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ANALYSIS OF CLIMATOLOGICAL AND AIR QUALITY OBSERVATIONS FROM GREATER ATHENS AREA

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Abstract—In this paper, the climatological and air quality observations obtained for the periods 1974–1990 and 1983–1990, respectively, in the Greater Athens Area, are analyzed. During this period, 80 air pollution episodes, which lasted 210 d in total, were detected. The analysis of the observations allows the interpretation of air quality characteristics in terms of the climatological and meteorological factors. The importance of some characteristic indices for air pollutant dispersion conditions, such as mixing height, ventilation coefficient, temperature at 850 hPa, and temperature inversions, is discussed. The results show that the air quality in the Athens Basin is strongly affected by the meteorological conditions, especially those which are in favor of local circulations. The worst air pollution episodes are associated with anticyclonic conditions and/or advection of warm air masses.

Key word index: Air pollution, urban climatology.

1. INTRODUCTION

The Greater Athens Area (GAA) has been plagued during the last two decades by air quality problems due to population shift, increased industrialization and continuously increasing motorized fleet. Moreover, the variability of the physiographic characteristics and the terrain complexity of the GAA leads to the formation of local atmospheric circulations which affect dramatically the pollutant transport and dispersion.

During the past two decades, air quality in the GAA has been the subject of several studies and many interesting conclusions have been extracted. More precisely, Lalas *et al.* (1982) concluded that the observations of the SO_2 concentration are correlated with the wind speed, minimum temperature and rain during winter and with the wind speed and direction, minimum temperature and relative humidity during summer. Lalas (1985) studied the correlation between the O_3 and NO_2 concentrations and the observed relative humidity, temperature and wind as well as with the previous day maximum concentration of each pollutant. Further, the development of sea(land)-breeze circulations was found to be crucial in the accumulation of pollutants in the GAA (Lalas *et al.*, 1983, 1987; Helmis *et al.*, 1987; Asimakopoulos *et al.*, 1992). Sea-breeze circulations associated with complex terrain are generally considered a very effective mechanism in transporting pollutants from their sources, even to distances 100–200 km inland (Edinger *et al.*, 1972; Chang *et al.*, 1989; Millan, 1993). Another aspect that has been studied is the correlation between nocturnal temperature inversions and high pollutant concentrations during winter (Katsoulis, 1988a, b). Furthermore, high pollutant concentration was often found to be associated with the presence of persistent stationary anticyclonic conditions (Lalas *et al.*, 1982; Katsoulis, 1988a) or situations where the sea-breeze circulation counterbalances the regional and/or synoptic-scale circulations (Kallos *et al.*, 1993).

Despite the fact that a lot of research has been devoted to the study of the local climatic conditions in relation to the air quality in the GAA many questions are still to be answered. In this context, the aim of the present study is to identify the synoptic conditions which are in favor of air pollution episodes, and to analyze the climatic behavior of the different meteorological parameters affecting air quality in relation to their variation during the days characterized as air pollution episode-days.

In the following section, a brief description of the GAA is given, and the prevailing weather conditions affecting the area are discussed. In Section 3 the data sets used in this study are presented. Then a classification of the air pollution episodes and the associated synoptic conditions is performed in Section 4. Section

5 is devoted to the analysis of the meteorological and air quality observations. Finally, the conclusions are given in Section 6.

2. DESCRIPTION OF THE AREA—GENERAL FLOW CHARACTERISTICS

The GAA, which includes the cities of Athens and Piraeus (and their suburbs), is located in a Basin surrounded by mountains on three sides and open to the sea (with the Saronic Gulf) on the fourth side (Fig. 1). The three main mountains are Hymettus (1050 m) to the E, Pendeli (1100 m) to the N–NNE, and Parnitha (1400 m) to the N–NNW. To the W of the Basin is the mountain Aegaleo, 450 m high. These mountains are mostly covered by bushes and only a small part is covered by pine forests. There are hills up to 200 m inside the Basin (Pnyka, Lycabettus, and Tourcovounia). The main axis of the Basin is SSW to NNE (25 km) and its area is approximately 450 km^2.

The population has been estimated at 3.6 million. Inside the GAA about 40% of the Greek industry (mainly small- to medium-scale factories) and almost 50% of all the automobiles registered in Greece are concentrated. The main sources of air pollution in the GAA are automobiles, industry and central heating during the cold months (Lalas *et al.*, 1982). The industrial area is concentrated at the S–SW edge of the Basin. Other important sources of air pollution are the Piraeus harbor located at W–SW, and the Hellinicon airport at the S–SSE edge of the Basin.

The complexity of the topographic characteristics of the GAA may cause variations of the flow fields and the mixing layer depth. These two parameters are crucial for the transport and dispersion of air pollutants (Pielke *et al.*, 1983; Ulrickson and Mass, 1990a, b). Moreover this topographic complexity along with the land–water distribution and land cover induce local circulations in the GAA area such as sea(land)-breezes, drainage and upslope flows. On a significant number of days the combination of local and synoptic conditions creates the appropriate conditions for air pollution episodes in the GAA. A detailed description of the weather conditions during air pollution episodes in the GAA is given in Kallos *et al.*

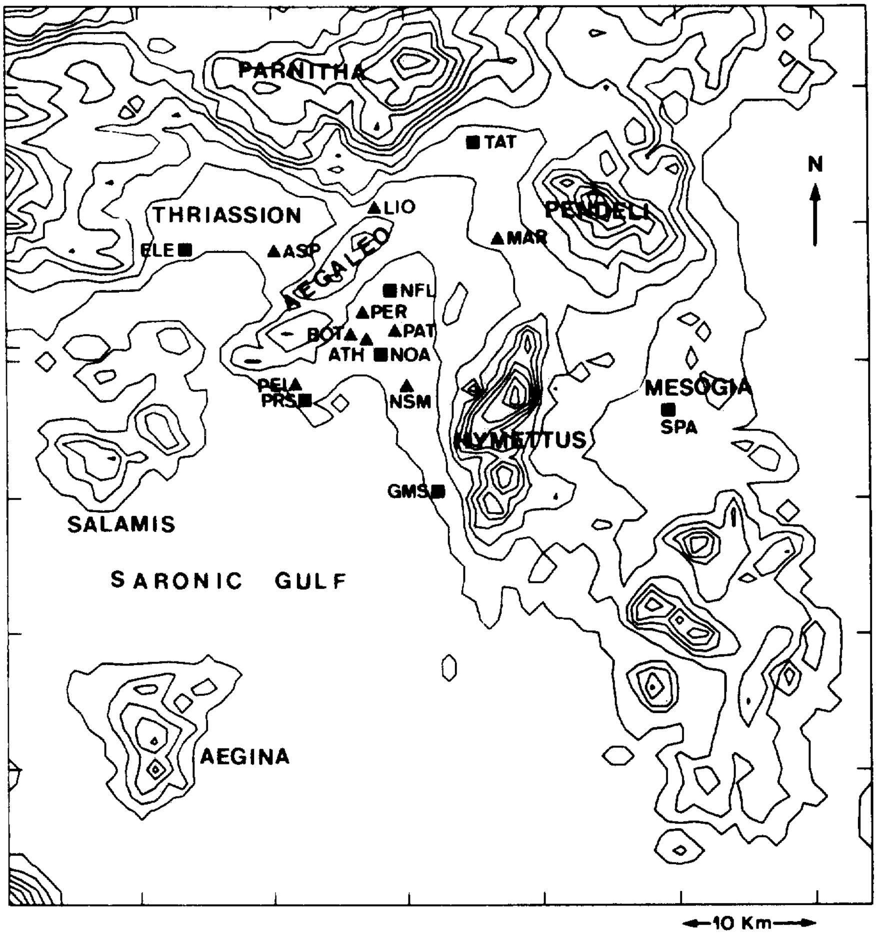

Fig. 1. Map of the Athens Basin. Elevation contours are every 100 m. Squares and triangles indicate the location of the meteorological and air quality surface stations, respectively.

(1993) and only a small summary is given in the following.

Weather conditions and air pollutant dispersion

The GAA climate is Mediterranean, characterized by warm and dry summers and relatively wet and mild winters. The daily mean temperature is 10°C during winter and 26°C during summer, the coldest month being January (9.2°C) and the warmest July (27.2°C). The annual mean rainfall is 418 mm and the annual mean relative humidity is 65% with the wettest month being February (75%) and the driest July (45%) (Maheras, 1976).

The atmospheric circulation within the Athens Basin results from the interaction of different scales: synoptic, regional, meso and microscale. During winter, poor dispersion conditions in the GAA are associated with the development of a high pressure system over the central Mediterranean, or with the development of warm advection in the lower troposphere in front of a low pressure system or within the warm sector of a cold front. On the contrary, good dispersion conditions in the same period occur after a cold front passage and in the case of the formation of a strong pressure gradient over the Aegean Sea or the formation of a low centered over Cyprus (Kallos and Kassomenos, 1992).

During summer, the dispersion conditions in the GAA depend on the relative strength of the high pressure system covering the Eastern Mediterranean and Balkan area and the balance between this system and the thermal low over the Anatolian Plateau. When the pressure gradient is weak, the synoptic circulation is weak from N and the local circulations define the dispersion conditions within the GAA. On the contrary, when the pressure gradient is strong, northerly winds (stronger during the day and weaker during the night) dominate, creating good ventilation in the Athens Basin. This wind pattern consists of a regional-scale phenomenon called Etesians (Carapiperis, 1951).

During the transient period, that is autumn and spring, weather conditions change regularly between winter and summer type. The worst air pollution episodes are associated with warm air advection, occurring when a trough is over the Iberian Peninsula and the Western Mediterranean and a ridge over the Central Mediterranean. For a synopsis of the synoptic conditions see also Kallos *et al.* (1993, Table 1).

Local circulations are observed and as a matter of fact influence the transport and dispersion of air pollutants over the GAA in different manners. They are usually observed during days of relatively weak synoptic flow. Such circulations are sea(land)-breeze, upslope and drainage flows, channelling, etc. Sea-breeze circulations develop during more than 30% of the days during spring and summer months (Prezerakos, 1986). They play a significant role in determining the diurnal variation and strength of photochemical pollution. The sea-breeze flows over the GAA consist of three main cells (Lalas *et al.*, 1982; Kallos, 1987; Steyn and Kallos, 1992). The first cell is from the Saronic Gulf toward Athens, with WSW to S surface winds during the day and N winds during the night. The second cell develops over Mesogia Plain (Fig. 1), with NE to E and SE surface winds during the day and W–NNW surface winds during the night. Finally, the third cell forms over the Thriassion Plain (Fig. 1), with S surface winds during the day and N during the night.

Sea-breeze circulations are observed in the Attica peninsula not only during summer and the transient period but also during winter (Carapiperis and Katsoulis, 1977). Kallos *et al.* (1993) reported that under stable conditions the regional-scale flow exhibits similar behavior to the sea-breezes over the Saronic Gulf and Athens Basin. Additionally, Kassomenons (1993) found that most of the cases reported as winter time sea-breezes are due to this regional-scale phenomenon, as the land–water temperature gradient is not strong enough to produce sea-breeze circulations.

3. DATA SETS

Meteorological data

The data analyzed in this study were provided from the surface network (six stations) of the Greek Meteorological Service (GMS) and the meteorological station of the National Observatory of Athens (NOA). The location of each station is indicated in Fig. 1. Further information on each of these stations is provided in Table 1. More precisely, temperature, relative humidity, wind speed, and wind direction were provided with a temporal resolution of 3 h from the GMS

Table 1. Some useful information about the meteorological stations

Station number	Abbreviated station name	Longitude/latitude	Height above MSL	Operating period
1	GMS	37.54/23.44	10	1974–1990
2	PER	37.56/23.28	2	1983–1990
3	NOA	37.53/23.43	107	1974–1990
4	NFL	38.03/23.44	136	1974–1990
5	TAT	38.06/23.44	237	1974–1990
6	ELE	38.04/23.47	30	1974–1990
7	SPA	37.58/23.55	0	1983–1990

network and 1 h from the NOA station. Cloud cover measurements were also provided from the GMS network with a time resolution of 3 h, and from the NOA station three times per day (at 0800, 1400 and 2000 LT).

Upper-air data of pressure, temperature, relative humidity, wind speed, and wind direction were provided from the upper-air station of the Greek Meteorological Service at the Hellinicon airport (station GMS) at 0200 and 1400 LT for the period 1974–1990.

Air quality data

Air quality data were provided from the monitoring network operated by PERPA (Branch of the Ministry of Environment, City Planning and Public Works). This network consists of nine stations providing measurements of SO_2, NO, NO_2, CO, O_3, and smoke. The station PAT also measures TSP and VOC, on an experimental basis, during the last few years. The location of these stations is also indicated in Fig. 1. Table 2 provides some additional information about this network.

4. CLASSIFICATION OF AIR POLLUTION EPISODES

During the past 20 years, the air pollution problem in the GAA has received increased public attention and ambient air quality standards have been defined. During air pollution "episodes", that is when air pollution reaches emergency action levels, restrictions are imposed, mainly in the traffic of civilian cars in Athens Basin. The defined ambient air quality and emergency limits are given in Table 3.

The analysis of air quality time series for the period 1983–1990 showed that only some constituents such as NO_2, O_3 and CO have reached the emergency action levels several times. The various pollutants exceed very often the ambient air quality standards for small time periods (1–2 h), but in the present study this is not considered an air pollution episode, because its duration is considered as small. In this study, the criteria for an air pollution episode are the following: *at least two constituents exceed ambient air quality limits in at least two monitoring stations, for a period not less than* 2 h, *and the phenomenon lasts for at least* 2 d. These criteria are more or less arbitrary but they have been imposed in order to select the worst air pollution episodes which occurred in the GAA. Following these criteria, 80 air pollution episodes, lasting 2–7 d each (210 d in total), were detected in the period 1983–1990. As can be seen in Fig. 2, almost half of the episodes have a duration of 2 d, while a duration of more than 5 d is very rare. Episodes lasting more than 7 d were not detected. Most episodes were detected during the transient period (34 out of the 80 episodes), and in winter (27 out of the 80 episodes), with April, October and December being the months with the greater number of pollution episodes and March with the least. During summer, only few episodes occurred (19 out of the 80 episodes). This can be explained by the fact that summer is the vacation period, and that during this period the prevailing winds (subregional and mesoscale), which are due to thermal circulations, are stronger and the mixing height is deeper.

The analysis of the prevailing synoptic conditions during air pollution episodes showed that these epi-

Table 2. Some useful information about the network of the air quality monitoring stations

Station number	Abbreviated station name	Height (m) above MSL	Operating period
1	PAT	10	1983–1990
2	ATH	5	1988–1990
3	BOT	4	1983–1990
4	MAR	4	1983–1990
5	LIO	10	1983–1990
6	ASP	—	1983–1987
7	NSM	4	1983–1990
8	PER	4	1989–1990
9	PEI	—	1983–1990

Table 3. Air pollutant limits imposed for the GAA

Air pollutant	Ambient air quality limit	Emergency action limit	Emergency situation
SO_2	200	300	500
NO_2	200	500	700
O_3	200	300	500
CO	15	25	35
Smoke	250	400	600

For NO_2, O_3, limits are in hourly values, for CO in mean 8 h values and for SO_2 and smoke in mean daily values. All values are in $\mu g\, m^{-3}$, except for the CO (in $mg\, m^{-3}$).

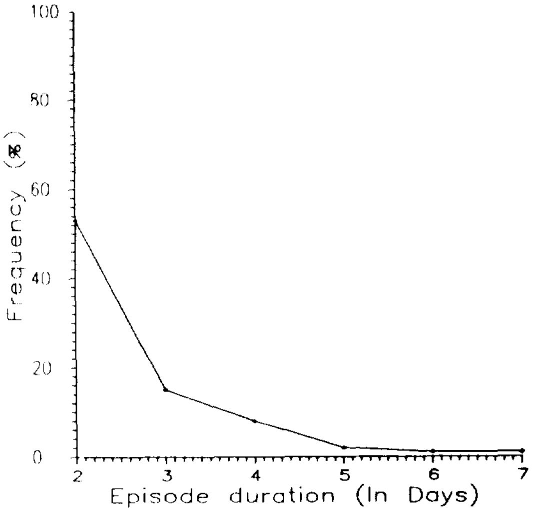

Fig. 2. Frequency of occurrence of air pollution episodes in the GAA according to their duration.

sodes are associated with four types of synoptic conditions:

(i) An anticyclone covers the Central and East Mediterranean.
(ii) Greece is within the warm sector of a low pressure system.
(iii) Greece is behind a cold front or a low and the wind field is weak (weak pressure gradient).
(iv) A weak pressure gradient exists over Greece and the Aegean Sea, due to the expansion towards E of the anticyclone located over the Central Mediterranean (summer case).

In Table 4, the distribution of the 80 air pollution episodes following the season and the prevailing synoptic conditions is given. It can be concluded that the type of synoptic conditions that is mostly associated with episodes is type (i) during all seasons. Air pollution episodes can also be classified according to the presence of warm air advection or generally the presence of warm air masses in the lower troposphere. This classification was performed using the analysis of the synoptic maps and upper-air observations from the airport of Athens. Strong warm air advection (of more than 4°C) in the lower troposphere for at least 3 d preceding the episode is observed for 49 out of the 80 air pollution episodes (see Table 5). Warm air advection is more intense during winter than during summer. Warm air masses can also be found over Athens due to large-scale subsidence. In this case, the temperature increase is smaller than 4°C. Moreover, a classification of air pollution episodes can be performed following the intensity of the pressure gradient at the surface. From this analysis it can be concluded that 137 out of the 210 d of air pollution episodes were associated with very weak or weak pressure gradient over Greece. This situation is more frequent during transient or winter time (see Table 6). A relatively strong pressure gradient during days of air pollution episodes is observed for only a small number of days and was associated with a modification of the prevailing synoptic situation.

Table 4. Distribution of air pollution episodes following the season and the type of the associated synoptic conditions for the time period 1983–1990 (see text for details)

Type of synoptic conditions	Winter	Summer	Transient	Total
(i)	14	6	16	36
(ii)	10	4	14	28
(iii)	3	1	4	8
(iv)	—	8		8
Total	27	19	34	80

Table 5. Classification of the 80 air pollution episodes according to the strength of warming of the lower tropospheric layers

Season	Winter	Summer	Transient	Total
Strong warm advection	17	13	19	49
Weak or no warm advection	10	6	15	31

Table 6. Classification of the 210 d of the air pollution episodes according to the surface pressure gradient

Surface pressure gradient	Season			
	Winter	Summer	Transient	Total
A	23	14	34	71
B	23	17	26	66
C	15	20	31	66
D	4	1	2	7

Letter A denotes a very weak pressure gradient (less than 5 hPa per 1000 km), B a relatively weak pressure gradient (5 hPa per 550–1100 km), C a relatively strong pressure gradient (5 hPa per 100–550 km) and D a strong pressure gradient (> 5 hPa per 100 km).

5. ANALYSIS OF METEOROLOGICAL AND AIR QUALITY OBSERVATIONS

In order to better understand the physical processes which influence air quality in the GAA, the wind fields and thermodynamic structure of the atmosphere should be studied. For this purpose, the sounding data with a resolution of 50 hPa, at 0200 and 1400 LT, and the surface observations have been processed in order to be used as a climatological base. These data were available for the time period 1974–1990. In this context, the observed winds at various characteristic levels above mean sea level (MSL) have been analyzed. Analysis was also made for the cloud cover in association with surface winds. Further, some characteristic indices for air pollutant dispersion conditions, such as mixing height, ventilation coefficient, temperature at 850 hPa, temperature inversions, have been calculated.

Surface wind observations

In order to study the wind conditions at the surface, wind roses have been constructed with the data of the seven surface stations at different periods of the day. It should be noted that some of the stations are directly influenced by the terrain conditions. More precisely, the surface stations GMS, ELE, and PRS are located near the coast, NOA is on a hill in the center of Athens, and TAT is at the foot of a high mountain (Parnitha mountain, Fig. 1). The station SPA is located in a suburban residential area within the Mesogia Plain and the NFL station is in a residential area in the center of Athens Basin. Figure 3 shows the wind roses constructed at various surface stations in the GAA at 0200 and 1400 LT, for the period 1974–1990.

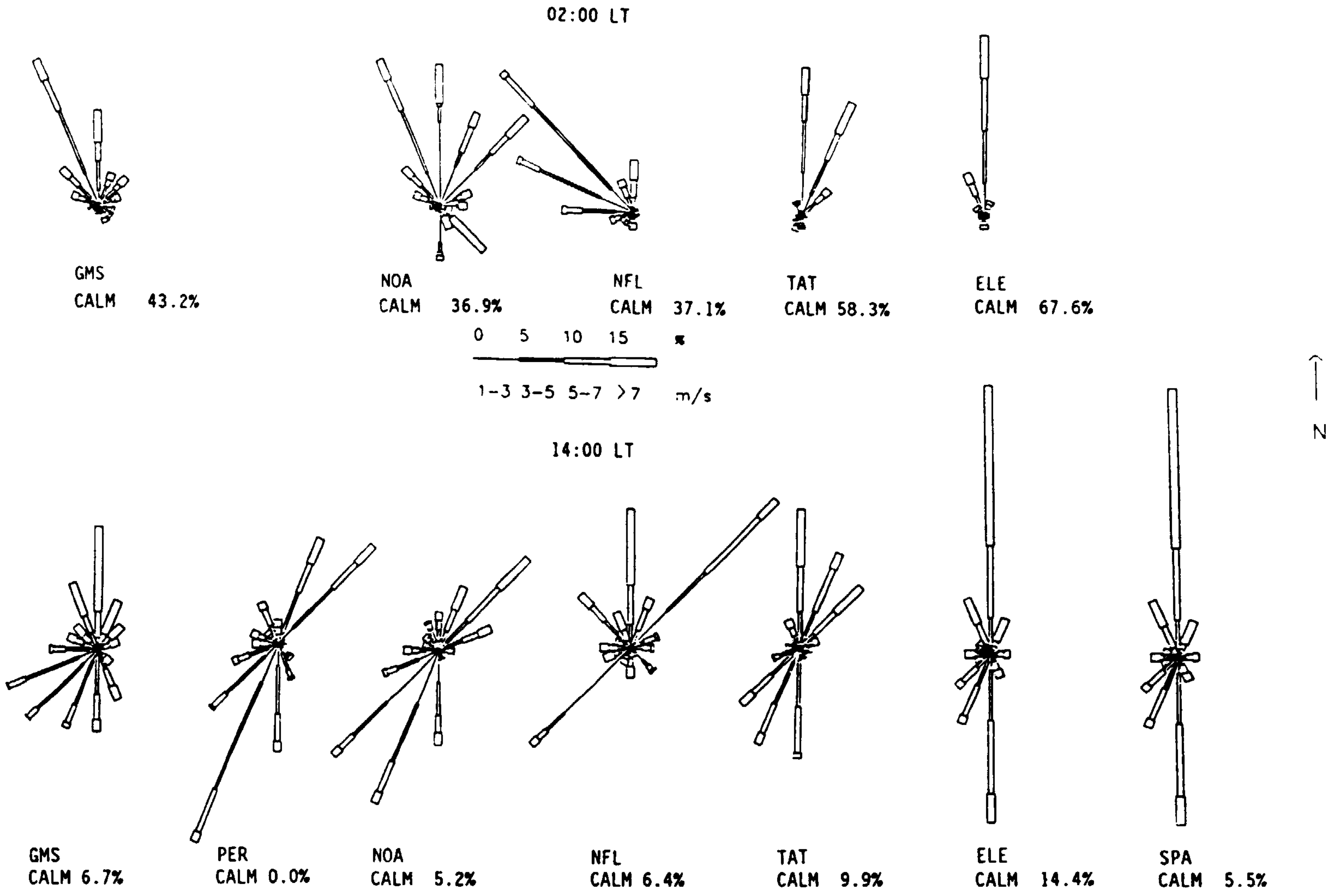

Fig. 3. Wind roses constructed from the surface observations at 0200 and 1400 LT, for the period 1974–1990. For each wind rose the abbreviated station name as well as the frequency of the calms are given.

During the night, all the stations located within the Basin record calms for more than half of the year. Calms are also observed at the ELE station in the Thriassion Plain for more than 2/3 of the nights. The prevailing winds are from N with weak (1–5 m s^{-1}) to medium (5–7 m s^{-1}) intensities. Weak northerly winds recorded by the coastal stations are associated with local phenomena such as land-breeze or katabatic flows. Weak northerly winds recorded at NFL and TAT are due to drainage winds. Stronger winds are due to synoptic conditions. During the day, calms are often recorded, except at PRS, and they are more frequent during the early morning hours. Relatively weak WSW to SSE winds are frequently recorded at the stations located within the Basin. These winds are mainly due to local circulations and more precisely to the combination of sea-breeze and upslope winds. The coastal stations record the presence of these southerly winds which begin early in the morning and last for a long time period of the day during all seasons. At the NOA and NFL stations, within the Basin, these S winds are observed later in the day and last for less time. At the TAT station the S winds are observed even later in the day and are less frequent during winter. At the NFL and TAT stations, NNE to NE winds are also observed during all the seasons and for a significant number of days. Therefore, it can be concluded that sea-breeze and upslope winds develop during all the year, but for a large number of days, especially during winter and the transient period, the thermal circulations are not strong enough in order to penetrate deeply within the Athens Basin. For a large number of days strong (>7 m s^{-1}) northerly winds, related to synoptic-scale circulations, are observed. The stations of ELE at the Thriassion Plain and SPA at the Mesogia Plain record preferably N or S winds. This is due to the orientation of these plains.

A more extensive analysis was performed for the 210 d which consist of the 80 worst air pollution episodes recorded in the period 1983–1990. Figure 4 shows the wind roses at the surface at 0200 and 1400 LT for the air pollution episode-days. The stations PRS and SPA were not operated during the night, and the NFL station was operated during the night for only a small time period. During the night, calms or very light winds prevail near the surface. Many stations recorded calms at a frequency of 75%, while moderate winds did not exceed 5% and strong winds were not observed. The prevailing wind directions are from N (NNW to NE) and can be attributed to local circulations (combination of katabatic, drainage winds and land breeze). These light winds and calms do not favor air pollutant dispersion. The NOA station is an exception due to its location and records a large number of S winds. During daytime, calms are remarkably frequent and certainly more frequent than climatic ones. As a matter of fact it can be concluded that air pollution episodes are characterized by calms or light winds at the surface which show remarkable diurnal variation. The prevailing wind directions are S–SW near the coast (at GMS and PRS) mostly related with sea-breeze circulations, and NNE–NE for a significant number of days at the northern part of the Athens Basin (at NFL and TAT). This must be due to the fact that for these days, the sea-breeze is not strong enough to penetrate deeply inside the Athens Basin. At the Thriassion Plain (ELE station) the observed southerly winds are related to the sea-breeze cell which develops in the area. Finally, at the Mesogia Plain (station SPA) northerly and southerly winds prevail due to sea-breezes or channelling of the regional-scale circulation along the Evoic Gulf. Comparison between Figs 3 and 4 gives some evidence of the influence of local circulations and stationary conditions on the poor dispersion of air pollutants.

Upper-air wind observations

The upper-air wind field analysis was based on the data provided by the soundings at Hellinikon airport. Figure 5 shows the wind roses at 100, 500, 1000, 1500, and 2000 m above MSL at 0200 and 1400 LT, constructed from the sounding data for the period 1974–1990. The levels presented in Fig. 5 were chosen because they are representative of the layers which are directly influenced by the terrain and/or they are within, at the limit of, or above, the mixing layer. Figure 6 shows the wind roses at the same levels as in Fig. 5, but for the air pollution episode-days for the period 1983–1990. It should be noted that Hellinicon airport is near the sea and as a matter of fact the sounding measurements, especially in the low layers, are directly influenced by the terrain conditions and the land–sea distribution. More precisely, special care must be taken when interpreting the S and SW winds.

During nighttime, calms are very frequent (28% for the climatological analysis) at 100 m, especially during transient and summer period. Light winds from N–NW prevail for 1/3 of the days. In the first 500 m, winds are partly induced by the local circulations while above this level they mostly depend on the synoptic-scale conditions. It is worth noting how the winds at 1500 m and above become progressively more intense and back towards westerly directions. This is more evident at the higher levels (not shown) which are under the influence of the planetary circulation. During winter, southerly winds associated with synoptic systems such as lows become more frequent and stronger above 1000 m. During summer, northerly winds prevail in the low as well as in the higher levels. This is due to regional-scale circulations, intensified by land-breezes or katabatic flows. During the transient period a progressive transition from winter to summer type conditions occurs, with increasing appearance and intensification of northerly winds along with decreasing appearance of southerly winds. The analysis of the air pollution episode-days showed that at 100 m calms appear at a frequency of 50% at night. Very light winds (1–3 m s^{-1}) prevail in the first 500 m, and light winds (3–5 m s^{-1}) prevail above, up to 1500 m. Very light winds along with the shallow

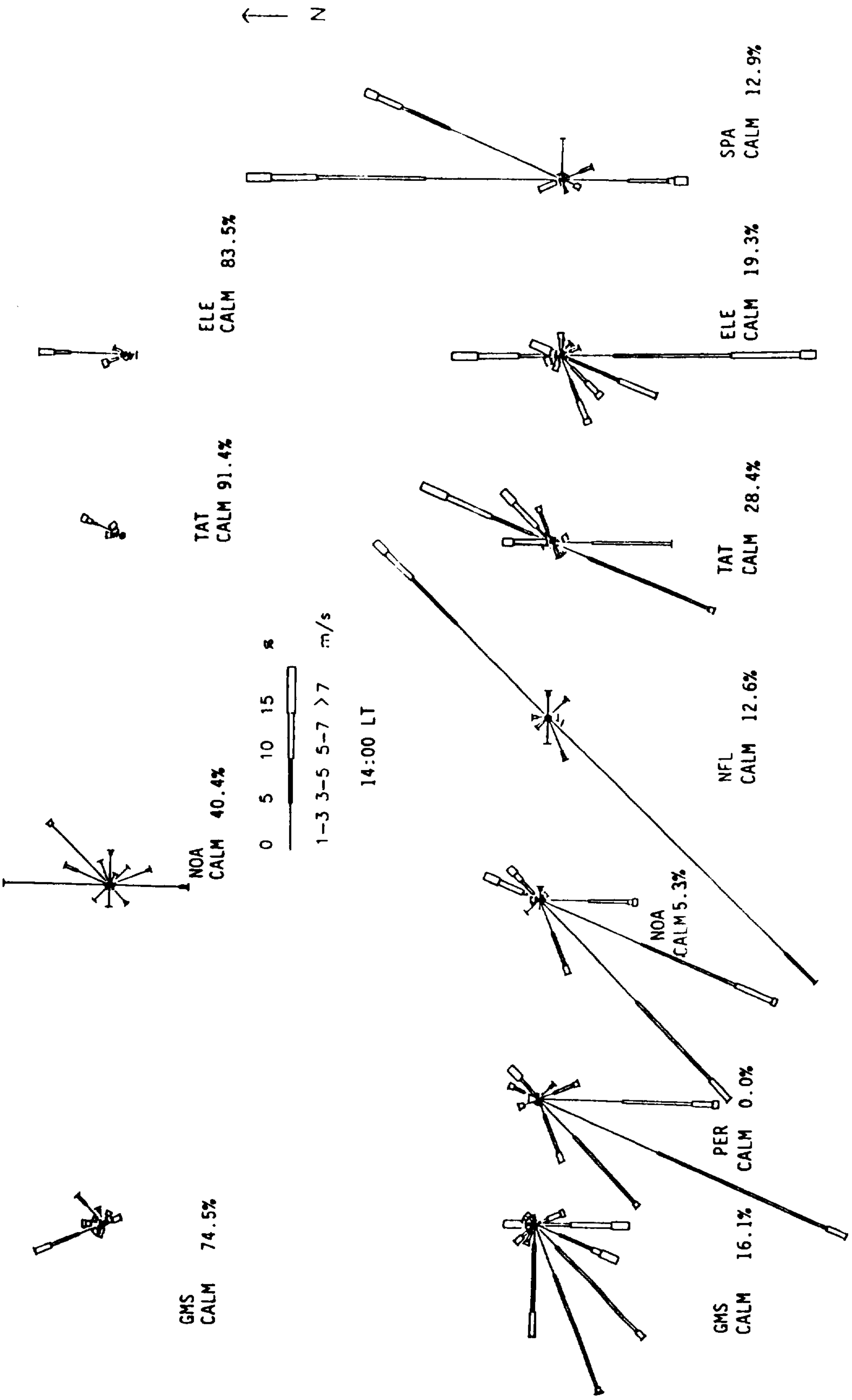

Fig. 4. As in Fig. 3 but for the air pollution episode-days for the period 1983–1990.

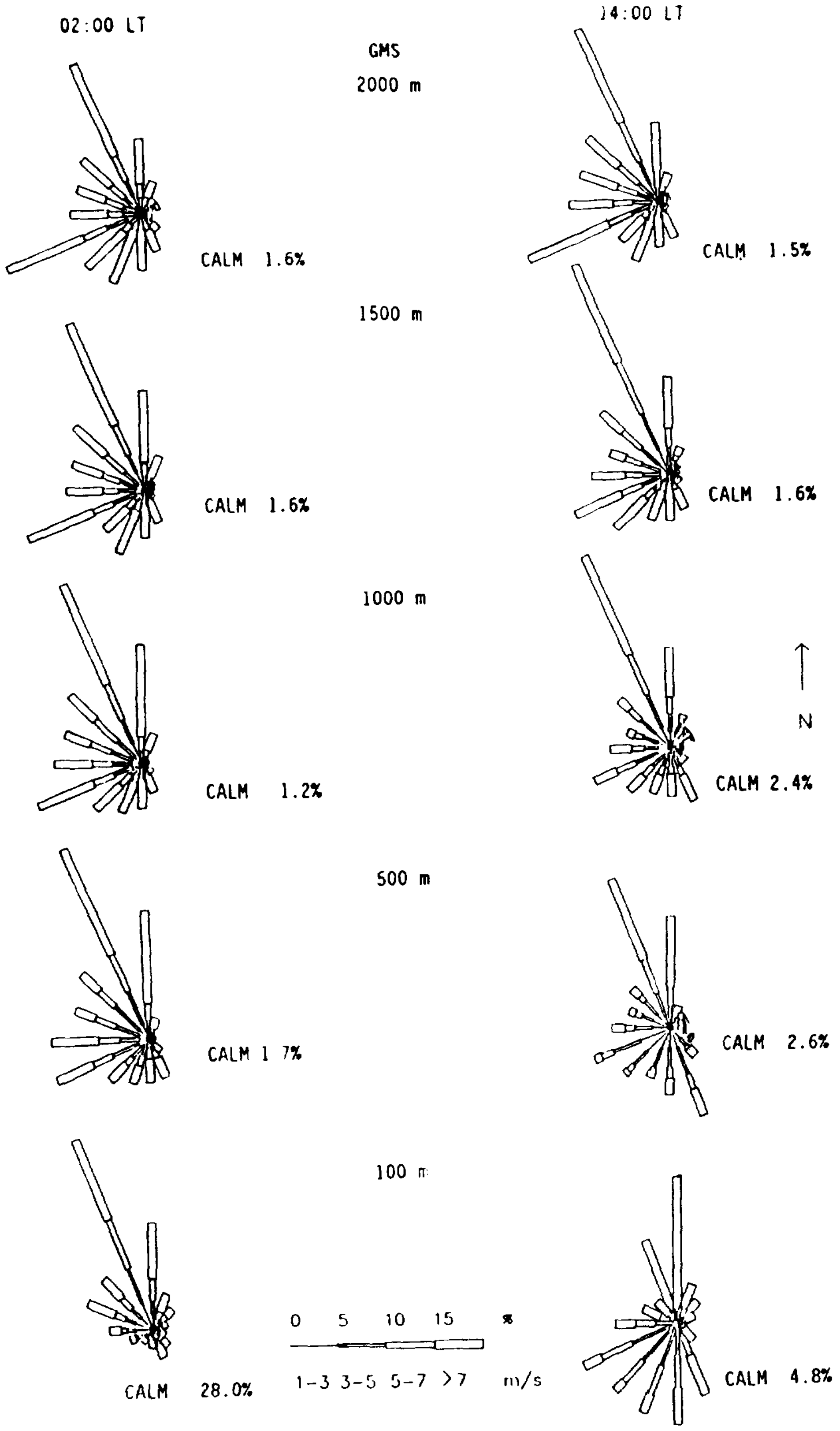

Fig. 5. Wind roses at different heights at 0200 and 1400 LT, respectively, for the period 1974–1990, constructed from the sounding data at Hellinicon airport.

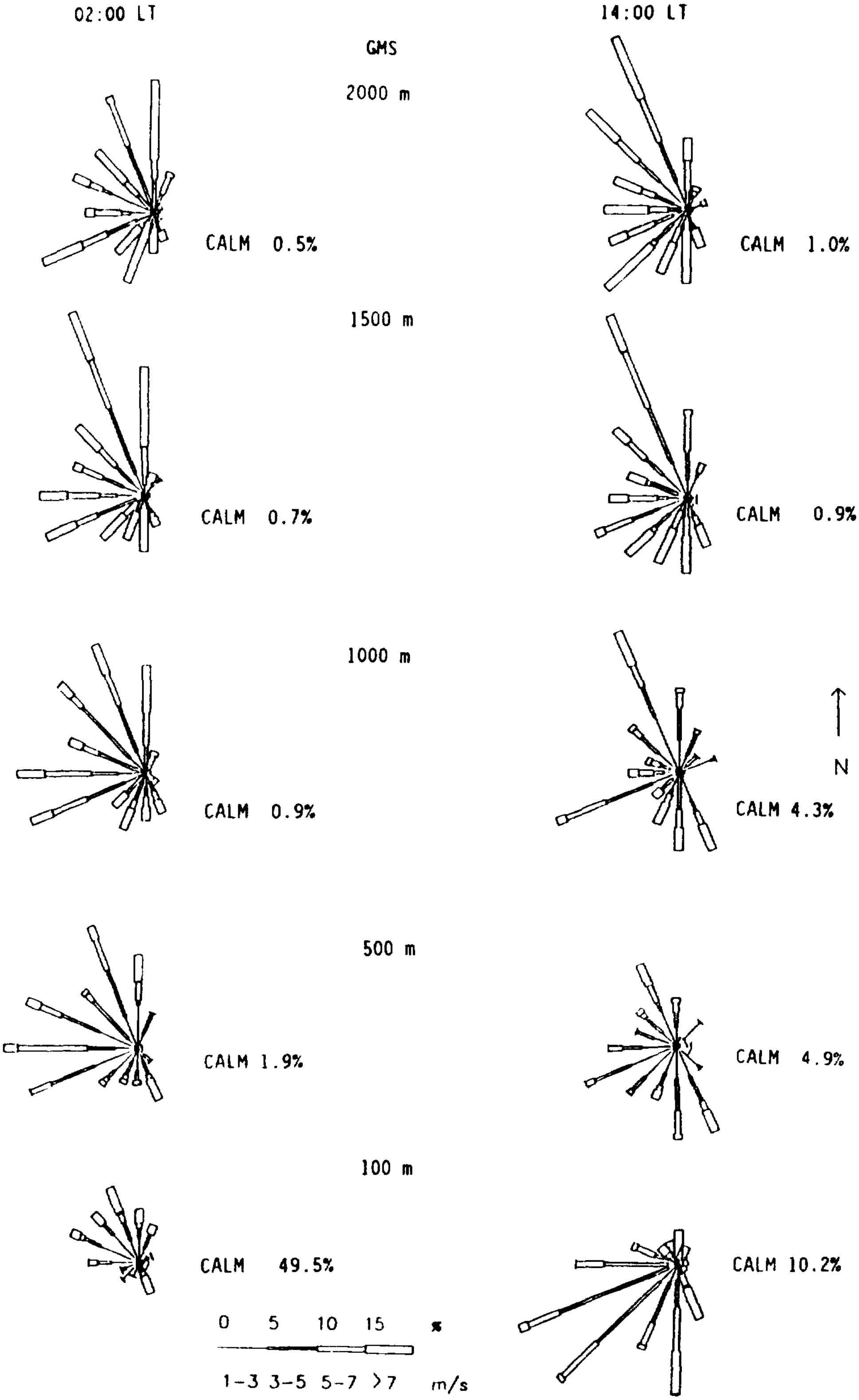

Fig. 6. As in Fig. 5 but for the air pollution episode-days for the period 1983–1990.

mixing layer create poor ventilation conditions in the area.

During the day, the appearance of calms falls to 5% even in the low levels, while in the first 1000 m southerly winds frequently appear, due to sea-breeze or other local circulations. In this layer N winds are less frequent than during nighttime but are stronger. During summer, the wind fields show a significant variability between nighttime and daytime, with southerly winds being more frequent at the low levels and northerly being more intense during day hours than during night. This phenomenon is due to the alternation of sea-breeze circulations and Etesians. During the transient period, southerly winds in low levels are more frequent than in nighttime due to the frequent development of sea-breezes while the appearance of northerly winds is associated with regional- and synoptic-scale circulations. In higher levels, synoptic-scale conditions dominate and winds show a small or no daily variability. The analysis of the air pollution episode-days showed that at 100 m calms appear at a frequency of 10%. Very light winds (1–3 m s^{-1}) prevail in the first 1000 m, and light winds (3–5 m s^{-1}) prevail above, up to 1500 m. Very light winds along with the shallow mixing layer create poor ventilation conditions in the area. SE to W winds that prevail in the low levels during the day hours are due to sea-breeze circulations, a mechanism that seems to be crucial during the episode-days. During winter and transient period episode-days, the main wind field characteristic is the frequent appearance of calms and very light southerly winds in the first 1000 m. During summer, calms are less frequent but winds are still very light in the first 1000 m. During all year, light N winds are also detected. It can be concluded that the air pollution episode-days are associated with light winds of various directions in the low levels, except when a sea-breeze develops.

Cloudiness

Cloudless sky is a very frequent phenomenon in the GAA. Almost 45% of the nights and 15% of the days are cloudless (0/8). Convergence of upslope flows over the mountains as well as updrafts due to surface heating can explain this difference between nighttime and daytime cloudiness. It is worth noting that the convergence due to thermal circulations does not necessarily lead to the formation of cumulus type clouds and storms due to the lack of sufficient moisture supply. Partial cloudiness due to the convergence occurs mainly at the northern part of the Basin near the mountains. This is the reason for the appearance of a relatively high percentage of partial cloudiness. Total cloud cover occurs with a frequency of 8% during night and day and it is associated with synoptic systems.

During summer, cloudless skies are more frequent (75% during night and 30% during day) and total cloud cover is seldom. This can be explained by the fact that anticyclonic synoptic conditions prevail during this season. The cases of partial cloud cover are associated with orographically induced clouds or with the edge of fronts traversing the area of Central Balkan. During winter, partial or total cloud cover is more frequent and it is due to frontal activity in the area. Cases of cloud-free skies are also observed during daytime and nighttime when high pressure systems prevail in the greater Balkan and East Mediterranean area.

A further analysis has been performed for the 210 d comprising the 80 air pollution episodes. During the episode-days cloud-free skies were observed during all seasons, at a frequency (62% at nighttime and 32% at daytime) greater than the one of the climatological analysis. Cloud-free nights favor the establishment of surface temperature inversions which persist when the next day's sky is also cloud-free. Surface inversions reduce atmospheric mixing, and therefore play a significant role in reducing pollutant dispersion. The results of the climatological and the episode-days analysis are summarized in Tables 7 and 8.

Mixing height

The mixing height is an important parameter associated with air quality conditions in an area. Small mixing heights induce poor dispersion of pollutants released from surface sources. Elsom and Chandler (1978) reported that the mean mixing height is well correlated with the mean daily smoke concentration in an urban area.

Table 7. Cloud cover at 0200 LT

	Cloudiness							
	0/8		< 4/8		> 4/8		8/8	
Season	A	B	A	B	A	B	A	B
All year	44.9	61.9	16.8	21.1	30.2	12.5	8.1	4.5
Winter	21.0	46.3	15.6	27.8	49.2	18.5	14.2	7.4
Summer	76.0	84.8	17.2	15.2	6.7	0.0	0.1	0.0
Transient	37.3	59.2	18.2	19.7	35.0	15.8	9.5	5.3

Letter A denotes the analysis of the climatological data for the period 1974–1990 and B the analysis of the days characterized as air pollution episode-days for the period 1983–1990.

Table 8. Cloud cover at 1400 LT

	Cloudiness							
	0/8		< 4/8		> 4/8		8/8	
Season	A	B	A	B	A	B	A	B
All year	13.7	31.8	41.6	37.0	37.3	26.1	7.4	5.1
Winter	4.8	24.1	24.7	37.8	58.0	31.5	12.5	7.4
Summer	28.4	58.7	61.6	37.0	9.9	4.3	0.1	0.0
Transient	7.7	21.0	38.3	36.9	44.5	35.5	9.5	6.5

Letter A denotes the analysis of the climatological data for the period 1974–1990 and B the analysis of the days characterized as air pollution episode-days for the period 1983–1990.

The mixing height observed in the afternoon has been calculated from the sounding data at 1400 LT (Hellinicon airport), following the method proposed by Holzworth (1967). This method does not provide satisfactory estimates of the night (at 0200) mixing height; therefore, the method proposed by Benkley and Schulman (1979) has been adopted. This method is based on the fact that mechanical mixing is the main turbulent mechanism during nighttime. In Fig. 7a and b the mean value and the standard deviation from the mean value of the mixing heights observed in the afternoon and at night, respectively, for the period 1974–1990, are shown. Mixing heights for the air pollution episode-days (denoted by dots) are also reported in the same figures.

The afternoon mixing height (Fig. 7a) shows an important annual variability with maximum values being observed by the end of July and the minimum by the end of December. The high values of mixing height observed during summer are due to the fact that the amount of the incoming solar radiation is higher during this season and as the soil is dry this radiation is preferably converted into sensible than latent heat flux, favoring the development of a deep mixing layer. On the contrary, during winter, the amount of the incoming solar radiation is less and as the soil is wet and covered with vegetation, most of this radiation is converted into latent heat; thus the vertical development of the mixing layer is reduced. During the transient period, the observed mixing height in the afternoon is deeper than in winter, due to the fact that the soil is warmer and the amount of the incoming solar radiation is greater.

The mean mixing height observed at night shows small variability and the climatological value is approximately 400 m, with the maximum values being observed during winter due to the stronger winds (Fig. 7b). As was already mentioned, calms or light winds prevail during nights (except in the case of strong synoptic winds) and as a matter of fact the night mixing height is reduced compared to the afternoon mixing height.

As expected, the mixing height values observed during the air pollution episode-days are smaller than the climatological ones (Fig. 7a and b). Most mixing height values observed during episode-days are less than 200 m at night and less than 500 m in the afternoon. The few higher mixing height values are observed during the days that the episode is ended or when partial cloudiness appears. Though, it is evident that during the air pollution episode-days the mixing height is shallow due to the suppression of the local circulations (smaller vertical development) and the prevailing winds are weak.

Ventilation coefficient

The ventilation coefficient is a parameter that indicates the efficiency of the atmosphere in dispersing air pollutants released from local sources. It is defined as the product of the mixing height with the mean wind speed within the mixing layer. Small values of the ventilation coefficient indicate poor efficiency in air pollutant dispersion. In Fig. 8a and b the variation of the mean value and the standard deviation of the ventilation coefficient at 1400 and 0200 LT, respectively, for the period 1974–1990, is reported. The variation of the ventilation coefficient is very similar to the mixing height variation with maximum values in July and August (9000 $m^2 s^{-1}$) and minimum in December and January (2000 $m^2 s^{-1}$). Pielke *et al.* (1991) propose the value of 6000 $m^2 s^{-1}$ as a value indicating efficient ventilation. From Fig. 8a it is evident that during summer the afternoon ventilation conditions are good. This is due to the deep mixing heights and strong thermal circulations (subregional and mesoscale). On the contrary, during winter and the transient season the ventilation coefficient values observed in the afternoon are less than 6000 $m^2 s^{-1}$, due to light prevailing winds, indicating poor ventilation conditions. During nighttime (Fig. 8b) ventilation coefficient values are small due to low mixing height and light prevailing winds. Winter values are larger than summer ones due to the fact that nighttime winter winds are stronger than nighttime summer ones. In Fig. 8a and b the ventilation coefficient values during air pollution episode-days are also reported (marked by dots). It is evident that these days are characterized by poor ventilation conditions with mean values smaller than the climatological ones (less than 1500 $m^2 s^{-1}$ during day and less than 150 $m^2 s^{-1}$ dur-

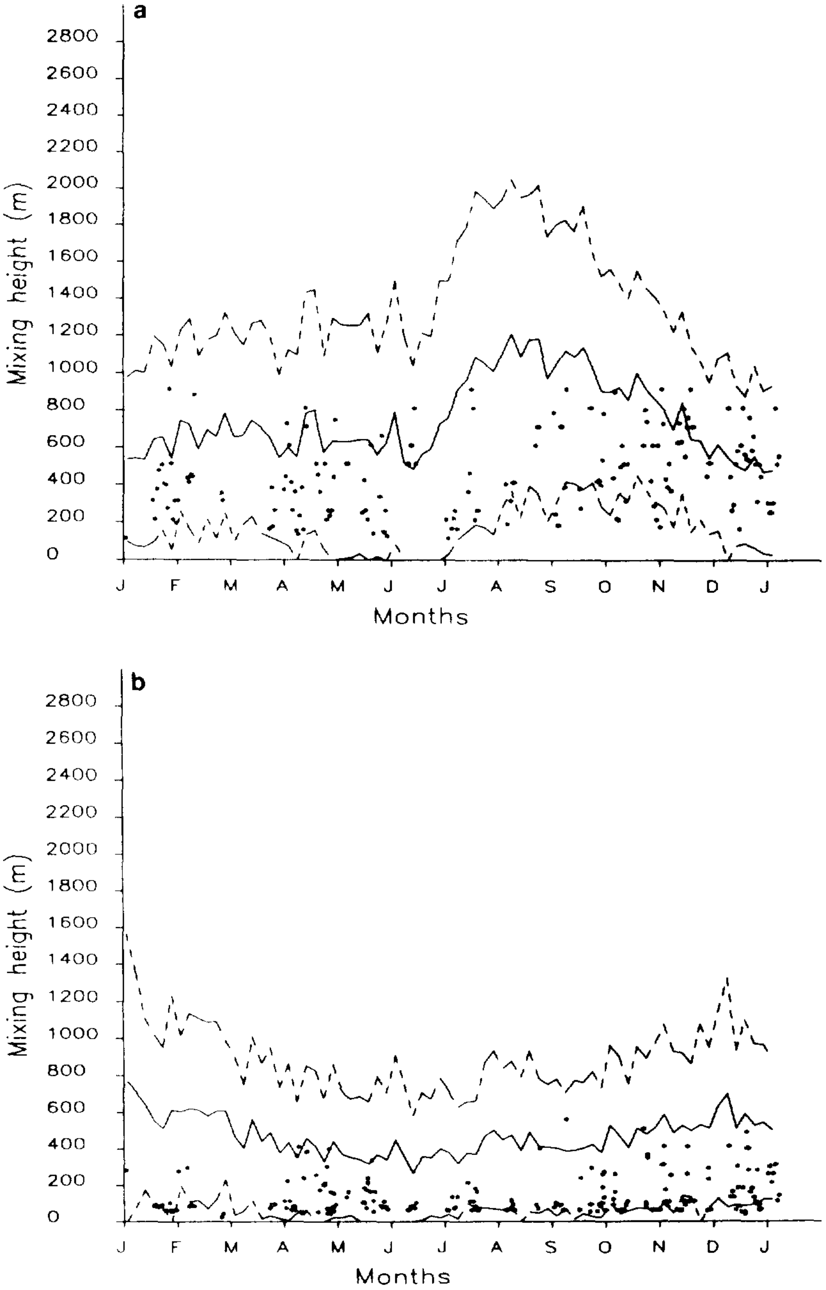

Fig. 7. Mean value (solid line) and standard deviation (dashed line) of the mixing height at (a) 1400 LT and (b) 0200 LT, for the period 1974–1990. Dots indicate the mixing height of the air pollution episode-days.

ing night). It is worth noting that there is no evidence of seasonal variability of the ventilation coefficient values characterizing the episode-days.

Temperature at 850 hPa

The temperature at 850 hPa is an important parameter, providing information about atmospheric stability. High temperature at 850 hPa relative to the same surface temperature indicates weak vertical dispersion and *vice versa*. Figure 9a and b shows the mean value and the standard deviation of the temperature at 850 hPa for 1400 and 0200 LT, respectively. The maximum values are observed in July (17°C) and the minimum in February (0°C). The same parameter for the episode-days is also reported in the same figures (marked by dots). It is evident that temperature at 850 hPa during episode-days is higher than the climatological values. Warm air masses which are present over the GAA during episode-days are associated with warm air advection or large-scale subsidence. The warmer the air masses at the 850 hPa level the more stable the atmosphere, and as a matter of

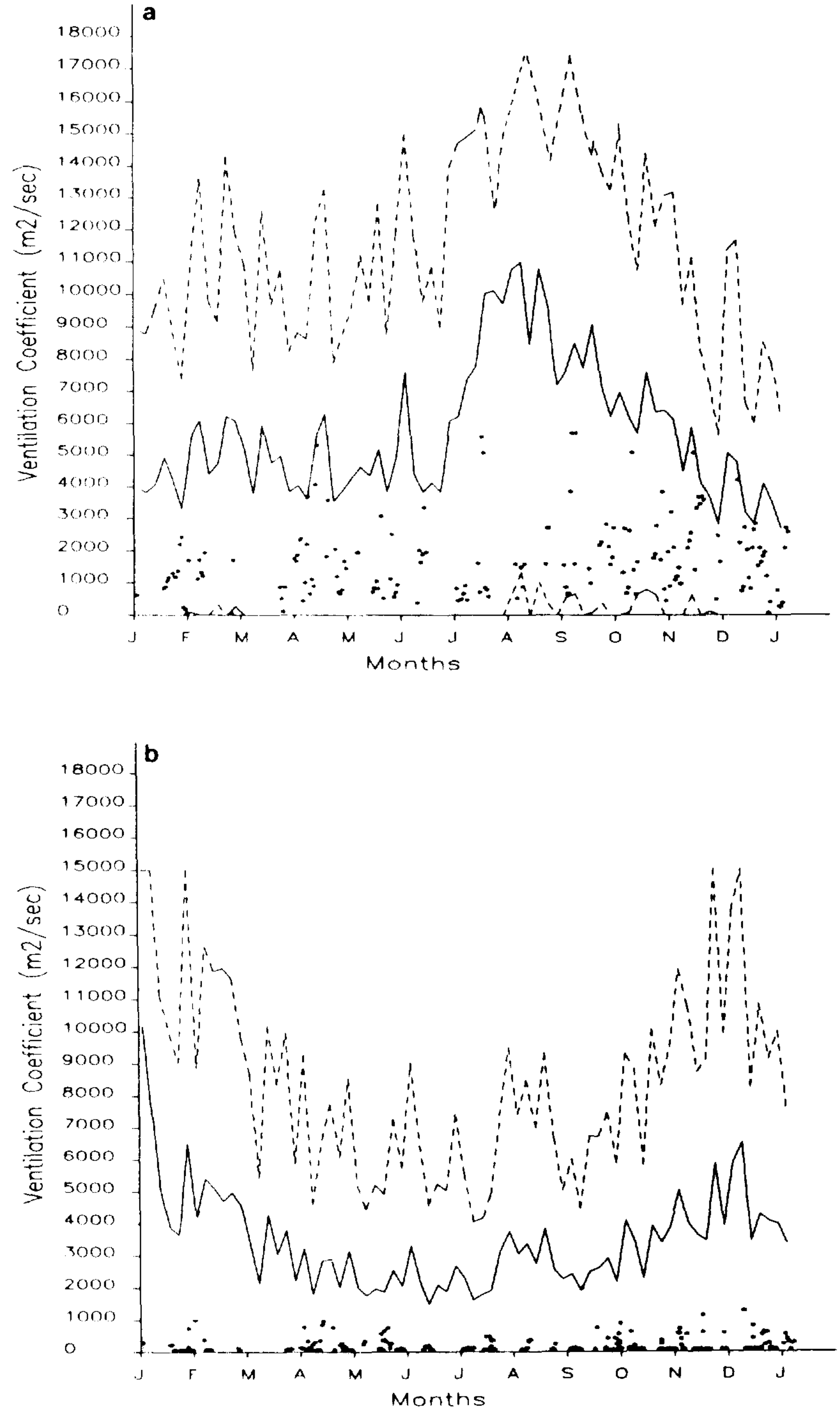

Fig. 8. Mean value (solid line) and standard deviation (dashed line) of the ventilation coefficient at (a) 1400 LT and (b) 0200 LT, for the period 1974–1990. Dots indicate the ventilation coefficient of the air pollution episode-days.

fact the vertical dispersion and local circulation development are reduced. For most of the cases during the air pollution episode-days which are associated with warm air mass transport over Athens, the maximum warming at the low tropospheric layers occurs even below 850 hPa (Kassomenos, 1993). Figure 10 shows such a case where the maximum warming occurred at the layer between 950 and 900 hPa. This case was one of the worst air pollution episodes which occurred in the Athens Basin.

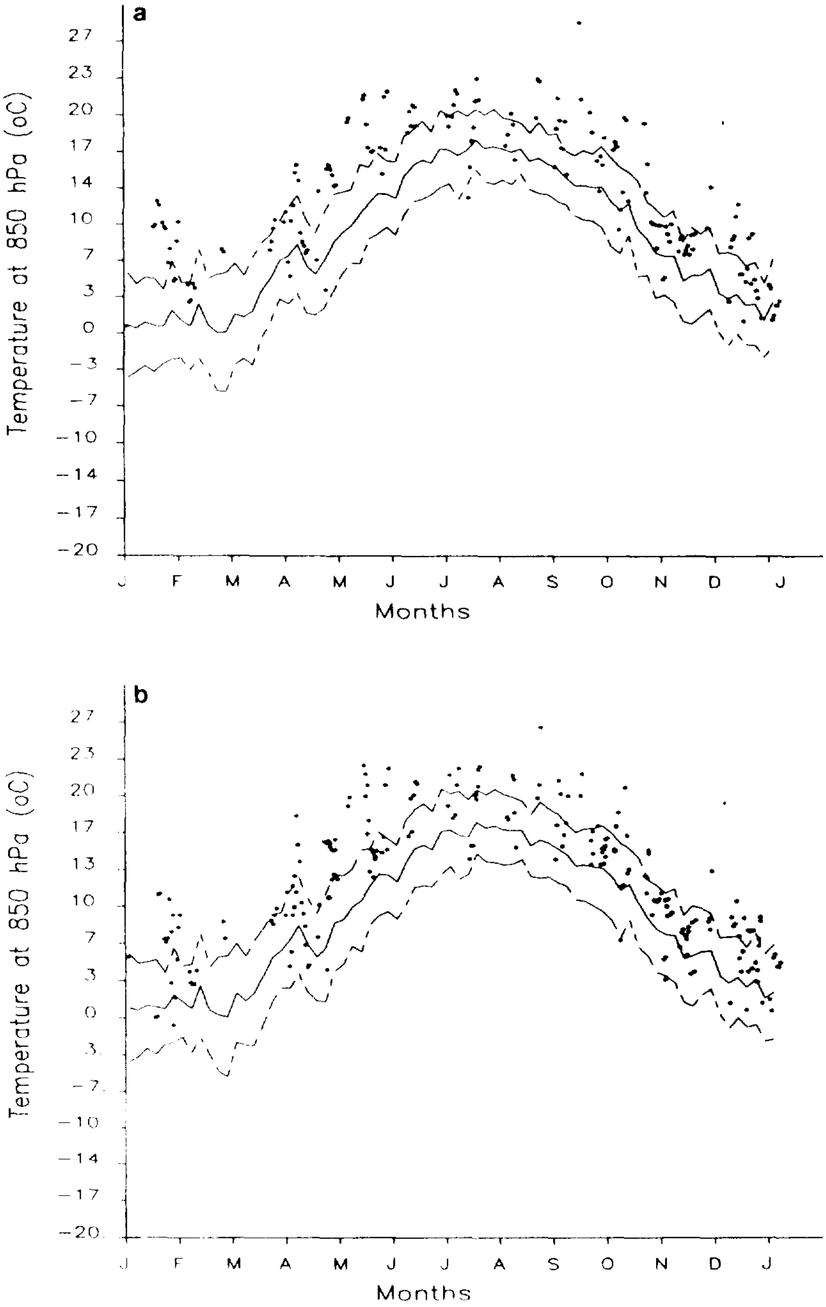

Fig. 9. Mean value (solid line) and standard deviation (dashed line) of the temperature at 850 hPa at (a) 1400 LT and (b) 0200 LT, for the period 1974–1990. Dots indicate the temperature at 850 hPa of the air pollution episode-days.

Temperature inversions

Many aspects of Athens air quality reflect the pronounced effect of persistent inversions (Katsoulis, 1988a). Surface inversion occurrence over the Athens Basin and especially nocturnal inversions were investigated by several researchers (Dikaiakos, 1973; Tselepidaki *et al.*, 1983; Katsoulis, 1988a). Nocturnal inversions are mainly due to radiative cooling and they are usually shallow. As was reported by Katsoulis (1988a), these inversions develop frequently during nighttime (for almost half of the nights), and rapidly erode during the day.

Nevertheless, it is the temperature inversion in the lower troposphere that mostly affects air quality, inducing poor dispersion. These elevated inversions develop when air masses resulting from large-scale subsidence stagnate and then sink over the area, or when warm air advection occurs in the lower troposphere. Large-scale subsidence is associated with

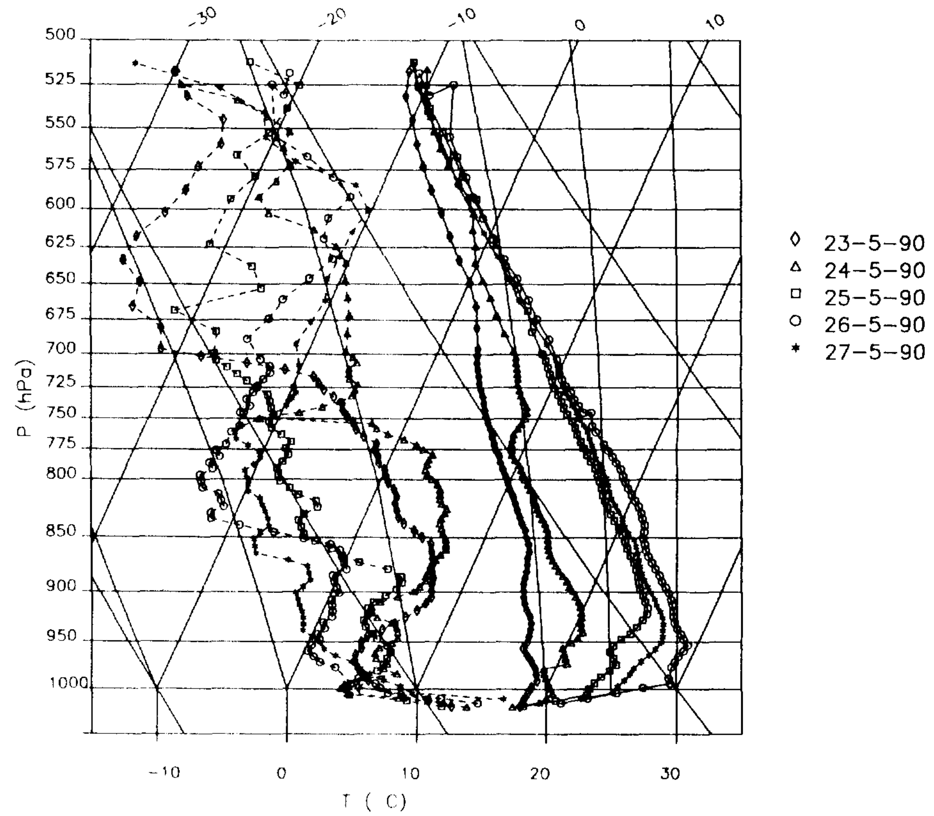

Fig. 10. Skew-T diagram constructed from the soundings at Hellinicon airport for five consecutive days (23–27 May 1990).

warming and inversion development (Millan *et al.*, 1988). Elevated inversions are not easily eroded and can persist for a longer time period, affecting the concentration of air pollutants in the lower troposphere and consequently air quality in the area. Temperature inversions generated due to warm advection are usually deeper and for several cases do not even break up during the day hours, especially during winter and transient seasons (Kallos *et al.*, 1993).

Temperature inversion climatology was not possible due to the low vertical resolution (every 50 hPa) of the available sounding data. Higher resolution sounding data were available during the episode-days for the period 1983–1990. The analysis of these data allowed the study of surface and/or elevated inversions. Nocturnal surface inversions occurred for 95% of the nights during the analyzed period with depths ranging from 60 to 700 m. In almost 80% of the cases the inversion depth is of the order of 300 m. These nocturnal inversions are intense but they seldom persist until the afternoon of the following day. The air pollution episode-days were associated with at least one night height inversion. For 80% of the episode-days the nocturnal elevated inversion persisted for approximately 12 h, 60% for 24 h, 40% for 36 h and 15% for more than 36 h. The bottom of the elevated inversion was located beneath 1000 m in half of the cases and the depth of the inversion layer was about 500 m in 90% of the cases. Thus, it can be concluded that elevated inversions persist over the GAA during episode-days affecting vertical dispersion and vertical development of local circulations.

6. CONCLUSIONS

In this paper a climatological and air quality analysis of the observations from the GAA has been performed. For this purpose, 17 years (1974–1990) of surface and upper-air data have been processed for use as a climatological base. The analysis of air quality time series for the period 1983–1990 showed that air pollution episodes in the Athens area appear for a significant number of days during all seasons. More precisely the 80 worst air pollution episodes, lasting from 2 to 7 d each (210 d in total), were identified in the period 1983–1990. Most of these episodes occurred during the transient period, and in winter, with April, October and December being the months with the higher number of pollution episodes.

The analysis showed that air quality in the Athens Basin is strongly affected by the meteorological conditions, especially those which are in favor of local circulations. The worst air pollution episodes are associated with the presence of an anticyclone over the Central and East Mediterranean and/or advection of warm air masses in the lower troposphere.

During the air pollution episode-days, stagnant conditions are more likely to occur (especially during winter and the transient period). Calms or light winds prevail in the low layers and the shallow mixing layer prevents venting. Clear skies, observed during these days, favor the development of persistent surface temperature inversions. The analysis of the thermodynamic structure of the atmosphere showed that during the episode-days the atmospheric conditions were very stable over the Athens area, inducing poor vertical mixing. Persistent elevated temperature inversions, which are in favor of the concentration of air pollutants over the area, are also observed. These elevated inversions are due to the horizontal transport of warm air masses (located from near the surface up to 700 hPa) or due to large-scale subsidence associated with anticyclonic conditions in the Mediterranean region.

As a conclusion it can be mentioned that the physiographic characteristics of the GAA induce mesoscale circulations in the area, and the interaction between synoptic, regional or subregional and mesoscale flows plays an important role in the formation of the appropriate atmospheric conditions which are in favor of air pollution episodes.

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