.453	1.1026	0.2080	non-cat medium/heavy vehicles(9,10)	
D.8	#1 Diesel Fuel Use by Heavy-duty Diesel Vehicles	38.523	1.4808	1.1343	heavy diesel vehicles(11)	D.9,D.10
D.9	Particle Traps on Heavy-duty Diesel Vehicles	36.240	6.6637	5.1044	heavy diesel vehicles(11)	D.8,D.10
D.10	Particle Traps & #1 Diesel Fuel for Heavy-duty Diesel Vehicles	74.763	6.8118	5.2178	heavy diesel vehicles(11)	D.8,D.9
D.11	Air Taxi Modification (Towing)	0.000	0.1354	0.1053	aircraft surface(12)	
D.12	0.5%S Residual Oil for Shipping — Berthing Operations	2.253	0.0442	0.0088	shipping residual oil(16)	
D.13	#1 Diesel Fuel Use by Railroads	5.011	0.2858	0.2189	railroad diesel(18)	
D.14	#1 Diesel Fuel Use in Off-road Diesel Engines	8.725	0.4771	0.3654	off-road diesel(19)	D.15,D.16
D.15	Particle Traps on Off-road Diesel Engines	19.535	2.0827	1.5953	off-road diesel(19)	D.14,D.16
D.16	Particle Traps & #1 Diesel Fuel Use for Off-road Diesel Engines	28.260	2.1432	1.6417	off-road diesel(19)	D.14,D.15
D.18	Catalysts on Off-road Gasoline Engines	15.615	0.0831	0.0157	off-road gasoline(20)	
D.19	Use of 0.10%S Residual Oil by Utilities	30.442	0.1232	0.0247	utility residual oil(23)	D.34
D.20	Use of 0.10%S Residual Oil by Refineries	1.367	0.0056	0.0011	refinery residual oil(28)	D.35
D.21	Use of 0.25%S Residual Oil in Industrial Boilers	0.445	0.0047	0.0009	industrial boiler residual oil(31)	D.22,D.36
D.22	Use of 0.10%S Residual Oil in Industrial Boilers	2.404	0.0100	0.0020	industrial boiler residual oil(31)	D.21,D.36
D.24	Catalysts on Gasoline Large Industrial IC Engines	0.113	0.0013	0.0001	industrial IC gasoline engine(35)	
D.25	#1 Diesel Fuel Use in Diesel Industrial IC Engines	1.566	0.0057	0.0057	industrial IC diesel engine(36)	D.26,D.27
D.26	Particle Traps on Diesel Industrial IC Engines	4.796	0.0257	0.0257	industrial IC diesel engine(36)	D.25,D.27
D.27	Particle Traps & #1 Fuel in Diesel Industrial IC Engines	6.362	0.0263	0.0263	industrial IC engine diesel(36)	D.25,D.26
D.28	Use of 0.25%S Residual Oil by Residential/Commercial	3.094	0.0248	0.0049	residential/commercial residual oil(39)	D.37
D.29	Paved Road Flushing	430.689	—	—	paved road dust(61)	D.30
D.30	Paved Road Flushing and Broom Sweep	556.628	—	—	paved road dust(61)	D.29
D.31	Radial Tire Use on Light-duty Vehicles	0.0	0.1167	0.0385	tire attrition(62)	
D.32	Use of Gas Logs in Fireplaces	23.897	4.2394	0.7199	fireplace(65)	
D.33	Charcoal Broiler Control	4.370	4.8541	0.0728	charcoal broilers(68)	
D.34	Substitute Natural Gas for Residual Oil in Utility Boilers	0.0	0.1971	0.0411	utility residual oil(23)	D.19
D.35	Substitute Natural Gas for Residual Oil in Refineries	0.0	0.0063	0.0019	refinery residual oil(28)	D.20
D.36	Substitute Natural Gas for Residual Oil in Industrial Boilers	0.0	0.0098	0.0027	industrial boiler residual oil(31)	D.21,D.22
D.37	Substitute Natural Gas for Residual Oil in Residential/Commercial	0.0	0.0245	0.0016	residential/commercial residual oil(39)	D.28
	Fine Particle Emissions in the Entire 4-County South Coast Air Basin		52.1055	14.5071		

(a) See Appendix D, Table D.38 for the numerical list of 74 source types.

however, more information would be needed concerning the market prices of a number of items. Some control measures may be indivisible (they must be used completely or not at all). Integer programming could be used to search for the optimal solution where each x_k is confined to take a value of 1 or 0 only. However, most of the control measures listed in Table 5.1 can be applied to a fraction of the source class population (e.g., half of the city busses, half of the paved road surfaces) without taxing the feasibility of the control program. Therefore, execution of the more difficult integer programming problem was not deemed to be necessary.

In several cases, additional benefits would be attained from the use of a control technique, beyond the carbonaceous particulate emission reduction, which make that control measure more attractive than pictured in Table 5.1. For example, catalytic converters have been required on automobiles primarily to reduce CO, NO_x, and hydrocarbon emissions, although some particulate emission reductions also occur. In formulating the present problem, a choice is faced. Either the catalysts on automobiles are viewed as "costless" since they will be required for other reasons, or the merits of the catalytic converter may be assessed as if it were a particulate control technique. In the calculations that follow, the latter course is taken. The determination of whether the cost of utilizing a control measure is justified will be based only on its effect on carbon particle air quality. If one wishes to consider that catalysts placed on light-duty vehicles are a sunk cost, then it is a simple matter to delete their cost from the cost of the aerosol carbon control program.

The column of annual costs in Table 5.1 contains the unit cost, c_k, of each control measure k. These values make up the unit cost vector $\underset{\sim}{c}$. If a control measure has a level of application of one unit, it is being applied uniformly to <u>all</u> sources in the four-county South Coast Air Basin even if the source is located outside the 50X50-mile air quality modeling grid. That is done in recognition of the fact that it is administratively impractical to separate the western Los Angeles basin, where the air quality modeling grid resides, from the remainder of the airshed.

The reduction of fine total carbon and elemental carbon emissions in the South Coast Air Basin which would result from each control measure is presented in Table 5.1. These values were obtained by multiplying the fraction reduction (found in Appendix D) by the rate of emissions in the South Coast Air Basin (from Appendix C) for each source type that the control measure affects. Estimates of the 1982 actual fine total carbon and elemental carbon emissions from all sources in the South Coast Air Basin are presented at the bottom of Table 5.1, for comparison. The maximum reduction of total carbon emissions is 24.86 T/day, attainable if every control measure in Table 5.1 is adopted (excluding the very expensive paved road dust controls; if more than one control measure is in conflict, the measure which produces the largest reduction is used). This amounts to 48% of the 1982 total carbon emissions in the South Coast Air Basin. The cost for that maximum reduction of total carbon emissions is estimated to be 481 × 10^6\$/yr. Approximately the same cost produces the maximum elemental carbon emissions reduction of 9.83 T/day, which amounts to 68% of the 1982 total for elemental carbon emissions in the air basin.

The emission reduction matrix, R, is constructed from the values presented in Appendix D, for total carbon (TC) and elemental carbon (EC) emissions reductions. A separate R matrix is developed for total carbon emissions and for elemental carbon emissions, and these two matrices are intended for use in separate linear programming calculations. Each r_{jk} is the fractional emissions reduction due to the application of control measure k at source type j. Since each control measure affects, at most, only a few source types, many of the r_{jk} are zero. The value of r_{jk} is non-zero if source type r is listed under control measure k in Table 5.1 (or Appendix D).

The multiplication of matrices T and R results in the matrix, TR, whose elements, $(tr)_{ik}$, represent the reductions in pollutant concentration at site i due to control measure k. A separate TR matrix was constructed for fine total primary carbon and fine elemental carbon concentration reductions.

The first 9 rows of the matrix B are constructed from the 9 groupings of incompatible controls listed in Table 5.2 (i.e., $N_1 = 9$). The n^{th} row contains the coefficients, b_{nk}, which equal 1 if control measure k is a member of conflict group n (0 otherwise). Subsequent rows are added to B for each control measure not included in any conflict group. Of the 33 control measures, only ten are not included

Table 5.2

Groupings of Incompatible Control Measures

Group 1: LT-DUTY DIESELS

- D.3 #1 DIESEL FUEL USE BY LIGHT-DUTY DIESEL VEHICLES
- D.4 PARTICLE TRAPS ON LIGHT-DUTY DIESEL VEHICLES
- D.5 PARTICLE TRAPS & #1 DIESEL FUEL USE FOR LT-DUTY DIESELS

Group 2: HEAVY DIESEL TRUCKS

- D.8 #1 DIESEL FUEL USE BY HEAVY DIESEL TRUCKS
- D.9 PARTICLE TRAPS ON HEAVY-DUTY DIESEL TRUCKS
- D.10 PARTICLE TRAPS & #1 DIESEL FUEL FOR HEAVY DIESEL TRUCKS

Group 3: OFF-ROAD DIESELS

- D.14 #1 DIESEL FUEL USE IN OFF-ROAD DIESEL ENGINES
- D.15 PARTICLE TRAPS ON OFF-ROAD DIESEL ENGINES
- D.16 PARTICLE TRAPS & #1 FUEL FOR OFF-ROAD DIESEL ENGINES

Group 4: UTILITY BOILERS - RESIDUAL OIL

- D.19 USE OF 0.10%S RESIDUAL OIL BY UTILITIES
- D.34 SUBSTITUTE NATURAL GAS FOR RESIDUAL IN UTILITY BOILERS

Group 5: REFINERY BOILERS - RESIDUAL OIL

- D.20 USE OF 0.10%S RESIDUAL OIL BY REFINERS
- D.35 SUBSTITUTE NATURAL GAS FOR RESIDUAL IN REFINERIES

Group 6: INDUSTRIAL BOILERS - RESIDUAL OIL

- D.21 USE OF 0.25%S RESIDUAL OIL IN INDUSTRIAL BOILERS
- D.22 USE OF 0.10%S RESIDUAL OIL IN INDUSTRIAL BOILERS
- D.36 SUBSTITUTE NATURAL GAS FOR RESIDUAL IN INDUS BOILERS

Table 5.2 (continued)

Group 7: DIESEL STAT IC ENGINES

D.25 #1 DIESEL FUEL USE IN DIESEL INDUSTRIAL IC ENGINES
D.26 PARTICLE TRAPS ON DIESEL INDUSTRIAL IC ENGINES
D.27 PARTICLE TRAPS & #1 FUEL IN DIESEL INDUSTRIAL IC ENGINE

Group 8: RES/COM BOILERS - RESIDUAL OIL

D.28 USE OF 0.25%S RESIDUAL OIL BY RESIDENTIAL/COMMERCIAL
D.37 SUBSTITUTE NATURAL GAS FOR RESIDUAL IN RES/COM BOILERS

Group 9: PAVED ROAD DUST

D.29 PAVED ROAD FLUSHING
D.30 PAVED ROAD FLUSHING AND BROOM SWEEP

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in any conflict group (10 columns of the first 9 rows of B contain no non-zero values), so ten additional rows are added to B (i.e., $N_2 = 10$, $N = N_1 + N_2 = 19$). Only one element, b_{nk}, is non-zero in each of these additional six rows. A value of 1 is placed in each additional row, such that every column k of the final B matrix has at least one non-zero value.

The linear program has the capacity to limit the availability of scarce resources needed by control measures. Examination of control measure D.34 (see Appendix D) reveals that costs and pollutant emissions may be lowered by burning natural gas rather than residual oil. However, natural gas is not always available for use as a boiler fuel. Two cases are examined. In the first case, it is assumed that no additional natural gas is available for boiler fuel beyond that which was actually burned in 1982. In the second case, an unlimited natural gas supply is allowed at 1982 prices. Both cases make use of matrix D, which contains only one row (i.e., M = 1), with elements, $d_{mk} = d_{1k}$, equal to the amount of natural gas required by control measure k, beyond that consumed in 1982. The natural gas supply required by control measures D.34 through D.37 is listed in Appendix D.

The vector $\underset{\sim}{s}$ contains only one value, $s_m = s_1$, which represents the natural gas available for the control strategy. For the limited natural gas case, $s_1 = 0$, whereas for the unlimited natural gas case, s_1 is set to a value which is larger than $\sum_{k=1}^{k} d_{mk}$ (the total natural gas required by all control measures).

The minimum cost of control to achieve an air quality goal under the two cases of natural gas supply may be compared. This comparison is useful in determining how much the availability of additional natural gas is worth, with respect to the improvement of carbon particle air quality. The air quality model shows that stationary fuel combustion sources were not responsible for a large fraction of the carbon particle concentration, so it is expected that the difference between control strategy costs in these two cases will not be large.

Finally, the vector of required air quality improvements $\underset{\sim}{q}$ must be constructed. Recall that each value, q_i, representing the air quality improvement required at site i, is equal to $p_i - g$, where p_i is the present pollutant concentration at site i, and g is the air quality goal to be met at all locations. The linear program will be solved a number of times with progressively stricter air quality goals. Initially, g is set near the present maximum annual average concentration at all sites. For each subsequent linear programming calculation, g is decreased by Δg until no feasible solution exists. For fine primary total carbon concentration control, Δg is set to be (−)0.4 $\mu g/m^3$, while the decrement of the fine elemental carbon concentration limit is (−)0.2 $\mu g/m^3$. By solving a number of successive linear programs, each with a slightly stricter air quality goal, a relationship will be developed between the cost of control and the concentration limit that could be met simultaneously at all receptor sites.

5.3.3 Results

The source to receptor transfer coefficients produced by the air quality model were used to determine the optimal control strategies for fine total carbon and fine elemental carbon particulate air quality in the Los Angeles area. The linear program of (5.11) through (5.13) was solved using the simplex method as implemented by a modified version of a computer code provided by Sandia National Laboratories (1979). The solution is the least costly set of control measures which would cause air pollutant concentrations to fall to or below a required concentration limit simultaneously at every receptor site.

The linear programming minimization problem was solved repeatedly, each time with a progressively stricter air quality requirement. The results are displayed in Figure 5.1 for fine primary total carbon control and in Figure 5.2 for fine elemental carbon control (limited natural gas case). Control measures are listed as each becomes a part of the optimal control strategy. (The number in parentheses next to each control measure in Figures 5.1 and 5.2 refers to the control measure number in Appendix D). As the allowable pollutant concentration limit is reduced, more and more controls become necessary.

Control measures are selected for inclusion in the optimal control strategy based on their cost and effectiveness in reducing ambient pollutant levels. Therefore control measures with zero costs were selected first, even though concentration reductions from these

Figure 5.1

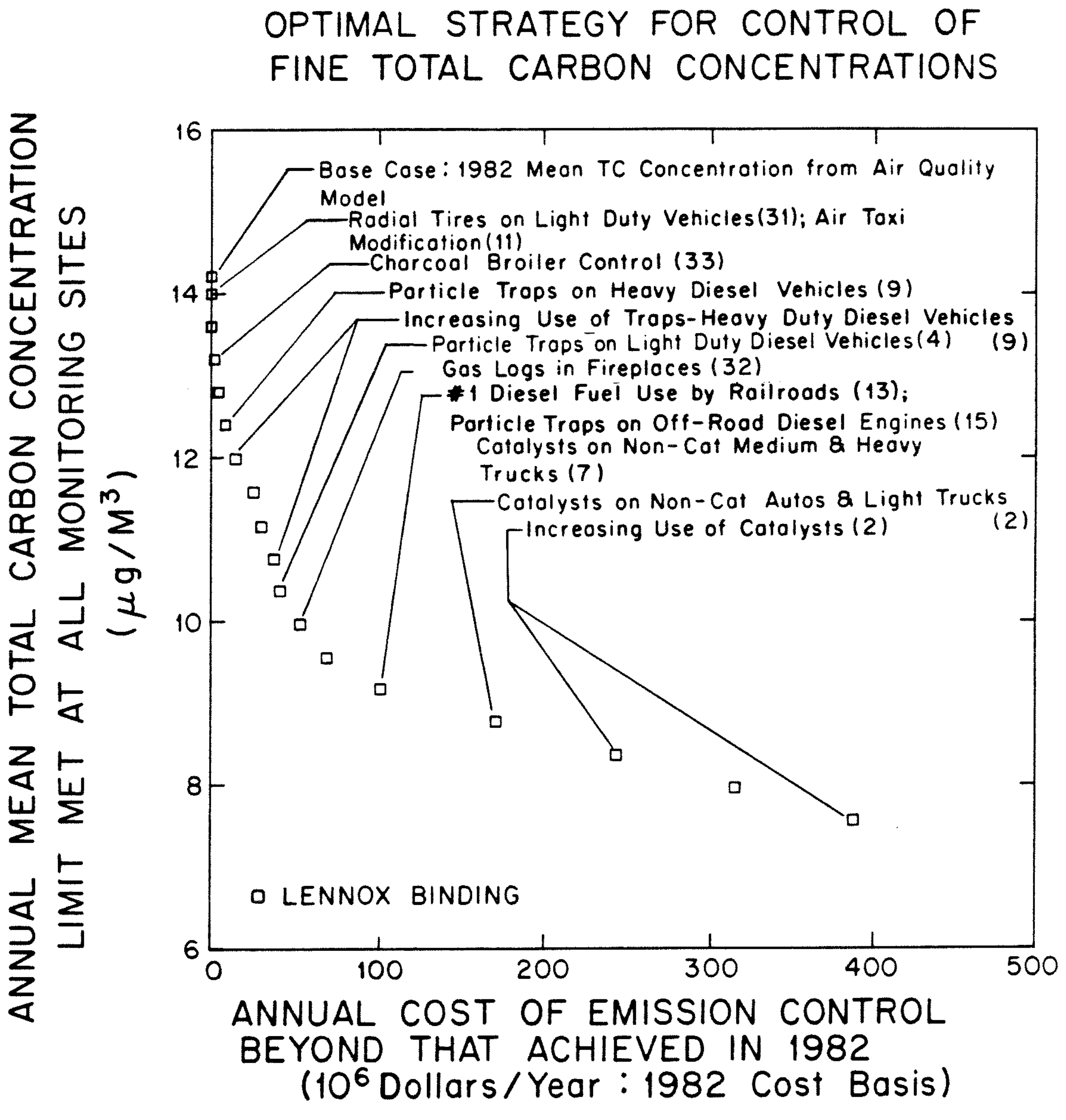
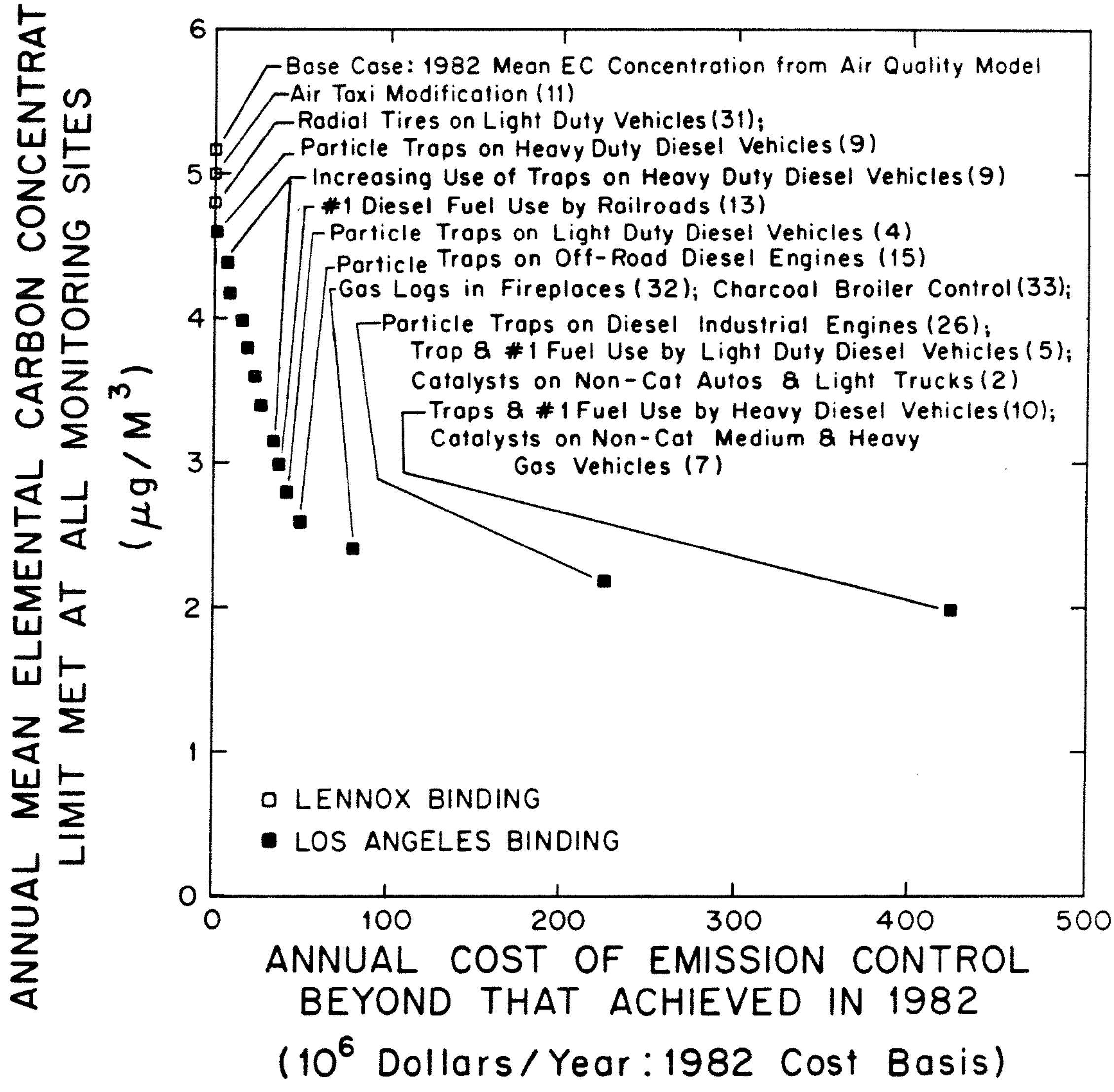

OPTIMAL STRATEGY FOR CONTROL OF FINE TOTAL CARBON CONCENTRATIONS
Base Case: 1982 Mean TC Concentration from Air Quality Model
Radial Tires on Light Duty Vehicles(31); Air Taxi Modification(11)
Charcoal Broiler Control (33)
Particle Traps on Heavy Diesel Vehicles (9)
Increasing Use of Traps-Heavy Duty Diesel Vehicles (9)
Particle Traps on Light Duty Diesel Vehicles(4)
Gas Logs in Fireplaces (32)
#1 Diesel Fuel Use by Railroads (13); Particle Traps on Off-Road Diesel Engines (15)
Catalysts on Non-Cat Medium & Heavy Trucks (7)
Catalysts on Non-Cat Autos & Light Trucks (2)
Increasing Use of Catalysts (2)
□ LENNOX BINDING
16
14
12
10
8
6
0
100
200
300
400
500
ANNUAL MEAN TOTAL CARBON CONCENTRATION LIMIT MET AT ALL MONITORING SITES ($\mu g/M^3$)
ANNUAL COST OF EMISSION CONTROL BEYOND THAT ACHIEVED IN 1982 (10^6 Dollars/Year : 1982 Cost Basis)

Figure 5.2

OPTIMAL STRATEGY FOR CONTROL OF FINE ELEMENTAL CARBON CONCENTRATIONS



controls are small. The additional cost of radial tires over bias-ply tires is offset by the longer life of radial tires (see Appendix D.31). The South Coast Air Quality Management District states that a fuel savings would occur if jet aircraft were towed when in taxi mode by special purpose vehicles (see Appendix D.11). Since these two control measures have no net cost, they are the most cost effective.

The next most cost effective control measures have non-zero costs, but result in large concentration reductions at all locations. These measures are aimed entirely at diesel engines in the case of fine elemental carbon particle control (see Figure 5.2). The annual cost of placing particle trap systems on all light and heavy duty diesel vehicles and off-road diesel engines, and switching from #2 diesel fuel to #1 diesel fuel in railroad use was estimated to be about 69×10^6\$/yr (see Appendices D.4, D.9, D.13, and D.15). These four control measures would have reduced the 1982 annual average fine elemental carbon concentrations at downtown Los Angeles by approximately 2.24 $\mu g/m^3$, which represents almost a 50% concentration reduction at that location.

The four diesel control measures are also an effective choice for reducing fine primary total carbon concentrations. Two additional controls on charcoal broilers and on fireplace emissions (see Appendices D.33 and D.32), which reduce emissions from large sources of fine organic carbon, are included near the beginning of the total carbon control strategy list (see Figure 5.1). It is estimated that these six controls would have reduced 1982 annual average fine total carbon concentrations at Lennox by about 4.3 $\mu g/m^3$ at an annual cost of less than 100 X 10^6\$/yr.

As the concentration limit is further reduced, more costly (less cost-effective) control measures are added to the least cost control strategy. Although several hundred million dollars per year is needed to produce the largest possible concentration reduction, a very large reduction is possible at a fraction of that cost, if only the most cost-effective control measures are employed. It is estimated that for a cost of 102 X 10^6\$/yr, the maximum annual average fine primary total carbon concentration may be reduced from above 14 $\mu g/m^3$ to 9.2 $\mu g/m^3$. The maximum annual average fine elemental carbon concentration may be reduced from above 5 $\mu g/m^3$ to 2.4 $\mu g/m^3$ at a cost of only 80 X 10^6\$/yr.

The two cases of natural gas supply were examined. The control measures, D.34 through D.37, requiring a natural gas supply in excess of 1982 levels have zero costs and hence are included immediately into the control strategies when the unlimited natural gas supply case is considered. The concentration reductions resulting from these four control measures are very small (annual average elemental carbon concentration reductions less than 0.006 $\mu g/m^3$ at all locations; total carbon concentration reductions less than 0.035 $\mu g/m^3$ at all locations) so that the control strategies produced with and without a further increase in natural gas levels are almost identical.

The control strategy optimization for <u>annual</u> average pollutant concentrations was compared to the same calculation for determining optimal control strategies for abatement of the peak monthly average pollutant concentrations. Transfer coefficients from the December 1982 air quality model calculation were used to compute optimal strategies for controlling peak monthly fine primary total carbon and fine elemental carbon concentrations. The linear programming results for peak monthly average concentrations were almost identical to those for annual average concentrations. Control measures were included in optimal control strategies in the same order for 1982 annual average concentrations as for December 1982 concentrations. It is expected therefore, that a control strategy which is chosen to be the most effective at reducing annual average carbon particle concentrations will also be optimal or near optimal for reducing peak monthly average carbon particle concentrations.

Optimal control strategies have been found for the reduction of annual average fine primary total carbon and fine elemental carbon concentrations in the Los Angeles area, as shown in Figures 5.1 and 5.2. These two strategies are similar, including mostly controls on diesel fuel combustion sources. These strategies do differ in some details. As mentioned previously, the emphasis on total carbon versus elemental carbon abatement should depend on the goal of the control program. A goal emphasizing mass concentration reduction favors total carbon control, while visibility improvement would be served best by a heavier emphasis on preferential removal of elemental carbon.

The effect of choosing between control strategies that emphasize fine elemental carbon control versus fine total carbon control is illustrated in Figure 5.3. The solid line represents the optimal strategies for controlling fine elemental carbon concentrations. It was constructed from the points in Figure 5.2. For a given number of dollars spent, that curve determines the lowest possible elemental carbon concentration limit, which is attainable by adopting the optimal set of control measures as prescribed in Figure 5.2. If, however, the optimal strategy for total carbon concentration reduction is adopted, higher elemental carbon concentrations would result at some levels of expenditure as shown by the dashed line in Figure 5.3.

The difference between the two strategies is largest when control costs are in the vicinity of $69 million per year. At this cost, optimization for total carbon control would result in a maximum annual elemental carbon concentration of about 2.72 $\mu g/m^3$. At the same cost, the optimal strategy for elemental carbon control would produce a maximum annual elemental carbon concentration of approximately 2.44 $\mu g/m^3$.

The maximum annual average total carbon concentrations which would result from the optimal control strategies for elemental carbon are shown on the dashed line in Figure 5.4. If $50 million per year is spent on control measures to produce the lowest possible maximum annual average elemental carbon concentration, then the maximum annual average total carbon concentration at any location would be about 10.8 $\mu g/m^3$. Adoption of the optimal strategy for total carbon

Figure 5.3 Control of elemental carbon concentration: comparison of optimal strategy for EC reduction to EC concentrations that result from optimal strategy for TC reduction.

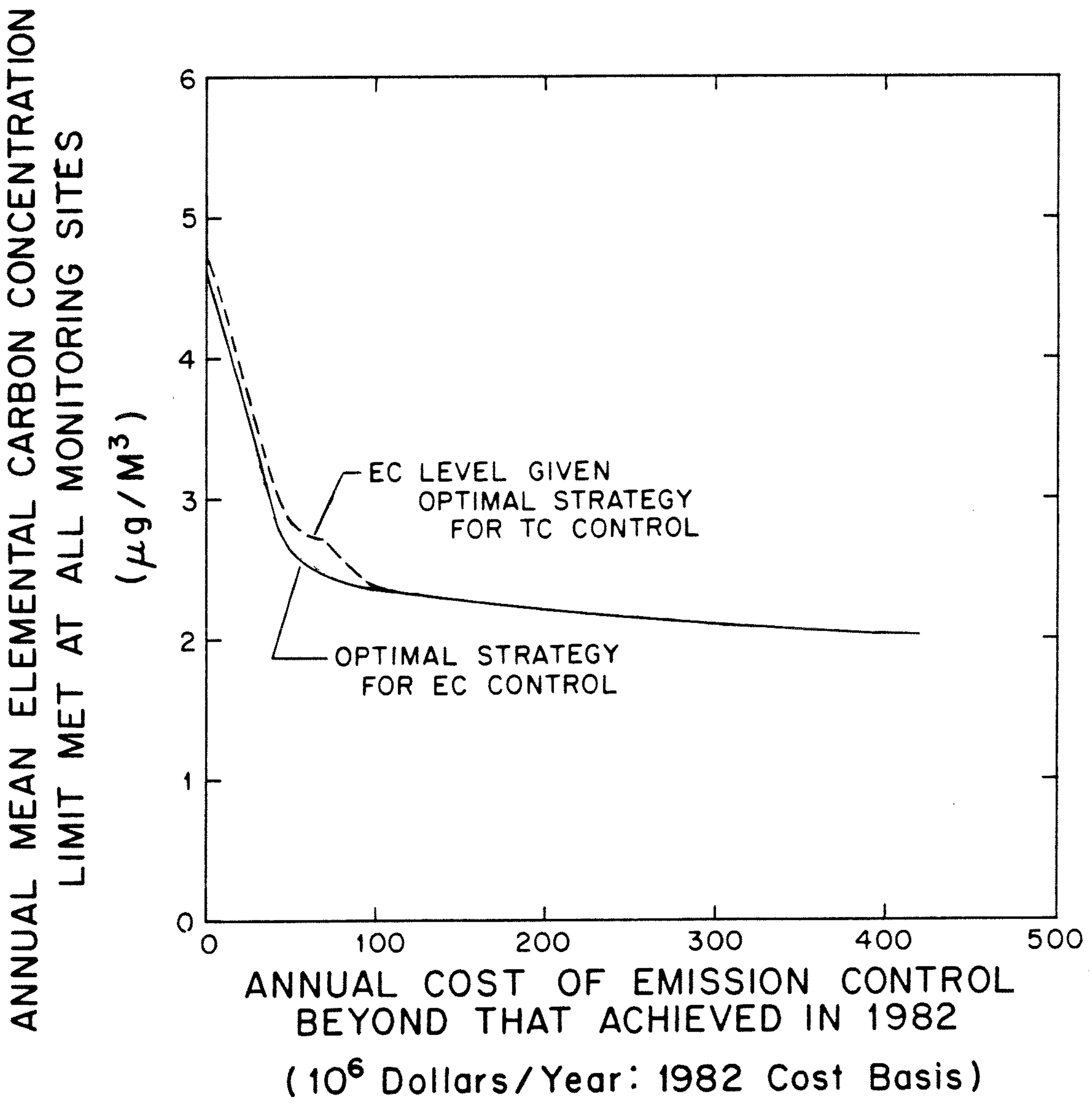
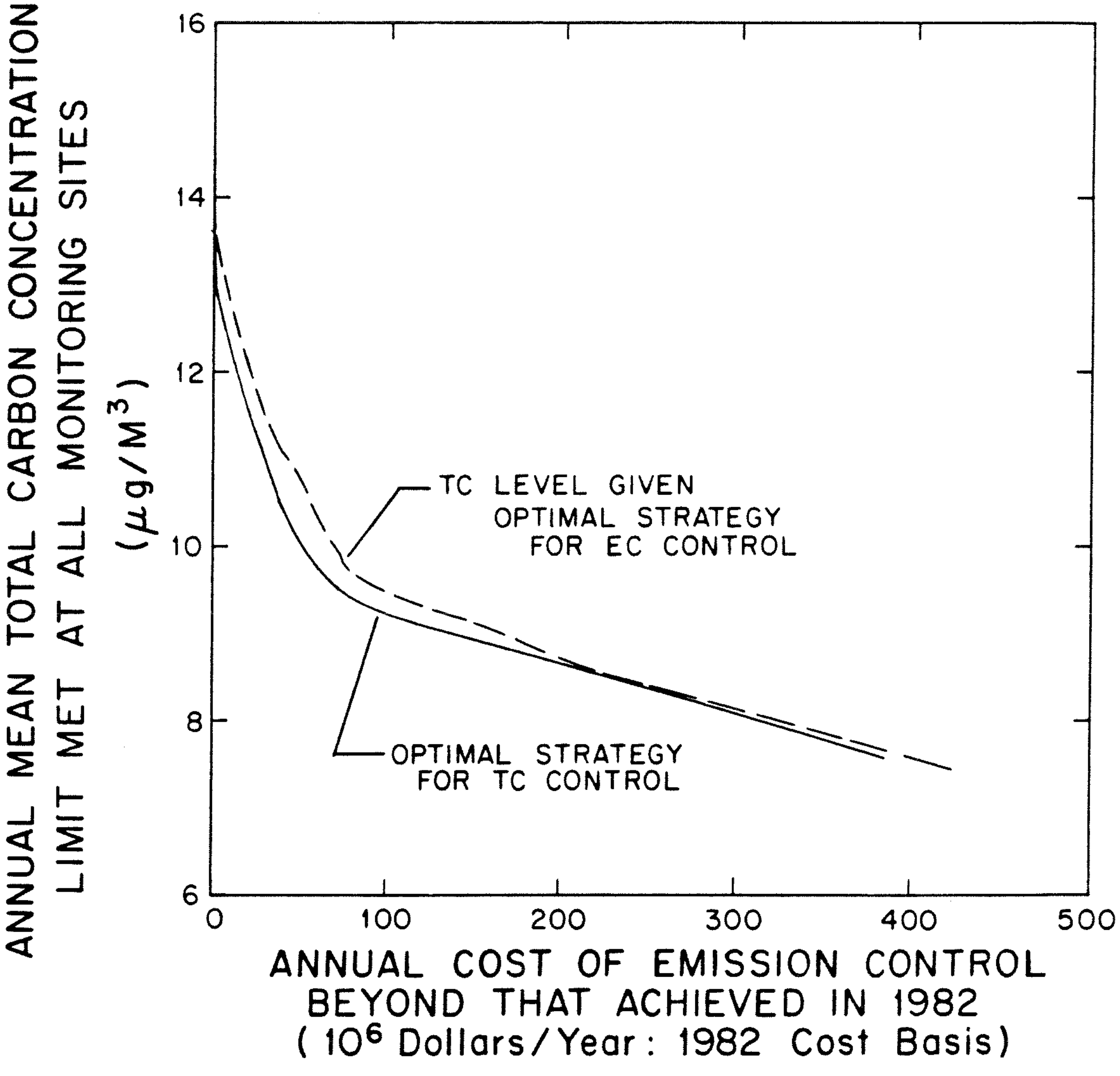


Figure 5.4 Control of total carbon concentration: comparison of optimal strategy for TC reduction to TC concentrations that result from optimal strategy for EC reduction.



control, at the same cost, would result in a maximum annual average total carbon concentration slightly higher than 10.0 $\mu g/m^3$.

Either of the two optimal control strategies, for costs greater than $100 million, produce similar maximum annual average elemental carbon concentrations, as shown in Figure 5.3. Overall, the greatest difference between the effects of the two control strategies is on maximum annual total carbon concentrations, as seen in Figure 5.4. Controls on charcoal broilers and fireplace emissions (controls D.33 and D.32) are absent from low cost strategies aimed at reducing elemental carbon concentrations. The largest discrepancy in the two curves of Figure 5.4 disappears beyond a cost of about $220 million.

5.4 Summary and Conclusions

In this chapter, a linear programming technique for air pollution control strategy optimization was applied to the problem of aerosol carbon control in the Los Angeles area. The technique combines source to receptor information derived from the air quality modeling study of Chapter 4 with data on the cost and emission reduction capabilities of a variety of control measures to determine the least costly combination of controls that would result in a required air quality improvement.

Source to receptor coefficients are supplied in the form of source class contributions to fine elemental carbon and total carbon concentrations from the air quality model application presented in Chapter 4. A set of 33 control measures were defined in terms of their costs and emission reduction effectiveness. The linear program was solved for both fine elemental carbon (EC) and fine total carbon (TC) control, for a number of different levels of air quality improvement.

It was found that, while a 68% basin-wide fine elemental carbon emissions reduction could be achieved at an annual cost of near $500 million, resulting in peak annual average EC concentrations under 2.0 $\mu g/m^3$ at all locations, it is possible to reduce the annual average EC concentrations from the 1982 peak of over 5 $\mu g/m^3$ to 2.4 $\mu g/m^3$ at a cost of only $80 million/year. Annual average primary fine TC concentrations may be reduced from the 1982 peak of over 14 $\mu g/m^3$ to 9.2 $\mu g/m^3$ at a cost of $102 million/year. More than triple that cost is required to produce a reduction of peak annual average primary TC concentration to 7.6 $\mu g/m^3$ (see Figures 5.1 and 5.2).

The control measures included in the optimal strategies for fine elemental carbon control are aimed almost entirely at reducing emissions from diesel fuel combustion applications. These control measures on diesel emissions are also cost-effective measures for fine primary total carbon control; however, the addition of several low cost control measures that produce large reductions in organic carbon emissions is needed as part of the optimal TC control strategies. The trade-offs implied by the choice of control strategy for TC versus EC were investigated. It has been determined that a control strategy that is optimal for TC control may be near-optimal for EC control (see Figure 5.3), whereas an emissions control strategy designed to optimize for EC control may produce peak TC concentrations that exceed those which would result from a control strategy optimized for TC by as much as 0.8 $\mu g/m^3$ annual mean (see Figure 5.4).

The effect of an increased availability of natural gas in the Los Angeles area was examined. Since the base case (1982) carbonaceous particulate emissions from boilers burning residual oil contribute only a small increment to overall aerosol carbon concentrations, the effect of an increased availability of natural gas on aerosol carbon concentrations is insignificant.

Optimal control strategies, designed to reduce 1982 annual average carbon particle concentrations, are almost identical to the optimal strategies for reducing aerosol carbon concentrations during the peak month of 1982 (December). Therefore, the control strategies that are most effective at reducing annual average carbon particle concentrations will be as effective as possible at reducing the peak monthly average concentrations.

The control strategy optimization technique described in this chapter was demonstrated to be a valuable tool for understanding how to control air pollution. In a complex multiple source urban setting, emission control costs for even a modest air quality improvement program can be enormous. By employing the combination of field experiments, air quality model development and control cost optimization procedures described in this study, air pollution control strategies for aerosol carbon in Los Angeles can be identified that cost less than about $100 million per year which will perform nearly as well as other strategies costing at least three times as much.

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CHAPTER 6

FUTURE RESEARCH

6.1 Introduction

Improvement of urban air quality by deliberate control of emission sources requires a thorough understanding of the phenomena associated with air pollution. It has been the objective of this work to further this knowledge, specifically for atmospheric fine aerosol carbon, by characterizing the existing pollution levels, and by developing methods that can be used by engineers to design aerosol carbon abatement programs. In the course of this work, a number of questions requiring further study have been identified. In this chapter, suggestions for future research into the behavior of atmospheric carbon particle air pollution are outlined.

6.2 Air Quality Observations

In Chapter 2, it was concluded that primary emissions are responsible for the majority of long-term average carbon particle concentrations in the Los Angeles area during 1982. The formation of secondary aerosol carbon in the atmosphere is expected to occur, and the reasons for not finding an obvious enrichment in organic aerosol relative to elemental carbon during summer months needs to be investigated further. The ambient aerosol monitoring program executed as part of this study involved collection of 24-hour average filter samples. Further insight into the importance of secondary formation of particulate carbon may be gained by contrasting these long-term average results with the conditions present during summer months in the middle of the day, when photochemical reactions are expected to be at their peak. Examination of the ratio of fine total carbon to fine elemental carbon for a number of summer mid-day events would help one to determine the extent to which secondary formation is occurring under photochemical smog episode conditions.

A more complete identification of the organic compounds present in atmospheric aerosols would aid in the understanding of pathways of secondary particulate matter formation. The extent to which secondary aerosol formation is occurring in the atmosphere could be better quantified, and information regarding the nature of toxic materials in the atmosphere would be enhanced, if aerosol samples representing a full annual cycle were analyzed for the details of the individual organic compound present. During the course of the air quality monitoring program described in Chapter 2, a quartz fiber filter was included in the sampling protocol that was intended to be reserved for organic compound identification. Detailed speciation of the organic material present on these filters may be achieved using high-resolution gas chromatography (GC) and high-resolution gas chromatography/mass spectrometry (GCMS) techniques. This work is in progress at present (Mazurek, 1985).

6.3 Air Quality Model Application

The air quality model described in Chapter 3 was used to predict long-term average fine primary carbon particle concentrations in the Los Angeles area during 1982. The computation of horizontal advective transport was based on a uniform wind field generated from data of a single wind monitoring location. The accuracy of the model predictions of fine primary carbon particle concentrations may be improved by employing a more sophisticated two-dimensional wind field. A considerable effort would then be required to gather more wind data and to generate continuous wind fields for every hour of the modeling period. In addition, the computer time required for computation will be greatly increased.

Further improvements of the air quality model application include reducing the size of the receptor grid cells which would provide a greater spatial resolution of model predictions. It would then be necessary to compile a more detailed spatially-resolved emissions inventory which matches the new receptor grid.

The model was designed to simulate the emission and transport of primary carbonaceous aerosol. A topic for future study would involve incorporating into the model an explicit secondary aerosol formation calculation. This would require a comprehensive knowledge of the physical and chemical kinetic mechanisms for organic aerosol formation. Also more detailed hydrocarbon emissions information would need to be compiled.

The modeling technique developed during this study has been shown to accurately simulate the long-term behavior of the transport of fine primary carbonaceous aerosol in the Los Angeles area. It would not be difficult to employ this model to simulate the transport of primary pollutants in other cities as well. The specific meteorological conditions in other urban air basins would have to be assessed to determine whether the assumptions built into the model are consistent with the nature of transport in that air basin. The model accounts for different physical processes independently of each other, so that it is possible to modify the computation of a single process without destroying the integrity of the model.

6.4 Emission Control Strategies

In Chapter 5, strategies for atmospheric carbon particle control were evaluated. Many of the control measures have implications regarding the control of other aerosol pollutant species as well. Local control agencies are faced with the problem of controlling a variety of pollutants. It would be desirable to incorporate source to receptor information for many aerosol species to design a control strategy for simultaneously reducing concentrations of sulfates, nitrates, carbonaceous species, and other toxic species which are present in urban atmospheres. A difficulty encountered in a multi-attribute control program is in assigning a weight to each species present regarding its detriment to the environment. Assumptions about the trade-offs between toxicity, overall mass burden, and visibility degradation must be made to determine the effectiveness of a proposed control strategy.

Results from an air quality model which accounts for secondary aerosol formation could be used to evaluate control strategies for the abatement ot secondary carbonaceous aerosol concentrations in the atmosphere. However, then a non-linear programming approach would be required. A further improvement to the control strategy optimization technique would involve the use of an integer program which would inhibit the selection of fractions of control measures when such a choice is infeasible.

Application of the linear programming technique presented in Chapter 5 demonstrates the usefulness of the air quality model for designing aerosol carbon pollution abatement strategies. More detailed information on the costs and emission reduction capabilities of control technologies is needed. In the future, when more complete information concerning control technologies is available, the air quality model results from this study may be directly applied to the optimization of a strategy for control of a number of primary pollutants, including fine primary carbon particles, in the Los Angeles area.

6.5 Conclusions

In this chapter, avenues for future research have been discussed. Scientific investigations into the phenomena of atmospheric processes will improve the capabilities of the air quality model. Application of the model to evaluation of emission control programs promises to contribute toward the improvement of urban air quality.

6.6 References for Chapter 6

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APPENDIX A

1982 EMISSIONS ESTIMATES IN THE 50X50-MILE MODELING GRID

Table A.1

Emissions Estimates for Mobile Sources in 50X50-mile grid

	Estimated 1982 Fuel Use (10^9 Btu/day)	Thous. VMT/day	Total Particulate Emission Factor		Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Total Particulate (kg/day)	%Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
			(kg/10^9 Btu)	(gm/mile)						Volatile Carbon % OC	Non-volatile Carbon % EC		
MOBILE SOURCES													
Highway Vehicles													
Catalyst Autos	515.2(a)	86996(a)		0.016(k)	1391.9	86% (v)	1197.1	39% (ff)	466.9	55%	45% (ff)	256.8	210.1
Non-catalyst Autos	305.6(a)	33385(a)		0.32 (l)	10683.2	36.4% (w)	3888.7	76.4% (w)	2971.0	78.7%	21.3% (w)	2388.1	632.8
Diesel Autos	14.0(a)	2494(a)		0.48 (m)	1197.1	93% (x)	1113.3	83.7%(gg)	931.9	23.4%	76.6%(gg)	218.1	713.8
Catalyst Light Trucks	96.0(a)	11882(a)		0.022(n)	261.4	86% (y)	224.8	39% (hh)	87.7	55%	45% (hh)	48.2	39.5
Non-catalyst Light Trucks	57.0(a)	4560(a)		0.44 (o)	2006.4	36.4% (z)	730.3	76.4% (z)	558.0	78.7%	21.3% (z)	439.1	118.8
Diesel Light Trucks	2.6(a)	341(a)		0.48 (m)	163.7	93% (aa)	152.2	83.7%(ii)	127.4	23.4%	76.6%(ii)	29.8	97.6
Catalyst Medium Trucks	58.9(a)	4993(a)		0.033(p)	164.8	86% (y)	141.7	39% (hh)	55.3	55%	45% (hh)	30.4	24.9
Non-catalyst Medium Trucks	40.1(a)	3399(a)		0.41 (q)	1393.6	36.4% (z)	507.3	76.4% (z)	387.6	78.7%	21.3% (z)	305.0	82.5
Gasoline Heavy Trucks	66.9(a)	3050(a)		0.77 (r)	2348.5	36.4% (z)	854.9	76.4% (z)	653.1	78.7%	21.3% (z)	514.0	139.1
Diesel Heavy Trucks	147.4(a)	5857(a)		1.39 (s)	8141.2	93% (aa)	7571.3	83.7%(ii)	6337.2	23.4%	76.6%(ii)	1482.9	4854.3
Motorcycles	3.8(a)	1503(a)		0.15 (t)	225.5	36.4% (z)	82.1	76.4% (z)	62.7	78.7%	21.3% (z)	49.3	13.4
LPG use for Carburetion	7.7(b)			(u)	1.6(u)								
Civil Aviation													
Jet Aircraft	47.0(c)		(c)		410.5(c)	~100% (bb)	410.5	96% (bb)	394.1	23.4%	76.6%(jj)	92.2	301.9
Aviation Gas	1.9(c)		(c)		43.8(c)	36.4%(cc)	15.9	76.4%(cc)	12.2	78.7%	21.3%(cc)	9.6	2.6
Commercial Shipping													
Residual Oil-fired Ships	11.9(d)		85.50(h)		1017.5	72% (dd)	732.6	11.3%(dd)	82.8	80%	20% (kk)	66.2	16.6
Diesel Ships	4.7(d)		49.17(i)		231.1	93% (ee)	214.9	83.7%(ii)	179.9	23.4%	76.6%(ii)	42.1	137.8
Railroad													
Diesel Oil	14.1(e)		81.95(j)		1155.5	93% (ee)	1074.6	83.7%(ii)	899.4	23.4%	76.6%(ii)	210.5	689.0
Miscellaneous													
Off Highway Diesel Vehicles	25.7(f)		78.67(f)		2024.1(f)	93% (ee)	1882.4	83.7%(ii)	1575.6	23.4%	76.6%(ii)	368.7	1206.9
Off Highway Gasoline Vehicles	(g)				295.3(g)	36.4%(cc)	107.5	76.4%(cc)	82.1	78.7%	21.3%(cc)	64.6	17.5
TOTAL MOBILE SOURCES									15864.9			6565.6	9299.1

Notes for Table A.1

(a) See Table A.6. Vehicle miles travelled (VMT) are computed for each vehicle type from traffic count data. Fuel use is then computed from mileage for each vehicle type, employing fuel economies from Table A.5.

(b) Based on fuel sales data for California from the Energy Information Administration (1983); see Appendix B, Table B.6.

(c) Average daily fuel use and particulate emissions at commercial airports were obtained from Federal Aviation Administration (1981) air traffic data plus U.S. Environmental Protection Agency (1982, section 3.2.1) calculation procedure.

(d) Based on procedure by Cass (1977).

(e) Consumption of fuel oil sold to railroads is assumed to be proportional to track mileage. Railroad track mileage in the 50X50-mile grid was measured on United States Geological Survey 7½ minute topographic maps and was estimated to be 1047.9 miles. Track mileage in the state of California of 8446 miles was obtained from the Federal Railway Administration as reported by Cass (1977, p. 628). Fuel sales data from the Energy Information Administration (1983) indicate that 7138 thousand barrels of distillate fuel oil were used by railroads in the state of California in 1982; see Appendix B, Table B.6. The grid contains 12.4% of the track mileage in the state; therefore, the fuel use in the grid is estimated to be 7138 X 12.4% = 885.6 (1000 bbls/yr) or 14.1 X 10^9 Btu/day.

(f) Total particulate emissions from off-highway diesels is 2024.1 kg/day in the 50X50-mile grid from the California Air Resources Board 1982 inventory of area source emissions (Ranzieri 1983). Using the particulate emissions factor of 24 lb/10^3 gal or 78.67 kg/10^9 Btu, the fuel use is estimated to be 25.7 X 10^9 Btu/day.

(g) Total particulate emissions from off-highway gasoline consumption in the 50X50-mile grid from the California Air Resources Board 1982 inventory of area source emissions (Ranzieri 1983). No information is available on the fuel use.

(h) Industrial boiler emission factor of 21.64 kg/10^9 Btu at 0.4% sulfur in fuel was scaled up to 85.50 kg/10^9 Btu at 1.58% sulfur in bunker fuel based on evidence of Taback et al. (1979) that shows that the particulate emissions rate from residual oil-fired boilers is roughly proportional to the fuel oil sulfur content.

(i) U.S. Environmental Protection Agency (1982, Table 3.2.3-2) gives 15 lb/10^3 gal or 49.17 kg/10^9 Btu.

(j) U.S. Environmental Protection Agency (1982, Table 3.2.2-1) gives 25 lb/10^3 gal or 81.95 kg/10^9 Btu.

(k) Laresgoiti and Springer (1977), at 0.3% sulfur in unleaded gasoline, obtained 0.016 g/mile for oxidation catalyst car; Muhlbaier and Williams (1982) reported a similar emissions factor (0.014 g/mile); and Schuetzle (1983, Table 8) reported a weighted average ot many published data for particulate emissions from catalyst automobiles (0.017 g/mile).

(l) 0.32 g/mile from Habibi (1973, Table VIII) (leaded fuel cars) adjusted downward to 0.0402 g/mile lead emitted. Total particulate emissions is computed only to complete the table; fine carbon emissions are calculated independently. See note (w), below.

(m) Pierson (1979) cites numerous researchers on the particulate emission rate from a light-duty diesel and reports a value of about 300 mg/km (or 0.48 g/mile). Many other researchers (Schuetzle 1983; Hyde et al. 1983; Gabele et al. 1982; Gibbs, Hyde, and Byer 1980; Williams and Chock 1980) have found similar emission rates ranging from 0.36 to 0.89 g/mile for light-duty diesel automobiles.

(n) Assuming the same particulate emission rate per gallon of fuel burned as light-duty catalyst automobiles. The weighted average fuel economy is 0.0474 gal/mile for catalyst autos and 0.0647 gal/mile for light trucks; see Table A.6. Scaling upward from the emission rate of 0.016 g/mile for catalyst autos (see note [k], above), this gives 0.022 g/mile (0.016 g/mile / 0.0474 gal/mile = 0.338 g/gal;
0.338 g/gal X 0.0647 gal/mile = 0.022 g/mile).

(o) Assuming the same particulate emission rate per gallon of fuel burned as light-duty non-catalyst automobiles. The weighted average fuel economy is 0.0733 gal/mile for non-catalyst autos and 0.1000 gal/mile for non-catalyst light trucks; see Table A.6. Scaling upward from the emission rate of 0.32 g/mile for non-catalyst autos (see note [l], above), this gives 0.44 g/mile (0.32 g/mile / 0.0733 gal/mile = 4.37 g/gal;
4.37 g/gal X 0.1000 gal/mile = 0.44 g/mile).

(p) Assuming the same particulate emission rate per gallon of fuel burned as light-duty catalyst automobiles and trucks (0.338 g/gal); see note (n), above. The weighted average fuel per mileage for catalyst medium trucks is 0.0943 gal/mile; see Table A.6. This gives 0.032 g/mile (0.338 g/gal X 0.0943 gal/mile).

(q) Assuming the same particulate emission rate per gallon of fuel burned as light-duty non-catalyst automobiles and trucks (4.37 g/gal); see note (o), above. The weighted average fuel per mileage for non-catalyst medium trucks is 0.0943 gal/mile; see Table A.6. This gives 0.41 g/mile (4.37 g/gal X 0.0943 gal/mile).

(r) Assuming the same particulate emission rate per gallon of fuel burned as other leaded gasoline (non-catalyst) autos and trucks (4.37 g/gal); see note (o), above. The weighted average fuel per mileage for gasoline (non-catalyst) heavy trucks is 0.1754 gal/mile; see Table A.6. This gives 0.77 g/mile (4.37 g/gal X 0.1754 gal/mile). Tests done by Dietzman, as reported in Lang et al. (1982), give a range of 0.58-0.89 g/mile. U.S. Environmental Protection Agency (1982, Table 3.1.4-13) gives a value of 0.91 g/mile.

(s) Pierson and Brachaczek (1983, Table 2) give 865 ± 161 mg/km (or 1.39 ± 0.26 g/mile). U.S. Environmental Protection Agency (1982, Table 3.1.5-1) gives 1.3 g/mile; and Baines, Somers, and Harvey (1979) report a Los Angeles diesel usage emission factor of 0.83 g/km (or 1.34 g/mile).

(t) U.S. Environmental Protection Agency (1982, pp. 3.1.7-1 and 3.1.7-2) report that 38% of the motorcycles in use have two-stroke engines emitting 0.33 g/mile and 62% have four-stroke engines which emit 0.046 g/mile. The weighted average is 0.15 g/mile.

(u) Total particulate emissions from LPG use for carburetion is 1.6 kg/day from the California Air Resources Board 1982 inventory of area source emissions (Ranzieri 1983). This source is very small and is hereafter neglected.

(v) Watson (1979, p. 100).

(w) The fine particle emission factor from leaded fuel auto fleet was assembled as follows: average lead content in 1982 was 0.82 g/gal (Shelton 1982-1983; 1/4 winter 1981-1982, 1/2 summer 1982, 1/4 winter 1982-1983). At 13.7 miles/gal (see Table A.5), lead consumption is 0.06 g/mile. From Huntzicker, Friedlander, and Davidson (1975), 70.5% of lead consumed in gasoline in Los Angeles is emitted as aerosol and 19% of aerosol lead emitted is in sizes less than 1 μm, giving 8.0 mg/mile fine aerosol lead or 13.5 mg/mile fine lead salts as $2PbBrCl \cdot NH_4Cl$. The emissions rate of particulate carbon for pre-catalyst autos burning leaded gasoline at low altitude is 89.0 mg/mile, from Gorse (1984). (Inference from Pierson and Brachaczek [1983, Table 2], gives 94.6 mg/mile, consistent with the emission rate from Gorse [1984].) Aerosol carbon is assumed to be concentrated in the fine particle fraction of the auto exhaust. Fine elemental carbon emissions are estimated to be 19.0 mg/mile by applying an elemental/total carbon factor of 21.3%, which is an average of results from four researchers: Johnson et al. (1981) (8%), Muhlbaier and Williams (1982) (26.5%), Gorse (1984) (<37%--known to be overestimated by as much as a factor of 2), and Watson (1979) (13.8%). Organic carbon remaining is (89.0 mg/mile - 19.0 mg/mile) = 70.0 mg/mile which becomes about 84.0 mg/mile as organic material. Total auto fine particle emissions become 116.5 mg/mile (13.5 mg/mile lead salts, 19.0 mg/mile elemental carbon, 84.0 mg/mile organic material). This fine aerosol is about 36.4% of the total aerosol emission factor (i.e., 0.1165/0.32 = 0.364). The fraction of the fine aerosol which is carbon is therefore 76.4% (i.e., 89.0/116.5).

(x) Taback et al. (1979, table p. A-5).

(y) Assumed size distribution similar to catalyst autos (unleaded gasoline); see note (v).

(z) Other non-catalyst (leaded gasoline) vehicles assumed to have the same size distribution and chemical composition as leaded auto exhaust; see note (w).

(aa) Assumed size distribution similar to diesel autos; see note (x).

(bb) Heywood, Fay, and Linden (1971).

(cc) Assumed similar to leaded auto exhaust; see note (w).

(dd) Assumed similar to industrial boilers burning residual oil (Taback et al. 1979, table p. A-3).

(ee) Assumed size distribution similar to heavy-duty diesel highway vehicles; see notes (aa) and (x).

(ff) Muhlbaier and Williams (1982) report that catalyst equipped cars at low elevation emit aerosol with the following properties: total mass 14 mg/mile, organic carbon 3.0 mg/mile, elemental carbon 2.5 mg/mile.

(gg) Average of nine source tests performed on light-duty diesels by Japar et al. (1984, Table I) (FTP runs only; carbon determination by thermal-optical method of Johnson et al. [1981], with pyrolysis correction). The value of 83.7% carbon is in excellent agreement with the results of Pierson and Brachaczek (1983) for the 1977 Tuscarora Tunnel experiment which yielded 83.8% carbon for heavy-duty diesel trucks. The organic/elemental carbon ratio (23.4/76.6) is also in good agreement with both Pierson and Brachaczek (1983) (29./71.) and Johnson et al. (1981) (27./73.).

(hh) Assumed chemical composition similar to catalyst autos (unleaded gasoline); see note (ff).

(ii) Assumed chemical composition similar to diesel autos; see note (gg).

(jj) Jet aircraft emissions measured in this manner are all "soot" (Heywood, Fay, and Linden 1971); assume chemical composition looks like diesel soot (Flagan 1980).

(kk) Johnson et al. (1981).

Table A.2

Emissions Estimates for Stationary Combustion Sources in 50X50-mile grid

	Estimated 1982 Fuel Use (10^9 Btu/day) (a)	Total Particulate Emissions Factor (kg/10^9 Btu)	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 μm	Fine Total Particulate (kg/day)	%Total Carbon in < 2.1 μm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
								Volatile Carbon % OC	Non-volatile Carbon % EC		
STATIONARY SOURCES											
Fuel Combustion											
Electric Utilities											
Natural Gas (boilers)	572.3	1.08(b)	618.1	92% (s)	568.6	7% (dd)	39.8	100%	small(rr)	39.8	0
Natural Gas (turbines)	38.3	5.99(c)	229.4	92% (s)	211.1	7% (dd)	14.8	100%	small(rr)	14.8	0
Residual Oil	112.1	9.09(d)	1019.0	95% (t)	968.0	20% (ee)	193.6	80%	20%(ss)	154.9	38.7
Distillate Oil (turbines)	0.40	16.35(e)	6.5	96.4% (u)	6.3	15% (ff)	0.9	42%	58%(tt)	0.4	0.5
Digester Gas	0.57	1.08(f)	0.6	92% (s)	0.6	7% (dd)	0.04	100%	small(rr)	0.04	0
Refinery Fuel											
Natural Gas	99.0	9.07(g)	897.9	92% (v)	826.1	7% (gg)	57.8	100%	small(uu)	57.8	0
Refinery Gas	333.6	9.07(g)	3025.8	92% (s)	2783.7	7% (hh)	194.9	100%	small(rr)	194.9	0
Residual Oil	5.25	21.64(h)	113.6	72% (w)	81.8	11.3%(ii)	9.2	80%	20%(ss)	7.4	1.8
Non-refinery Industrial/Low Priority Commercial Fuel											
Natural Gas	307.2	7.56(i)	2322.4	92% (s)	2136.6	7% (hh)	149.6	100%	small(rr)	149.6	0
LPG	4.10	7.56(i)	31.0	92% (s)	28.5	7% (hh)	2.0	100%	small(rr)	2.0	0
Residual Oil	7.27	21.64(h)	157.3	72% (x)	113.3	11.3%(ii)	12.8	80%	20%(ss)	10.2	2.6
Distillate Oil	26.5	23.55(j)	624.1	96.4% (y)	601.6	15% (kk)	90.2	42%	58%(tt)	37.9	52.3
Digester Gas (IC engines)	5.70	20.41(k)	116.3	99% (z)	115.2	21% (ll)	24.2	77%	23%(ll)	18.6	5.6
Coke Oven Gas	0	7.56(l)	0	92% (s)	-	7% (hh)	-	100%	small(rr)	-	-
Gasoline (IC engines)	4.54(m)	23.49(m)	106.6(m)	99% (aa)	105.5	20% (mm)	21.1	90%	10%(mm)	19.0	2.1
Distillate Oil (IC engines)	5.43(n)	109.81(n)	596.0(n)	93% (bb)	554.3	4% (nn)	22.2	small	100%(vv)	0	22.2
Residential/High Priority Commercial Fuel											
Natural Gas	721.6	8.06(o)	5816.1	92% (s)	5350.8	12% (oo)	642.1	67%	33%(ww)	430.2	211.9
LPG	13.0	8.06(p)	104.8	92% (s)	96.4	12% (pp)	11.6	67%	33%(ww)	7.8	3.8
Residual Oil	23.4	21.64(q)	506.4	72% (w)	364.6	11.3%(ii)	41.2	80%	20%(ss)	33.0	8.2
Distillate Oil	17.1	21.64(q)	370.0	96.4% (u)	356.7	15% (ff)	53.5	42%	58%(tt)	22.5	31.0
Coal	0.43	378.0 (r)	162.5	62% (cc)	100.8	96% (qq)	96.7	78%	22%(xx)	75.5	21.3
TOTAL FUEL COMBUSTION							1678.2			1276.3	402.0

Notes for Table A.2

(a) See Appendix B, except for stationary gasoline and distillate internal combustion engines; see notes (m) and (n).

(b) Danielson and Graves (1976, p. 77); 0.015 lb/equivalent bbl (1.08 kg/10^9 Btu) from Los Angeles tests.

(c) U.S. Environmental Protection Agency (1982, Table 3.3.1-2) gives 14 lb/10^6 ft^3 or 5.99 kg/10^9 Btu.

(d) Taback et al. (1979, pp. 2-9); 3 lb/1000 gal (9.09 kg/10^9 Btu) used for 0.25% sulfur oil.

(e) U.S. Environmental Protection Agency (1982, Table 3.3.1-2) gives 5 lb/10^3 gal or 16.35 kg/10^9 Btu.

(f) Electric utility boiler natural gas combustion emission factor used; see note (b).

(g) Danielson and Graves (1976, p. 77); 0.126 lb/equivalent bbl (9.07 kg/10^9 Btu).

(h) Danielson and Graves (1976, p. 77); 0.30 lb/equivalent bbl (21.64 kg/10^9 Btu) for combustion of industrial residual fuel oil.

(i) Danielson and Graves (1976, p. 77); 0.105 lb/equivalent bbl (7.56 kg/10^9 Btu). LPG combustion is assumed to emit at the same rate as industrial natural gas combustion on an equivalent heat input basis. This is the same assumption as made by the U.S. Environmental Protection Agency (1982, Table 1.5-1) except that the natural gas emission factor of Danielson and Graves (n.d.) is lower.

(j) Taback et al. (1979, Table 2-1), KVB data, 7.2 lb/10^3 gal (23.55 kg/10^9 Btu).

(k) Average of two tests by Taback et al. (1979, p. 4-100) performed on digester gas-fired IC engine; 0.045 lb/10^6 Btu (20.41 kg/10^9 Btu).

(l) Assumed similar to industrial natural gas combustion on an equivalent heat input basis.

(m) Fuel use is derived from total particulate emissions (106.6 kg/day) which is from the Air Resources Board of California inventory of industrial point and area source emissions (Ranzieri 1983). U.S. Environmental Protection Agency (1982, Table 3.3.3-1) gives 6.47 lb/10^3 gal or 23.49 kg/10^9 Btu.

(n) Fuel use is derived from total particulate emissions (596.0 kg/day) which is from the Air Resources Board of California inventory of industrial point and area source emissions (Ranzieri 1983). U.S. Environmental Protection Agency (1982, Table 3.3.3-1) gives 33.5 lb/10^3 gal or 109.81 kg/10^9 Btu.

(o) Danielson and Graves (1976, p. 77); 0.112 lb/equivalent bbl (8.06 kg/10^9 Btu).

(p) Assumed same as residential natural gas on an equivalent heat input basis. This is the same assumption as made by the U.S. Environmental Protection Agency (1982, Table 1.5-1) except that the natural gas emission factor of Danielson and Graves (n.d.) is lower.

(q) Assumed same as industrial boiler burning residual fuel oil; see note (h).

(r) U.S. Environmental Protection Agency (1982, Table 1.1-2), assuming hand-fired stove use, 20 lb/ton coal (378.0 kg/10^9 Btu).

(s) Assumed similar to size distribution from large refinery heaters burning natural gas; see note (v).

(t) Taback et al. (1979, table p. A-8).

(u) Assumed similar to size distribution from industrial boiler burning distillate oil; see note (y).

(v) Taback et al. (1979, table p. A-29).

(w) Assumed similar to size distribution from industrial boiler burning residual fuel oil; see note (x).

(x) Taback et al. (1979, table p. A-3).

(y) Taback et al. (1979, table p. A-4).

(z) Taback et al. (1979, table p. 4-99).

(aa) Taback et al. (1979, table p. A-6).

(bb) Taback et al. (1979, table p. A-5).

(cc) Assumed similar to fireplace wood combustion profile from Watson (1979). Possibly a poor assumption, but data on fireplace coal combustion are lacking.

(dd) Assumed based on refinery heater test by Taback et al. (1979); see note (gg). Electric utility source test by Manfredi and Mansour (1975) showed that particulate matter emitted from LADWP Scattergood Unit 3 when burning natural gas consisted mostly of Fe, Na, Si, and Ca compounds. Mansour (n.d.) confirms that power plant samples when burning gas during that test were not dark in color.

(ee) Taback et al. (1979, table p. A-8).

(ff) Assumed similar to industrial boiler burning distillate oil; see note (kk).

(gg) Taback et al. (1979, table p. A-29).

(hh) Assumed similar to refinery heaters burning natural gas; see note (gg).

(ii) Assumed similar to industrial boiler burning residual fuel oil; see note (jj).

(jj) Taback et al. (1979, table p. A-3).

(kk) Taback et al. (1979, table p. A-4).

(ll) Taback et al. (1979, table 4-36, p. 4-101); average of impinger catches.

(mm) Taback et al. (1979, table p. A-6).

(nn) Taback et al. (1979, table p. A-5).

(oo) Muhlbaier and Williams (1982) report that 12% of aerosol mass is carbon from ten samples taken downstream of a small furnace. Note that the overall emission factor for carbonaceous aerosol from domestic natural gas combustion becomes (8.06 kg/10^9 Btu X 0.12) = 0.97 kg C/10^9 Btu = 0.97 μg C/Btu. Source tests by Hansen, Benner, and Novakov (1978) show that domestic natural gas combustion sources emit carbon at a rate of between 0.2 to 2.5 μg C/Btu, in good agreement with the emission rate used in this study.

(pp) Assumed similar to residential natural gas combustion; see note (oo).

(qq) No data are available on carbon mass as a fraction of fine particle mass emissions from coal combustion in fireplaces; therefore, an extreme upper limit has been used.

(rr) Assumed similar to large refinery heaters burning natural gas; see note (uu).

(ss) Johnson et al. (1981) for residual fuel oil combustion with pyrolysis correction.

(tt) Johnson et al. (1981) for distillate fuel oil combustion with pyrolysis correction.

(uu) Taback et al. (1979, table p. A-29). All carbon collected during source test was volatile.

(vv) Taback et al. (1979, table p. A-5). Volatile carbon collected during source test was less than 0.1% of total carbon.

(ww) Muhlbaier and Williams (1982) report that two-thirds of the carbon found on ten samples taken downstream of a small furnace was present as organics.

(xx) Chemical composition of carbon present is based on volatile organic to non-volatile carbon ratio for fine particles from fireplace combustion of wood given by Watson (1979). Assumptions made for this source class are poor, but the source class is very small.

Table A.3

Emissions Estimates for Industrial Processes in 50X50-mile grid

	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Suspended Particulate < 2.1 µm (kg/day)	% Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
						Volatile Carbon % OC	Non-volatile Carbon % EC		
	(a)								
STATIONARY SOURCES									
Industrial Process Point Sources									
Petroleum Industry									
Refining (FCCU)	1591.2	54% (b)	859.2	3.8%(b)	32.7	75%	25% (b)	24.5	8.2
Other	335.2	100% (c)	335.2	≤83% (q)	278.2	100%	0% (q)	278.2	0
Organic Solvent Use									
Surface Coating	2847.2	91.5%(d)	2605.2	55% (d)	1432.9	100%	0% (d)	1432.9	0
Printing	25.6	91.5%(d)	23.4	55% (d)	12.9	100%	0% (d)	12.9	0
Degreasing	6.2	100% (c)	6.2	≤83% (q)	5.1	100%	0% (q)	5.1	0
Other	128.0	100% (c)	128.0	≤83% (q)	106.2	100%	0% (q)	106.2	0
Chemical									
Organic	2360.6	94.5%(e)	2230.8	33% (e)	736.2	94%	6% (e)	692.0	44.2
Inorganic	151.2	94.5%(f)	142.9	0%	0	-	-	-	-
Metallurgical									
Primary	392.8	98.2%(g)	385.7	59.2%(g)	228.4	100%	0% (g)	228.4	0
Secondary	1449.8	88.5%(h)	1283.1	13% (h)	166.8	100%	0% (h)	166.8	0
Fabrication	547.1	77% (i)	421.3	0% (i)	0	-	-	-	-
Mineral	3772.6	55.1%(j)	2078.7	10.2%(j)	212.0	74.4%	25.6%(j)	157.7	54.3
Waste Burning	264.9	84.5%(k)	223.8	30% (k)	67.2	30%	70% (k)	20.1	47.0
Wood Processing	370.8	56% (l)	207.6	41.2%(l)	85.6	87%	13% (l)	74.4	11.1
Food and Agriculture	1653.7	1% (m)	16.5	30% (m)	5.0	100%	0% (m)	5.0	0
Asphalt Roofing	377.1	93% (n)	350.7	24% (n)	84.2	96%	4% (n)	80.8	3.4
Textile	218.6	1% (o)	2.2	≤83% (q)	1.8	100%	0% (q)	1.8	0
Rubber and Plastics	43.0	100% (c)	43.0	≤83% (q)	35.7	100%	0% (q)	35.7	0
Coke Calciner	266.4	100% (c)	266.4	89.8%(r)	239.2	0%	100% (r)	0	239.2
Miscellaneous Industrial	1865.3	69.5%(p)	1296.4	32.7%(p)	423.9	92.8%	7.2%(p)	393.4	30.5
TOTAL PROCESS POINT SOURCES					4154.0			3715.9	437.9

Notes for Table A.3

(a) Total particulate emissions data are from the Air Resources Board of California inventory of industrial point and area source emissions (Ranzieri 1983).

(b) Based on FCC unit CO boiler profile from Taback et al. (1979, table p. A-30).

(c) Assumed to be all fine, < 2.1 μm.

(d) Based on paint spray booth profile (oil-based paint) from Taback et al. (1979, table p. A-24).

(e) Based on urea manufacturing profile as a typical organic chemical product; Taback et al. (1979, table p. A-26).

(f) Assumed similar to size distribution for organic chemical manufacturing; see note (e).

(g) The total particulate matter from primary metallurgical production is from many sources. Size distribution and chemical profile data are available from Taback et al. (1979, tables pp. A-14, A-15, and A-33) for steel sinter operations, open hearth furnace, and basic oxygen furnace. Additionally, coke oven volatiles are assumed to be < 2.1 μm organics. These four sources account for 43% of the total particulate emissions from primary metals production. Data used in this table represent a composite of these four profiles, in proportion to the contribution of each source to the total particulate emissions in the SCAB (32.0% sinter plant profile, 3.6% open hearth furnace profile, 12.8% basic oxygen furnace profile, and 51.6% coke oven volatiles).

(h) Based on aluminum foundry profile from Taback et al. (1979, table p. A-13).

(i) Based on steel abrasive blasting profile from Taback et al. (1979, table p. A-12). Total carbon collected during source test was reported to be less than 0.1% of fine particulate matter.

(j) Profiles are available from Taback et al. (1979) for eight processes which account for 30.5% of the total particulate emissions from mineral processes; calcination of gypsum (p. A-16), brick grinding and screening (p. A-17), cement production (p. A-18), glass melting furnace (p. A-19), rock crushers (p. A-35), rock screening (p. A-36), asphaltic concrete batch plant (p. A-22), and fiberglass forming line (p. A-20). Data used in this table represent a composite of these eight profiles, in proportion to the contribution of each source to the total particulate emissions in the SCAB (2.7% gypsum, 18.3% brick grinding, 36.8% cement, 17.5% glass, 7.9% rock crushers, 0.4% rock screening, 10.6% asphalt batch plant, and 5.8% fiberglass).

(k) Based on wood waste boiler profile from Taback et al. (1979, table p. A-7). These emissions are probably from special purpose permitted incinerators for which local source test data on chemical composition are lacking.

(l) Based on an average of wood resawing and wood sanding operations from Taback et al. (1979, tables pp. A-26 and A-28).

(m) Based on feed and grain operations profile from Taback et al. (1979, table p. A-31). Source category actually includes emissions from wool and cotton fabrications, meat packing, rendering, cooking, etc. All carbon present is assumed to be organic carbon.

(n) Taback et al. (1979, table p. A-21).

(o) Size distribution data are not available for particulate emissions from fabric production. It is assumed that almost all particles emitted are larger than 2.1 μm.

(p) No data; value assumed to be the average of all other industrial process point sources listed above (in the SCAB; see Appendix C, Table C.3).

(q) Assumed to be a typical organic liquid: organic mass $\simeq$ 1.2 times carbon present (Wolff et al. 1982, Countess et al. 1980, Groblicki 1981).

(r) Petroleum coke is 89.2% carbon and 10.4% volatile material, based on proprietary information from a Long Beach area coke supplier. Similar results may be found in Kerr McGee Corporation (1982). The volatile (organic material) is removed during the calcining process, leaving the remaining 89.6% of the mass to be emitted to the atmosphere as fine particulate matter. The 10.4% of petroleum coke, which is organic material, becomes about 8.7% as carbon; therefore, the elemental carbon fraction of the coke is 89.2 - 8.7 = 80.5%. The carbon fraction of the emissions is then 80.5/89.6 = 89.8% (all elemental carbon).

Table A.4

Emissions Estimates for Fugitive Sources
in 50X50-mile grid

	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Total Particulate (kg/day)	% Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon: Volatile Carbon % OC	Partition of Carbon: Non-volatile Carbon % EC	Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
<u>FUGITIVE SOURCES</u>									
Road and Building Construction	66906.2(a)	32% (g)	21410.0	0% (g)	0	–	–	–	–
Agricultural Tilling	2727.7(a)	30.5%(h)	831.9	0% (h)	0	–	–	–	–
Livestock Feedlots	1886.1(a)	54% (i)	1018.5	2% (i)	20.4	100%	0% (i)	20.4	0
Unpaved Road Dust	4039.6(a)	24% (j)	969.5	0% (j)	0	–	–	–	–
Paved Road Dust	129705.0(a)	27% (k)	35020.4	15.1% (v)	5288.1	96.7%	3.3% (v)	5113.6	174.5
Tire Attrition	4604.1(b)	25% (l)	1151.0	87% (w)	1001.4	67%	33% (w)	670.9	330.5
Brake Lining Attrition	6445.7(c)	100% (m)	6445.7	28% (x)	1804.8	82%	18% (x)	1479.9	324.9
Forest Fires (seasonal)	1722.2(a)	86% (n)	1481.1	63% (y)	933.1	94%	6% (y)	877.1	56.0
Structural Fires	357.5(a)	86.5%(o)	309.2	30% (o)	92.8	68%	32% (cc)	63.1	29.7
Fireplaces	6556.1(d)	42% (p)	2753.6	(z)	1612.6	(z)	(z)	1269.6	343.0
Cigarettes	1669.0(e)	100% (q)	1669.0	82.5% (q)	1376.9	97%	3% (q)	1335.6	41.3
Charcoal Broilers	5414.4(r)	100% (r)	5414.4	82.3% (r)	4456.1	98.5%	1.5% (r)	4389.2	66.8
Agricultural Burning	5.8(a)	94% (s)	5.5	52% (aa)	2.8	91%	9% (aa)	2.6	0.3
Sea Salt	30131.3(f)	8% (t)	2410.5	0% (bb)	0	–	–	–	–
Roofing Tar Pots	921.9(a)	100% (u)	921.9	81.7% (u)	753.2	99.9%	0.1% (u)	752.4	0.8
TOTAL FUGITIVE SOURCES					17342.2			15974.4	1367.8

Notes for Table A.4

(a) Total particulate emissions data are from the Air Resources Board of California spatially resolved inventory of point and area source emissions (Ranzieri 1983).

(b) See Table A.7.

(c) See Table A.8.

(d) See Table A.9.

(e) Taback et al. (1979, pp. 2-70, 2-71), estimate that each year an average of 0.1538 lb of particulate matter is emitted per person from cigarette smoke. There are 8,734,856 people in the 50X50-mile grid (see Appendix B, Table B.1) yielding 1.34×10^6 lb/yr or 1669.0 kg/day.

(f) Taback et al. (1979, pp. 2-85 to 2-92), estimate 20,000 tons/year of sea salt emissions (particles < 10 μm). The size distribution data indicate that 76% of particles are < 10 μm, yielding 26,316 tons/year or 65,406.9 kg/day of total particulate emissions in the SCAB. It is assumed that 46.1% of the SCAB emissions are in the 50X50-mile grid (shipping lane distance fraction from bunker fuel emissions calculation; see note [d], Table A.1) giving 30,131.3 kg/day in the grid. This estimate is not very precise, but the source class contributes no particulate carbon; see note (cc).

(g) Taback et al. (1979, table p. A-46).

(h) Taback et al. (1979, table p. A-50).

(i) Taback et al. (1979, table p. A-44); assumed to be organic carbon.

(j) Taback et al. (1979, table p. A-45).

(k) Taback et al. (1979, figure p. 2-58).

(l) Average of data from Pierson and Brachaczek (1974, pp. 1295 and 1296).

(m) Assumed to be all fine, < 2.1 μm.

(n) Taback et al. (1979, table p. A-48).

(o) Taback et al. (1979, table p. A-37).

(p) Taback et al. (1979, table p. A-39).

(q) Taback et al. (1979, table p. A-41), give 100% in the fine fraction. Source tests on cigarettes (Gray, Cass, and Turpin 1985) yield 82.5% total carbon, and 97% of the carbon was found to be organic. Taback et al. (1979, table p. A-41) found similar results for the total carbon in the fine fraction (85%).

(r) The Air Resources Board of California uses an estimate of 3000 lb/year for the total particulate emissions rate from a typical charcoal broiler facility to compute annual emissions for this source class (Grisinger 1982). This value is checked against the results of a study by Bornstein (1978), which indicates an emission rate of 1360 kg (or 2998 lb) per facility per year (all in particle sizes less than 2.1 µm). Since these results are in agreement, the total particulate emissions inventory from the ARB is used. Source tests on charcoal broilers indicate that all material emitted is in the fine fraction. Of the 82.3% found to be carbon, 98.5% was organics (Gray, Cass, and Turpin 1985).

(s) Taback et al. (1979, table p. A-47).

(t) Taback et al. (1979, figure p. 2-92).

(u) Source tests on roofing tar pots indicate that all material emitted is in the fine fraction. Of the 81.7% found to be carbon, 99.9% was organics (Gray, Cass, and Turpin 1985).

(v) Source tests of paved road dust give 15.1% total carbon, and 96.7% of the carbon was found to be organics (Gray, Cass, and Turpin 1985). The carbon content of roadside soil was found to be 7.3% by Pierson and Brachaczek (1983, table p. 18); and fine particle analysis on street dust by Watson (1979, table p. 94), gives 92% organics.

(w) 87% carbon computed from formula for oil extended synthetic tire rubber given by Morton (1973); 29% of tire tread batch is ISAF carbon black. Carbon present is thus found as about 67% organics, 33% elemental carbon.

(x) Based on automobile brake lining chemical composition given by Lynch (1968), plus the assumption that resins and polymers are 83% carbon by weight, and assuming that carbon present is emitted as aerosol without combustion or pyrolysis.

(y) Based on slash burning fine particulate matter analysis from Watson (1979, table p. 107).

(z) See Table A.9.

(aa) Based on simulated field burning fine particulate matter analysis from Watson (1979, table p. 109).

(bb) Taback et al. (1979, table p. A-42).

(cc) Based on carbon emission rates from soft wood from Muhlbaier and Williams (1982, Table 2, p. 190).

Table A.5

Fuel Economy Calculation for 1982 Automobile Fleet

Age (years)	Model Year	% Vehicles in Use	% Diesels per Year	(α) % Gasoline Vehicles in Use	(β) %Diesel Vehicles in Use	(γ) Annual Avg. Mileage	(α)(γ)	(β)(γ)	(α)(γ)/sum Fraction VMT Gasoline	(β)(γ)/sum Fraction VMT Diesel	Fuel Economy Gasoline (mpg)	Inverse Fuel Economy Gasoline (gal/mi)	Weighted Avg. Inverse Fuel Econ Gasoline (gal/mi)	Fuel Economy Diesel (mpg)	Inverse Fuel Economy Diesel (gal/mi)	
		(a)	(b)			(c)					(d)			(e)		
1	1982	7.77	4.6	7.41	0.36	15900	1178.60	56.83	0.111	0.0054	26.2	0.038	0.0474 (21.10 mpg)	27.0	0.0370	0.0405 (24.69 mpg)
2	1981	7.77	5.9	7.31	0.46	15000	1096.74	68.76	0.104	0.0065	25.1	0.040		25.9	0.0386	
3	1980	8.76	4.6	8.36	0.40	14000	1169.99	56.41	0.111	0.0053	23.5	0.043		24.2	0.0413	
4	1979	9.20	2.2	9.00	0.20	13100	1178.69	26.51	0.111	0.0025	20.3	0.049		20.9	0.0478	
5	1978	8.50	0.4	8.47	0.03	12200	1032.85	4.15	0.098	0.0004	19.9	0.050		20.5	0.0488	
6	1977	6.73	0.1	6.72	0.01	11300	759.73	0.76	0.072	0.00007	18.3	0.055		18.9	0.0529	
7	1976	5.51	0.1	5.50	0.01	10300	566.96	0.57	0.054	0.00005	17.5	0.057		18.0	0.0556	
8	1975	5.37	0.1	5.36	0.01	9400	504.28	0.50	0.048	0.00005	15.8	0.063		16.3	0.0613	
9	1974	6.45	0.1	6.44	0.01	8500	547.70	0.55	0.052	0.00005	14.2	0.070	0.0733 (13.65 mpg)	14.6	0.0685	
10	1973	5.78	-	5.78	-	7600	439.28	-	0.042		13.6	0.074				
11	1972	4.90	-	4.90	-	6700	328.30	-	0.031		13.6	0.074				
12	1971	3.88	-	3.88	-	6700	259.96	-	0.025		13.6	0.074				
≥13	1970(-)	19.38	-	19.38	-	6700	1298.46	-	0.123		13.6	0.074				
				sum = (α)(γ) + (β)(γ)			= 10576.58		average annual mileage/vehicle							

	Fraction VMT	Weighted Average (gal/mi)	Weighted Average Mi/Gal (mpg)
Light-duty gasoline catalyst (unleaded)	0.7080	0.0474	21.66
Light-duty gasoline non-catalyst (leaded)	0.2717	0.0733	13.71
Light-duty diesel automobiles	0.0203	0.0405	24.93

Notes for Table A.5

(a) Percent distribution of fee-paid registrations by age of vehicle, 1982, from California Department of Finance (1982, Table J-5).

(b) Values for 1980 and previous years are from Diesel Impacts Study Committee (1982, pp. 1 and 90). Values for 1981 and 1982 are from *Automotive News*, as cited by Holman and Lauderdale (1983, p. 7).

(c) U.S. Environmental Protection Agency (1982, Table 3.1.2-5).

(d) Motor Vehicle Manufacturers' Association (1983, p. 74).

(e) Fuel economy for 1982 diesel automobiles is 27.0 mpg from Cadle (1983). It is assumed that the fuel economy improvements for newer diesel automobiles are proportional to that observed for newer gasoline automobiles.

Table A.6

Vehicle Miles Travelled and Fuel Usage for Each Vehicle Type in 1982

Vehicle Class	Vehicle Type	Fraction of Daily VMT Within Class	Class Fraction	Fraction of Daily Total VMT	Weighted Avg. (gal/mi)	50X50-mile grid		4-County SCAB	
						Thous. VMT/day	Fuel Use (10^9 Btu/day)	Thous. VMT/day	Fuel Use (10^9 Btu/day)
			(b)				(i)		(i)
Autos			0.7754						
	Catalyst	0.7080 (a)		0.5490	0.0474 (c)	86996	515.2	101641	601.9
	Non-catalyst	0.2717		0.2107	0.0733 (c)	33385	305.6	39005	357.1
	Diesel	0.0203		0.0157	0.0405 (c)	2494	14.0	2914	16.3
Light Trucks			0.1059						
	Catalyst	0.7080 (a)		0.0750	0.0647 (d)	11882	96.0	13882	112.2
	Non-catalyst	0.2717		0.0288	0.1000 (e)	4560	57.0	5328	66.6
	Diesel	0.0203		0.0021	0.0553 (d)	341	2.6	398	3.0
Medium Trucks			0.0530						
	Catalyst	0.5951 (b)		0.0315	0.0943 (f)	4994	58.9	5835	68.8
	Non-catalyst	0.4049		0.0214	0.0943 (f)	3398	40.1	3970	46.8
	Diesel	—		—	—	—	—	—	—
Heavy Trucks									
	Gas (Leaded)		0.0193	0.0193	0.1754 (f)	3050	66.9	3564	78.1
	Diesel		0.0370	0.0370	0.1818 (f)	5857	147.4	6843	172.2
Motorcycles									
	Gas (Leaded)		0.0095	0.0095	0.0200 (g)	1503	3.8	1756	4.4
ALL CLASSES TOTAL						158460 (h)	1307.5	185136 (j)	1527.4
	Catalyst Total			0.6555		103872	670.1	121358	782.9
	Non-catalyst Total			0.2897		45896	473.4	53623	553.0
	Diesel Total			0.0548		8692	164.0	10155	191.5

Notes for Table A.6

(a) See Table A.5.

(b) Air Resources Board of California (1983) data from EMFAC 1982 vehicle emissions model for the South Coast Air Basin.

(c) Light duty fuel economy calculation; see Table A.5.

(d) Assuming improvement in newer light truck fuel economy proportional to that observed for newer automobiles.

(e) U.S. Environmental Protection Agency (1982, Table 3.1.4-7).

(f) Medium and heavy-duty truck fuel economy from EPA test data as reported by the Air Resources Board of California (1980, Table II-10).

(g) Motorcycle fuel economy from Motor Vehicles Facts and Figures '76 as reported by Air Resources Board of California (1980, Table II-10).

(h) Freeway traffic data from Caltrans (California Department of Transportation 1983) give 67,661.6 thousand vehicle miles travelled per day on the 50X50-mile grid. This is added to the surface traffic total of 90,800.0 thousand vehicle miles per day from Cass, Hahn, and Noll (1982) (updated to 1982) to give 158,461.6 thousand vehicle miles travelled per day in 1982.

(i) The heating value of gasoline is 5248×10^3 Btu/bbl (or 124,952 Btu/gal). The heating value of diesel is 5812×10^3 Btu/bbl (or 138,381 Btu/gal) from Cass (1977, p. 598).

(j) Total vehicle miles travelled by all vehicles in the South Coast Air Basin (four counties) is 185,136 thousand VMT/day from Air Resources Board of California (1983) EMFAC.

Table A.7

Tire Attrition 1982

							50X50-mile grid		SCAB	
	1976 Estimated Annual Mileage/ Vehicle	No. of Tires	Vehicles SCAB	1976 SCAB 10^6 Tire Miles/ Year	10^6 Counted Vehicles Miles/Yr.	Weighted Avg. No. Tires/ Counted Vehicle	1982 VMT (Thous. VMT/day)	Tire Attrition (kg/day)	1982 VMT (Thous. VMT/day)	Tire Attrition (kg/day)
	(a)	(a)	(a)	(b)	(c)			(d)		(d)
Counted Vehicles										
Light Duty Vehicles										
Autos	9634	4	4641484	178864	44716					
Comm'l 2-axle <5000# curb wt	9634	4	750176	28909	7227					
TOTAL				207773	51943	4.000	141161	3557.3	164924	4156.1
Medium Duty Vehicles										
Comm'l 2-axle 5000-10,000# curb wt	8822	4	79683	2812	703					
Comm'l 3-axle 5000-10,000# curb wt	49125	10	413	203	20					
TOTAL				3015	723	4.168	8392	220.4	9805	257.5
Heavy Duty Vehicles										
Comm'l 2-axle >10,000# curb wt	8822	6	20883	1105	184					
Comm'l 3-axle >10,000# curb wt	49125	10	22475	11041	1104					
Comm'l 4-axle >10,000# curb wt	8822	14	313	39	3					
TOTAL				12185	1291	9.438	8907	529.6	10407	618.8
COUNTED VEHICLE TOTAL					53957		158460 (e)	4307.3	185136 (e)	5032.4
Trailers										
1-axle <5000# curb wt	3854	2	161367	1244						
2-axle <5000# curb wt	3854	4	30096	464						
3-axle <5000# curb wt	3854	6	610	14						
1-axle 5000-10,000# curb wt	3528	2	24303	17						
2-axle 5000-10,000# curb wt	44213	8	23372	8267						
3-axle 5000-10,000# curb wt	44213	6	257	68						
4-axle 5000-10,000# curb wt	3528	8	29	1						
1-axle >10,000# curb wt	7940	4	1484	47						
2-axle >10,000# curb wt	44213	8	16253	5749						
3-axle >10,000# curb wt	7940	12	156	15						
4-axle >10,000# curb wt	7940	16	29	4						
TRAILER TOTAL				16044				296.8 (g)	55050 (f)	346.8
ALL VEHICLE TOTAL								4604.1		5379.2

Notes for Table A.7

(a) Data for 1976 from Halberg (1980).

(b) Tire miles are computed by multiplying annual mileage per vehicle, number of tires and vehicles in the South Coast Air Basin (SCAB). This calculation is performed using 1976 data to get the average number of tires per counted vehicle and the relative number of trailer tire miles to counted vehicle tire miles.

(c) One vehicle count is made for each vehicle (not including trailers) in the SCAB by multiplying annual mileage and number of vehicle.

(d) Suspended aerosol emission rate of 0.0063 gm/tire/mile based on average of results by Pierson and Brachaczek (1974, pp. 1295 and 1296).

(e) See Table A.6 for 1982 grid and SCAB total vehicle miles travelled (VMT).

(f) Vehicle tire miles for trailers was scaled by 1.252 to reflect the increase from 1976 AQMD counted VMT to 1982 VMT (i.e., 53,957 X 10^6 VMT/yr or 147,827 X 10^3 VMT/day X 1.252 = 185,1136 X 10^3 VMT/day, and 16,044 X 10^6 tire miles/yr or 43,956 X 10^3 tire miles/day X 1.252 = 55,050 X 10^3 tire miles/day). This value represents thousand tire miles per day.

(g) It is assumed that tire miles for trailers in the 50X50-mile grid are of the same proportion to the SCAB as vehicle miles (85.6%); see Table A.6.

Table A.8

Brake Lining Attrition 1982

	1976 Estimated Annual Mileage	Adjusted 1982 Annual Mileage Per Vehicle	Vehicles in SCAB	% VMT Using Front Disc Brakes	Particulate Emission Factors ($lbs/10^6$ VMT) (d)		1982 Particulate Emissions SCAB		
					With Disc	Without Disc	With Front Disc (kg/day)	Without Disc (kg/day)	Total (kg/day)
	(a)	(b)	(a)	(c)					
Light Duty Vehicles									
Autos	9634	12065	4641484	80%	14.6 + 43.4	43.4 X 2	3229.1	1208.1	4437.2
Comm'l 2-axle <5000# curb wt	9634	12065	750176	80%	14.6 + 43.4	43.4 X 2	521.9	195.3	717.2
Medium Duty Vehicles									
Comm'l 2-axle 5000-10,000# curb wt	8822	11048	79683			125 X 2			273.5
Comm'l 3-axle 5000-10,000# curb wt	49125	61523	413			125 X 3			11.8
Heavy Duty Vehicles									
Comm'l 2-axle >10,000# curb wt	8822	11048	20883	100%		233 X 2	133.6		133.6
Comm'l 3-axle >10,000# curb wt	49125	61523	22475	100%		83 + 233 X 2	943.4		943.4
Comm'l 4-axle >10,000# curb wt	8822	11048	313	100%		83 + 233 X 3	3.4		3.4
Trailers									
1-axle <5000# curb wt	3854	4827	161367			43.4			42.0
2-axle <5000# curb wt	3854	4827	30096			43.4 X 2			15.7
3-axle <5000# curb wt	3854	4827	610			43.4 X 3			0.5
1-axle 5000-10,000# curb wt	3528	4418	24303			125 X 1			16.7
2-axle 5000-10,000# curb wt	44213	55371	23372			125 X 2			402.1
3-axle 5000-10,000# curb wt	44213	55371	257			125 X 3			6.6
4-axle 5000-10,000# curb wt	3528	4418	29			125 X 4			0.1
1-axle >10,000# curb wt	7940	9944	1484	100%		233 X 1	4.3		4.3
2-axle >10,000# curb wt	44213	55371	16253	100%		233 X 2	521.2		521.2
3-axle >10,000# curb wt	7940	9944	156	100%		233 X 3	1.3		1.3
4-axle >10,000# curb wt	7940	9944	29	100%		233 X 4	0.3		0.3
							SCAB TOTAL		7530.8
							GRID TOTAL (e)		6445.7

Notes for Table A.8

(a) Data for 1976 from Halberg (1980).

(b) 1976 AQMD data multiplied by 1.252 to coincide with 1982 VMT data (not including trailers) in the South Coast Air Basin; see Table A.7, note (f).

(c) Taback et al. (1979, p. 2-88). All past-1970 GM passenger cars equipped with front disc brakes.

(d) Taback et al. (1979, pp. 283-288).

(e) The emissions in the 50X50-mile grid are proportional to the SCAB emissions in the same ratio as vehicle miles travelled; see Table A.6.

Table A.9.1

Fireplace Emissions 1982

	Residences	% Residences Burning Wood	Residences Burning Wood	Avg. Cords/ Residence-Yr. (Wood Burners)	Fraction of Wood Type	Cords/ Residence-Yr. (Wood Burners)	Cords Burned/ Year	kg Mass/ Cord	10^6 kg Wood Burned/ Year	Total Particulate Emission Factor (g/kg wood)	Total Particulate Emissions (kg/day)
	(a)	(b)		(b)	(b)			(c)		(d)	
Los Angeles County	2808130										
Orange County	716791										
TOTAL	3524921	20.3%	715559	0.286							
Softwood					0.664	0.190	135888	1469.7	199.7	6.20	3392.4
Hardwood					0.336	0.096	68762	1796.2	123.5	9.99	3380.5
Total											6772.9
50X50-mile grid (f)	3412124										6556.1
San Bernardino County	299174										
Riverside County	224844										
TOTAL	524018	50.0%	262009	1.083							
Softwood					0.373	0.404	105841	1469.7	155.6	6.20	2642.3
Hardwood					0.627	0.679	177915	1796.2	319.6	9.99	8746.6
Total											11388.9
Total 4-County SCAB	4048939										18161.8

Table A.9.2

Fireplace Emissions 1982

	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Total Particulate < 2.1 µm	% Total Carbon in < 2.1 µm Fraction	Total Fine Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
						Volatile Carbon % OC	Non-volatile Carbon % EC		
		(e)		(d)		(d)	(d)		
Los Angeles and Orange Counties									
Softwood	3392.4	42%	1424.8	66.1%	941.8	68.3%	31.7%	643.3	298.6
Hardwood	3380.5	42%	1419.8	51.0%	724.1	92.3%	7.7%	668.3	55.8
Total	6772.9		2844.6		1665.9			1311.6	354.3
50X50-mile grid (f)	6556.1		2753.6		1612.6			1269.6	343.0
San Bernardino and Riverside Counties									
Softwood	2642.3	42%	1109.8	66.1%	733.6	68.3%	31.7%	501.0	232.5
Hardwood	8746.6	42%	3673.6	51.0%	1873.5	92.3%	7.7%	1729.3	144.3
Total	11388.9		4783.3		2607.1			2230.3	376.8
Total 4-County SCAB	18161.8		7627.9		4273.0			3541.9	731.1

Notes for Table A.9

(a) Total dwellings by county in South Coast Air Basin, 1980, from Southern California Association of Governments (1982, p. 70) using population statistics and data on persons per dwelling unit.

(b) As part of this study, a survey was conducted throughout the South Coast Air Basin to determine the average level of woodburning in residential fireplaces. The results of this survey produced data on the fraction of residences in each county burning wood, how much wood, what type of wood, and seasonal variation of usage. These data are presented in this table (seasonal variation: 70.8% winter, 10.1% spring, 2.3% summer, 16.8% autumn; 83 responses).

(c) Based on cord weights of red oak (hardwood) and yellow pine (softwood) from Baumeister, Avallone, and Baumeister (1978, pp. 6-124 and 7-13).

(d) Muhlbaier and Williams (1982, Table 2, p. 190).

(e) Taback et al. (1979, table p. A-39).

(f) Emissions in the 50X50-mile grid are assumed to be in proportion to the on-grid fraction of the Los Angeles and Orange Counties population. The fraction of the two-counties population residing in the grid is 0.968 (Southern California Association of Governments 1982).

Table A.10
Correspondence between source types used in this study and California Air Resources Board category of emission source (CES, SCC) numbers

source type used in emission inventory (a)		California Air Resources Board category of emmission source (CES, SCC) numbers (b)
19	Off Highway Diesel	AAA47480,AAA54379,AAA54437,AAA54452, AAA54478,AAA54494,AAA54536,AAA54593
20	Off Highway Gasoline	AAA47449,AAA47464,AAA54387,AAA54411
35	Industrial IC Gasoline	AAA66746,20200301
36	Industrial IC Distillate	AAA54353,20200102,20200902
42	Petrochemical FCCU	30600201
43	Petrochemical Other	30600401,30600501,30600805,30600999, 30601301,30699998,30699999,40300199, 40399999
44	Organic Solvent Coating	AAA18697,AAA19034,AAA19109,AAA19315, AAA20107,AAA24794,AAA24877,AAA24935, AAA25056,AAA25213,AAA27920,AAA27920, AAA27995,AAA28464,AAA31583,AAA31963, AAA37861,AAA42358,AAA42416,40200101, 40200110,40200199,40200210,40200301, 40200399,40200401,40200410,40200499, 40200501,40200599,40200601,40200603, 40200701,40200799,40200801,40200803, 40201001,40201002,40288801,40299999
45	Organic Solvent Printing	40500101,40500201,40500301,40500401
46	Organic Solvent Degreasing	40100103,40100299
47	Organic Solvent Other	49099999

(a) Emissions for these source types have been compiled in Tables A.1 through A.4. The number corresponds to the source type number in Table D.38 (second column).

(b) The Califonia Air Resources Board uses CES numbers for area sources (first three digits: AAA) and SCC numbers for point sources (Ranzieri 1983).

Table A.10 (continued)

	source type used in emission inventory	California Air Resources Board category of emmission source (CES, SCC) numbers
48	Chemical Organic	30100199,30100901,30100902,30100999,30101501,30101599,30101801,30101802,30101899,30101903,30102699,30103204,30199999
49	Metal Primary	30300199,30300302,30300303,30300304,30300399,30300801,30300819,30300821,30300901,30300913,30300914,30300999,30301003,30303005,30388801,30400301,30400350,30400699,30400701,30400702,30400704,30400705,30400706,30400799
50	Metal Secondary	30400101,30400102,30400103,30400109,30400199,30400203,30400205,30400208,30400209,30400212,30400217,30400219,30400221,30400223,30400224,30400402,30400403,30400407,30400408,30400499,30400501,30400599,30400801,30400803,30400808,30400828,30400899,30488801,30499999
51	Mineral	30500201,30500205,30500299,30500302,30500311,30500605,30500606,30500609,30500610,30500613,30500616,30500617,30500619,30500699,30500799,30500801,30500803,30500899,30501101,30501199,30501201,30501204,30501205,30501299,30501401,30501402,30501404,30501406,30501410,30501411,30501503,30501599,30501701,30501703,30502006,30502501,30502599,30503203,30503299,30588801,30588802,30599999
52	Waste Burning	10201201,50200505,50300101,50300102,50300108
53	Wood and Paper Products	30700401,30700402,30799999
54	Asphalt Roofing	30500104,30500105,30500199
55	Rubber and Plastics	30800699
56	Coke Calciner	30601401

Table A.10 (continued)

	source type used in emission inventory	California Air Resources Board category of emmission source (CES, SCC) numbers
57	Food and Agriculture	30200901,30200999,30201301,30203299, 30299998,30299999
58	Textile	33000199,33000399
59	Miscellaneous Industrial	AAA10108,39999999
60	Livestock Dust	AAA47340
61	Paved Road Dust	AAA47456
64	Structural Fires	AAA47324
67	Agricultural Burning	AAA47258
68	Charcoal Broilers	AAA60418
69	Roofing Tar Pots	AAA66738
70	Chemical Inorganic	30101701,30102308,30103601,30103701, 30113003
71	Metal Fabrication	30903099,30999999
72	Road/Building Construction	AAA47357,AAA47365,AAA47373,AAA47381, AAA54551,AAA60400
73	Agricultural Tilling	AAA47332
74	Unpaved Road Dust	AAA47399,AAA47407,AAA47415,AAA47431
-	Wild Fires (c)	AAA47308,AAA47316
-	Tire Burning (c)	AAA57307
-	LPG for Carburetion (c)	AAA58727

(c) Source class is not input to the air quality model.

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APPENDIX B

1982 FUEL USE DATA

Table B.1

1980 Population by Region

	1980 Population	Fraction of California	Fraction of 6-County	Fraction of 4-County SCAB
	(a)			
50X50-mile grid (b)	8,734,856	36.9%	77.5%	83.1%
4-County SCAB (c)	10,508,922	44.4%	93.3%	100%
6-County Basin (d)	11,266,521	47.6%	100%	
California State Total	23,667,902	100%		

Notes for Table B.1

(a) From the Southern California Association of Governments (1982).

(b) For definition of the grid; see Figure 4.1.

(c) Contains Los Angeles, Orange, Riverside, and San Bernardino Counties.

(d) Contains Los Angeles, Orange, Riverside, San Bernardino, Ventura, and Santa Barbara Counties.

Table B.2

Electric Generating Stations 1982 Fuel Use

Power Plant	County	Grid Location Coordinates I	Grid Location Coordinates J	Natural Gas Boilers (Equivalent bbls/yr) (a)	Natural Gas Turbines (Equivalent bbls/yr) (a)		Residual Fuel Oil (Equivalent bbls/yr) (a)	Distillate (Equivalent bbls/yr) (a)	Digester Gas (Equivalent bbls/yr) (a)
SCE El Segundo	LA	7	12	5,373,103.50	0		190,911.0	0	0
DWP LA Scattergood	LA	7	13	1,028,281.19	0		348,730.0	0	18,254.30
SCE Redondo	LA	8	10	5,641,818.50	0		11,682.0	0	0
DWP LA Valley	LA	8	24	116,017.51	0		45,675.0	0	14,529.00
Burbank Magnolia	LA	10	22	631,502.06	59,292.0		7340.0	0	0
Glendale Airway	LA	11	21	283,391.50	216,602.0		715.0	77.0	0
SCE Northridge	LA	3	25	0	169,072.0		0	0	0
DWP LA Harbor	LA	11	7	137,130.41	11,491.0		21,026.0	1439.0	0
LB Gas Dept. (1)	LA	14	8	0	801.0		0	0	0
SCE Long Beach	LA	12	7	12,894.50	1,687,470.0		0	15,080.0	0
LB Gas Dept. (2)	LA	16	9	0	960.0		0	0	0
Pasadena Glenarm	LA	15	20	599,898.81	7,835.0		0	0	0
SCE Mt. Vernon	LA	25	18	0	44,781.0		0	0	0
SCE Alamitos	LA	16	7	10,852,545.00	13,072.0		2,333,868.0	5,721.0	0
DWP Haynes	LA	16	7	3,212,852.00	0		3,064,680.0	0	0
SCE H. Beach	Orange	19	3	5,269,042.00	7,161.0		468,774.0	542.0	0
SCE Etiwanda	SBdo	off grid		4,054,134.75	4,515.0		173,554.0	1988.0	0
SCE Highgrove	SBdo	off grid		78,694.70	0		18,986.0	0	0
SCE San Bernardino	SBdo	off grid		573,207.56	0		200,654.0	0	0
Ormond Beach	Ventura	off grid		28,166,950.00 (MCF/yr)	0		545,468.0	0	0
Mandalay	Ventura	off grid		9,782,188.00 (MCF/yr)	0		304,818.0	5571.0	0
				(10^9 Btu/day)	(10^9 Btu/day)	Total Natural Gas (10^9 Btu/day)	(10^9 Btu/day)	(10^9 Btu/day)	(10^9 Btu/day)
TOTAL GRID (b)		16 utilities		572.32	38.29	610.61	112.08	0.395	0.566
TOTAL 4-CO. SCAB (c)		19 utilities		653.55	38.37	691.92	118.86	0.429	0.566
TOTAL 6-CO. BASIN (d)		21 utilities		763.76	38.37	802.13	133.54	0.525	0.566

Notes for Table B.2

(a) Data from South Coast Air Quality Management District (1983) electric utility fuel use reports for 1982. Ventura County data from the Air Pollution Control District (1983).

(b) Each equivalent barrel of fuel has a heating value of 6.3×10^6 Btu/equiv.bbl (or 1.06×10^6 Btu/MCF).

(c) Includes Los Angeles, Orange, Riverside, and San Bernardino Counties.

(d) Includes Los Angeles, Orange, Riverside, San Bernardino, Ventura, and Santa Barbara Counties.

Table B.3

Refineries Fuel Use 1982

Refinery	County	Grid Location Coordinates		Residual Fuel Oil (Equivalent bbls/yr)	Natural Gas (Equivalent bbls/yr)	Refinery Gas (Equivalent bbls/yr)
		I	J			
				(a)	(a)	(a)
Newhall Refining	LA	off grid		5,251.0	93,113.061	28,455.829
Standard Oil of California	LA	7	12	231,189.0	1,444,488.990	4,141,342.457
Mobile Oil	LA	9	10	0.0	196,274.673	3,410,700.430
Union Oil	LA	11	8	0.0	778,004.489	2,015,775.272
Fletcher Oil & Refining	LA	11	9	0.0	37,290.828	347,632.531
Golden Eagle Refinery	LA	11	10	0.0	48,574.657	47,864.169
Shell Oil, Wilmington	LA	12	10	0.0	314,923.842	1,138,756.653
Shell Oil, Dominguez	LA	12	10	0.0	574,024.331	880,800.292
Champlin Petroleum	LA	12	8	0.0	12,498.178	957,762.669
Texaco Inc.	LA	12	8	0.0	307,701.665	1,824,471.343
Atlantic Richfield	LA	12	9	43,515.0	856,525.160	3,019,616.466
Macmillan Ring-free Oil	LA	14	8	0.0	51,849.670	663.955
Marlex Oil & Refining I	LA	14	9	0.0	53,075.009	1,999.441
Edgington Oil	LA	14	11	1894.0	224,006.833	16,220.333
Douglas Oil	LA	15	12	5940.0	139,437.336	233,262.134
Powerline Oil	LA	17	13	21,350.0	305,240.180	668,341.003
Gulf Oil	LA	18	12	118.0	390,836.013	623,792.801
				(10^9 Btu/day)	(10^9 Btu/day)	(10^9 Btu/day)
TOTAL GRID (b)	16 refineries			5.25	98.98	333.62
TOTAL (c)	17 refineries			5.34	100.59	334.12

Notes for Table B.3

(a) Data from South Coast Air Quality Management District (1983) electric utility fuel use reports for 1982.

(b) Each equivalent barrel of fuel has a heating value of 6.3×10^6 Btu/equiv.bbl.

(c) Newhall Refining is in Los Angeles County but outside of the 50X50-mile grid.

Table B.4

Residential and High Priority Commercial Natural Gas Sales, 1982

	COUNTY									
		Los Angeles								
	Orange	So. Cal. Gas Co.	Long Beach Gas Co.	San Bernardino	Riverside	Santa Barbara	Ventura	TOTAL GRID (10^9 Btu/day)	TOTAL 4-CO SCAB (10^9 Btu/day)	TOTAL 6-CO BASIN (10^9 Btu/day)
	(a)	(a)	(b)	(a)	(a)	(a)	(a)	(f)	(g)	(h)
Residential Natural Gas Use (MCF/yr) (c)	45,823,497.4	160,440,064.5	8,002,238.0 (b)	19,303,560.5	7,502,997.8	5.322,729.0	12,075,307.6		700.10	750.63
High Priority Commercial Natural Gas Use (MCF/yr) (c)	9,504,176.3	36,489,017.8	1,819,956.0 (b)	3,605,984.3	1,837,433.2	1,862,494.7	2,531,487.1		154.66	167.42
Total Residential/ High Priority Commercial Natural Gas Use (MCF/yr)	55,327,673.7	196,929,082.3	9,822,194.0 (b)	22,909,544.8	9,340,431.0	7,185,223.7	14,606,794.7		854.76	918.05
Gridded Residential Natural Gas Use (MCF/yr) (d)	42,661676,.1	149,369,700.0	7,450,083.6					579.32		
Weighted Average Monthly Total Grid Residential								585.9		
Gridded High Priority Commercial Natural Gas Use (MCF/yr) (e)	9,200,043.7	35,321,369.2	1,761,717.4					134.41		
Weighted Average Monthly Total Grid High Priority Commercial								135.7		
Total Gridded Residential/ High Priority Commercial Natural Gas Use (MCF/yr)	51,861,718.7	184,691,069.2	9,211,801.0					713.73		
Weighted Average Monthly Total Grid Residential/ Commercial								721.6		

Notes for Table B.4

(a) Data from Southern California Gas Company (1983) reports of natural gas sales by county and FPC priority number for 1982. Los Angeles County is supplied by the Southern California Gas Company and also by the City of Long Beach Gas Department.

(b) Data from the City of Long Beach Gas Department monthly natural gas deliveries for 1982 (Kortz 1983). This represents 92.1% of the priority P1 natural gas delivered in Long Beach, which is the same fraction of P1 sold to residential/high-priority commercial users in Los Angeles County during 1982 as reported by the Southern California Gas Company (1983). The remaining 7.9% is assumed to be industrial P1. This 9,822,194 MCF is assumed to be divided into residential and high priority commercial using the proportions found in Los Angeles for P1 fuel sales by the Southern California Gas Company.

(c) FPC priority number P1 only. (Residential users are all classified P1.)

(d) The 50X50-mile grid comprises 93.1% of the population in Los Angeles and Orange Counties (Cass 1977). It is assumed that residential natural gas use is distributed spatially proportional to population distribution.

(e) The 50X50-mile grid comprises 96.8% of the employment in Los Angeles and Orange Counties (Cass 1977). It is assumed that commercial natural gas use is distributed spatially proportional to employment distribution.

(f) The natural gas sales for the calendar year 1982 reported by the Southern California Gas Company do not agree with the total of the monthly gas sales for the same period presented in the same report. Both the annual total and the sum of the monthly values are presented here.

(g) Includes Los Angeles, Orange, Riverside, and San Bernardino Counties.

(h) Includes Los Angeles, Orange, Riverside, San Bernardino, Ventura, and Santa Barbara Counties.

Table B.5

Industrial and Low Priority Commercial Natural Gas Sales, 1982

County	Industrial Natural Gas Use (MCF/yr)	Low Priority Commercial Natural Gas Use (MCF/yr)	Total Industrial Low Priority Commercial Natural Gas Use (MCF/yr)	
	(c)	(d)		
Orange (a)	36,338,823.3	3,270,117.3	39,608,940.6	
Los Angeles				
So. Cal. Gas Co. (a)	249,619,080.6	39,064,738.3	288,683,818.9	
Long Beach Gas Co. (b)	18,106,099.4 (b)	2,833,557.6 (b)	20,939,657.0 (b)	
San Bernardino (a)	24,505,501.7	2,220,592.8	26,726,094.5	
Riverside (a)	2,262,233.1	889,539.9	3,1511,773.0	
Santa Barbara (a)	1,907,290.6	717,569.6	2,624,860.2	
Ventura (a)	39,816,393.3	995,194.5	40,81,587.8	
	(10^9 Btu/day)	(10^9 Btu/day)	(10^9 Btu/day)	Weighted Average Monthly Total Grid Industrial/ Commercial (10^9 Btu/day)
Total Industrial/Low Priority Commercial (e)				
2-County (f)	883.04	131.17	1014.21	
4-County (g)	960.77	140.21	1100.98	
6-County (h)	1081.94	145.18	1227.12	
Utilities (i)				
2-County			610.61	
4-County			691.92	
6-County			802.13	
Refineries (j)				
2-County			100.59	
4-County			100.59	
6-County			100.59	
Total Non-refinery Non-utility Industrial/Low Priority Commercial (k)				
2-County			303.01	
50X50-mile grid (1)			293.31 (m)	307.2 (m)
4-County SCAB			308.47	
6-County Basin			324.40	

Notes for Table B.5

(a) Data from Southern California Gas Company (1983) reports of natural gas sales by county and FPC priority number for 1982. Los Angeles County is supplied by the Southern California Gas Company and also by the City of Long Beach Gas Department.

(b) Data from the City of Long Beach Gas Department monthly natural gas deliveries for 1982 (Kortz 1983). This represents 7.9% of the priority P1 natural gas and all of the lower priority natural gas delivered; see note (b), Table B.4. The 20,939,657 MCF is assumed to be divided into industrial and low priority commercial using the proportions found in Los Angeles County for fuel sales by the Southern California Gas Company.

(c) All FPC priorities. This includes gas supplied to utilities and refineries which is subtracted below.

(d) All FPC priorities lower than P1.

(e) Includes gas supplied to utilities and refineries.

(f) Includes Orange and Los Angeles Counties.

(g) Includes Los Angeles, Orange, Riverside, and San Bernardino Counties.

(h) Includes Los Angeles, Orange, Riverside, San Bernardino, Ventura, and Santa Barbara Counties.

(i) From Table B.2.

(j) From Table B.3. All 17 refineries are in Los Angeles County.

(k) Non-refinery, non-utility industrial and low priority commercial natural gas usage is obtained by subtracting the natural gas used by utilities and refineries from the total industrial and low priority commercial natural gas use.

(l) The natural gas use by non-refinery, non-utility industrial and low priority commercial establishments in the 50X50-mile grid is assumed to be 96.8% of the natural gas use in Los Angeles and Orange Counties (2-county). This is the fraction of the 2-county employment in the grid (Cass 1977).

(m) The natural gas sales for the calendar year 1982 reported by the Southern California Gas Company do not agree with the total of the monthly gas sales for the same period presented in the same report. Both the annual total and the sum of the monthly values are presented here.

Table B.6

Deliveries of Fuels in 1982

	California (1000 bbls/yr)	6-County Basin (1000 bbls/yr)	6-County Basin (10^9 Btu/day)	4-County SCAB (10^9 Btu/day)	50X50-mile Grid (10^9 Btu/day)
	(a)				
Distillate Fuel Oil					
Residential/Commercial	4482	1380.5 (c)	22.03 (k)	20.55 (o)	17.08 (o)
Industrial (b)	4794	2301.1 (d)	36.72 (k)	27.92 (p)	26.54 (p)
Railroad	7138	1557.0 (e)	24.85 (k)	22.42 (e)	14.13 (e)
Residual Fuel Oil					
Residential/Commercial	5697	1754.7 (f)	30.22 (l)	28.19 (o)	23.43 (o)
Industrial (b)	973	467.0 (g)	8.04 (l)	7.65 (q)	7.27 (q)
Liquefied Petroleum Gas (LPG)					
Internal Combustion Engines	1697.5	814.8 (h)	8.48 (m)	8.07 (q)	7.67 (q)
Residential/Commercial	5220.0	1607.8 (i)	16.74 (m)	15.61 (n)	12.98 (n)
Industrial (b)	907.5	435.6 (j)	4.54 (m)	4.31 (q)	4.10 (q)
Digester Gas--Industrial			6.30 (n)	5.99 (q)	5.70 (q)
Coke Oven Gas--Industrial			37.53 (n)	37.53 (r)	0 (r)
Coal--Residential/Commercial			0.55 (n)	0.51 (n)	0.43 (n)

Notes for Table B.6

(a) Deliveries of fuels in 1982 for the state of California from the Energy Information Administration (1983). Liquefied petroleum gas (LPG) was reported by the state of California in 10^3 gal/yr, so those values are divided by 42 (gal/bbl).

(b) Non-refinery, non-utility industrial fuel.

(c) Southern California portion of residential and commercial oil use in California is 0.4 from Stanford Research Institute (1973). The 6-county basin fuel use is assumed to be a fraction of the Southern California fuel use based on population density. From the 1980 census of population in California counties (U.S. Bureau of the Census 1982), 77% of Southern California population is in the six counties; therefore, 4482 X 0.4 X 0.77 = 4482 X 0.308 = 1380.5 X 10^3 bbls/yr.

(d) 64% of the state of California's industrial oil use is in Southern California from Stanford Research Institute (1973), and 75% of the non-refinery industrial heating demand in Southern California is in the 6-county basin from Cass (1977); therefore, 4794 X 0.64 X 0.75 = 4794 X 0.48 = 2301.1 X 10^3 bbls/yr. This contains some fuel used for internal combustion engines; see note (o), below.

(e) Railroad fuel is assumed to be used geographically in proportion to track mileage. The track mileage in railroad yards was counted for each track to account for the heavy traffic in those areas. From Cass (1977, p. 628), track miles were summed for the 6-county basin and were found to be 1842.3 miles, which is 21.8% of the 8446.6 miles of railroad track in California. The 4-county SCAB track mileage was obtained by subtracting the 180.0 miles in the counties of Santa Barbara and Ventura, leaving 1662.3 miles in the 4-county SCAB (19.7% of the state). The track miles existing on the 50X50-mile grid totalled 1047.9 miles (12.4% of the state).

(f) 30.8% of the California residential and commerical oil is consumed in the 6-county basin (see note [c], above); therefore, 5697 X 0.308 = 1754.7 X 10^3 bbls/yr.

(g) 48% of the California industrial oil use is in the 6-county basin (see note [d], above); therefore 973 X 0.48 = 467.0 X 10^3 bbls/yr.

(h) The Energy Information Administration (1983) gives 71,294 X 10^3 gal/yr for LPG use by internal combustion engines in California during 1982. Assuming usage is proportional to population, this gives 71,294 $\times 10^3$ gal ÷ 42 gal/bbl (= 1697.5 bbls/yr) $\times$ 48% = 814.8 $\times 10^3$ bbls/yr; see note (d).

(i) The Energy Information Administration (1983) gives 219,239 $\times 10^3$ gal/yr for LPG use by residential and commercial customers in California for 1982. The fraction of LPG used by customers in the 6-county basin is estimated to be 30.8% (see note [c], above); therefore, 219,239 $\times 10^3$ gal/yr ÷ 42 gal/bbl (= 5220.0 bbls/yr) $\times$ 30.8% = 1607.8 bbls/yr.

(j) LPG use in the state of California for chemical and industrial uses totalled 214,216 $\times 10^3$ gal in 1982 from the Energy Information Administration (1983). Also, 17.8% of chemical/industrial LPG use was for industrial customers (including a small amount of refinery fuel) in the United States during 1982. Assuming this proportion holds for California LPG use, then 214,216 $\times 10^3$ gal/yr $\times$ 17.8% ÷ 42 gal/bbl = 907.5 bbls/yr $\times 10^3$ bbls/yr. It is assumed that 48% of the California LPG use is in the 6-county basin (see note [d], above); therefore, 907.5 $\times$ 48% = 435.6 $\times 10^3$ bbls/yr.

(k) Assumed distillate fuel oil heating value of 5825 $\times 10^3$ Btu/bbl from Cass (1977, p. 598).

(l) Assumed residual oil heating value of 6287 $\times 10^3$ Btu/bbl from Cass (1977, p. 598).

(m) Assumed LPG heating value of 3800 $\times 10^3$ Btu/bbl from Cass (1977, p. 598).

(n) No recent information available. Assumed 1973 value from Cass, Boone, and Macias (1981) as an estimate for 1982.

(o) Assuming the fuel use in the 6-county basin is distributed geographically in proportion to population, then 93.3% of the 6-county basin fuel use is in the 4-county SCAB and 77.5% of the 6-county basin fuel use is in the 50X50-mile grid.

(p) The fraction of fuel used in the 4-county SCAB is assumed to be equal to the ratio of industrial natural gas usage in the four counties to industrial usage in the six counties, which is 95.1% from Table B.5. This gives 34.92 $\times 10^9$ Btu/yr for the 4-county industrial distillate oil used. This includes distillate oil used by internal combustion engines, which is estimated to be 7.00 $\times 10^9$ Btu/day in the 4-county SCAB and 5.43 $\times 10^9$ Btu/day in the 50X50-mile grid, from the Air Resources Board of California 1982 inventory of area and point source emissions (Ranzieri 1983); see note (n), Table A.2. Therefore, the total for industrial distillate not including IC fuel in the 4-county SCAB is 34.92 - 7.00 = 27.92 $\times 10^9$ Btu/day. It is further assumed that the fraction of the 4-county SCAB distillate oil used within the 50X50-mile grid is equal to the ratio of industrial natural gas usage in the grid versus the four counties, which is 95.1%; see Table B.5. Therefore, the grid total is 27.92 X 95.1% = 26.54 X 10^9 Btu/day.

(q) Assuming the fuel use for industrial customers is proportional to the natural gas used in the 6-county, 4-county, and 50X50-mile grid gives 95.1% of the 6-county basin industrial fuel is in the 4-county SCAB and 90.4% of the 6-county basin industrial fuel is in the 50X50-mile grid.

(r) All the coke oven gas use is in the 4-county SCAB but outside the 50X50-mile grid.

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APPENDIX C

1982 EMISSIONS ESTIMATES IN THE 4 COUNTY SOUTH COAST AIR BASIN

The following tables contain estimates of particle emissions in the 4 county South Coast Air Basin during 1982. The methodology used to construct Tables C.1 through C.4 is the same as that used in Tables A.1 through A.4, respectively. Therefore explanatory notes are omitted from tables in Appendix C. The interested reader will find explanations of the calculations in the notes following the corresponding table in Appendix A.

Table C.1

Emissions Estimates for Mobile Sources in 4 County South Coast Air Basin (a)

	Estimated 1982 Fuel Use (10^9 Btu/day)	Thous. VMT/day	Total Particulate Emission Factor		Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Total Particulate (kg/day)	%Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
			(kg/10^9 Btu)	(gm/mile)						Volatile Carbon % OC	Non-volatile Carbon % EC		
MOBILE SOURCES													
Highway Vehicles													
Catalyst Autos	601.9	101641		0.016	1626.3	86%	1398.6	39%	545.4	55%	45%	300.0	245.5
Non-catalyst Autos	357.1	39005		0.32	12481.6	36.4%	4543.3	76.4%	3471.1	78.7%	21.3%	2731.7	739.3
Diesel Autos	16.3	2914		0.48	1398.7	93%	1300.8	83.7%	1088.8	23.4%	76.6%	254.8	834.0
Catalyst Light Trucks	112.2	13882		0.022	305.4	86%	262.6	39%	102.4	55%	45%	56.3	46.1
Non-catalyst Light Trucks	66.6	5328		0.44	2344.3	36.4%	853.3	76.4%	651.9	78.7%	21.3%	513.1	138.9
Diesel Light Trucks	3.0	398		0.48	191.0	93%	177.7	83.7%	148.7	23.4%	76.6%	34.8	113.9
Catalyst Medium Trucks	68.8	5835		0.033	192.6	86%	165.6	39%	64.6	55%	45%	35.5	29.1
Non-catalyst Medium Trucks	46.8	3970		0.41	1627.7	36.4%	592.5	76.4%	452.7	78.7%	21.3%	356.2	96.4
Gasoline Heavy Trucks	78.1	3564		0.77	2744.3	36.4%	998.9	76.4%	763.2	78.7%	21.3%	600.6	162.6
Diesel Heavy Trucks	172.2	6843		1.39	9511.8	93%	8845.9	83.7%	7404.1	23.4%	76.6%	1732.5	5671.5
Motorcycles	4.4	1756		0.15	263.4	36.4%	95.9	76.4%	73.3	78.7%	21.3%	57.6	15.6
LPG use for Carburetion	8.1				1.6								
Civil Aviation													
Jet Aircraft	49.3				434.5	~100%	434.5	96%	417.1	23.4%	76.6%	97.6	319.5
Aviation Gas	2.4				54.6	36.4%	19.9	76.4%	15.2	78.7%	21.3%	11.9	3.2
Commercial Shipping													
Residual Oil-fired Ships	14.8		85.50		1265.5	72%	911.2	11.3%	103.0	80%	20%	82.4	20.6
Diesel Ships	6.3		49.17		309.8	93%	288.1	83.7%	241.1	23.4%	76.6%	56.4	184.7
Railroad													
Diesel Oil	22.4		81.95		1835.7	93%	1707.2	83.7%	1428.9	23.4%	76.6%	334.5	1094.5
Miscellaneous													
Off Highway Diesel Vehicles	39.0		78.67		3064.5	93%	2850.0	83.7%	2385.4	23.4%	76.6%	558.2	1827.2
Off Highway Gasoline Vehicles	--				429.9	36.4%	156.5	76.4%	119.6	78.7%	21.3%	94.1	25.5
TOTAL MOBILE SOURCES									19476.5			7908.1	11568.1

(a) See Table A.1 for calculation procedure.

Table C.2

Emissions Estimates for Stationary Combustion Sources in 4 County South Coast Air Basin (a)

	Estimated 1982 Fuel Use (10^9 Btu/day)	Total Particulate Emissions Factor (kg/10^9 Btu)	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Total Particulate (kg/day)	%Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon: Volatile Carbon % OC	Partition of Carbon: Non-volatile Carbon % EC	Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
STATIONARY SOURCES											
Fuel Combustion											
Electric Utilities											
Natural Gas (boilers)	653.6	1.08	705.9	92%	649.4	7%	45.5	100%	small	45.5	0
Natural Gas (turbines)	38.4	5.99	230.0	92%	211.6	7%	14.8	100%	small	14.8	0
Residual Oil	118.9	9.09	1080.8	95%	1026.8	20%	205.4	80%	20%	164.3	41.1
Distillate Oil (turbines)	0.43	16.35	7.0	96.4%	6.8	15%	1.0	42%	58%	0.4	0.6
Digester Gas	0.57	1.08	0.6	92%	0.6	7%	0.04	100%	small	0.04	0
Refinery Fuel											
Natural Gas	100.6	9.07	912.4	92%	839.4	7%	58.8	100%	small	58.8	0
Refinery Gas	334.1	9.07	3030.3	92%	2787.9	7%	195.2	100%	small	195.2	0
Residual Oil	5.34	21.64	115.6	72%	83.2	11.3%	9.4	80%	20%	7.5	1.9
Non-refinery Industrial/Low Priority Commercial Fuel											
Natural Gas	308.5	7.56	2332.3	92%	2145.7	7%	150.2	100%	small	150.2	0
LPG	4.31	7.56	32.6	92%	30.0	7%	2.1	100%	small	2.1	0
Residual Oil	7.65	21.64	165.5	72%	119.2	11.3%	13.5	80%	20%	10.8	2.7
Distillate Oil	27.9	23.55	657.0	96.4%	633.4	15%	95.0	42%	58%	39.9	55.1
Digester Gas (IC engines)	5.99	20.41	122.3	99%	121.0	21%	25.4	77%	23%	19.6	5.8
Coke Oven Gas	37.5	7.56	283.5	92%	260.8	7%	18.3	100%	small	18.3	0
Gasoline (IC engines)	5.16	23.49	121.2	99%	120.0	20%	24.0	90%	10%	21.6	2.4
Distillate Oil (IC engines)	7.00	109.81	768.7	93%	714.9	4%	28.6	small	100%	0	28.6
Residential/High Priority Commercial Fuel											
Natural Gas	854.8	8.06	6889.7	92%	6338.5	12%	760.6	67%	33%	509.6	251.0
LPG	15.6	8.06	125.7	92%	115.7	12%	13.9	67%	33%	9.3	4.6
Residual Oil	28.2	21.64	610.2	72%	439.4	11.3%	49.6	80%	20%	39.7	9.9
Distillate Oil	20.6	21.64	445.8	96.4%	429.7	15%	64.5	42%	58%	27.1	37.4
Coal	0.51	378.0	192.8	62%	119.5	96%	114.7	78%	22%	89.5	25.2
TOTAL FUEL COMBUSTION							1890.5			1424.2	466.3

(a) See Table A.2 for calculation procedure.

Table C.3

Emissions Estimates for Industrial Processes in 4 County South Coast Air Basin (a)

	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 µm	Fine Suspended Particulate < 2.1 µm (kg/day)	% Total Carbon in < 2.1 µm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
						Volatile Carbon % OC	Non-volatile Carbon % EC		
STATIONARY SOURCES									
<u>Industrial Process Point Sources</u>									
Petroleum Industry									
Refining (FCCU)	1591.2	54%	859.2	3.8%	32.7	75%	25%	24.5	8.2
Other	342.4	100%	342.4	≤83%	284.2	100%	0%	284.2	0
Organic Solvent Use									
Surface Coating	3131.6	91.5%	2865.4	55%	1576.0	100%	0%	1576.0	0
Printing	32.0	91.5%	29.3	55%	16.1	100%	0%	16.1	0
Degreasing	29.6	100%	29.6	≤83%	24.6	100%	0%	24.6	0
Other	154.1	100%	154.1	≤83%	127.9	100%	0%	127.9	0
Chemical									
Organic	2435.3	94.5%	2301.4	33%	759.4	94%	6%	713.9	45.6
Inorganic	151.2	94.5%	142.9	0%	0	–	–	–	–
Metallurgical									
Primary	6211.1	98.2%	6099.3	59.2%	3610.8	100%	0%	3610.8	0
Secondary	1906.8	88.5%	1687.5	13%	219.4	100%	0%	219.4	0
Fabrication	556.4	77%	428.4	0%	0	–	–	–	–
Mineral	14257.1	55.1%	7855.7	10.2%	801.3	74.4%	25.6%	596.2	205.1
Waste Burning	297.9	84.5%	251.7	30%	75.5	30%	70%	22.7	52.9
Wood Processing	372.4	56%	208.5	41.2%	85.9	87%	13%	74.8	11.2
Food and Agriculture	2442.3	1%	24.4	30%	7.3	100%	0%	7.3	0
Asphalt Roofing	377.1	93%	350.7	24%	84.2	96%	4%	80.8	3.4
Textile	237.8	1%	2.4	≤83%	2.0	100%	0%	2.0	0
Rubber and Plastics	77.2	100%	77.2	≤83%	64.1	100%	0%	64.1	0
Coke Calciner	266.4	100%	266.4	89.8%	239.2	0%	100%	0	239.2
Miscellaneous Industrial	2098.7	69.5%	1458.6	32.7%	477.0	92.8%	7.2%	442.6	34.3
TOTAL PROCESS POINT SOURCES					8487.6			7887.9	599.9

(a) See Table A.3 for calculation procedure.

Table C.4

Emissions Estimates for Fugitive Sources
in 4 County South Coast Air Basin
(a)

	Total Particulate Emissions (kg/day)	Mass Fraction < 2.1 μm	Fine Total Particulate (kg/day)	% Total Carbon in < 2.1 μm Fraction	Fine Total Carbon (kg/day)	Partition of Carbon		Fine Organic Carbon (kg/day)	Fine Elemental Carbon (kg/day)
						Volatile Carbon % OC	Non-volatile Carbon % EC		
<u>FUGITIVE SOURCES</u>									
Road and Building Construction	90341.0	32%	28909.1	0%	0	–	–	–	–
Agricultural Tilling	68200.9	30.5%	20801.3	0%	0	–	–	–	–
Livestock Feedlots	38073.6	54%	20559.7	2%	411.2	100%	0%	411.2	0
Unpaved Road Dust	33009.3	24%	7922.2	0%	0	–	–	–	–
Paved Road Dust	158306.6	27%	42742.8	15.1%	6454.2	96.7%	3.3%	6241.2	213.0
Tire Attrition	5379.2	25%	1344.8	87%	1170.0	67%	33%	783.9	386.1
Brake Lining Attrition	7530.8	100%	7530.8	28%	2108.6	82%	18%	1729.1	379.6
Forest Fires (seasonal)	13564.8	86%	11665.7	63%	7349.4	94%	6%	6908.4	441.0
Structural Fires	396.0	86.5%	342.5	30%	102.8	68%	32%	69.9	32.9
Fireplaces	18161.8	42%	7627.9		4273.0			3541.9	731.1
Cigarettes	2008.6	100%	2008.6	82.5%	1657.1	97%	3%	1607.4	49.7
Charcoal Broilers	6342.0	100%	6342.0	82.3%	5219.5	98.5%	1.5%	5141.2	78.3
Agricultural Burning	28.8	94%	27.1	52%	14.1	91%	9%	12.8	1.3
Sea Salt	65406.9	8%	5232.6	0%	0	–	–	–	–
Roofing Tar Pots	1028.7	100%	1028.7	81.7%	840.4	99.9%	0.1%	839.6	0.8
TOTAL FUGITIVE SOURCES					29600.3			27286.6	2313.8

(a) See Table A.4 for calculation procedure.

APPENDIX D

ESTIMATES OF THE COSTS AND EMISSION REDUCTIONS OF FINE PARTICLE CONTROL MEASURES

The costs and fine carbon particle emission reductions for the control measures used in this study are summarized in Chapter 5, Table 5.1. The source types affected by each control measure are identified by numbers which appear below the titles of the control measures. These numbers correspond to the source type identification numbers listed in the right-hand column of Table D.38.

Cost Calculation D.1

Unleaded Gasoline Use by Non-catalyst Autos and Light Trucks

Sources Affected: 3,4

Cost: 82.924 X 10^6\$/yr

1. Difference in retail price between unleaded and leaded gas, national average 1982: 6.7¢/gal or \$536.20/10^9 Btu from Energy Information Administration (1982).
2. SCAB 1982 fuel use: 423.7 X 10^9 Btu/day (from Table C.1).

Total Cost = (\$536.20/10^9 Btu) (423.7 X 10^9 Btu/day)
X (365 days/yr) = 82.924 X 10^6\$/yr

Purpose:

This is not a control measure for aerosol carbon emission reduction. The cost of unleaded fuel is needed in order to evaluate Control Measure D.2 which involves replacement of non-catalyst autos and light trucks by catalyst equipped vehicles.

Control Measure D.2

Catalysts on Non-catalyst Autos and Light Trucks

Sources Affected: 3,4

Cost: 236.352 X 10^6\$/yr

1. Unleaded fuel must be used. Cost: 82.926 X 10^6\$/yr (see Cost Calculation D.1).
2. Catalyst cost: \$155 per system for 1978 Federal System (this system would be adequate to achieve carbon particle emission reduction cited) from Cross (1982). Convert to 1982 dollars by multiplying by 0.512/0.344 (Dept. of Labor 1985), which gives a cost of \$230.70/system.
3. Assume 5 year payback period at 10% interest which yields a capital recovery factor of 0.26380. This gives an annual cost of \$60.86/vehicle-yr for the catalyst system.
4. Number of light-duty autos and trucks in SCAB, 1982, is esimated to be 6,243,184 from the California Air Resources Board (1983a). From Table A.5, 40.38% of the automobile fleet was non-catalyst in 1982 giving approximately 2,521,000 light-duty non-catalyst vehicles.

Total Cost = (\$60.86/vehicle-yr) (2,521,000 vehicles)
+ 82.924 X 10^6\$/yr = 236.352 X 10^6\$/yr

Fine TC Reduction: 3.7387 T/day

1. Fine total carbon emission factors:
Noncat: 9.72 kg/10^9 Btu (see Table C.1).
Catalyst: 0.91 kg/10^9 Btu (see Table C.1).
2. Fine total carbon emissions from sources: 4.1230 T/day (SCAB, Table C.1).

Reduction = (4.1230 T/day) (1 - 0.91/9.72) = 3.7387 T/day

TC fraction reduction = 0.9068
EC fraction reduction = 1 - (0.45) (1 - 0.9068)/(0.213) = 0.8031
(see Table A.1 for EC/TC ratios)

Control Measure D.3

#1 Diesel Fuel Use by Light-duty Diesel Vehicles

Sources Affected: 6,7

Cost: 4.317×10^6\$/yr

1. Diesel price difference: 8.5¢/gal (Difference of arithmetic averages for #1 and #2 diesel fuel from 1982 Lundberg Survey from Turner 1985). $(\$0.085/\text{gal}) \left(\frac{42 \text{ gal}}{\text{bbl}}\right) \left(\frac{1 \text{ bbl}}{5825 \times 10^3 \text{ Btu}}\right) =$ $\$612.88/10^9$ Btu.
2. SCAB 1982 fuel use: 19.3×10^9 Btu/day (from Table C.1).

$$\text{Total Cost} = (\$612.88/10^9 \text{ Btu})\ (19.3 \times 10^9 \text{ Btu/day})\ (365 \text{ days/yr}) = 4.317 \times 10^6 \$/\text{yr}$$

Fine TC Reduction: 0.2475 T/day

1. Particulate emissions are reduced 20% by switching from #2 diesel to #1 diesel (from Burley and Rosebrock 1979, SAE 790923, fig. 6).
2. Fine total carbon emissions from sources: 1.2375 T/day (SCAB, Table C.1).

Reduction = (0.20) (1.2375) = 0.2475 T/day

TC fraction reduction = 0.20
EC fraction reduction = 0.20

Conflicts: D.4, D.5

Control Measure D.4

Particle Traps on Light-duty Diesel Vehicles

Sources Affected: 6,7

Cost: 8.148×10^6\$/yr

1. California Air Resources Board (1983b) cites a number of sources including manufacturers and independent consultants concerning estimates of the consumer cost of a fuel additive ceramic monolith trap-oxidizer system for light-duty diesel vehicles. Estimates of the initial cost ranged from \$140 to \$450, although the CARB believes the lower end of the range to be most realistic. Their findings are supported by cost estimates of Weaver et al. (1983), who estimated an initial cost of \$180 to \$342. Assume an initial cost of \$280/vehicle (approximate middle of both ranges stated).
2. Assume 5 year payback period at 10% interest which results in a capital recovery factor of 0.26380. This gives an equivalent annual charge for the capital cost of \$73.86/vehicle-yr.
3. Number of light-duty diesel vehicles in SCAB, 1982 estimated as 92,400 from California Air Resources Board (1983a; 6,243,184 light-duty vehicles) and Table A.5 (diesels make up 1.48% of light-duty fleet).
4. Weaver et al. (1983) estimated the loss in fuel economy due to the trap to be about 2%. Total fuel use by light-duty diesels in 1982 was 19.3×10^9 Btu/day (SCAB, Table C.1) or 50.91×10^6 gal/yr . Dividing by 92,400 vehicles gives 550.9 gal/vehicle-yr. At \$1.30/gal, this gives additional cost of \$14.32/vehicle-yr. The total cost is then \$88.18/vehicle-yr.

$$\text{Total Cost} = \left(\frac{\$88.18}{\text{vehicle-year}}\right)(92{,}400 \text{ vehicles})$$

$$= 8.148 \times 10^6 \$/\text{yr}$$

Control Measure D.4 (continued)

Fine TC Reduction: 0.9900 T/day

1. Collection efficiencies ranging from 50% to greater than 90% have been reported for the cellular ceramic filters (CARB 1982; Weaver 1983; Urban et al. 1983; Ludecke and Dimick 1983; Miller et al. 1983; Montierth 1984; Ullman et al. 1984; Howitt and Montieth 1981; Wade et al. 1983; Wiedemann et al. 1983, 1984; Ludecke and Bly 1984; General Motors 1983). A mean value of 80% would probably be attained for large scale use.
2. Fine total carbon emissions from sources: 1.2375 T/day (SCAB, Table C.1).

Reduction = (0.80) (1.2375) = 0.9900 T/day

TC fraction reduction = 0.80
EC fraction reduction = 0.80

Conflicts: D.3, D.5

Control Measure D.5

Particle Traps & #1 Diesel Fuel Use for Lt-duty Diesel Vehicles

Sources Affected: 6,7

Cost: 12.465 X 10^6\$/yr

1. Cost of #1 diesel fuel: 4.317 X 10^6\$/yr (see Control D.3).
2. Particle trap system cost: 8.148 X 10^6\$/yr (see Control D.4).

Total Cost = 4.317 + 8.148 = 12.465 X 10^6\$/yr

Fine TC Reduction: 1.0395 T/day

1. 20% reduction due to #1 diesel fuel use (see Control D.3).
2. Additionally, 80% of the remaining 80% is removed by trap (see Control D.4).
3. Fine total carbon emissions from sources: 1.2375 T/day (SCAB, Table C.1).

Reduction = (1.2375 T/day) [0.20 + 0.80 (0.80)] = 1.0395 T/day

TC fraction reduction = 0.84
EC fraction reduction = 0.84

Conflicts: D.3, D.4

Cost Calculation D.6

Unleaded Gasoline Use by Non-catalyst Medium & Heavy Vehicles

Sources Affected: 9,10

Cost: 24.445×10^6 \$/yr

1. Difference in retail price between unleaded and leaded gas: \$536.20/10^9 Btu (see Control D.1).
2. SCAB 1982 fuel use: 124.9×10^9 Btu/day (from Table C.1).

$$\text{Total Cost} = (\$536.20/10^9\ \text{Btu})\ (124.9 \times 10^9\ \text{Btu/day})\ (365\ \text{day/yr}) = 24.445 \times 10^6\ \$/\text{yr}$$

Purpose:

This is not a control measure for aerosol carbon emission reduction. The cost of unleaded fuel is needed in order to evaluate Control Measure D.7 which involves replacement of non-catalyst medium and heavy vehicles by catalyst equipped vehicles.

Control Measure D.7

Catalysts on Non-Catalyst Medium & Heavy Gas Vehicles

Sources Affected: 9,10

Cost: 66.453 X 10^6\$/yr

1. Unleaded fuel must be used. Cost: 24.445 X 10^6\$/yr (see Cost Calculation D.6).
2. Catalyst cost: \$353/system (average of estimates by EPA, GM, and Chrysler for 1979 system) from Cross (1982). Convert to 1982 dollars by multiplying by 0.461/0.344 (Dept. of Labor 1985) which gives a cost of \$473.06/system.
3. Assume 5 year payback period at 10% interest which results in a capital recovery factor of 0.26380. Then the annual cost is \$124.79/vehicle-yr for the catalyst system.
4. Number of medium and heavy non-catalyst vehicles in SCAB, 1982 is 336,631 from California Air Resources Board (1983a).

Total Cost = (\$124.79/vehicle-yr) (336,631 vehicles)
+ 24.445 X 10^6\$/yr = 66.453 X 10^6\$/yr

Fine TC Reduction: 1.1026 T/day

1. Fine total carbon emission factors:
   Noncat: 9.72 kg/10^9 Btu (see Table C.1).
   Catalyst: 0.91 kg/10^9 Btu (see Table C.1).
   (Note: Small differences between these emission factors and those found by dividing TC emissions by fuel use in Table C.1 are due to roundoff. These emission factors per unit fuel burned are assumed to be the same as for light-duty vehicles; see Control D.2.)
2. Fine total carbon emissions from sources: 1.2159 T/day (SCAB, Table C.1).

Reduction = (1.2159 T/day) (1 - 0.91/9.72) = 1.1026 T/day

TC fraction reduction = 0.9068
EC fraction reduction = 0.8031 (see Control D.2)

Control Measure D.8

#1 Diesel Fuel Use by Heavy-duty Diesel Vehicles

Sources Affected: 11

Cost: 38.523 X 10^6\$/yr

1. Diesel price difference: \$612.9/10^9 Btu (see Control D.3).
2. SCAB 1982 fuel use: 172.2 X 10^9 Btu/day (from Table C.1).

Total Cost = (\$612.9/10^9 Btu) (172.2 X 10^9 Btu/day) (365 day/yr)
= 38.523 X 10^6\$/yr

Fine TC Reduction: 1.4808 T/day

1. 20% reduction (see Control D.3).
2. Fine total carbon emissions from sources: 7.4041 T/day (SCAB, Table C.1).

Reduction = (0.20) (7.4041 T/day) = 1.4808 T/day

TC fraction reduction = 0.20
EC fraction reduction = 0.20

Conflicts: D.9, D.10

Control Measure D.9

Particle Traps on Heavy-duty Diesel Vehicles

Sources Affected: 11

Cost: 36.240×10^6\$/yr

1. Weaver et al. (1984) estimates a lifecycle cost (assuming average vehicle life of 8 years) for a Monolith/Additive particle trap system of \$2471.58/vehicle if the trap is cleaned periodically (including the cost of periodic cleaning) or \$3906.74/vehicle if the trap must be replaced instead of cleaned (including replacement costs). These costs include estimates for maintenance and loss in fuel consumption. Using the average of these two costs gives a lifecycle cost of \$3189.16/vehicle.
2. Amortizing this cost over 8 years at 10% interest results in a capital recovery factor of 0.18744, which gives an annual cost of \$597.78/vehicle-yr.
3. Number of heavy-duty diesels in SCAB, 1982 is 60,624 from California Air Resources Board (1983a).

Total Cost = (\$597.78/vehicle-yr) (60,624 vehicles)
= 36.240×10^6\$/yr

Fine TC Reduction: 6.6637 T/day

1. This trap system can be designed to be over 90% effective from Weaver et al. (1984).
2. Fine total carbon emissions from sources = 7.4041 T/day (SCAB, Table C.1).

Reduction = (0.90) (7.4041 T/day) = 6.6637 T/day

TC fraction reduction = 0.90
EC fraction reduction = 0.90

Conflicts: D.8, D.10

Control Measure D.10

Particle Traps & #1 Diesel Fuel for Heavy-duty Diesel Vehicles

Sources Affected: 11

Cost: 74.763 X 10^6\$/yr

1. Cost of #1 diesel fuel: 38.523 X 10^6\$/yr (see Control D.8).
2. Particle trap system cost: 36.240 X 10^6\$/yr (see Control D.9).

Total Cost = 38.523 + 36.240 = 74.763 X 10^6\$/yr

Fine TC Reduction: 6.8118 T/day

1. 20% reduction due to #1 diesel fuel use (see Control D.3).
2. Additionally, 90% of the remaining 80% is removed by trap (see Control D.9).
3. Fine total carbon emissions from sources: 7.4041 T/day (SCAB, Table C.1).

Reduction = (7.4041 T/day) [0.20 + 0.90 (0.80)] = 6.8118 T/day

TC fraction reduction = 0.92
EC fraction reduction = 0.92

Conflicts: D.8, D.9

Control Measure D.11

Air Taxi Modification (Towing)

Sources Affected: 12

Cost: $0 (overall savings expected)

This control measure is proposed as part of the 1982 Air Quality Management Plan for the South Coast Air Basin. The South Coast Air Quality Management District (1982) has determined that the fuel savings involved should exceed the cost of the change in operations.

Fine TC Reduction: 0.1354 T/day

1. Of the 417.1 kg/day TC emitted from jet aircraft in the SCAB (see Table C.1), emissions at the surface account for 227.8 kg/day (idle and takeoff cycles -- using USEPA calculation procedure, see Table A.1; note [c]; TC (kg/day) from idle: 193.32; takeoff: 34.44; climbout: 87.49; approach: 101.84). Idle operations, therefore, account for 84.9% of emissions from surface operations.
2. Most of the particulate emissions during idle can be avoided by towing the aircraft into and out of the terminal (even considering tow truck fuel use). A conservative estimate is a 70% reduction. See South Coast Air Quality Management District (1982) for a desription of this control measure.

Reduction = (0.849) (0.70) (0.2278 T/day) = 0.1354 T/day

TC fraction reduction = 0.5943
EC fraction reduction = 0.5943

Control Measure D.12

0.5%S Residual Oil for Shipping — Berthing Operations

Sources Affected: 16

Cost: 2.253×10^6\$/yr

1. Low sulfur fuel oil (0.5%S) is to be used for berthing operations only. Fuel costs will increase approximately \$2 per barrel (from Nazemi et al. 1981) or \$318.12/10^9 Btu.
2. Of the 14.8×10^9 Btu/day residual oil use in the SCAB for shipping operations in 1982 (see Table C.1), 9.5×10^9 Btu/day was used during berthing operations (see Table A.1; note [d]).
3. Additionally, Nazemi et al. (1981) estimate an extra labor cost required for fueling operations of 1.15×10^6\$/yr.

Total Cost = (9.5×10^9 Btu/day) (\$318.12/10^9 Btu) (365 days/yr) +1.15×10^6\$/yr = 2.253×10^6\$/yr

Fine TC Reduction: 0.0442 T/day

1. Assume particulate emissions are reduced by 67% for switching from 1.5%S to 0.5%S fuel oil (based on observations by Taback et al. [1979]—particle emissions are proportional to sulfur content).
2. Only 64% of the emissions from residual oil combustion (9.5/14.8; see above) are operated on with this control measure (berthing operations only).
2. Fine total carbon emissions from sources: 0.1030 T/day (SCAB, Table C.1).

Reduction = (0.67) (0.64) (0.1030 T/day) = 0.0442 T/day

TC fraction reduction = 0.4288
EC fraction reduction = 0.4288

Control Measure D.13

#1 Diesel Fuel Use by Railroads

Sources Affected: 18

Cost: 5.011×10^6 \$/yr

1. Diesel price difference: \$612.9/10^9 Btu (see Control D.3).
2. SCAB 1982 fuel use: 22.4×10^9 Btu/day (from Table C.1).

$$\text{Total Cost} = (\$612.9/10^9 \text{ Btu})(22.4 \times 10^9 \text{ Btu/day})(365 \text{ day/yr})$$
$$= 5.011 \times 10^6 \$/\text{yr}$$

Fine TC Reduction: 0.2858 T/day

1. Assumed 20% reduction (see Control D.3).
2. Fine total carbon emissions from sources: 1.4289 T/day (SCAB, Table C.1).

Reduction = (0.20) (1.4289 T/day) = 0.2858 T/day

TC fraction reduction = 0.20
EC fraction reduction = 0.20

Control Measure D.14

#1 Diesel Fuel Use in Off-road Diesel Engines

Sources Affected: 19

Cost: 8.725×10^6 \$/yr

1. Diesel price difference: \$612.9/10^9 Btu (see Control D.3).
2. SCAB 1982 fuel use: 39.0×10^9 Btu/day (from Table C.1).

Total Cost = (\$612.9/10^9 Btu) (39.0×10^9 Btu/day) (365 day/yr)
= 8.725×10^6 \$/yr

Fine TC Reduction: 0.4771 T/day

1. Assumed 20% reduction (see Control D.3).
2. Fine total carbon emissions from sources: 2.3854 T/day (SCAB, Table C.1).

Reduction = (0.20) (2.3854 T/day) = 0.4771 T/day

TC fraction reduction = 0.20
EC fraction reduction = 0.20

Conflicts: D.15, D.16

Control Measure D.15

Particle Traps on Off-road Diesel Engines

Sources Affected: 19

Cost: 19.535×10^6 \$/yr

1. Number of off-road diesel vehicles in SCAB, 1982, estimated to be 75,194, of which 44,827 are light-duty and 30,367 are heavy-duty vehicles, from California Air Resources Board (1984) and data of Ranzieri (1983).
2. Light-duty engine particle trap system cost: \$73.86/vehicle-yr (see Control D.4; not including additional fuel cost due to loss in fuel economy).
3. Heavy-duty engine particle trap system cost: Capital cost (data from Weaver et al. 1984): \$1121.04; using 5 year payback period at 10% interest gives capital recovery factor of 0.26380, so annual capital cost is \$295.73/yr; Maintenance cost: \$5/yr (approximation based on ratio of fuel usage for individual off-road engines and heavy diesel trucks and maintenance cost for heavy diesel trucks from Weaver et al. [1984]); Replacement cost (one per 5 year lifetime): \$776 (from Weaver et al. 1984); amortized over 5 years gives \$145.46/yr. Total cost (not including additional fuel cost due to reduction in fuel economy): \$446.19/vehicle-yr.
4. Total fuel use by off-road diesel engines in 1982 was 39.0×10^9 Btu/day (SCAB, Table C.1) or 102.9×10^6 gal/yr. Assuming a loss in fuel economy of 2% and \$1.30/gal, this gives additional fuel cost of 2.675×10^6 \$/yr.

Total Cost = (\$73.86/vehicle-yr) (44,827 vehicles)
+ (\$446.19/vehicle-yr) (30,367 vehicles)
+ 2.675×10^6 \$/yr = 19.535×10^6 \$/yr

Control Measure D.15 (continued)

Fine TC Reduction: 2.0827 T/day

1. From Ranzieri (1983), light-duty off-road vehicles (CARB categories AAA54536 and AAA54379; see Table A.10; source type 19) accounted for 26.9% of the emissions in this source class.
2. Particulate fraction reductions: 80% (light-duty; see Control D.4) and 90% (heavy-duty; see Control D.9).
3. Fine total carbon emissions from sources: 2.3854 T/day (SCAB, Table C.1).

$$\text{Reduction} = [(0.269)(0.80) + (0.731)(0.90)]\ (2.3854\ \text{T/day}) = 2.0827\ \text{T/day}$$

TC fraction reduction = 0.8731
EC fraction reduction = 0.8731

Conflicts: D.14, D.16

Control Measure D.16

Particle Traps & #1 Diesel Fuel Use for Off-road Diesel Engines

Sources Affected: 19

Cost: 28.260 X 10^6\$/yr

1. Cost of #1 diesel fuel: 8.725 X 10^6\$/yr (see Control D.14).
2. Particle trap system cost: 19.535 X 10^6\$/yr (see Control D.15).

Total Cost = 8.725 + 19.535 = 28.260 X 10^6\$/yr

Fine TC Reduction: 2.1432 T/day

1. Light-duty vehicles are 26.9% of this source class (by emissions; see Control D.15).
2. Particulate fraction reductions: 84% (light-duty; see Control D.5) and 92% (heavy-duty; see Control D.10).
3. Fine total carbon emissions from sources: 2.3854 T/day (SCAB, Table C.1).

Reduction = [(0.269)(0.84) + (0.731)(0.92)] (2.3854 T/day)
= 2.1432 T/day

TC fraction reduction = 0.8985
EC fraction reduction = 0.8985

Conflicts: D.15, D.16

Cost Calculation D.17

Unleaded Gasoline Use by Off-road Gasoline Engines

Sources Affected: 20

Cost: 1.840×10^6 \$/yr

1. Difference in retail price between unleaded and leaded gas: \$536.20/10^9 Btu (see Control D.1).
2. SCAB 1982 fuel use estimated as 12.3×10^9 Btu/day (from Table C.1, using approximate particulate emission factor of 35.0 kg/10^9 Btu from light-duty non-catalyst vehicles).
3. This measure is operable on off-road recreational vehicles and forklifts (source categories AAA47464, AAA54387, and AAA54411; see Table A.10; source 20) but not on residential utility equipment (category AAA47449). The fraction of this source class falling into categories AAA47464, AAA54387, and AAA54411 is 76.6% (by emissions, from Ranzieri [1983]), so controllable fuel use is assumed to be (0.766) (12.3×10^9 Btu/day) = 9.4×10^9 Btu/day.

Total Cost = (\$536.20/10^9 Btu) (9.4×10^9 Btu/day) (365 day/yr)
= 1.840×10^6 \$/yr

Purpose:

This is not a control measure for aerosol carbon emission reduction. The cost of unleaded fuel is needed in order to evaluate Control Measure D.18 which involves replacement of non-catalyst off-road vehicles by catalyst equipped vehicles.

Control Measure D.18

Catalysts on Off-road Gasoline Engines

Sources Affected: 20

Cost: 15.615 X 10^6\$/yr

1. Unleaded fuel must be used. Cost: 1.840 X 10^6\$/yr (see Cost Calculation D.17).
2. Assume catalysts used are similar to those used for light-duty vehicles. Annual cost is \$60.86/vehicle-yr (see Control D.2).
3. Number of vehicles in source categories AAA47464, AAA54387, and AAA54411 (see Cost Calculation D.17) is estimated to be 226,346 from California Air Resources Board (1984) data.
4. Catalyst cost: (\$60.86/vehicle-yr) (226,346 vehicles) = 13.775 X 10^6\$/yr.

Total Cost = 1.840 + 13.775 = 15.615 X 10^6\$/yr

Fine TC Reduction: 0.0831 T/day

1. Assume similar emissions reduction as light-duty catalyst use: 90.68% (see Control D.2).
2. Fine total carbon emissions from sources: 0.1196 T/day (SCAB, Table C.1).
3. Controllable sources account for 76.6% of this source class (see Cost Calculation D.17).

Reduction = (0.9068) (0.766) (0.1196 T/day) = 0.0831 T/day

TC fraction reduction = (0.9068) (0.766) = 0.6946
EC fraction reduction = (0.8031) (0.766) = 0.6152 (see Control D.2)

Control Measure D.19

Use of 0.10%S Residual Oil by Utilities

Sources Affected: 23

Cost: 30.442×10^6 \$/yr

1. Difference in price between 0.25%S and 0.10%S residual oil is estimated to be \$4.41/bbl or \$701.45/10^9 Btu from Energy Information Administration (Monthly Petroleum Price Report, Dec. 1982 and Annual Energy Review, 1982) and data from Robert Elrod (1985) of Southern California Edison Co.
2. SCAB 1982 fuel use: 118.9×10^9 Btu/day (from Table C.2).

$$\text{Total Cost} = (\$701.45/10^9\ \text{Btu})\ (118.9 \times 10^9\ \text{Btu/day})\ (365\ \text{day/yr})$$
$$= 30.442 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: 0.1232 T/day

1. Assume particulate emissions are in proportion to sulfur content, based on observations by Taback et al. (1979). This gives a reduction of 60%.
2. Fine total carbon emissions from sources: 0.2054 T/day (SCAB, Table C.2).

Reduction = (0.60) (0.2054 T/day) = 0.1232 T/day

TC fraction reduction = 0.60
EC fraction reduction = 0.60

Conflicts: D.34

Control Measure D.20

Use of 0.10%S Residual Oil by Refineries

Sources Affected: 28

Cost: 1.367×10^6 \$/yr

1. Difference in price between 0.25%S and 0.10%S residual oil is estimated to be \$701.45/10^9 Btu (see Control D.19).
2. SCAB 1982 fuel use: 5.34×10^9 Btu/day (from Table C.2).

Total Cost = (\$701.45/10^9 Btu) (5.34×10^9 Btu/day) (365 day/yr)
= 1.367×10^6 \$/yr

Fine TC Reduction: 0.0056 T/day

1. Assume particulate emissions are in proportion to sulfur content, based on observations by Taback et al. (1979). This gives a reduction of 60%.
2. Fine total carbon emissions from sources: 0.0094 T/day (SCAB, Table C.2).

Reduction = (0.60) (0.0094 T/day) = 0.0056 T/day

TC fraction reduction = 0.60
EC fraction reduction = 0.60

Conflicts: D.35

Control Measure D.21

Use of 0.25%S Residual Oil in Industrial Boilers

Sources Affected: 31

Cost: 0.445×10^6 \$/yr

1. Difference in price between 0.50%S and 0.25%S residual oil is estimated to be \$1.89/bbl or \$300.62/10^9 Btu from Energy Information Administration (Monthly Petroleum Price Report, Dec. 1982 and Annual Energy Review, 1982) and data from Robert Elrod (1985) of Soutern California Edison Co. Assume that this price difference is representative of the price difference between fuel oil in the range [0.25%S to 0.50%S] vs. oil meeting [$\leq$ 0.25%S] specifications.
2. Approximately 53% of residual oil used in industrial boilers is in the range $0.25\% \leq \%S \leq 0.50\%$, from industrial fuel use survey (South Coast Air Quality Management District 1983).
3. SCAB 1982 fuel use: 7.65×10^9 Btu/day (from Table C.2).

$$\text{Total Cost} = (0.53)\ (\$300.62/10^9\ \text{Btu})\ (7.65 \times 10^9\ \text{Btu/day}) \times (365\ \text{day/yr}) = 0.445 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: 0.0047 T/day

1. Assume particulate emissions are in proportion to sulfur content, based on observations by Taback et al. (1979). This gives a reduction of 50% in emissions for 50% reduction in fuel sulfur content.
2. Control is only operative on 53% of residual oil use (see note [2], above).
3. Fine total carbon emissions from sources: 0.0135 T/day (SCAB, Table C.2). Controllable carbon emissions:
$$(0.0135\ \text{T/day})\ \left(\frac{0.53/0.5}{0.47 + 0.53/0.5}\right) = 0.0094\ \text{T/day.}$$

Reduction = (0.50) (0.0094 T/day) = 0.0047 T/day

TC fraction reduction = 0.3464
EC fraction reduction = 0.3464

Conflicts: D.22, D.36

Control Measure D.22

Use of 0.10%S Residual Oil in Industrial Boilers

Sources Affected: 31

Cost: 2.404×10^6 \$/yr

1. Cost for getting all industries down to 0.25%S: 0.445×10^6 \$/yr (see Control D.21).
2. Difference in price between 0.25%S and 0.10%S residual oil is \$701.45/10^9 Btu (see Control D.19) (assumed to represent price increase for reducing maximum allowable sulfur content from 0.25%S to 0.10%S).
3. SCAB 1982 fuel use: 7.65×10^9 Btu/day (from Table C.2).

$$\text{Total Cost} = (\$701.45/10^9\ \text{Btu})\ (7.65 \times 10^9\ \text{Btu/day})\ (365\ \text{day/yr}) + 0.445 \times 10^6\ \$/\text{yr} = 2.404 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: 0.0100 T/day

1. Assume particulate emissions are in proportion to sulfur content, based on observations by Taback et al. (1979). This gives an emissions reduction of 60% (for sulfur content reduction from 0.25%S to 0.10%S).
2. Reduction achieved from getting all industries down to 0.25%S: 0.0047 T/day (see Control D.21).
3. Fine total carbon emissions from sources: 0.0135 T/day (SCAB, Table C.2).

$$\begin{aligned}\text{Reduction} &= 0.0047\ \text{T/day} + (0.60)\ [(0.0135 - 0.0047)\ \text{T/day}] \\ &= 0.0100\ \text{T/day}\end{aligned}$$

TC fraction reduction = 0.7386
EC fraction reduction = 0.7386

Conflicts: D.21, D.36

Cost Calculation D.23

Unleaded Gasoline Use in Large Industrial IC Engines

Sources Affected: 35

Cost: 0.060×10^6\$/yr

1. Difference in retail price between unleaded and leaded gas: \$536.20/10^9 Btu (see Control D.1).
2. SCAB 1982 fuel use: 5.16×10^9 Btu/day (from Table C.2).
3. This measure is operable on industrial IC engines (pt. source category 20200301; see Table A.10; source 35). The industrial IC engine source class in emission inventory of Table C.2 includes many types of small gasoline engines that are too small to merit consideration. Large engines which might be considered for control account for only 5.94% of the emissions stated in Table C.2 (from Ranzieri 1983). The fuel use that could be controlled is assumed to be (0.0594) (5.16×10^9 Btu/day) = 0.307×10^9 Btu/day.

$$\text{Total Cost} = (\$536.20/10^9\ \text{Btu})\ (0.307 \times 10^9\ \text{Btu/day})\ (365\ \text{day/yr})$$
$$= 0.060 \times 10^6\ \$/\text{yr}$$

Purpose:

This is not a control measure for aerosol carbon emission reduction. The cost of unleaded fuel is needed in order to evaluate Control Measure D.24 which involves replacement of non-catalyst industrial IC engines by catalyst equipped engines.

Control Measure D.24

Catalysts on Gasoline Large Industrial IC Engines

Sources Affected: 35

Cost: 0.113 X 10^6\$/yr

1. Unleaded fuel must be used. Cost: 0.060 X 10^6\$/yr (see Cost Calculation D.23).
2. The number of industrial gasoline IC engines is not known exactly. Assume same average heat input per engine as diesel industrial IC engines. From Control D.26, there were 9671 diesel units in the SCAB, 1982, consuming fuel at a rate of 7.00 X 10^9 Btu/day, so number of gasoline industrial IC engines in pt. source category 20200301 (see Cost Calculation D.23) is estimated to be (0.307/7.00) (9671 units) = 424 units.
3. Assuming catalysts used are similar to those used for medium/heavy vehicles. Annual cost of catalyst is \$124.79/unit-yr (see Control D.7).

Total Cost = (\$124.79/unit-yr) (424 units) + 0.060 X 10^6\$/yr
= 0.113 X 10^6\$/yr

Fine TC Reduction: 0.0013 T/day

1. Assume similar emissions reduction as medium/heavy-duty catalyst use: 90.68% (see Control D.7).
2. Fine total carbon emissions from sources: 0.0240 T/day (SCAB, Table C.2).
3. Controllable sources account for 5.94% of this source class (see Cost Calculation D.23).

Reduction = (0.9068) (0.0594) (0.0240 T/day) = 0.0013 T/day

TC fraction reduction = (0.9068) (0.0594) = 0.0539
EC fraction reduction = (0.8031) (0.0594) = 0.0477 (see Control D.2)
(Reduction is relative to entire source category of industrial gasoline IC engines shown in Table C.2.)

Control Measure D.25

#1 Diesel Fuel Use in Diesel Industrial IC Engines

Sources Affected: 36

Cost: 1.566×10^6 \$/yr

1. Diesel price difference: \$612.9/10^9 Btu (see Control D.3).
2. SCAB 1982 fuel use: 7.00×10^9 Btu/day (from Table C.2).

$$\text{Total Cost} = (\$612.9/10^9\ \text{Btu})\ (7.00 \times 10^9\ \text{Btu/day})\ (365\ \text{day/yr}) = 1.566 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: 0.0057 T/day

1. Assumed 20% reduction (see Control D.3).
2. Fine total carbon emissions from sources: 0.0286 T/day (SCAB, Table C.2).

$$\text{Reduction} = (0.20)\ (0.0286\ \text{T/day}) = 0.0057\ \text{T/day}$$

TC fraction reduction = 0.20
EC fraction reduction = 0.20

Conflicts: D.26, D.27

Control Measure D.26

Particle Traps on Diesel Industrial IC Engines

Sources Affected: 36

Cost: 4.796×10^6 \$/yr

1. Number of diesel IC engines in this source category in the SCAB, 1982, estimated to be 9671 units (data on number of units in 1979 from California Air Resources Board [1984], emission factors from Grisinger [1982], and 1982 emissions inventory from Ranzieri [1983]).
2. Assume traps used are similar to those used for heavy-duty diesel engines. From Control D.15, the annual cost (including capital cost, maintenance, and replacement costs) is estimated to be \$446.19/unit-yr.
3. SCAB 1982 fuel use for industrial IC engines: 7.00×10^9 Btu/day (from Table C.2) or 18.5×10^6 gal/yr. Assuming a loss in fuel economy due to the particle trap of 2%, and \$1.30/gal, this gives additional fuel cost of 0.481×10^6 \$/yr.

$$\text{Total Cost} = (\$446.19/\text{unit-yr})\ (9671\ \text{units}) + 0.481 \times 10^6\ \$/\text{yr}$$
$$= 4.796 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: 0.0257 T/day

1. Assume 90% efficient control (similar to heavy-duty trucks--see Control D.9).
2. Fine total carbon emissions from sources: 0.0286 T/day (SCAB, Table C.2).

Reduction = (0.90) (0.0286 T/day) = 0.0257 T/day

TC fraction reduction = 0.90
EC fraction reduction = 0.90

Conflicts: D.25, D.27

Control Measure D.27

Particle Traps & #1 Fuel in Diesel Industrial IC Engines

Sources Affected: 36

Cost: 6.362×10^6\$/yr

1. Cost of #1 diesel fuel: 1.566×10^6\$/yr (see Control D.25).
2. Particle trap system cost: 4.796×10^6\$/yr (see Control D.26).

Total Cost = $1.566 + 4.796 = 6.362 \times 10^6$\$/yr

Fine TC Reduction: 0.0263 T/day

1. 20% reduction due to #1 diesel fuel use (see Control D.3).
2. Additionally, 90% of the remaining 80% is removed by trap (see Control D.9).
3. Fine total carbon emissions from sources: 0.0286 T/day (SCAB, Table C.2).

Reduction = (0.0286 T/day) [0.20 + 0.90 (0.80)] = 0.0263 T/day

TC fraction reduction = 0.92
EC fraction reduction = 0.92

Conflicts: D.25, D.26

Control Measure D.28

Use of 0.25%S Residual Oil by Residential/Commercial

Sources Affected: 39

Cost: 3.094×10^6 \$/yr

1. Difference in price between 0.50%S and 0.25%S residual oil is \$300.62/10^9 Btu (see Control D.21).
2. SCAB 1982 fuel use: 28.2×10^9 Btu/day (from Table C.2).

Total Cost = (\$300.62/10^9 Btu) (28.2×10^9 Btu/day) (365 day/yr)
= 3.094×10^6 \$/yr

Fine TC Reduction: 0.0248 T/day

1. Assume particulate emissions are in proportion to sulfur content, based on observations by Taback et al. (1979). This gives a reduction of 50%.
2. Fine total carbon emissions from sources: 0.0496 T/day (SCAB, Table C.2).

Reduction = (0.50) (0.0496 T/day) = 0.0248 T/day

TC fraction reduction = 0.50
EC fraction reduction = 0.50

Conflicts: D.37

Control Measure D.29

Paved Road Flushing

Sources Affected: 61

Cost: 430.689×10^6\$/yr

1. 1983 flusher truck cost: \$84.47/street mile from Yamanishi (1983).
2. Equivalent street mileage in 4-county SCAB: 42,276 miles (road mileage data from Higgins [1982] and Black [1982]; It was assumed that freeways have as many lanes as 5 surface streets, thus freeway mileage was multiplied by 5 before being added to surface streets to arrive at this total).
3. Assume streets are flushed every third day.
4. Deflate 1983 price by 0.341/0.344 to get 1982 dollars from Consumer Price Index (Department of Labor 1985).

$$\text{Total Cost} = (\$84.47/\text{mile})\ (42{,}276\ \text{miles})\ \left(\frac{1}{3\ \text{days}}\right)\ (365\ \text{day/yr}) \times (\ 0.341/0.344\ ) = 430.689 \times 10^6\ \$/\text{yr}$$

Fine TC Reduction: Not computed

1. 68.1% control efficiency for fine particulate emissions from Cuscino et al. (1982).
2. Road dust contribution to ambient air quality was determined by receptor modeling approach (see Chapter 4, Section 4.2.1). Fraction reduction for control is applied directly to ambient road dust concentration contribution estimate at each monitoring site to determine effect of control measure. (Applying this control measure to the original estimate of road dust emissions from Ranzieri [1983] gives a fine TC reduction of (0.681) (6.4542 T/day) = 4.3953 T/day; see Table C.4.)

TC fraction reduction = 0.681
EC fraction reduction = 0.681
(Fraction is applied directly to air quality contribution.)

Conflicts: D.30

Control Measure D.30

Paved Road Flushing and Broom Sweep

Sources Affected: 61

Cost: 556.628×10^6\$/yr

1. 1983 flusher truck cost: \$84.47/street mile from Yamanishi (1983).
2. 1983 broomsweeping cost: \$12.35 per curb-mile or \$24.70/street mile from Yamanishi (1983).
3 Equivalent street mileage in 4-county SCAB: 42,276 miles (see Control D.29)
4. Assume streets are flushed and broomswept every three days.
5. Deflate 1983 price by 0.341/0.344 to get 1982 dollars from Consumer Price Index (Department of Labor 1985).

$$\text{Total Cost} = [(\$84.47 + \$24.70)/\text{mile}]\ (42{,}276\ \text{miles})\ \left(\frac{1}{3\ \text{days}}\right)$$
$$\times\ (365\ \text{day/yr})\ (\ 0.341/0.344\ ) = 556.628 \times 10^6\$/\text{yr}$$

Fine TC Reduction: Not computed

1. 71.8% control efficiency for fine particulate emissions from Cuscino et al. (1982).
2. Road dust contribution to ambient air quality was determined by receptor modeling approach (see Chapter 4, Section 4.2.1). Fraction reduction for control is applied directly to ambient road dust concentration contribution estimate at each monitoring site to determine effect of control measure. (Applying this control measure to the original estimate of road dust emissions from Ranzieri [1983] gives a fine TC reduction of (0.718) (6.4542 T/day) = 4.6341 T/day; see Table C.4.)

TC fraction reduction = 0.718
EC fraction reduction = 0.718
(Fraction is applied directly to air quality contribution.)

Conflicts: D.29

Control Measure D.31

Radial Tire Use on Light-duty Vehicles

Sources Affected: 62

Cost: $0

Radial tires have higher cost but wear proportionately longer than bias-ply tires.

Fine TC Reduction: 0.1167 T/day

1. Approximately 70% of tires on road in 1982 were radials (domestic passenger cars) from Standard & Poor's Corporation (1981).
2. 50% longer life from Firestone Study in Standard & Poor's Corporation (1981) implies 1/3 reduction in emissions rate.
3. Tire attrition from light-duty vehicles accounts for 77.26% of the tire wear in the SCAB (see TableA.7).
4. Fine total carbon emissions from sources: 1.170 T/day (SCAB, Table C.4).
5. Current bias-ply total fine carbon emissions from light-duty vehicles:

$$(0.7726)\ (1.170\ \text{T/day})\ \left(\frac{0.30 \times 1.5}{(0.30 \times 1.5) + 0.70}\right) = 0.3537\ \text{T/day}.$$

Reduction = (0.33) (0.3537 T/day) = 0.1167 T/day

TC fraction reduction = 0.0998
EC fraction reduction = 0.0998

Control Measure D.32

Use of Gas Logs in Fireplaces

Sources Affected: 65

Cost: $23.897 \times 10^6 \$/\mathrm{yr}$

1. Approximate cost of new gas log unit: \$200 (typical middle range price of gas log set, with installation; quoted at Floyd S. Lee, Pasadena, 1985). Assume ten-year payback period at 10% interest, giving a capital recovery factor of 0.16275.
2. Number of residences burning wood in SCAB is 977,568 (see Table A.9).

Gas log fireplace cost = (0.16275/yr) (977,568 residences)
$\times$ (\$200/residence) = $31.820 \times 10^6 \$/\mathrm{yr}$

3. Assume natural gas use replaces logs at same energy level, i.e., same number of Btu/year.
   <u>Hardwood</u>: 246,677 cords/yr (see Table A.9) $\times$ 30.4×10^6 Btu/cord (Baumeister et al. 1978, p. 7-19) = 7499.0×10^9 Btu/yr.
   <u>Softwood</u>: 241,729 cords/yr (see Table A.9) $\times$ 26.0×10^6 Btu/cord (Baumeister et al. 1978, p. 7-19) = 6285.0×10^9 Btu/yr.

Natural gas cost = $13{,}783.93 \times 10^9$ Btu/yr $\times$ $\$3500/10^9$ Btu
= $48.244 \times 10^6 \$/\mathrm{yr}$

(Natural gas price estimated from author's home utility bill.)

4. Assume half the wood burned is purchased as firewood. Approximate 1985 cost of cord of firewood is \$230/cord (quote from Glatts Lumber, Pasadena, August 1985).

Firewood cost savings = (488,406 cords/yr) (0.50) (\$230/cord)
= $56.167 \times 10^6 \$/\mathrm{yr}$

Total Cost = $31.820 + (48.244 - 56.167) = 23.897 \times 10^6 \$/\mathrm{yr}$

Control Measure D.32 (continued)

Fine TC Reduction: 4.2394 T/day

1. Fine total carbon emissions factors:
   Residential natural gas: 0.8898 kg/10^9 Btu (see Table A.2).
   Fireplace: 113.15 kg/10^9 Btu (see Table A.4).
2. Fine total carbon emissions from sources: 4.2730 T/day (SCAB, Table C.4).

Reduction = (4.2730 T/day) (1 - 0.8898/113.15) = 4.2394 T/day

TC fraction reduction = 0.9921
EC fraction reduction = 1 - (0.33) (1 - 0.9921)/(0.1711) = 0.9847

Control Measure D.33

Charcoal Broiler Control

Sources Affected: 68

Cost: 4.370×10^6 $/yr

1. Approximate cost of mist eliminator system for typical charbroiler facility (i.e., "The Conqueror" manufactured by Hardee's Food Systems) is between $4500 and $5500 (includes installation) from Stahl (1985). Assume $5000 per facility. Assume five-year payback period at 10% interest which gives a capital recovery factor of 0.26380. Then annual capital cost is $1319.00/yr.
2. Maintenance cost is approximately $1000-1500/year from Stahl (ibid.). Assume $1250/year.
3. The number of charcoal broilers in the South Coast Air Basin, 1982, is calculated to be 1701 from California Air Resources Board data (Ranzieri 1983) on total particulate emissions of 6342.0 kg/day (see Table C.4) divided by the CARB emission factor of 3000 lb/facility (Grisinger 1982).

Total Cost = (1701 facilities) ($1319/yr + $1250/yr)/facility
= 4.370×10^6 $/yr

Fine TC Reduction: 4.8541 T/day

1. Mist eliminator (i.e., "The Conqueror" manufactured by Hardee's Food Systems) removes 93% of particulate by weight (from Bornstein 1978 and Stahl 1985).
2. Fine total carbon emissions from sources: 5.2195 T/day (SCAB, Table C.4).

Reduction = (0.93) (5.2195) = 4.8541 T/day

TC fraction reduction = 0.93
EC fraction reduction = 0.93

Control Measure D.34

Substitute Natural Gas for Residual Oil in Utility Boilers

Sources Affected: 23

Cost: $0 (savings to utilities if natural gas is available)

1. Natural gas price is approximately $\$5000/10^9$ Btu from Robert Elrod (1985) of Southern California Edison Co.
2. Residual oil price (0.25%S) is estimated to be $33.39/bbl = $\$5310.96/10^9$ Btu from Energy Information Administration (1982) data and data from Robert Elrod (1985).
3. SCAB 1982 residual fuel oil use: 118.9×10^9 Btu/day (from Table C.2).

$$\text{Savings} = [(5310.96 - 5000.00)\$/10^9 \text{ Btu}]\,(118.9 \times 10^9 \text{ Btu/day}) \times (365 \text{ day/yr}) = 13.495 \times 10^6 \$/\text{yr}$$

Fine TC Reduction: 0.1971 T/day

1. Fine total carbon emission factors for utility boiler fuels:
   Natural gas: 0.0696 kg/10^9 Btu (see Table A.2).
   Residual oil: 1.7271 kg/10^9 Btu (see Table A.2).
2. Fine total carbon emissions from sources: 0.2054 T/day (SCAB, Table C.2).

$$\text{Reduction} = (0.2054 \text{ T/day})\,(1 - 0.0696/1.7271) = 0.1971 \text{ T/day}$$

TC fraction reduction = 0.9597
EC fraction reduction = 1.0000 (see Table A.2, note [rr])

Conflicts: D.19

Natural gas resource: 118.9×10^9 Btu/day

Control Measure D.35

Substitute Natural Gas for Residual Oil in Refineries

Sources Affected: 28

Cost: $0 small savings (see Control D.34)

Fine TC Reduction: 0.0063 T/day

1. Fine total carbon emission factors for refinery boiler fuels:
   Natural gas: 0.5841 kg/10^9 Btu (see Table A.2).
   Residual oil: 1.7606 kg/10^9 Btu (see Table A.2).
2. Fine total carbon emissions from sources: 0.0094 T/day (SCAB, Table C.2).

Reduction = (0.0094 T/day) (1 - 0.5841/1.7606) = 0.0063 T/day

TC fraction reduction = 0.6682
EC fraction reduction = 1.0000 (see Table A.2, note [uu])

Conflicts: D.20

Natural gas resource: 5.34 X 10^9 Btu/day

Control Measure D.36

Substitute Natural Gas for Residual Oil in Industrial Boilers

Sources Affected: 31

Cost: $0 small savings (see Control D.34)

Fine TC Reduction: 0.0098 T/day

1. Fine total carbon emission factors for industrial boiler fuels:
   Natural gas: 0.4869 kg/10^9 Btu (see Table A.2).
   Residual oil: 1.7606 kg/10^9 Btu (see Table A.2).
2. Fine total carbon emissions from sources: 0.0135 T/day (SCAB, Table C.2).

Reduction = (0.0135 T/day) (1 - 0.4869/1.7606) = 0.0098 T/day

TC fraction reduction = 0.7235
EC fraction reduction = 1.0000 (see Table A.2, note [rr])

Conflicts: D.21, D.22

Natural gas resource: 7.65 X 10^9 Btu/day

Control Measure D.37

Substitute Natural Gas for Residual Oil in Residential/Commercial

Sources Affected: 39

Cost: $0 small savings (see Control D.34)

Fine TC Reduction: 0.0245 T/day

1. Fine total carbon emission factors for residential/commercial boiler fuels:
   Natural gas: 0.8898 kg/10^9 Btu (see Table A.2).
   Residual oil: 1.7606 kg/10^9 Btu (see Table A.2).
2. Fine total carbon emissions from sources: 0.0496 T/day (SCAB, Table C.2).

Reduction = (0.0496 T/day) (1 - 0.8898/1.7606) = 0.0245 T/day

TC fraction reduction = 0.4946
EC fraction reduction = 1 - (0.33) (1 - 0.4946)/(0.20) = 0.1577
(see Table A.2 for EC/TC ratios)

Conflicts: D.28

Natural gas resource: 28.2 × 10^9 Btu/day

Table D.38
Source class list correspondence

source classes input to the air quaility model (a)	source types used in emission and control inventories (b)
Mobile Sources	
1 CAT AUTO/LT TRUCKS	1 CATALYST AUTOS
	2 CATALYST LT TRUCKS
2 NON-CAT AUTO/LT TRUCK	3 NON-CAT AUTOS
	4 NON-CAT LIGHT TRUCKS
	5 MOTORCYCLES
3 DIESEL AUTO/LT TRUCK	6 DIESEL AUTOS
	7 DIESEL LIGHT TRUCKS
4 MED/HEAVY GAS TRUCKS	8 CATALYST MED TRUCKS
	9 NON-CAT MED TRUCKS
	10 GAS HEAVY TRUCKS
5 HEAVY DIESEL TRUCKS	11 HEAVY DIESEL TRUCKS
6 AIRCRAFT SURFACE	12 AIRCRAFT SURFACE
	13 AVIATION GAS
7 AIRCRAFT MIDDLE ALT	14 AIRCRAFT MIDDLE ALT
8 AIRCRAFT HIGH ALT	15 AIRCRAFT HIGH ALT
9 SHIPPING RESID OIL	16 SHIPPING RESID OIL
10 SHIPPING DIST OIL	17 SHIPPING DIST OIL
11 RAILROAD DIESEL	18 RAILROAD DIESEL
12 OFF-ROAD DIESEL	19 OFF-ROAD DIESEL
13 OFF-ROAD GASOLINE	20 OFF-ROAD GASOLINE

(a) These are the 47 source classes input to the air quality model (see Chapter 4). Source types within each source class have similar emission characteristics.

(b) These are the 74 source types identified in the emission inventory (Tables A.1 through A.4) and the control strategy inventory (Tables D.1 through D.37).

Table D.38 (continued)

source classes input to the air quaility model	source types used in emission and control inventories
Stationary Combustion Sources	
14 UTILITIES ALL FUELS	21 UTILITIES BOILER NG
	22 UTILITIES TURBINE NG
	23 UTILITIES RESID OIL
	24 UTILITIES DISTILLATE
	25 UTILITIES DIGAS
15 REFINERIES ALL FUELS	26 REFINERIES NAT GAS
	27 REFINERIES REF GAS
	28 REFINERIES RESID OIL
16 INDUSTRIAL BOILERS	29 INDUS BOILERS NG
	30 INDUS BOILERS LPG
	31 INDUS BOILERS RESID
	32 INDUS BOILERS DIST
	33 INDUS BOILERS COG
17 INDUSTRIAL IC ENGINE	34 INDUS IC DIGAS
	35 INDUS IC GASOLINE
	36 INDUS IC DISTILLATE
18 RES/COMM ALL FUELS	37 RES/COMM NAT GAS
	38 RES/COMM LPG
	39 RES/COMM RESID OIL
	40 RES/COMM DISTILLATE
	41 RES/COMM COAL

Table D.38 (continued)

source classes input to the air quaility model	source types used in emission and control inventories
Stationary Industrial Process Sources (c)	
19 PETRO FCCU	42 PETRO FCCU
20 PETRO OTHER	43 PETRO OTHER
21 ORG SOLV COAT/PRINT	44 ORGANIC SOLVENT COAT 45 ORGANIC SOLVENT PRNT
22 ORG SOLV OTHER	46 ORG SOLV DEGREASING 47 ORGANIC SOLV OTHER
23 CHEMICAL	48 CHEMICAL ORGANIC
24 PRIMARY METALS	49 PRIMARY METALS
25 SECONDARY METALS	50 SECONDARY METALS
26 MINERAL	51 MINERAL
27 WASTE BURNING	52 WASTE BURNING
28 WOOD PROCESSING	53 WOOD PROCESSING
29 ASPHALT ROOFING	54 ASPHALT ROOFING
30 RUBBER/PLASTICS	55 RUBBER/PLASTICS
31 COKE CALCINER	56 COKE CALCINER
32 MISC INDUSTRIAL	57 MISC:FOOD AND AGRI 58 MISC:TEXTILE 59 MISC:INDUSTRIAL

(c) For the correspondence between source types used in this study and California Air Resources Board category of emission source (CES, SCC) numbers, see Table A.10.

Table D.38 (continued)

source classes input to the air quaility model	source types used in emission and control inventories
Fugitive Sources (c)	
33 LIVESTOCK DUST	60 LIVESTOCK DUST
34 PAVED ROAD DUST	61 PAVED ROAD DUST
35 TIRE ATTRITION	62 TIRE ATTRITION
36 BRAKE LIN ATTRITION	63 BRAKE LIN ATTRITION
37 STRUCTURAL FIRES	64 STRUCTURAL FIRES
38 FIREPLACES	65 FIREPLACES
39 CIGARETTES	66 CIGARETTES
40 AGRI BURNING	67 AGRI BURNING
41 CHARCOAL BROILERS	68 CHARCOAL BROILERS
42 ROOFING TAR POTS	69 ROOFING TAR POTS
43 CHEMICAL INORGANIC	70 CHEMICAL INORGANIC
44 METAL FABRICATION	71 METAL FABRICATION
44 ROAD/BLDNG CONST	72 ROAD/BLDNG CONST
46 AGRI TILLING	73 AGRI TILLING
47 UNPAVED ROAD	74 UNPAVED ROAD

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APPENDIX E

FINE PARTICLE CONCENTRATIONS AT ELEVEN LOCATIONS IN THE SOUTH COAST AIR BASIN DURING 1982

Appendix E contains the results of the air quality monitoring program conducted in the Los Angeles area during 1982 (see Chapter 2). The locations monitored were Azusa, Burbank, Long Beach, Lennox, Pasadena, West Los Angeles, Los Angeles (central), Upland, Rubidoux, Anaheim, and San Nicolas Island. A 24-hour sample was collected at each location on every sixth day in conjunction with the NASN sampling schedule. Tabulated in this appendix are the daily average concentrations (and error bounds) for the following fine (d_p < 2.1 μm) aerosol species: Total mass, organic carbon, elemental carbon, NO_3^-, $SO_4^=$, NH_4^+, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, As, Se, Br, Rb, Sr, Y, Zr, Mo, Pd, Ag, Cd, In, Sn, Sb, Ba, La, Hg, and Pb. Also included are the daily fine particle fractions of total mass, $SO_4^=$, NO_3^-, and Pb which were obtained by dividing the fine aerosol concentrations by the corresponding species concentration found in the total suspended particulate matter data reported by the South Coast Air Quality Management District, El Monte, California (all locations except Burbank, Upland, and San Nicolas Island). Monthly and annual averages of these values are also tabulated. Throughout this appendix, missing data are indicated by the value -10.0 or -9.9.

Appendix E and Appendix F are contained in a separate volume. The data are available by contacting the Environmental Quality Laboratory, Caltech, Pasadena, California 91125.

APPENDIX F

SOURCE CLASS CONTRIBUTIONS TO 1982 ANNUAL AVERAGE CARBON PARTICLE AIR QUALITY

Appendix F contains the contributions to fine total carbon and fine elemental carbon concentrations at seven receptor sites from each of 74 source classes, as computed by the air quality model (see Chapter 4). Estimates of emissions are also presented for each source class (see Appendix A and Appendix C).

Appendix E and Appendix F are contained in a separate volume. The data are available by contacting the Environmental Quality Laboratory, Caltech, Pasadena, California 91125.