SYNOPTIC AND MESOSCALE WEATHER CONDITIONS DURING AIR POLLUTION EPISODES IN ATHENS, GREECE

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Abstract. Based on regular climatological and air quality data from the Greater Athens Area (GAA), the air pollution episodes observed in Athens during the period 1983–1990 were analysed and classified. The main characteristics of atmospheric conditions during days with high air pollution concentrations are summarized too. Model simulations show that the worst air pollution episodes in Athens occur during days with a critical balance between synoptic and mesoscale circulations and/or during days with warm advection in the lower troposphere.

1. Introduction

The cities of Athens and Pireus (and their suburbs) are located in a basin surrounded by mountains from three directions and open to the sea from the fourth (see Fig. 1). The main axis of the basin is SSW to NNE and is approximately 25 km in length. Its width is approximately 17 km. There are three main mountains, Hymettus to the E, Pendeli to the N-NNE and Parnitha to the N-NNW with elevations up to 1400 m. To the W of the basin is mountain Aegaleo with its peak elevation at 450 m. These mountains are physical barriers with small gaps between them. The opening of the basin to the sea is toward Saronic Gulf. Almost the entire basin of Athens could be considered as an urban area. The population of Athens, Pireus and their suburbs is approximately 3,600,000. To the E of mountain Hymettus is the plain of Mesogea while to the W of mountain Aegaleo is the Thriasion plain. The mountains around Athens are mostly covered with bushes. Only a small portion of their surface is covered by pine forests. There are three hills up to 200 m inside the basin (Pnyka, Lycabettus and Tourcovounia). In an area like Athens with such complicated physiographic characteristics, the flow fields and the Planetary Boundary Layer (PBL) depth show temporal and spatial variations. The flow fields and the PBL depth are crucial parameters for dispersion in an area (Pielke *et al.*, 1983; Glendening *et al.*, 1986; McKendry, 1989; Ulrickson and Mass, 1990a,b). There are seasonal and diurnal variations of the wind fields and PBL depths. Seasonal variations are mainly related to the persistent synoptic weather patterns and surface conditions. Synoptic conditions occuring during air pollution episodes will be described below. Surface conditions such as soil moisture, vegetation cover, etc. play an important role in the development of local circulations and of PBL depth (Segal *et al.*, 1989a,b; 1992; Avissar and Pielke, 1989; Pielke and Avissar, 1990). Because of the topographic, land-water distribution and land cover characteristics

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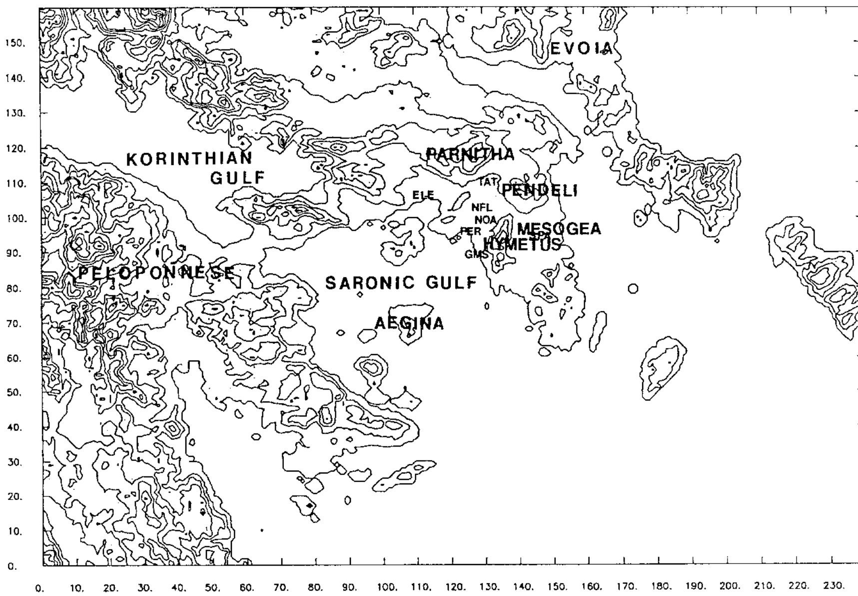

Fig. 1. The topography of southeastern Greece. Contours are every 250 m. The numbers at the axes show the distance in km from the southwestern corner of the domain.

of the area, local circulations such as sea (land)-breezes, drainage and upslope flows usually develop. Clear-sky conditions help in to the formation of temperature inversions during night-hours.

The main sources of air pollutants in the GAA are automobiles, industry and central heating during the cold months (Lalas *et al.*, 1982).

More than a million automobiles of all types are operating in the region. The lack of a high speed peripheral road network and the high number of automobiles operating are the main reasons for the slow traffic observed every day. The automobiles are considered as the main source of photochemical pollutants observed in the region. These were the reasons for the traffic restrictions imposed by the local authorities during the last eight years. According to these restrictions, only civilian cars with odd or even ending numbers on their tags are allowed to enter the center of Athens alternatively during the day-hours. During days with very high concentrations of air pollutants, some additional restrictions in the traffic of civilian cars and taxis are imposed for the Athens basin.

The industrial zones are located in the SSW part of the city of Athens and in the Thriasion plain. Some other sources are located in the harbour of Pireus while the contribution of air pollutants from ships and aircraft cannot be negligible.

The combination of emissions (mainly from traffic) with the appropriate atmospheric conditions is responsible for air pollution episodes in the GAA. Air pollution episodes occur during all seasons on a significant number of days. During these days, the concentrations of various air pollutants exceed the state limits. However, air quality in Athens cannot be considered worse than observed in other cities in Europe having the same problem.

2. Weather Conditions During Air Pollution Episodes

2.1. Synoptic conditions

The climate of the NE Mediterranean cannot easily be characterized as maritime or continental. Summer-months (June, July, August and September) are characterized as dry with almost no rain while winter (November, December, January and February) is the rainy season. Spring and autumn (March, April, May and October) are transient seasons where summer and winter-type weather patterns are interchanging. Transient seasons are not symmetrical but show some common characteristics.

Based on the above separation for each season, an attempt was made to classify the weather patterns which favor poor dispersion conditions in the Athens basin.

2.1.1. Summer season.

A typical weather pattern which appears during summer is the following: A high pressure system covers the Eastern Mediterranean and Balkan area up to the Black sea. Over the West and Central Mediterranean there is a ridge. A thermal low over the Anatolian Plateau is evident during day-hours because of heating of the dry land. The balance between these two systems defines the weather conditions over eastern Greece and the Aegean Sea. When the high pressure system is strengthened, it extends in an easterly direction and the pressure gradient across the Aegean is weakened. The synoptic circulation is weak from the N and therefore local circulations develop. During these days, thermal circulations dominate in the area of Athens. In contrast, when the high pressure system weakens, the thermal low over the Anatolian Plateau extends toward W and the pressure gradient over the Aegean becomes stronger. During these days the winds over the Aegean Sea are from the N, stronger during the day and weaker during the night. This kind of wind pattern is called Etesians or meltemi (Carapiperis, 1951). The synoptic flow dominates the sea breeze over Athens and the winds are from the N. This phenomenon lasts from two to five days and the dispersion conditions over Athens are good. Poor dispersion conditions occur when the synoptic flow is in near equilibrium with the sea breeze (almost stagnant conditions). When the sea breeze dominates the synoptic circulation, the dispersion conditions are better than the stagnant case but worse than on days with Etesians.

2.1.2. Winter season.

Winter is characterized by a low index circulation and the passage of low pressure systems over Greece is relatively frequent. When a low is over the Ionian Sea or western Greece, the winds over Athens are from the S to SE directions. The same occurs when Athens is within the warm sector of the low. After the passage of the cold front, the winds are from the NW to N. Similar veering of the winds occurs with the passage of a cold front moving from the NW toward Greece. This front is usually called Balkan front. During these circumstances, warm advection is observed in the lower troposphere, the atmosphere is stable because of the elevated temperature inversions observed during days with clear sky. During these days, dispersion conditions in Athens are poor. This phenomenon occurs for one to two days except for cases with a stationary low over South Italy and the Ionian Sea which may remain in the same position for four to five days. During these days, regularly, the southerly flow is relatively strong and dispersion conditions in Athens are good. Following the passage of the low or cold front, the sky is usually clear, and during the night, surface inversions form; therefore dispersion conditions are poor especially during the morning hours. In the case of the formation of a strong pressure gradient over the Aegean Sea (or the formation of a low in the area of Cyprus) and after the passage of the cold front, the dispersion conditions in Athens are good because of the relatively strong winds and the generation of mechanical turbulence. A similar pattern for dispersion was found by Pielke *et al.* (1987, 1991); Yu and Pielke (1986), for the United States.

The development of a high pressure system over the Central Mediterranean which extends toward the E and covers the area of Greece is the weather pattern associated with poor dispersion conditions in Athens. Sometimes this sytem has its center over the Balkan area and remains stationary for several days. This is a common pattern observed usually during mid-January for approximately two weeks. These days with clear sky conditions, a weak northerly synoptic flow and dry air are called Halkyon days (Dikaiakos, 1983). During these days, strong temperature inversions form during the night which, sometimes, do not breakup even around noon (Katsoulis, 1988a,b).

2.1.3. Transient seasons.

As was mentioned above, during these seasons the weather type regularly changes between summer and winter conditions, relatively quickly during spring and slower during autumn. Poor dispersion conditions over Athens occur during days with an anticyclone covering the Central and Eastern Mediterrranean and the Balkan area as well. Weak pressure gradients must occur over the Aegean Sea. The worst air pollution episodes observed during these months are associated with advection of warm air-masses from North Africa over the relatively cool Mediterranean Sea. During these days, the air near the ground is relatively cool and warmer aloft. These stable atmospheric conditions, in combination with weak flow, do not permit the development of a deep mixing layer and consequently air quality in Athens becomes poor. Such synoptic conditions usually occur when a trough is over the Iberian Peninsula and the Western Mediterranean and a ridge is over the Central Mediterranean. For some of these cases, warm advection is observed very low in the troposphere and is difficult to identify even on the 850 hPa synoptic map.

The characteristics of the synoptic conditions decribed above are summarized in Table I. The classification scheme presented in Table I has similarities with the scheme developed by Pielke *et al.* (1987) but its structure is according to the specific synoptic patterns usually observed in the region of Greece and Aegean Sea.

2.2. SYNOPTIC CLASSIFICATION

In order to classify these weather patterns, regular climatic (surface and upper-air), air quality data and synoptic maps were analyzed for the period 1974–1990. There are seven meteorological stations operating in the GAA, five inside the Athens basin, one in the Thriasion (ELE) and one in the Mesogea (SPA) plains. The upper-air station is located at the airport of Athens and is operated from the Greek Meteorological Service (GMS), while the other four surface stations are in Pireus (PER), the National Observatory of Athens (NOA), Nea Philadelphia (NFL) and Tatoi (TAT). The position of each station is shown in Fig. 1. In the Athens basin there is a network of eight air pollution monitoring stations operating since 1983. For these stations hourly concentrations of primary and secondary air pollutants are recorded.

The 3-hour observations from the meteorological stations were analysed for 1974–1990. Surface wind analysis showed that, for some of the stations, calms account for more than 50% during night-hours while during day-hours this percentage does not exceed 10%. Light winds (1–5 m/s) are quite frequent for all stations, day and night, while strong winds are observed mainly during day-hours. The prevailing wind directions are from the N to NE during night while during day-hours these are from SW to SSW and N to NE for all stations in the Athens basin. For the two stations outside of the basin (ELE and SPA), the winds show a preference for the N and S directions. The wind roses estimated from the radiosonde observations (GMS) at heights of 10, 500 and 2000 m are shown in Fig. 2. As it is seen, this station is influenced by local circulations because of its position near the coast. Moderate and strong winds from the NW or N are observed during all hours mainly at upper levels. W to SW winds are observed in the upper levels and near ground only during day-hours.

As was found from the analysis of the climatological data recorded in the above mentioned stations, Athens is characterized by its clear-sky conditions. Almost 45% of nights and 15% of days are with clear-skies and approximately 8% with overcast ones. During summer months there are usually no days with overcast skies while during the transient seasons 10% are typically overcast. These climatic conditions allow for the development of deep mixing layers during day-hours and quite shallow boundary layers during the night.

Using the detailed radiosonde data from station GMS, the mixing heights were estimated for day and night-hours. The afternoon mixing height calculations were based on the radiosondes at 14:00 LT while the night mixing heights were from

TABLE I
Synoptic classification for days with air pollution episodes in Athens.

	I	II	III	IV
GENERATION	High pressure system starts to develop over northeast Mediterranean and/or south Europe. Over Central Mediterranean there is a ridge which sometimes is associated with a through over Mediterranean and Iberian Peninsula. Warm air masses are observed initially over Central Mediterranean and south Italy.	A low pressure system is located over Central Mediterranean and moves eastward. The anticyclonic system over the Balkan peninsula starts weakening. Usually this low is relatively shallow.	A cold front moves from the NW toward the Balkan Peninsula and Greece. Ahead of the cold front the synoptic circulation is relatively weak.	An anticyclonic system covers most of the Mediterranean and northeast Europe. A thermal low covers the Anatolian plateau during the day-hours. This combination establishes a pressure gradient over the Aegean Sea and consequently over Athens.
EVOLUTION	The anticyclonic system moves eastward toward Greece. Warm air masses are advected toward Greece and the lower tropospheric layers are very stable.	Greece is inside the warm sector of the low. The advection of warm air masses stabilizes the lower troposphere	After the passage of the cold front, relatively cool air masses are observed over Greece. The synoptic flow is from the NW and is relativelty weak. Clear sky conditions support the formation of surface temperature inversions.	When the anticyclonic system extends eastward, or becomes stronger, the pressure gradient over the Aegean Sea weakens. Local circulations starts to develop.
END	High pressure systems over Central Europe extend eastward and a cold front passes over the Balkan peninsula or Greece establishing a NW or N flow.	After the passage of the cold front, a northerly flow (dry and cool air) is observed over Greece and the Aegean Sea near the surface and aloft. These lows move toward the ESE, E or NE suring the different seasons.	For some cases, the pressure gradients strenghten and a strong northerly flow occurs over Greece and the Aegean Sea. For others, a low pressure system moves toward Greece.	When the anticyclonic system weakens, the thermal low extends westward and the pressure gradient over the Aegean Sea becomes stronger. This is a typical weather pattern during the summer

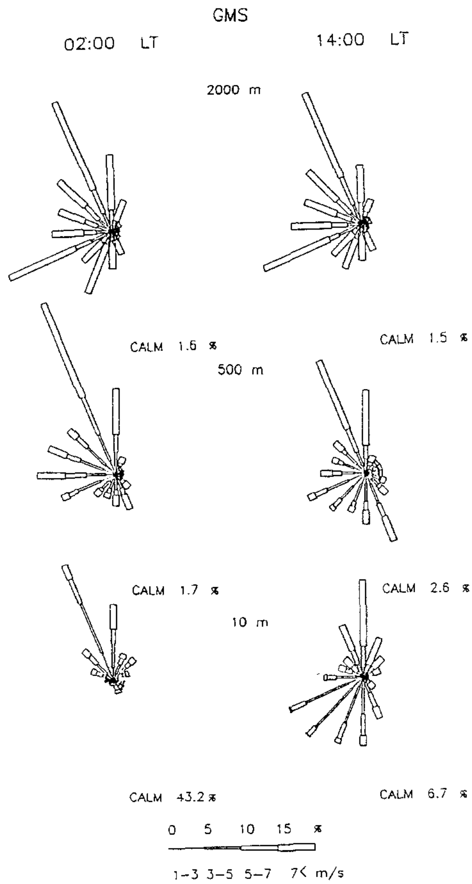

Fig. 2. Wind roses at different heights for the period 1974–1990.

the radiosondes at 02:00 LT. It was found that for 45% of the examined cases, the afternoon mixing height was less than 750 m while 20% of the time it was more than 1500 m. In general, afternoon mixing heights are higher during the warm season and lower during the cold one. For night-hours, mixing heights of less than 250 m account for the 31% of the cases while cases with heights between 250 and 750 m account for 36% of the total. For a small percentage of the total cases the night-hour mixing height is higher than 1500 m. Estimated mixing heights of less than 50 m are considered as not realistic and were rejected.

Based on air quality data from the monitoring network, the days with high concentrations characterized as air pollution episodes were selected. This selection was made according to the following criteria: The imposed state limits must be violated in at least two monitoring stations, for at least two hours, for at least two

TABLE II
Analysis of occurence of air pollution episodes in Athens for different seasons and synoptic categories for the period of 1983–1990

	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 III
Classification of air pollution episodes in Athens according to the appearence of warm advection in the lower troposphere. Strong warm advection is considered when there is a rise in temperature greater than 4° during the previous three days from the first day of the episode. Time period 1983–1990.

SEASON	STRONG WARM ADVECTION	WEAK OR NOT AT ALL
WINTER	17	10
SUMMER	13	6
TRANSIENT	19	15
TOTAL	49	31

consecutive days, and for at least two recorded air pollutants. For the years 1983–1990, 80 episodes were selected for a total number of 210 days. The distribution of these episodes for each season and each synoptic category described in Table I, is shown in Table II. The largest number of air pollution episodes was found during the transient seasons with winter following. It was also found that most of the episodes were observed during the synoptic conditions of category I and II. Table III shows the classification of air pollution episodes according to the existence (or not) of warm advection in the lower troposphere. The synoptic charts and the detailed radiosonde observations at GMS were used for this classification. As is seen in this table, for most of the cases, an increase of temperature of more than 4° C ocurred during the previous three days from the first day of the episode. Warm advection occurs mainly during the transient and winter seasons. Table IV shows the classification of the air pollution episode days according to each season and the strenght of the surface pressure gradient. For most of the days with violation of the imposed state limits for air quality, a very weak or relatively weak pressure gradient was found in the area of Greece. This is especially true during transient and winter seasons. A few days with relatively strong pressure gradients and poor

TABLE IV
Classification of the pollution episodes in Athens according to the observed pressure gradients in the area of Greece: (A) Very weak pressure gradients (weaker than 5 hPa per 1100 km), (B) relatively weak (5 hPa per 550–1100 km), (C) relatively strong (5 hPa per 100–550 km), and (D) strong (greater than 5 hPa per 100 km). Time period 1983–1990.

	PRESSURE GRADIENT			
SEASON	A	B	C	D
WINTER	23	23	15	4
SUMMER	14	17	20	1
TRANSIENT	34	26	31	2
TOTAL DAYS	71	66	66	7

air quality were found. The high concentrations of air pollutants recorded during these days are related to the existence of air pollutants from the previous days.

2.3. Local Conditions

Due to the orientation of the Athens basin and the mountains surrounding it, the flow field shows a preference in two directions: one from the N or NE and the other from the SW. Northerly winds usually persist when the synoptic-scale flow is stronger than the sea-breeze. This usually occurs when there is a strong pressure gradient over the Aegean Sea and Greece. Northerly winds are usually strong and favour the ventilation of the Athens basin. Southwesterly winds usually occur during days with local circulations stronger than the synoptic one or with strong SW flow because of the existence of a low over the Central Mediterranean and Ionian Sea. Strong SW synoptic winds usually occur during the cold period of the year. Sometimes, the low over the Central Mediterranean advects warm air masses over Greece. When the low weakens, the advected warm air masses stabilize the lower trophosphere and poor dispersion conditions might occur in Athens.

During days with relatively weak synoptic flow, local circulations are usually observed. Such local circulations are sea (land) breezes, and upslope and drainage flows. There are three main cells of sea-breezes which develop in the area of Attiki. One is from the Saronic Gulf toward Athens. Near the surface it blows from the WSW to S during day-hours while during night-hours it is mainly from the N. The second cell forms over Mesogea plain (East of Hymettus) where winds near the surface vary from NE to E and SE during day-hours and from the W-NNW during the night. The third cell forms over the Thriasion Plain (West of Aegaleo) and blows mainly from the S during day-hours and from the N during the night. The sea-breeze circulation over Athens and the Saronic Gulf was known from ancient times. The Athenian General Themistocles took advantage of the sea-breeze in order to defeat the Persian fleet near the island of Salamis. References to this event are given in Steyn and Kallos (1992). The depth of the onshore flow is 500 to 1000 m above the ground, where the return flow usually merges with the synoptic one which is usually from the NW quadrant. The sea-breeze over most of the Athens basin shows an anti-clockwise rotation as was found by Steyn and Kallos (1992). These three sea-breeze cells interact through the gaps between the mountains. These interactions define the conditions under which polluted air masses from the area of Athens are exiting the basin or not. During most day-hours, air masses from Athens move out of the basin through the gaps between Pendeli and Parnitha, and Hymettus and Pendeli. In contrast, through the gap between Parnitha and Aegaleo, polluted air-masses from the industrialized area of the Thriasion Plain move toward Athens. Under certain circumstances, polluted air-masses from the Thriasion Plain still move over Aegaleo toward Athens during the day or over the Saronic Gulf during the night and later, with the aid of the sea breeze, over Athens (Asimacopoulos *et al.*, 1991). This kind of transport also occurs during days with S or SW synoptic flow. The western suburbs of Athens are affected by this kind of transport.

Typically, during summer-months, the sea-breeze over Athens is relatively strong (Prezerakos, 1986). As was found from analysis of wind data from several places within the Athens basin, the winds are from the SSW to SW 4–6 m/s during days with fully developed sea breeze cells. Because of the orientation of the coastline and the mountain slopes, the sea breeze occupies all the basin quickly in the morning and significant amounts of polluted air are transported out through the gaps between the mountains. There is a significant number of days where the synoptic flow is relatively strong and the sea-breeze progresses slowly or does not penetrate through the entire basin (Helmis *et al.*, 1987). During these days, the observed SWly winds are lighter than those recorded during days with full development of the sea breeze, and the air quality in Athens is poor. For days with full development of sea-breezes, air quality is poor during morning and evening hours.

Sea-breeze circulations develop not only during summer and transient seasons but also during the winter (Carapiperis and Katsoulis, 1977). This is due to soil type (rocky mountain slopes), lack of vegetation, orientation of the slopes and the insolation. Because of this, the land becomes warmer than the sea and a pressure gradient forms during day-hours with clear-sky conditions. Of course, this kind of sea-breeze is weak and usually does not penetrate deeply inside the Athens basin.

The analysis of surface winds, at various locations, for the days characterized as air pollution episodes, is shown in Fig. 3. As is seen, during the night, calms or very light winds are observed while during day the winds are mainly from the WSW to SSW with speeds rarely exceeding the 5 m/s in the Athens basin. At the stations NFL and TAT which are located at the northern part of the Athens basin, a significant number of days with NNE or NE winds was found. This must be due

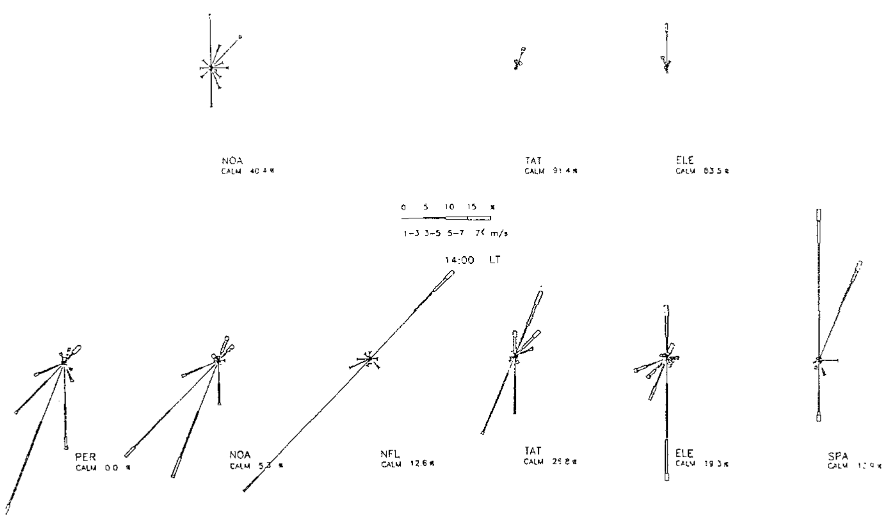

Fig. 3. Wind roses constructed for the air-pollution episode days at various stations in the GAA.

to the fact that for these days, the sea breeze is not strong enough to penetrate deeply inside the Athens basin. For the other two stations ELE and SPA, located in the Thriasion and Mesogea plains rescpectively, the winds show a preference for southerly and northerly directions. This is due to the orientation of these plains. Fig. 4 shows the wind roses for the air pollution episode-days, at different heights, estimated from the radiosondes released during night and day-hours from the station GMS. This analysis shows that, during days with high concentrations of air pollutants, the synoptic winds are from the W and N sectors.

3. Flow Field Simulations

Several model simulations for the Athens area have been performed during the last ten years. Most of these simulations are limited to a small domain around Athens and only for typical summer sea-breeze cases (e.g. Kallos and Kassomenos, 1991 and references therein). This was mainly due to the limited computer resources available and due to the belief that air pollution episodes in Athens are associated with sea-breezes. As was shown above, during days with full development of sea-breeze cells, the air quality of Athens is considered as poor during morning and evening-hours. Poor dispersion conditions are associated with stagnant conditions (synoptic-scale flow in near equilibrium with local circulations) or/and warm advection aloft.

In this study, the results of a model simulation will be shown. The case is May 25, 1990 with weak pressure gradients over Greece and warm advection aloft. During

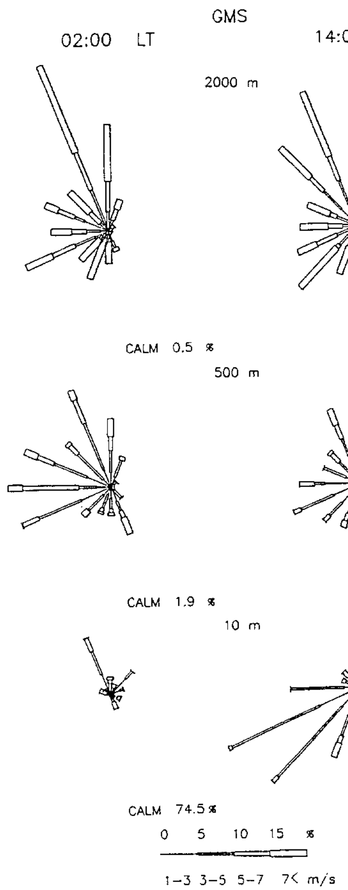

Fig. 4. Wind roses constructed for the air-pollution episode days at different heights for the upper air station GMS.

this day, the sea-breeze was developed but it was not as strong as it usually is during summer. The synoptic flow was from the W-WNW at the lower atmospheric layers and NW aloft with speeds ranging from 2 to 7 m/s. At noon, the flow was from the WSW in the lower layers. A strong temperature inversion was observed up to 920 mb during the night; the inversion did not break-up during day-hours (Kallos and Kassomenos, 1991). This inversion was due to warm advection at the layers of the trophosphere and did not allow the vertical development of local circulations in the Athens area. The sea-breeze started late in the morning as is shown in Fig. 5. It started later than usual and was not as strong. During night and morning hours the winds were very light at almost all stations while at noon they are from the SSW veering to S in the afternoon. Mixing height calculations during this day showed

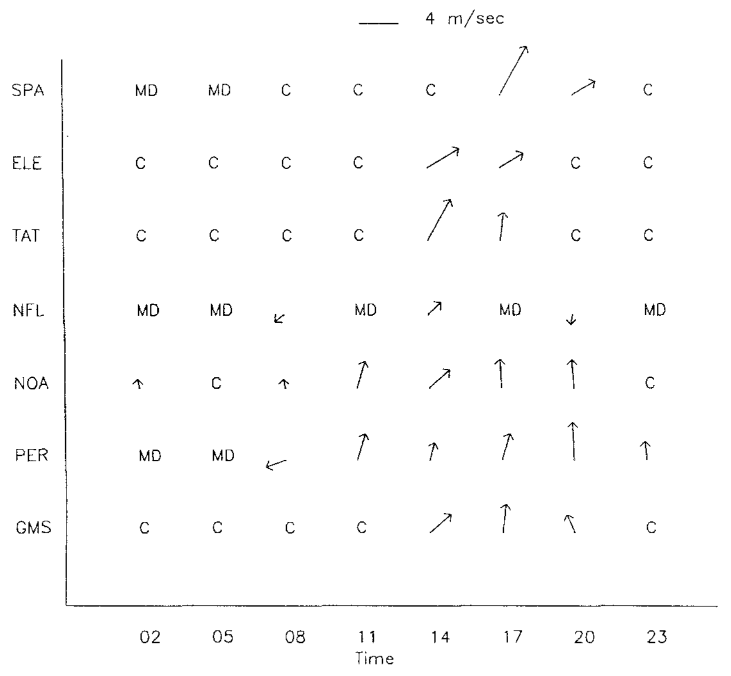

Fig. 5. Observed surface winds at different locations in Attiki during May 25, 1990. Missing data and calms are shown by "MD" and "C" respectively.

that the afternoon mixing height was about 150 m while the night mixing height was approximately 60 m. The same conditions also occured one day before and one day after. This air pollution episode was one of the worst in Athens. On May 27 the mixing heights were 600 m and 175 m, respectively, and the episode ended.

The model used for this simulation is the Colorado State University Regional Atmospheric Modelling System (RAMS) which was developed from the groups of R. Pielke and W. Cotton (e.g. see Pielke *et al.*, 1992; Xian an Pielke, 1991). This model has nesting capabilities and several options for lateral and top boundary conditions, turbulence, surface, radiation and cloud parameterizations. Three model domains were used (see Fig. 6). The coarsest domain covered all of Greece, the Aegean Sea and a portion of Turkey with grid increments of 16 km. The intermediate domain covered the NE part of Peloponnese, the Saronic Gulf and a large portion of mainland Greece and the island of Evoia with horizontal grid increments of 4 km. The finest grid covered most of the Saronic Gulf and the area of Attiki with grid separation of 2 km. The three domains had 45x43, 38x38 and 36x32 horizontal grid points and 27 vertical levels distributed up to 11 km. The simulation started at 2:00 LT and ended 24 hours later. The data used for initialization were upper-air data (radiosonde) from the airport of Helliniko in Athens (station GMS).

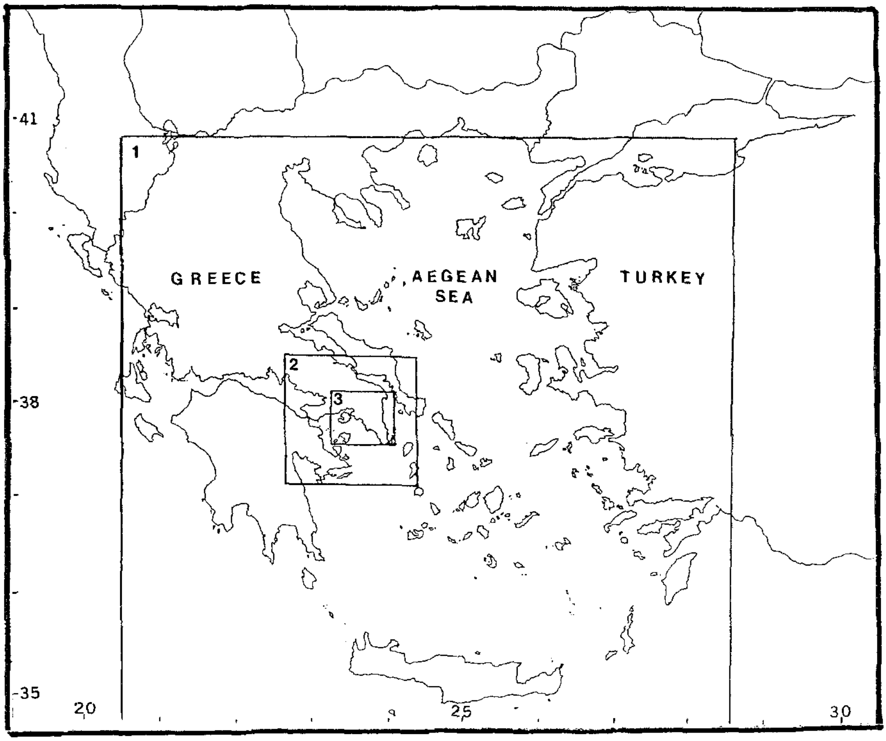

Fig. 6. Map of Greece and the surrounding area. The three model-domains used for the simulation are also shown.

Land-use data, such as vegetation index, urban areas, soil-type, etc. were derived from satellite images and cartographic maps while the roughness length over land was determined at each grid cell according to the land-use. Other capabilities of the model used for this simulation are the second-order turbulence closure, absorbing layer (Rayleigh friction) at the top five model levels and zero-gradient lateral boundary conditions for the coarsest grid.

Fig. 7 shows the wind fields 40 m above the ground at the three model domains, at 6:00 LT. The flow is NW to W over the mountainous areas of Greece; it becomes W in the area S of Peloponnese and SW to S over Saronic Gulf. Light winds are observed over the Aegean Sea (Fig. 7a). Only a portion of the coarsest grid is presented here in order to improve plotting resolution. The numbers at the X and Y axes show the distance in km from the center of the coarsest grid. Fig. 7b shows the wind fields at the 4 km grid domain. At this domain, the flow over the Saronic Gulf is from SSE veering to SE near the island of Aegina and E over the western part. The flow over Athens is mainly from the NE with speeds of 1–2 m/s. Over the sea between Attiki and Evoia, the flow is mainly from the N. Fig. 7c shows the flow at the finest The main features are the same as in the 4 km grid domain but with more detail. The flow is described in detail at the gaps between the mountains. Later in

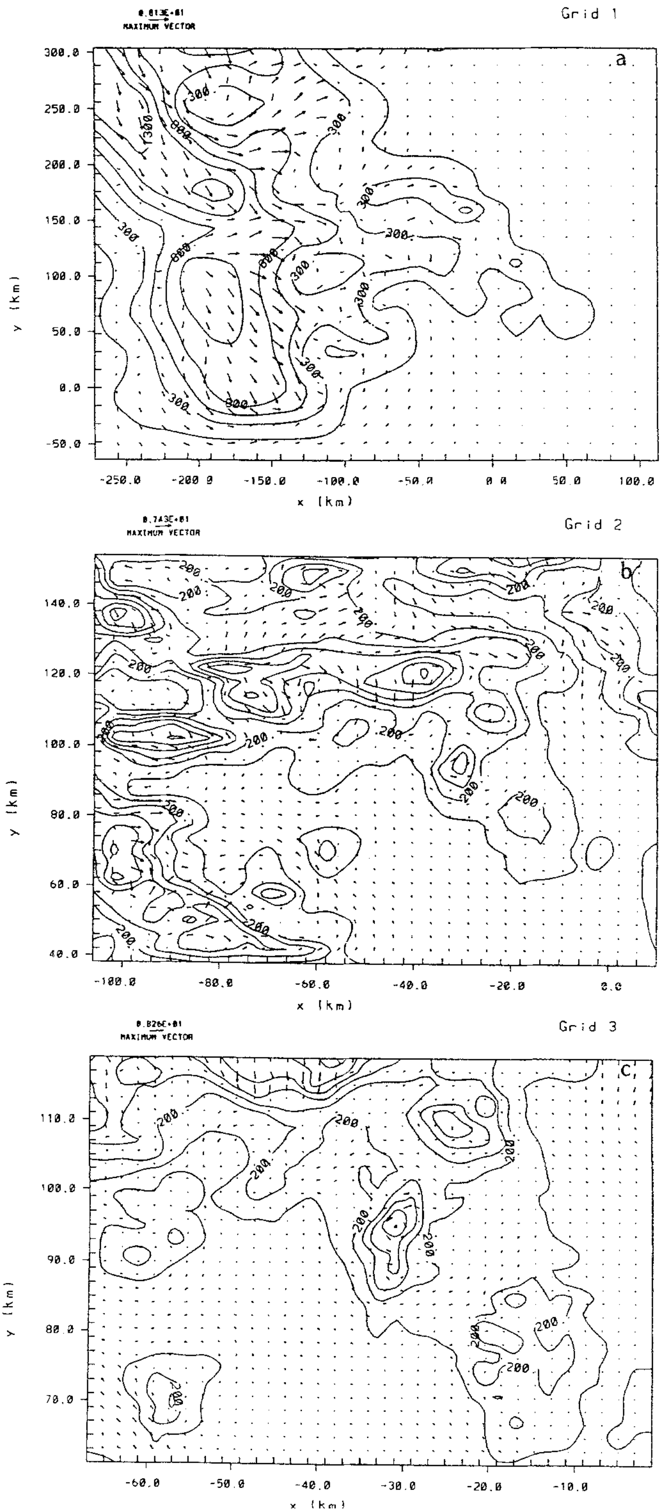

Fig. 7. Wind fields at the three model-domains, 40 m above ground, at 06:00 LT. (a) 16 km grid increments, (b) 4 km grid increments, and (c) 2 km grid increments.

the morning, when the sun rises and the land is heated, local circulations start to develop. Fig. 8 shows the flow fields near the surface (40 m above the ground) at 14:00 LT when the local circulations are at their peak. As is shown in Fig. 8a, the topographic features of mainland Greece block the regional-scale circulation. The flow is stronger near the coasts, it goes around Peloponnese and is directed toward the Saronic Gulf. Inside the Saronic Gulf, the southerly flow splits and one portion is directed through the gap between the Hymettus and Keratea mountains toward the Mesogea plain, a second toward the Athens basin while the third is directed to the western Saronic and passes over the Isthmus of Korinth (Fig. 8b). Air masses from the Athens basin exit through the two gaps at the northern edge (Fig. 8c). Wind speeds over the Saronic Gulf and Athens basin are within the range of 2–5 m/s. The sea breezes diminish late in the afternoon and in the evening-hours, light drainage flows start to appear. Fig. 9 shows the wind fields 40 m above the ground at the three model domains, at 22:00 LT. The regional-scale flow is still from the SW to S over the Saronic Gulf and the sea E of Peloponnese (Fig. 9a). Over the Athens basin, the flow is very weak with speeds of 1–2 m/s from variable directions(Fig. 9b,c). Over the northern part of Saronic Gulf the flow is from the SE. A relatively strong SWly flow is observed at the gap between Hymettus and Keratea mountains and over Mesogea. During the night-hours wind speeds are even lower. A general characteristic of the flow during this day was its small vertical extent because of the elevated inversion which did not break-up at all during the day. Most of the temporal and spatial flow variations occurred within the lowest 1 km of the troposphere. Fig. 10 shows a vertical cross section (N-S) of the potential temperature and wind (v and w components) along the Athens basin at 14:00 LT. This figure shows that the lower atmosphere is very stable over the sea and land except for a few hundred meters just above the land. The vertical extent of the inflow part of sea breeze is up to 400 m. Fig. 11 shows the horizontal wind field 1100 m above the ground at 14:00 LT. The winds at this level are from the W with speeds around 4 m/s. There is no influence of the sea breezes at this level. The only influence in the flow field is from the mountains. At the other levels above it, the winds veer to NW.

The intention of the model simulation presented in this paper was to show the diurnal variation of the mesoscale circulations in the area of Athens during a day with very stable atmospheric conditions. As discussed above, this is a case which appears frequently and is associated with some of the worst air pollution episodes in Athens. Additional simulations for other typical cases are under way.

4. Conclusions

In this work, the synoptic and mesoscale weather conditions occuring during air-pollution episodes in Athens were described. Air-pollution episodes in Athens area appear for a significant number of days during all seasons. Usually, their duration is two to four days and rarely last longer. For a small number of days,

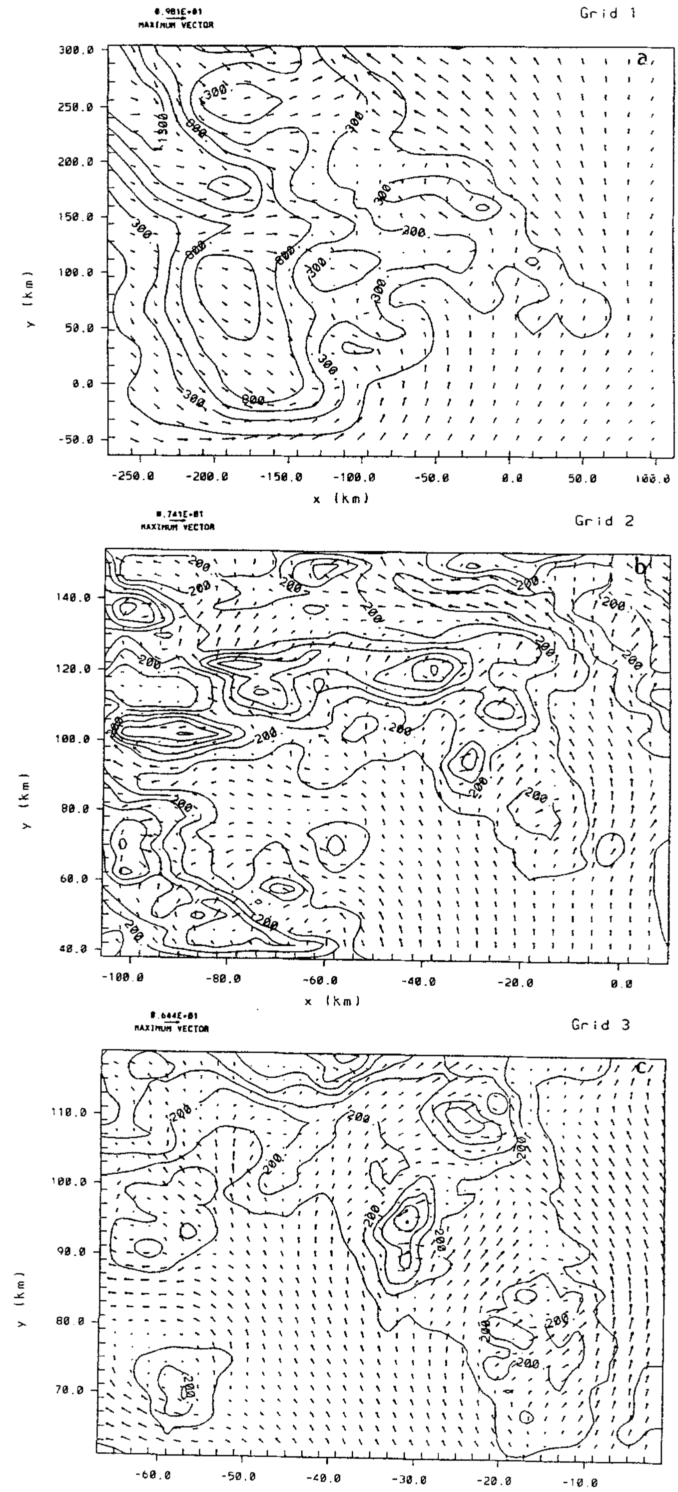

Fig. 8. Wind fields at the three model-domains, 40 m above ground, at 14:00 LT. (a) 16 km grid increments, (b) 4 km grid increments, and (c) 2 km grid increments.

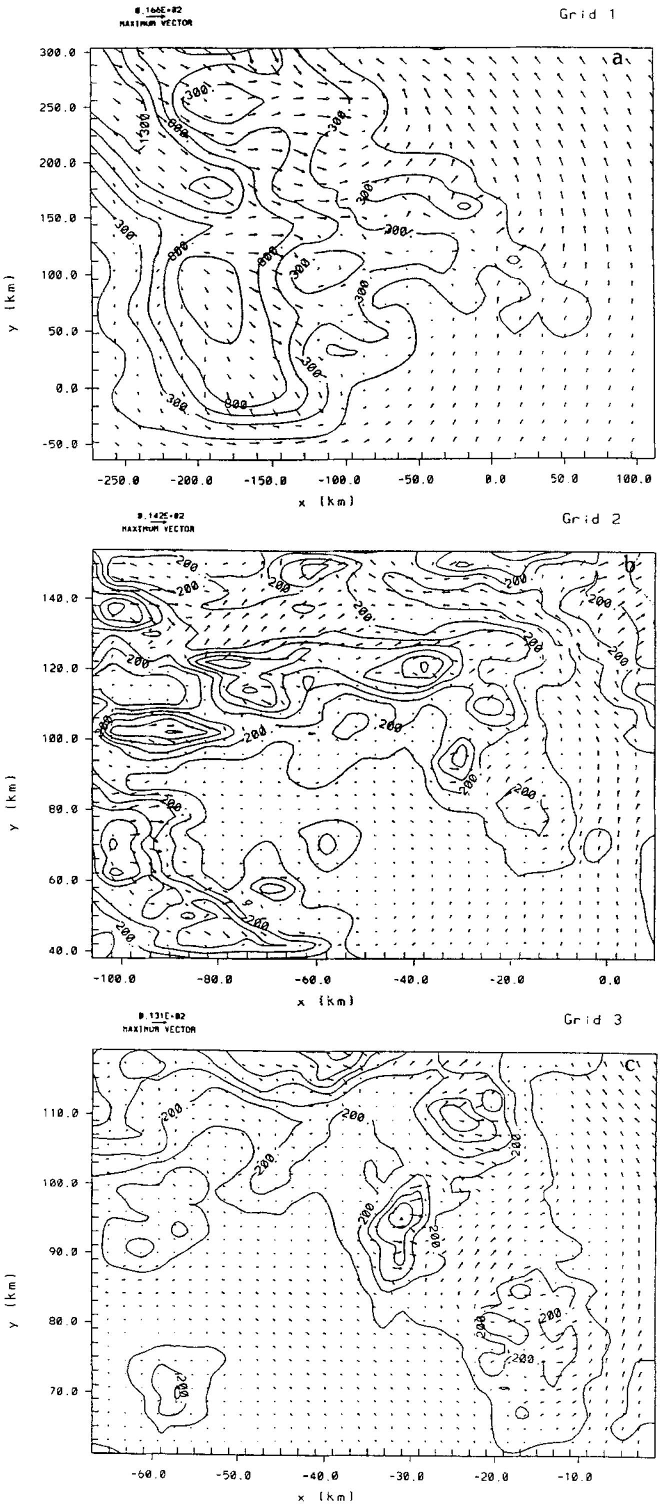

Fig. 9. Wind fields at the three model-domains, 40 m above ground, at 22:00 LT. (a) 16 km grid increments, (b) 4 km grid increments, and (c) 2 km grid increments.

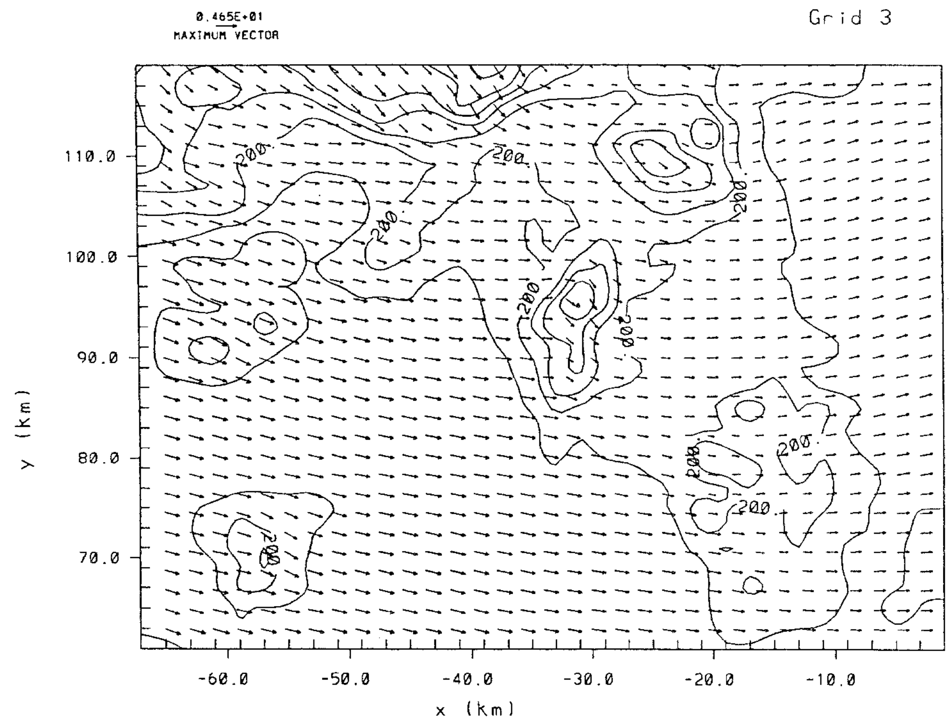

Fig. 10. Vertical cross-section of the potential temperature and winds (v and w components) along the Athens basin at 14:00 LT. The grid increments are 2 km while the contour interval is 1° K.

concentrations of air pollutants (primary, secondary and particulates) reach very high levels. The air quality standards are violated for a significant number of days. Clear-sky conditions favour these processes. Bad dispersion is a result of a combination of synoptic conditions and local physiographic characteristics. In general, during transient and winter seasons, stagnant conditions are more likely to occur. During spring, warm advection over the relatively cool sea and wet land causes very stable atmospheric conditions over the GAA, the mixing layer is very shallow and mesoscale circulations do not fully develop.

Sea breezes are usually thought to be associated with air pollution episodes in Athens. As was shown above, this is not the case. The worst episodes are usually associated with stagnant conditions and/or with warm advection in the lower troposphere. During days with full development of the sea breeze cells in the region, air quality in Athens is regularily poor during the morning and evening hours. It was also found that the synoptic – mesoscale flow interactions play a very important role in the formation of appropriate atmospheric conditions for the formation of air pollution episodes.

In general, most of the models used for sea breeze simulations could provide some general characteristics of the flow over Athens quite accurately (e.g. SSW or SW flow over Athens) because the key features are due to the topography and

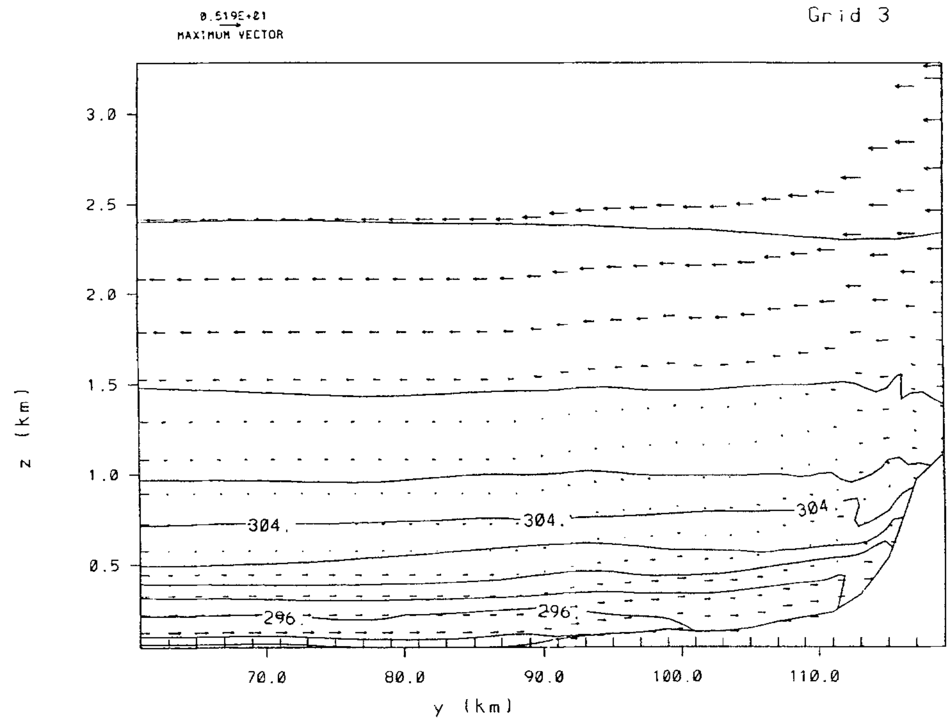

Fig. 11. The horizontal wind field at the 2 km grid increment model-domain, 1100 m above ground, at 14:00 LT.

land-sea distribution. The mesoscale flow over GAA is a combination of sea (land) breezes and upslope (downslope) flows. In the case where simple mesoscale models are used, the different-scale flow interactions cannot be accurately described. They must at least cover a large area (at least a part of NE Peloponnese, the Isthmus of Korinth and the southern part of island of Evoia) with grid increments of less than 4 km in order to resolve the flow in critical areas and describe very interesting phenomena such as recirculation of air pollutants. Atmospheric models with nesting capabilities are more appropriate for such simulations. The use of photochemical models in this area is very problematic because an accurate and detailed emission inventory required does not exist.

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