Assessment of the Potential for Photochemical Air Pollution in Athens: A Comparison of Emissions and Air-Pollutant Levels in Athens with Those in Los Angeles

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ABSTRACT

The average areal density of pollutant emissions in Athens is estimated to be two to six times greater than in the Los Angeles basin. Concentration levels of the primary air pollutants, CO and SO_2, are several times larger in Athens than in Los Angeles. Concentrations of the photochemical pollutants, NO_2 and O_3, however, are greater at Los Angeles stations inland 20 or more kilometers from the coast. The relatively lower levels of photochemical pollution in Athens are partially explained by differences in the summer atmospheric-circulation systems and the scale of the basins. Also, the concentration of NO in central Athens is so great as to inhibit the formation of O_3.

1. Introduction

The degradation in air quality in Athens over the past 20 years is of major concern to both the citizenry and the Greek government. Meteorological factors, largely winds and turbulence, play an important role in determining pollution levels for a given rate of pollutant emission. Because of the interannual variability of meteorological conditions and the complexity of the atmospheric photochemical reactions, it is difficult to project the severity of future pollution episodes in Athens from present levels, since the recent period has been one of almost exponential growth in automotive traffic and emissions. It is the purpose of this article to gain perspective for the assessment of the air-pollution potential in Athens by a comparison of emission rates and pollution levels with those in Los Angeles, where emission rates have stabilized. Los Angeles has a similar climatological and topographical setting as Athens and has had perhaps the most complete study and documentation of air pollution of any city in the world (e.g., Reynolds et al. 1973, 1974; Roth et al. 1974; Blumenthal et al. 1978; Glendening 1990).

Athens and Los Angeles are both situated in coastal basins opening toward the sea to the southwest, with high mountains to the north and east. These similarities in the topographic structure and coastal exposure of the basins are illustrated by topographic maps drawn to the same scale (Fig. 1a). Although similar in structure to Los Angeles, the Athens basin (A in Fig. 1a), in which 90% of the population lives and works, is an order of magnitude smaller in area. The Thriassion basin (θ in Fig. 1a), primarily devoted to industry, is separated from the Athens basin by the Aegaleos Mountains—approximately 400 m in altitude—which provide some confinement of pollutants to the basin in which they are emitted. The 37 pollution-monitoring sites of the South Coast Air Quality Management District (SCAQMD) are indicated by circles in Fig. 1a. The 14 pollution-monitoring stations currently maintained by the Greek Ministry for the Environment all lie within the 43-km × 26-km rectangular area outlined on the Athens map in Fig. 1a. The station sites have been assigned numbers for later reference and are shown in Fig. 1b, in which the map scale has been expanded by a factor of 4. Table A1 in the Appendix lists station name and function. We shall adopt this same convention for the ratio of map scales in all subsequent comparisons of pollution in Athens and Los Angeles.

Besides the difference in area, there are important differences in topographical features that should be noted in a comparison of pollutant potential in the two basins. The mountains surrounding the Los Angeles basin form an almost unbroken barrier to boundary-layer flow, while there is a gap between the mountains north of Athens. This channel leading to the northeast coast of the Attic Peninsula gives the Athens basin ac-

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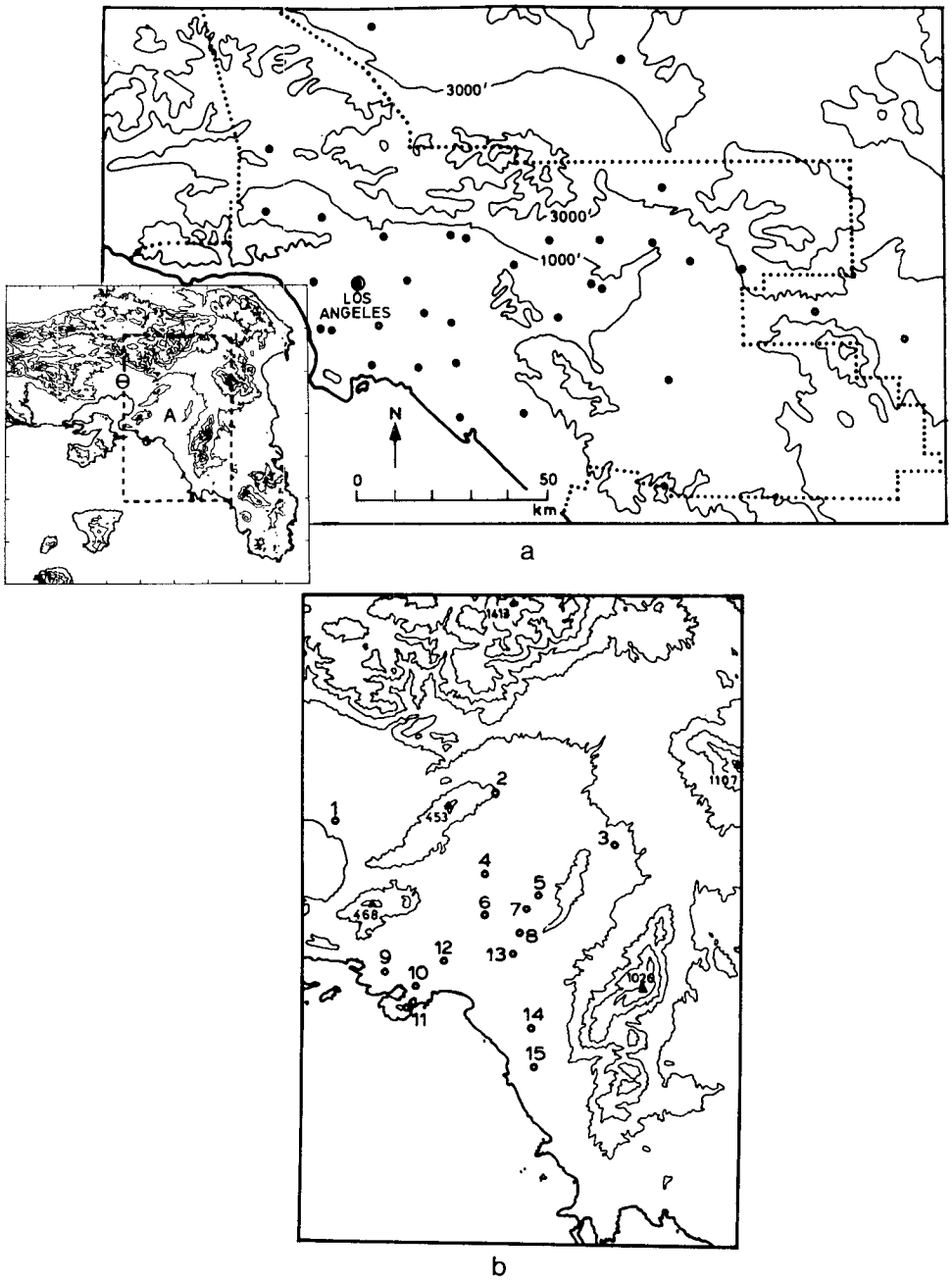

FIG. 1. Topographic maps: (a) Athens–Thriasion basin with contours at 200-m intervals (left) and the Los Angeles basin with contours labeled in feet (right); (b) the rectangular area outlining the Athens basin shown at expanded map scale, with circles marking pollution-monitoring stations identified by number.

cess to the Etesians, the system of persistent northerly summer winds over the Aegean, as will be discussed in the section on meteorological factors. Note also that the minor mountain ranges in the Athens basin are aligned southwest to northeast and do not block flow into or out of the basin. The Santa Anna mountain chain, however, forms a major barrier to a direct boundary-layer flow between the coast and the communities in the northeast quadrant of the Los Angeles basin.

Urban dimensions and estimates of pollutant-emission rates for Athens and Los Angeles are compared in Table 1. The comparison for each parameter is summarized by the ratio of the value for Los Angeles to that for Athens given in the third column. One notes that on a per capita basis, pollutant emissions in Los

TABLE 1. Comparison of urban dimensions and pollutant-emission estimates for Los Angeles (south coast air basin) and Athens–Thriasion basins $A + \theta$. Data sources and clarification of entries are given in the Appendix.

	Los Angeles	Athens	Ratio: Los Angeles/Athens
Population (millions)	11.2	3.5	3.2
Area (km^2)	12 000	625	19
	Rate of emissions (tons per day)		
Carbon monoxide	5 000	889	5.6
Hydrocarbons	1 270	187	6.8
Nitrogen oxides	985	109	9.0
Sulfur oxides	140	49	2.9

Angeles are estimated to be two to three times greater than in Athens, with the exception of SO for which the per capita emissions are almost equal. Since the Athens–Thriasion basin is, however, much smaller, the average areal emission density (emission per unit surface area)—and therefore the potential for pollution—is two to six times greater in Athens than in Los Angeles.

2. Comparison of pollutant concentration

The atmospheric concentration of primary pollutants, compounds that are undesirable in the form that they are emitted (e.g., CO), will be directly proportional to the rate of emission but, of course, also dependent on the atmospheric processes of transport, dilution, and removal. A comparison of emissions and concentration of primary pollutants thus provides a means for establishing the relative importance of these atmospheric processes that modify the local concentration.

Besides primary pollutants, an equal or greater health hazard is presented by the photochemical pollutants, which, as their name implies, are compounds formed in chemical reactions stimulated by solar radiation, the reacting compounds being the primary or precursor pollutants. While an increase in emission of precursor compounds can be expected to result in an eventual increase in photochemical pollutants, chemical reactions take time, and reaction rates are sensitive to temperature and the relative concentration of reactants (Lin et al. 1988; Tilden and Seinfeld 1982). Thus, the relation between emission rates and photochemical-pollution levels is much less direct than for primary pollutants.

The sources of pollutants are not distributed uniformly either in Athens or Los Angeles, and atmospheric concentration will vary with distance from the source and with local meteorological conditions. With a limited number of monitoring stations, it is not a trivial matter to determine representative values of areal pollution. For Los Angeles, the monitoring network maintained by SCAQMD is sufficiently dense so that systematic patterns of pollution are evident.

a. Primary pollutants (CO and SO_2)

Not all the pollutants are monitored at every monitoring station in either Los Angeles or Athens. Monitoring of SO_2 in Athens was undertaken by various agencies as early as 1971. The Ministry of the Environment took over pollution monitoring in Athens in 1974 and has expanded the network so there are annual average values of SO_2 available for 11 stations during the four years, 1987–90, although not all stations operated continuously during this period. The annual arithmetic mean (AAM) SO_2 concentration in Athens averaged for the observational period 1987–90 is shown in Fig. 2a; units are parts per billion (ppb). The corresponding map of AAM SO_2 concentration at the 19 Los Angeles stations for 1987 is given in Fig. 2b.

Although SO_2 emissions by mobile sources are estimated to represent only 10% of the total load, the region of highest SO_2 concentration in Athens roughly corresponds with the area of greatest traffic density, which is a maximum in the city center and has a secondary maximum in the port area of Pireas. The region of greatest SO_2 concentrations in Los Angeles is displaced south of the city center, possibly as a result of additional SO_2 emissions by oil refineries along the coast (Reynolds et al. 1973). Gradients in mean SO_2 concentration in Los Angeles are small, so that the station average of 2.9 ppb is a fairly representative areal-average concentration. We estimate from Fig. 2a that the areal-average concentration in Athens is 12 ppb, or greater than four times that for Los Angeles.

Carbon monoxide is the least reactive of the primary pollutants and is almost exclusively a product of automotive exhaust. The average of AAM CO concentration for the eight Athens stations for the period 1987–90 is shown in Fig. 3a; units are parts per million (ppm). The pattern of concentration isopleths is nearly identical with those for SO_2 in Fig. 2a, although, of course, CO concentration is approximately 200 times larger. Concentrations of CO in both cities occasionally reach levels that are recognized as harmful to human health. Since background concentrations of CO are relatively low in Los Angeles, concern is centered on the occurrence of the extreme values experienced in pollution episodes, and AAM values of CO were not published. One measure of the CO threat presented in Fig. 3b is the maximum 8-h-average concentration observed in 1987 at 23 Los Angeles reporting stations. The 10-ppm isopleth outlining the area of higher CO concentration is shifted to the north, as compared to that for the maximum for SO_2 (Fig. 2b), to more nearly coincide with the pattern of traffic density. The maximum 8-h CO concentration in a single year is not as stable a statistic as the AAM value. In Athens the greatest number of CO-reporting stations for any year

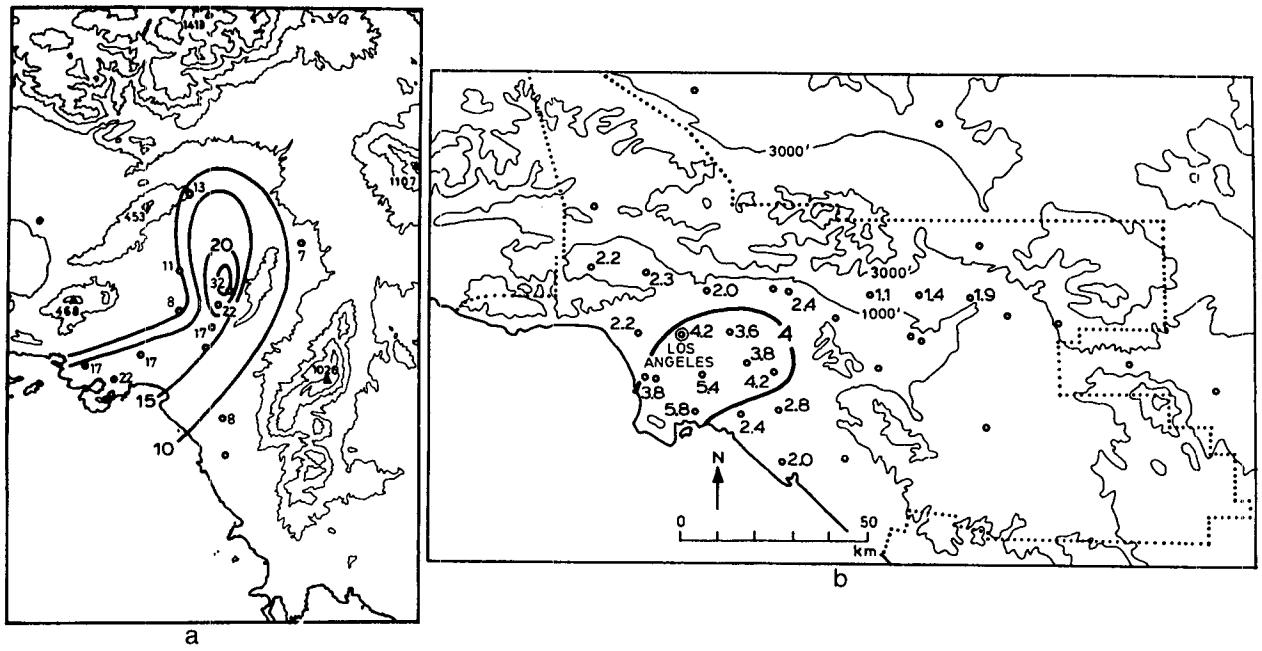

FIG. 2. Annual arithmetic mean concentration of SO_2 (ppb): (a) Athens, average for the period 1987–90; (b) Los Angeles, 1987.

was only six, and in order to provide a comparison with Los Angeles data, both AAM and maximum 8-h concentrations are shown in Table 2 for all reporting stations for the period 1987–90. One notes that the maximum 8-h CO concentrations at Patision (station 5) consistently exceed 20 ppm, the maximum value observed at any Los Angeles station in 1987. Of the total Athens station record of 18 values of 8-h maximum CO concentration, 16 of these reports equaled or exceeded 10 ppm—the isopleth value shown on the

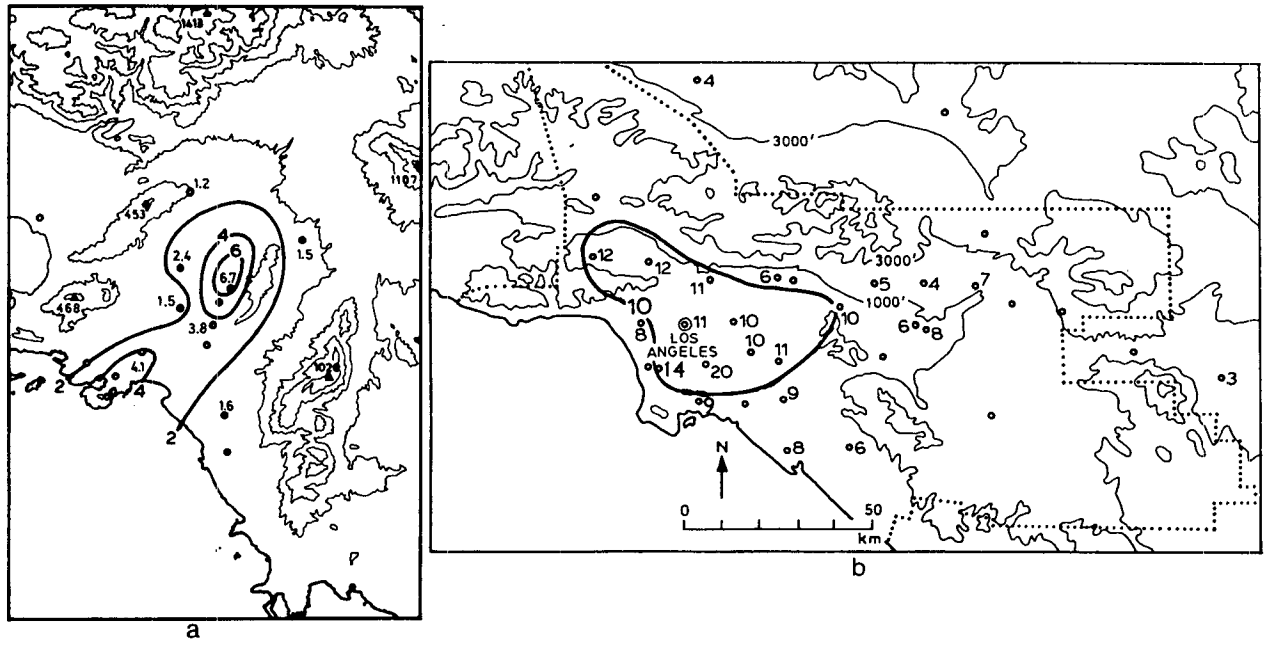

FIG. 3. Carbon monoxide concentrations (ppm): (a) Athens, average of annual arithmetic mean for 1987–90; (b) Los Angeles, maximum 8-h average, 1987.

TABLE 2. Summary of carbon monoxide–monitoring record for Athens stations for the period 1987–1990. Concentration in parts per million.

Station number	Location	1987 AAM	1987 Maximum 8 h	1988 AAM	1988 Maximum 8 h	1989 AAM	1989 Maximum 8 h	1990 AAM	1990 Maximum 8 h
2	Liosia	1.0	3.3	*		*		*	
3	Marousi	*		*		*		1.5	9.9
4	Peristeri	*		*		*		2.5	10.4
5	Patision	5.9	26.9	6.5	21.2	7.4	29.9	6.5	22.5
6	Geoponiki	1.1	12.1	1.6	22.9	1.6	18.2	1.3	6.1
8	Athenas	*		3.6	18.9	4.3	23.1	4.2	19.3
10	Peireas	3.8	15.8	4.1	11.3	4.6	14.3	3.6	16.1
14	Nea Smyrni	1.4	8.6	1.5	10.8	1.7	15.4	1.6	11.2

* Station not in operation.

Los Angeles map (Fig. 3b). It is apparent that extremely high values of CO pollution occur somewhat more frequently in Athens.

Another measure of the CO pollution threat is given by reporting the number of days per year in which the concentration exceeds a standard value. The California standard for 8-h average CO concentration is 9.1 ppm. The greatest number of days of exceedance by any of the LA stations in 1987 was 47, observed at Lynwood in 1987. Eleven of the 23 Los Angeles stations reported no 8-h values exceeding 9.1 ppm. In Athens in 1988, Patision (station 5) reported 208 days of exceedance, and the least station value of days of exceedance was 5, observed at Nea Smyrni (station 14). A summary of the station records for Athens and Los Angeles is given in the Appendix (Table A2). Because neither maximum value nor days of exceedance for one year are robust statistics, it is not possible to give a precise comparison; however, even a conservative estimate would place the average CO pollution level in Athens to be at least twice that for Los Angeles.

b. Photochemical pollutants (nitrogen oxides and ozone)

The primary oxide of nitrogen in automotive exhaust is the monoxide NO. Irradiated by the sun, the primary pollutant mixture undergoes a series of reactions that rapidly convert NO to NO_2, which is in itself an undesirable oxidant; of greater significance, however, is the fact that NO_2 is a fundamental reagent in the photochemical atmospheric reactions forming ozone smog.

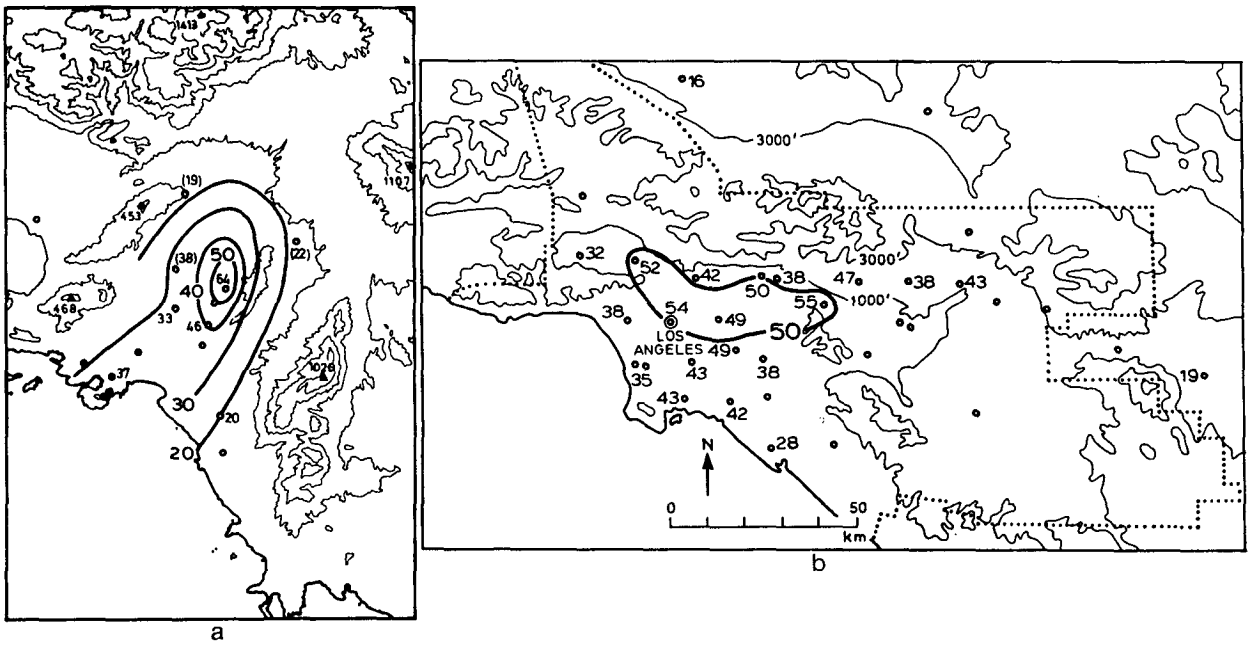

FIG. 4. Arithmetic annual mean concentration of NO_2 (ppb): (a) Athens, average for the period 1987–90; (b) Los Angeles, 1987.

TABLE 3. Summary of ozone-monitoring records for Athens stations for the period 1987–90.

Station number	Location	1987 Days ⩾ 100 ppb	1987 Maximum 1 h	1988 Days ⩾ 100 ppb	1988 Maximum 1 h	1989 Days ⩾ 100 ppb	1989 Maximum 1 h	1990 Days ⩾ 100 ppb	1990 Maximum 1 h
2	Liosia	9	170	26	185	68	180	67	184
3	Marousi	*		*		*		13**	188
4	Peristeri	*		*		*		1**	107
5	Patision	0	84	0	91	0	88	0	75
6	Geoponiki	26	138	22	187	18	151	34	188
10	Peireas	*		14	137	7	127	2	108
14	Nea Smyrni	0	93	0	93	3	185	12	133

* Station not in operation.
** Approximately 30 days of missing data during summer.

The AAM concentration of NO_2 at eight Athens stations averaged for the observational period 1988–90 is shown in Fig. 4a. The general pattern is similar to that of the primary pollutants, with the greatest concentration in the central city. In Los Angeles, the region of maximum average NO_2 concentration is located north of the city center, 30 km inland. Mean NO_2 concentration gradients are small in the Los Angeles basin, so that the average of the station values of 39.9 ppb is a representative areal-average concentration. In Athens the NO_2 concentration in the city center is greater than in Los Angeles, but the average over the basin is somewhat less. A summary of the average NO and NO_2 values at Athens stations for 1988 is given in the Appendix in Table A3. Except for Liosia (station 2), AAM NO concentrations exceed AAM NO_2 values. The monoxide concentration was not reported for the Los Angeles stations, possibly because the concentration is low. If so, the total NO or NO_2 concentration in Athens may be greater than in Los Angeles.

Ozone is generally considered to be the deleterious component of photochemical smog in the Los Angeles area. The SCAQMD publishes data for each station on the number of days per year in which 1-h-average O_3 concentration exceeds the California state standard of 100 ppb, and also the maximum 1-h-average concentration observed in that year. These same measures of O_3 pollution for the seven Athens stations for the years 1987–90 are given in Table 3. The number of days of exceedance vary considerably from year to year,

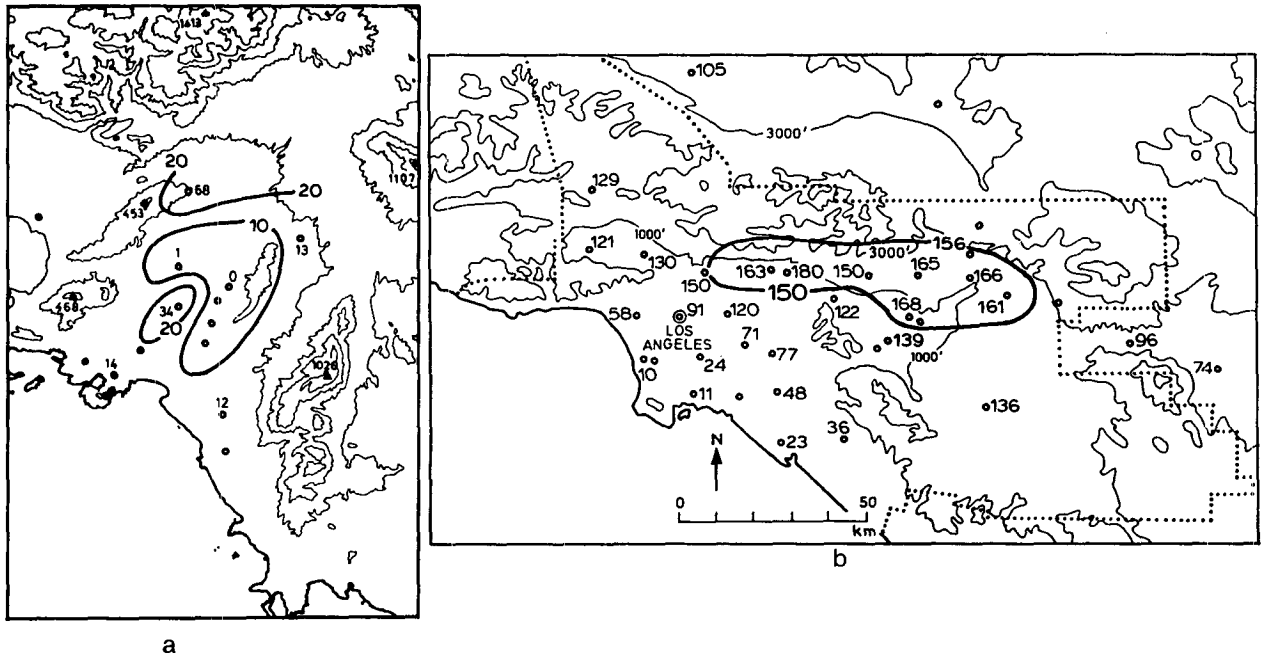

FIG. 5. Number of days per year in which 1-h-average ozone concentration exceeds 100 ppb: (a) Athens, maximum days for any year in the period of observation 1987–90; (b) Los Angeles, 1987.

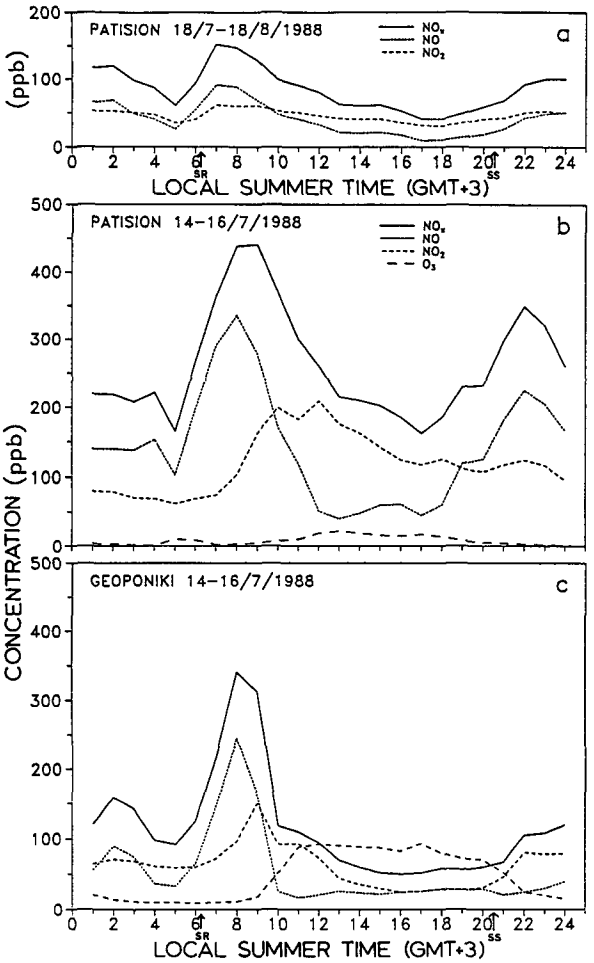

FIG. 6. Mean hourly concentration of pollutants (a) during a month of Etesians, and (b) and (c), during a 3-day pollution episode. Patision (station 5) is near the city center, and Geoponiki (station 6) is 3 km west.

but are generally lower than those observed at Los Angeles stations. So as not to underestimate O_3 pollution levels in Athens, we show a map of the station values of the maximum number of days of exceedance in any year during the observational period 1987–90 (Fig. 5a). The corresponding map of days of exceedance for Los Angeles stations in 1987 is shown in Fig. 5b. In Los Angeles, the number of days of exceedance of the ozone standard is lowest for coastal stations and increases quite regularly with distance inland, reaching a maximum of more than 150 days per year in the northeast sector of the basin. These stations are located behind the Santa Anna Mountains, more than 50 km from the coast. In Athens, ozone levels are lowest in the city center where the concentration of primary pollutants is a maximum. The greatest number of days of exceedance of the O_3 standard is found at Liosia (station 2), which is also the Athens observing station located farthest inland from the coast. The maximum number of days of exceedance, however, is less than 70 at Liosia; only seven Los Angeles coastal stations report lower values.

It is possible that, as in Los Angeles, higher O_3 values could be observed in the northern reaches of the Athens basin if O_3 were monitored there. There is not, however, a large area of the valley remaining unmonitored, since the north coast of the Attic Peninsula is just 30 km distant from Liosia (station 2), and the channel width is less than 10 km. One can conclude only that the present level of O_3 pollution in Athens is less than half that in Los Angeles.

3. Comparison of meteorological conditions affecting pollutant levels

As noted earlier, the emission of pollutants per unit area in the Athens basin is estimated to be two to six times greater than in Los Angeles. Primary pollutant concentrations in Athens are indeed several times greater than in Los Angeles. Secondary pollutant concentrations in Athens, however, are of the same magnitude or less. The reason for the lower level of photochemical pollution in Athens—in spite of the greater emission density of precursors—can be partially explained by a difference in the summer meteorological conditions in the two regions.

Photochemical-pollution episodes are largely phenomena restricted to the warmer half of the year. The mean wind pattern in the atmospheric boundary layer in summer in Athens is a persistent northeasterly flow of relatively high constancy. The Athens basin, as noted earlier, is exposed to the summer monsoon circulation about the Arabian heat low, the northerly winds in the Aegean called the Etesians. The Etesians, although of unusually high constancy for midlatitude wind systems, are occasionally interrupted by the passage of weak pressure troughs, particularly in the spring before the Etesians are well established and in the fall as they begin to weaken. In this situation, a sea-breeze circulation may set up a southwesterly flow into the valley, a condition that can lead to severe photochemical-pollution levels in the basin (Lalas et al. 1983).

To illustrate the importance of the role played by the Etesians in controlling summer pollution levels in Athens, hourly average values of pollutant concentration are shown for Patision (station 5), near the city center, for a month of constant Etesians (Fig. 6a). Figure 6b gives the average hourly concentration of pollutants at Patision during a 3-day period in which the Etesians were weak and a sea breeze set up during the day. Note that even though NO precursor concentrations at Patision were very high (three to four times the Etesians level), the O_3 concentration is negligible. Ozone concentrations at Patision are in fact lower than present levels at many rural sites in the United States. The maximum 1-h ozone concentration at Patision in

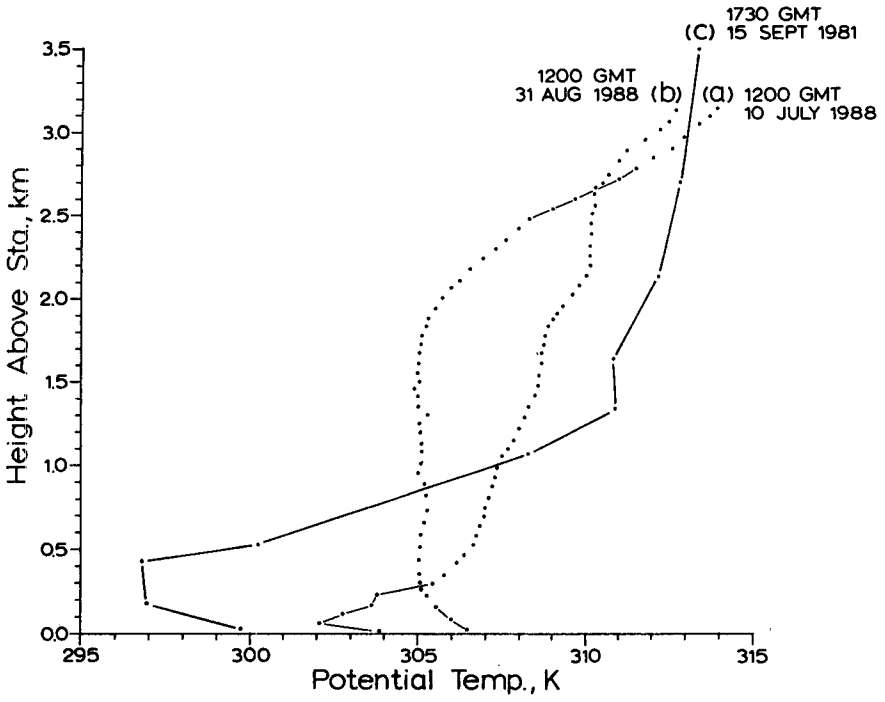

FIG. 7. Comparison of Athens and Los Angeles potential-temperature profiles: (a) Athens, typical Etesians conditions; (b) Athens, sea breeze; (c) Los Angeles (UCLA), typical summer–autumn conditions (after Glendening 1990).

the four years of record was 91 ppb (Table 3), while the maximum 1-h concentrations at three remote forest sites in the United States were all greater than 125 ppb (Lefhon and Lucier 1991).

The mean hourly concentration of pollutants during the breakdown of the Etesians at Geoponiki (station 6), 3 km west of the city center, is shown in Fig. 6c. With the decrease of NO after 0900 LST, ozone concentration at Geoponiki rises rapidly, approaching the California standard danger level of 100 ppb.

In summer, the Los Angeles basin lies on the eastern edge of the semipermanent Pacific high pressure cell, and gradient winds are light northerly. Since this wind system is weak, there is usually a strong westerly sea-breeze circulation during the day. The sea surface temperature in the Los Angeles coastal waters is 10 K colder than that in the Saronikos Gulf, so the land–sea temperature differential driving the sea breeze is greater in Los Angeles.

There is also a difference in the average stability in the atmospheric boundary layer that reduces the rate of dispersion and dilution of pollutants in the Los Angeles basin. Large-scale subsidence in the Pacific high pressure cell maintains a strong persistent inversion over the Los Angeles basin. The Etesians' circulation has a lesser inversion aloft and brings a northerly flow into the Athens basin where surface heating and convection create a deep unstable mixing layer. The contrast in stability is shown by plots of the potential-temperature soundings for Los Angeles and Athens given in Fig. 7. Sounding (a) was made on a day of Etesians showing the typical mixing-layer depth of 2 km. Sounding (c) (after Glendening 1990) was made during a sea-breeze circulation in Los Angeles showing a mixing-layer depth of less than 500 m. Sounding (b) was made in a sea-breeze circulation in Athens. Although the mixing layer is quite shallow, the capping inversion is only 4 K warmer than the surface, while at Los Angeles the difference is greater than 10 K.

4. Summary and conclusions

The average pollutant-emission density in Athens is estimated to be two to six times greater than in Los Angeles. Primary pollutant concentrations are also greater in Athens, perhaps by a factor of 3–5. Photochemical-pollutant concentrations, however, are of the same order or lower in Athens than in Los Angeles. A partial explanation for the lower concentration of ozone in Athens is found in the contrasting summer meteorological conditions in the Athens and Los Angeles basins. In Athens, the prevailing wind is a northeasterly flow that rapidly transports pollutants out of the basin. On the southern California coast, the dominant wind during the day is a westerly sea breeze that transports pollutants into the basin. Large-scale subsidence in the Pacific high pressure cell creates a strong inversion that traps pollutants in a shallow surface mixing layer. In

TABLE A1. Identification of Athens pollution monitoring and meteorological observing stations as of 1990.

Station number	Location	Type of observations: Gaseous pollutants	Particulates	Meteorological observations
1	Elefsina		×	
2	Liosia	×	×	×
3	Marousi	×		×
4	Peristeri	×		×
5	Patision	×	×	
6	Geoponiki	×	×	
7	Ministry of Health	×	×	
8	Athenas Street	×	×	
9	Drapetsona	×		
10	Peireas	×	×	×
11	Tzanio Hospital	×	×	
12	Rentis	×	×	
13	National Observatory*		×	×
14	Nea Smyrni	×	×	
15	Hellenic Meteorological Service*			×

* Not operated by ΠΕΡΠΑ.

the case of O_3 pollution, which is considerably lower in Athens than in Los Angeles, it appears that the Athens basin is too small for the given emission density and circulation to permit the dilution of precursors that is necessary for the completion of the photochemical reactions creating O_3. In engineering terms, the Athens basin is an inefficient producer of O_3 because the reactor volume is too small and the flow rate is too large to handle the present loading of primary reagents.

Pollutant emissions in Athens are presently at such a high level that serious pollution episodes occur with every protracted interval of light winds. It would be necessary to reduce emissions by a factor of 2–3 to remove this threat. Photochemical pollution does not reach intolerable levels in Athens more frequently because of the persistent summer winds ventilating the basin. The Etesians, although persistent, do vary from year to year, by Carapiperis measure of intensity having a coefficient of variation of approximately 25% (Repapis et al. 1975). Fluctuations in the frequency of photochemical-pollution episodes of similar magnitude can be anticipated if present emission rates are maintained. Ozone concentrations, at least in central Athens, may not decrease with a decrease in emissions of the NO precursor. Comparing Fig. 6b and Fig. 6c, it appears that the concentration of NO in the center city has reached levels that inhibit the formation of ozone.

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APPENDIX

Data Sources

Emission estimates and pollution data for Athens for 1988 were taken from technical reports of the Di-

TABLE A2. Comparison of station records for number of days per year in which 8-h-average CO concentration exceeds 9.1 ppm.

Station number	Athens 1988: Location	Athens 1988: Number of days	Los Angeles 1987: Location	Los Angeles 1987: Number of days
5	Patision	208	Lynwood	47
8	Athenas	41*	Hawthorn	22
10	Peireas	21	Burbank	11
6	Geoponiki	15	La Habra	3
14	Nea Smyrni	5	4 stations	1
			11 stations	0

* Estimated; station started operation on 4 March 1988.

TABLE A3. Annual arithmetic mean nitrogen oxide concentration at Athens stations. Averaged for the period 1988–90.

Station number	Location	NO_2 (ppb)	NO_x (ppb)	Ratio: NO_x/NO_2
2	Liosia	19	28	1.5
3	Marousi	22	60	2.7
4	Peristeri	38	86	2.3
5	Patision	64	226	3.5
6	Geoponiki	33	89	2.7
10	Peireas	37	91	2.5
14	Nea Smyrni	20	48	2.4

rectorate for Air Pollution Control, Ministry of Environment, Planning and Public Works of Greece (1989). This agency is officially referred to by its Greek acronym, ΠΕΡΠΑ. Emission estimates for sulfur oxides are given as metric tons of SO_2, and nitrogen oxides as tons of NO_2. The greater-Athens population figure of about 3.5 million was taken from the 1991 census.

Emission estimates and population figures for Los Angeles were provided by G. Colovos (1989, personal communication). Los Angeles air-pollution monitoring data were taken from the Air Quality Data 1987, a report by the SCAQMD. The map of Los Angeles with pollution monitoring sites was taken from Lin (1982).

REFERENCES

Blumenthal, D. L., W. H. White, and T. B. Smith, 1978: Anatomy of a Los Angeles smog episode: Pollution transport in the daytime sea-breeze regime. *Atmos. Environ.*, **12,** 893–907.

California Air Resources Board, 1987: Air quality data 1987. South Coast Air Quality Management District.

Glendening, J. W., 1990: A mixed-layer simulation of daytime boundary-layer variations within the Los Angeles basin. *Mon. Wea. Rev.*, **118,** 1531–1550.

Lalas, D., D. Asimakopoulos, D. Deligiorgi, and C. G. Helmis, 1983: Sea breeze circulation and photochemical pollution in Athens. *Atmos. Environ.*, **17,** 1621–1632.

Lefohn, A. S., and A. A. Lucier, 1991: Spatial and temporal variability of ozone exposure in forested areas of the United States and Canada: 1978–1988. *J. Air Waste Manage. Assoc.*, **41,** 694–699.

Lin, G.-Y., 1982: Oxidant predictions by discriminant analysis in the south coast air basin of California. *Atmos. Environ.*, **16,** 135–143.

Lin, X., M. Trainer, and S. C. Liu, 1988: On the nonlinearity of the tropospheric ozone production. *J. Geophys. Res.*, **93,** 15 879–15 888.

ΠΕΡΠΑ, Directorate for Air Pollution Control, Ministry of Environment, Physical Planning and Public Works, Greece, 1989a: The atmospheric pollution in the area of Athens. Tech. Rep.

——, 1989b: Measurements of atmospheric pollution in the area of Athens for the year 1988. Tech. Rep.

Repapis, C. C., C. S. Zerefos, and B. Tritakis, 1977: On the Etesians over the Aegean. *Proc. Acad. Athens,* **52,** 572–606.

Reynolds, S. D., P. M. Roth, and J. Seinfeld, 1973: Mathematical modeling of photochemical air pollution. I: Formulation of the model. *Atmos. Environ.*, **7,** 1033–1061.

——, M.-K. Liu, T. A. Hecht, P. M. Roth, and J. Seinfeld, 1974: Mathematical modeling of photochemical air pollution. III: Evaluation of the model. *Atmos. Environ.*, **8,** 563–596.

Roth, P. M., P. J. W. Roberts, M.-K. Liu, S. D. Reynolds, and J. Seinfeld, 1974: Mathematical modeling of photochemical air pollution. II: A model and inventory of pollutant emissions. *Atmos. Environ.*, **8,** 97–130.

Tilden, J. W., and J. H. Seinfeld, 1982: Sensitivity analysis of a mathematical model for photochemical air pollution. *Atmos. Environ.*, **16,** 1357–1364.