

Synoptic and local scale atmospheric circulation associated with air pollution episodes in an urban Mediterranean area

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Abstract Air pollution episodes in urban coastal areas follow certain pre-determined patterns, being associated with certain local meteorological conditions and emission of primary pollutants. In this study, the synoptic and local scale atmospheric circulation that prevails during air pollution episodes in a coastal major city in Greece, Thessaloniki, is examined for a period of 15 years (1989–2004). The study signifies the importance of studying air pollution meteorological patterns between coastal areas with different terrain characteristics. For Thessaloniki, it was found that the episodes occur mainly during the cold period of the year, while four types of synoptic scale circulation were recognized (I, II, III, IV) and five patterns of the local scale circulation (A1, A2, B1, B2 and B3). The highest percentage of episodes is associated with the

presence of an anticyclone over the northern Greece (types I and IV), being characterized by weak or very weak surface pressure gradient intensity, according to the position and extension of the anticyclone. Moreover, a temperature increase of at least 1°C during the previous 3 days is required in the lower troposphere. Consistent with the synoptic conditions, the development of the sea breeze plays a crucial role in the occurrence of the episodes, even in the cold period of the year, when the sea breeze can still develop with smaller frequency and intensity. Finally, it was found that a small number of episodes is related with the advection of polluted air masses from the industrial area in the northwest of the city and from the Eordaia area in the west, which is the largest lignite producing area of Balkans.

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1 Introduction

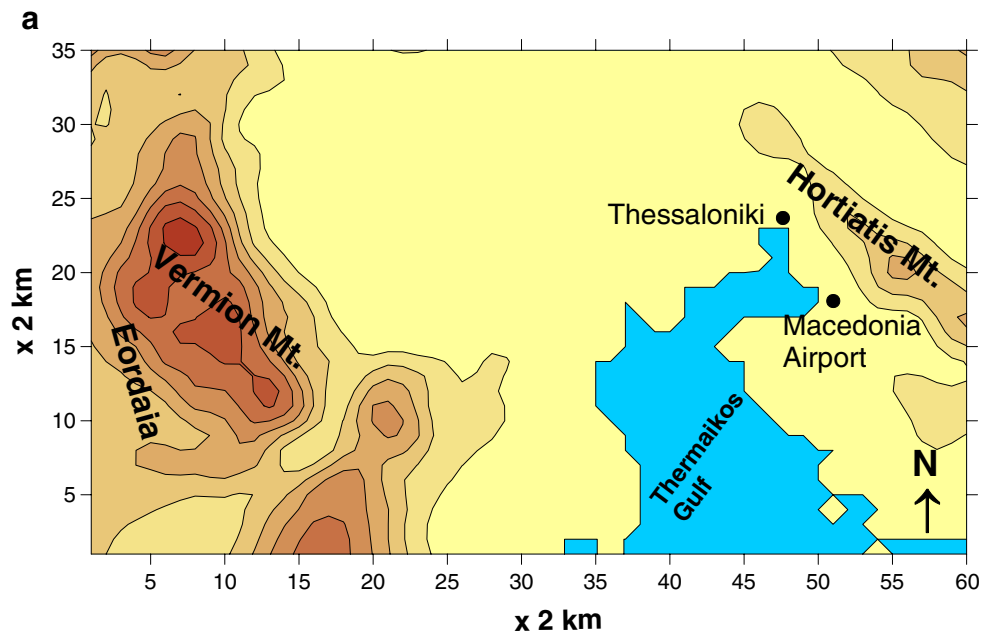
The atmospheric circulation is considered to play an important role in the status of air quality over an urban area through its controlling effect on local meteorological conditions (Comrie and Yarnal 1992; Dorling and Davies 1995; Kallos et al. 1991; Kassomenos et al. 1998a, 2003a). In turn, the local scale circulation, being generated by the landscape variability and complicated land water distribution such as sea breeze cell and drainage flow, greatly influences the air pollution dispersion (Lalas et al. 1987; Helmis et al. 1997b; Kassomenos et al. 1998b). Moreover, the understanding of the relationship of the pollutants' concentration with the prevailing circulation, both synoptic and local scale, is considered crucial for the forecasting of air pollution episodes. This relationship is primarily examined by classifying the atmospheric circulation on a climatological basis (Yarnal 1993; Kassomenos 2003a, b; Kassomenos et al. 2003b; Sindosi et al. 2003).

In urban coastal areas, the role of the sea breeze in the formation of air pollution episodes is actually to advect back to the city, early in the morning, polluted air masses which had been carried offshore during the previous night by the land breeze and trapped in the stable layer above the water, as was described by Lalas et al. (1987), Ding et al. (2004); Baumgardner et al. (2006). Thus, substantial enhancement of pollutant concentrations on the ground near the shoreline and far inland were reported during the morning hours. Lo et al. (2006) has further demonstrated that the urban heat island effect weakens the land breeze and creates circulation convergent zones, enhancing the pollutant trapping and accumulation.

The city of Thessaloniki, the second largest Greek city, is located in central Macedonia, northern Greece (40.5°N, 22.9°E). The Greater Thessaloniki Area (GTA) extends in

approximately 200km² and is inhabited by nearly 1 million people, being surrounded by fairly high mountains in the east-northeast (mount Hortiatis), by nearly flat terrain in the west and by the Thermaikos Gulf in the south (see Fig. 1a). GTA, as an important industrial and highly urbanized region, with a rapidly increasing (~6.5%/year) vehicle fleet (more than 500,000 vehicles are operating in the region), is frequently characterized by air pollution problems (Petракakis et al. 2005a, b; Kelessis et al. 2006a, b). Central heating and transportation are better distributed in the GTA than the industrial activities, which are centred in the southwestern sector of the city. Another important characteristic is that, unlike other large cities, the emissions follow a seasonal variation, but are almost the same for the different working days of the week and maintain a well-determined 24-hour pattern.

Fig. 1 **a** Topography of Greater Thessaloniki Area (GTA). The location of Macedonia Airport is displayed where radiosonde data are taken. **b** Map of the Thessaloniki city, displaying the positions of the monitoring stations of the Municipal Air Quality Network of Thessaloniki. The scale along the *x*-axis is 11.7 km while along *y*-axis is 8.5 km



The terrain complexity and pronounced terrain features of the GTA form local flow regimes, depending on the background flow, that play a key role in the occurrence of air pollution episodes in Thessaloniki (Helmis et al. 1997a; Güsten et al. 1997), as was demonstrated in other coastal areas. More specifically, during the day, the dominant local flow regime is the sea breeze cell that develops as Thessaloniki bay cell during the morning, with low intensity and directions perpendicular to the shoreline, while early in the afternoon it becomes the wider and stronger Thermaikos gulf cell with uniform southerly direction (Helmis et al. 1997a). During the night, the wind pattern is influenced by the land breeze in connection with katabatic winds by the neighbouring orographic barriers.

The objective of this study is: (1) to understand the association of atmospheric circulation over GTA with air pollution episodes in the city, by classifying the related surface synoptic and local scale circulation and (2) following the coupling of the atmospheric circulation between the two scales, to explain certain temporal characteristics of the air pollution episodes in Thessaloniki.

2 Data and methodology

Air quality data were employed from six air pollution monitoring stations that operate under the responsibility of the Environmental Department of the Municipality of Thessaloniki (Fig. 1b) for the period 1989–2004. The stations provide mean hourly concentration data of SO₂, PM₁₀, CO, NO₂ and O₃. Two stations (P1, P5) are located in the commercial city center (with heavy traffic), and four stations in residential areas, (P2, P4) with moderate traffic and (P3, P6) with low traffic. The air pollutants measurements at all stations were performed at 3.5 m above ground (except P5, which measures at 27.0 m above ground). Table 1 presents details of the air pollution monitoring stations in Thessaloniki.

The criteria for defining an episode day are the following (Petrakakis et al. 2006): the concentration of at least two

constituents exceeds ambient air quality limits (according to EC Directives) for the pollutants SO₂, CO, NO_x, O₃, PM₁₀ at least at two monitoring stations, for a period not less than 2 h. These criteria reflect the local air quality conditions, as formed by the analysis of 16 years data in annual reports, issued by the Department of Environment in the Municipality of Thessaloniki, while have been imposed to select the worst air pollution episodes that occurred in the GTA. Moreover, they are similar with the ones that have been used by Kallos et al. (1991) for Athens. Then, an episode consists of one or more consecutive episode days, determining the episode duration.

The synoptic scale atmospheric circulation over the GTA was examined during each episode day, with the aid of mean sea level pressure maps at 00:00 and 12:00 UTC for each episode day, as derived from the European Meteorological Bulletin for the examined period 1989–2004. Following the synoptic scale classification scheme (see section 4.1 for description), each episode day is assigned to one synoptic type.

The synoptic scale circulation was further investigated according to the surface pressure gradient intensity and thermal advection in the lower troposphere, since these factors relate to the efficiency of the horizontal and the thermal mixing, respectively, and determine the degree of interaction between local and synoptic scale circulation.

The surface large-scale pressure gradient intensity was estimated with the aid of the reanalysis NCEP/NCAR grid point data of mean sea level pressure available on a 2.5°×2.5° latitude/longitude grid on a daily basis. According to the large-scale surface pressure gradient, the episodes were categorized in four classes (see Table 2), following Kallos et al. (1991).

The thermal advection in the lower troposphere is represented by the maximum day to day temperature change ΔT at 850 hPa during the previous three days from the first day of each episode (Helmis et al. 1997b). The temperature change was estimated with the aid of the radiosonde data that were taken at the Thessaloniki airport “Macedonia” at 00:00 LST. More specifically, the episodes were categorized into five classes (see Table 2).

Table 1 Operational municipal air quality stations (P1-P6) in urban Thessaloniki area

Station	Location	Latitude/longitude	Height asl (m)	Description
P1, M1	Egnatia-Venizelou	40°38'15"/22°56'30"	11.6	Urban-traffic
P2	Martiou-Karakasi	40°36'05"/22°57'38"	12.4	Urban-traffic
M2	Pedio Areos	40°37'21"/22°57'21"	5.1	Urban
P3, M3	Eptapirgio-Agrafon	40°38'34"/22°57'38"	173.5	Urban-residential
P4	Lagada-Koutifari	40°39'12"/22°56'06"	18.3	Urban-traffic
P5	Square Dimokratias	40°38'25"/22°56'20"	38.6	Urban traffic background
P6, M4	Toumpa-Malakopi	40°36'43"/22°59'29"	89.3	Urban-residential

M1-M4 refers to the meteorological stations, with M1, M3 and M4 operating at the same locations with the air quality stations. The description refers to the air quality stations

Table 2 Categorization of air pollution episodes according to the pressure gradient intensity and temperature advection

Pressure gradient intensity (hPa/100 km)		Temperature advection (°C/24 h)	
Strong	>5	Strongly warm	>4
Moderate	1–5	Moderately warm	3–4
Weak	0.5–1	Weakly warm	1–3
Very weak	<0.5	Weak or no advection	-1–1
		Cold	<-1

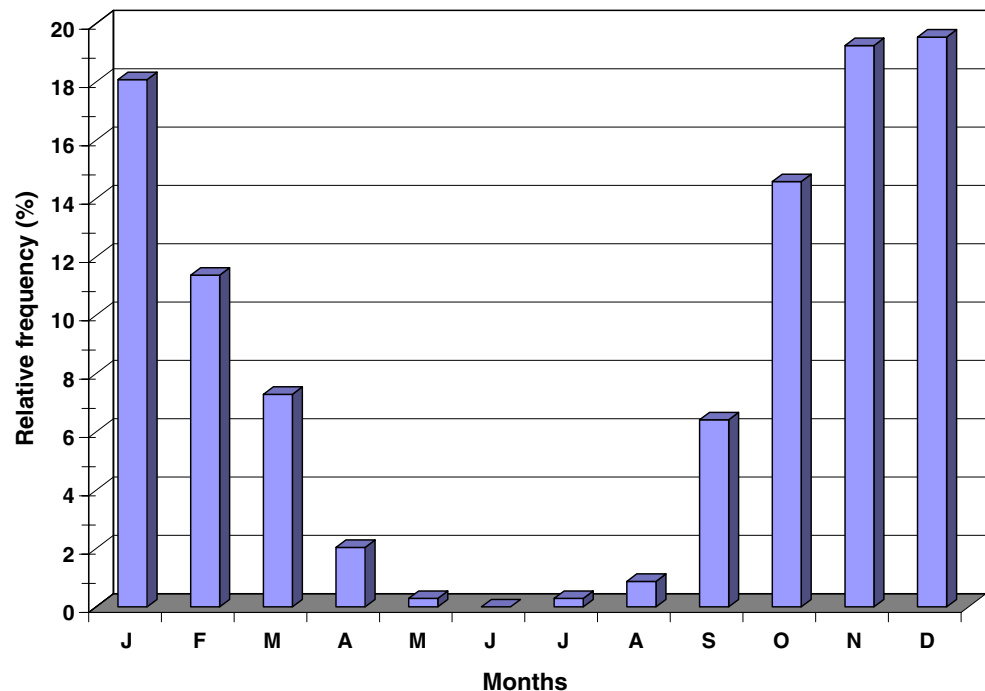
The local scale atmospheric circulation was investigated for each episode day, based on the expected direction of the sea breeze and the direction/intensity of the background wind. Following the local scale classification scheme (see section 4.2 for description), each episode day is characterized by a local flow pattern. For this purpose, 10-min meteorological data from two stations (M1 and M3) were employed for each episode day during the period 1989–2004, in combination with radiosonde data at 00:00 and 12:00 UTC. Supplementary meteorological data from another two stations (M2 and M4), available for shorter and not continuous periods, further aided the analysis of local scale circulation, when it was required. All stations are installed in open areas at a height of around 10 m, except M1, which is installed at a height of 20 m, preventing any influence from other buildings. M1 is located in the city centre (33 m asl) together with air pollution station P1, at a distance of 650 m from the coast that is directly influenced by the sea and M3 at a distance of

2,400 m from the sea, at the top of a hill (175 m asl) at the same location with the air pollution station P3 (see Fig. 1b and Table 1). The supplementary station M2 is located in the city centre (15 m asl), at a distance of 490 m from the coast, while M4 is located at the same location with P6, at a distance of 2,950 m from the sea, at a height of 89 m asl.

In this study, the warm period is considered to consist of June, July, August and September, being characterized as a dry period with almost no rain, while the cold period covers November, December, January and February, which is the main rainy season (Maheras et al. 2004). The remaining months (March, April, May and October) are considered as transient months, when warm and cold-type weather patterns are interchanging while showing some common climatic characteristics (Kallos et al. 1991; Kassomenos 2003a, b).

3 Characteristics of air pollution episodes

Following the above-mentioned criteria, during the period 1989–2004, 163 air pollution episodes were detected, lasting 1–8 days each or accordingly 347 episode days. Almost 50% of the episodes last only 1 day. The maximum duration was observed in January 1992, when the episode lasted 8 days and the concentration of all measured pollutants exceeded the threshold values at more than two stations. Almost all episodes are related with excessive PM₁₀. Only 11 episode days are associated with ozone exceedances and occur mainly in winter.

Fig. 2 Monthly relative frequency distribution (%) of episode days in Thessaloniki for the period 1989–2004

As can be seen in Fig. 2, the air pollution episodes in Thessaloniki occur from October to March, with maximum frequency of episode days being observed in December (20%) and November (19%). Moreover, these months are characterized by maximum episode duration. It should be noted that this frequency peak of episodes in December and November is consistent with the corresponding peak of calm days in Thessaloniki (Livadas and Sahsamanoğlu 1973). During winter, the episodes are attributed to CO and PM₁₀ exceedances (28.2 and 28%, respectively), while smoke is an important contributor (by 21%). The episode frequency decreases in the warm period, while very few or no episodes occur in May, June and July.

According to Fig. 3, the number of episode days in Thessaloniki increased in the early 1990s, peaking in 1992. The deterioration of air quality status during this year was also observed in Athens and was due to low temperature conditions that caused higher residential emissions (Kassomenos et al. 1999). After 1998, the frequency of the episodes clearly reduced, without exceeding 9 days/year. This is consistent with the decreasing trends of SO₂, CO and smoke in the city centre, which can be attributed to the improvement of fuel quality, the technological innovations in industry and the renewal of the vehicle fleet (Pantelidou et al. 2001; Petrakakis et al. 2005c). Despite the apparent decrease of episode frequency in the last years, the tendencies of NO₂ and O₃ (Pantelidou et al. 2001; Petrakakis et al. 2005b) are still positive and PM₁₀ concentrations (Petrakakis et al. 2005a) are still far above EU limits. This was supported by the fact that the occurrence of air pollution episodes

during the last 5 years is attributed to NO₂ and PM₁₀ concentration exceedances (not shown).

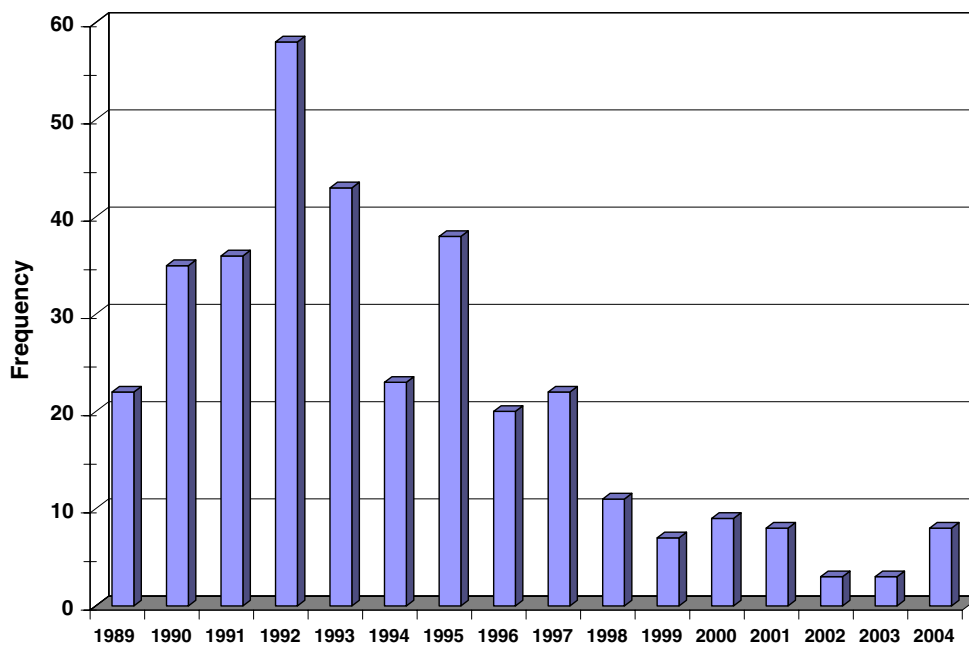
The analysis of the wind field (Fig. 4a) during air pollution episodes at station M1 demonstrated that wind blowing from the southern and southwestern sector mostly favours the episodes, with a total frequency of 33%. It should be noted that the southerly/southwesterly direction is very frequent (up to 23%) during the whole examined period, as can be seen from Fig. 4b. However, there is a percentage of episodes associated with northerly/northwesterly wind (Fig. 4a), which is a very common feature over the GTA (see Fig. 4b).

4 Classification results

4.1 Synoptic scale classification

In order to study the connection of the synoptic scale atmospheric circulation to the occurrence of air pollution episodes in Thessaloniki, the environment-to-circulation approach was followed (Yarnal 1993). More specifically, the circulation patterns specifically assessed at the mean sea level on the episode days were identified. The classification was made for each episode day separately, based on the corresponding surface charts at 00:00 and 12:00 LST on that day and each day was characterized by a synoptic type. When different synoptic types were observed at the two consecutive charts on a specific episode day, then that day was not taken into account in the classification scheme.

Fig. 3 Inter-annual frequency variations of air pollution days in Thessaloniki for the period 1989–2004



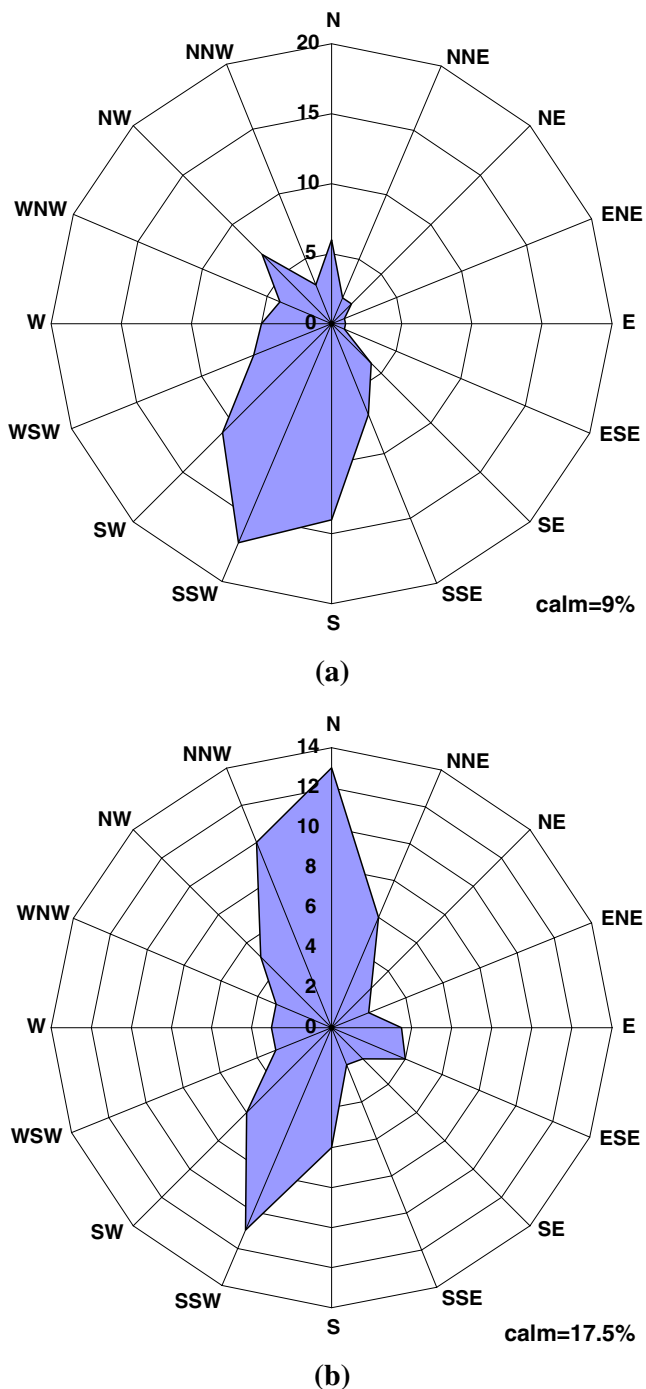


Fig. 4 Wind direction rose with respect to: **a** relative frequency of air pollution episode days in Thessaloniki, **b** relative frequency during the whole examined period (1989–2004)

Similar manual classification schemes were employed by Kallos et al. (1991) and Helmis et al. (1997b) for the Greater Athens Area. The advantage of this scheme, as compared to a computer based one, is the convenience to be used in a forecast office on an operational basis, since it requires routinely used weather maps rather than grid point data. However, the scheme, as a manual one, suffers from

the subjective interpretation of the individual forecaster, especially for ambiguous data.

Four synoptic types were distinguished that are described as follows:

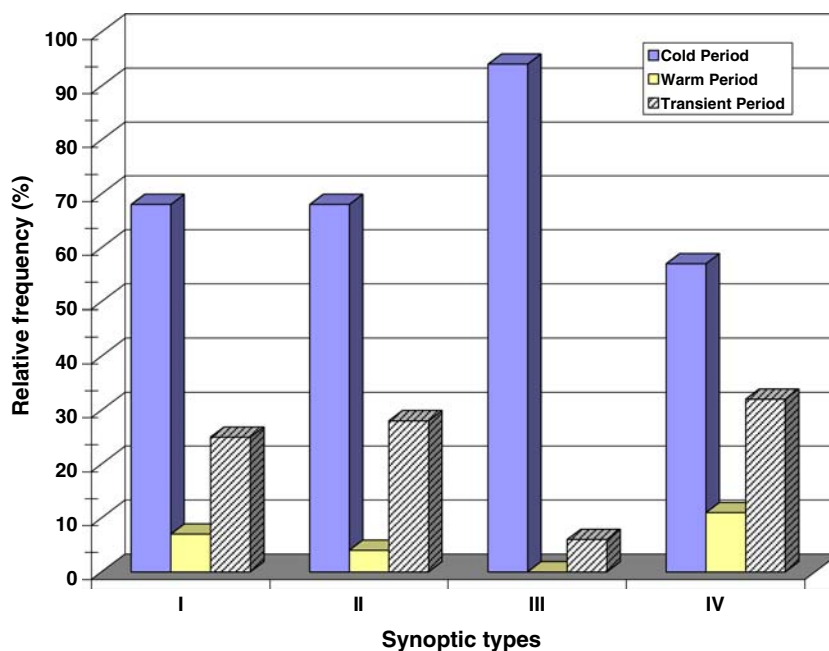
- Type I. An anticyclone covered Northern Greece, being centered over Russia or Central Europe or Balkans. This type is characterized by calm or weak wind conditions with variable directions.
- Type II. The GTA is affected by the warm sector of a frontal depression that has moved from the west or north, establishing wind from the southern sector.
- Type III. A cold front has passed over GTA, moving from the north. Northwesternly flow establishes behind the front.
- Type IV. This type is characterized by an anticyclone covering the Mediterranean Sea, combined with a low-pressure system in the east. When the anticyclone extends eastwards or strengthens, a weak northerly flow develops over GTA.

The classification analysis of the episode days demonstrated that similar synoptic conditions occur during air pollution episodes both in Athens and Thessaloniki. More specifically, it was found that type I mostly favours the episodes in Thessaloniki with a frequency of 45% and type IV follows with a frequency of 35%. The other two types, II and III are observed more rarely, in 15 and 5% of the episode days, respectively.

Following the seasonal analysis of the synoptic types, Fig. 5 gives the seasonal relative frequency distribution of each type. It becomes evident that all synoptic types show the highest frequency in the cold period, while still favouring air pollution episodes during the transient months. As was expected, all synoptic types are characterized by the lowest frequency in the warm period.

The analysis of the pressure gradient intensity during the episode days in Thessaloniki revealed that there is no episode being characterized by strong pressure gradient intensity. According to Fig. 6, the vast majority of the episodes is characterized as weak (42%) or very weak (23%), a fact that verifies the weak synoptic flow prevailing during air pollution episodes. However, a significant number of episodes (35%) is associated with moderate pressure gradient intensity. From Fig. 6, where the most frequent types I and IV are distributed according to the pressure gradient intensity, it can be seen that both types are mostly characterized by weak or very weak pressure gradient intensity, implying limited horizontal mixing and accumulation of air pollutants. More specifically, type I prevails with higher frequency of very weak pressure gradient as compared to type IV, while type IV appears higher frequency (53%)

Fig. 5 Relative frequency (%) of the synoptic types for the cold, warm and transient period



when the pressure gradient intensity is weak. A frequency of 34% and 25% of types I and IV, respectively, is associated with moderate pressure gradient intensity.

According to Fig. 7, where the number of episodes is displayed according to the thermal advection in the lower troposphere, almost 64% of the episodes require a temperature increase of at least 1°C/24 h during the previous 3 days, while for 23%, the increase is higher than 4°C/24 h (strong warm advection). A percentage of 24% is characterized by very weak or no advection while a smaller percentage (12%) is observed when

weak cold air advection occurs. It should be noted that warm air advection plays more important role in the occurrence of air pollution episodes in the other major Greek city, Athens, since almost half of the air pollution episodes was found to be associated with strong warm advection (Kallos et al. 1991).

Under weak flow conditions, the contribution of the warm air advection to the occurrence of air pollution episodes can be explained by the fact that the transported warm air masses allow the stabilization of the lower troposphere and limit the vertical mixing. Furthermore, the increased humidity of these

Fig. 6 Relative frequency (%) distribution of the air pollution episodes (all types) and types I and IV according to the surface large-scale pressure gradient intensity

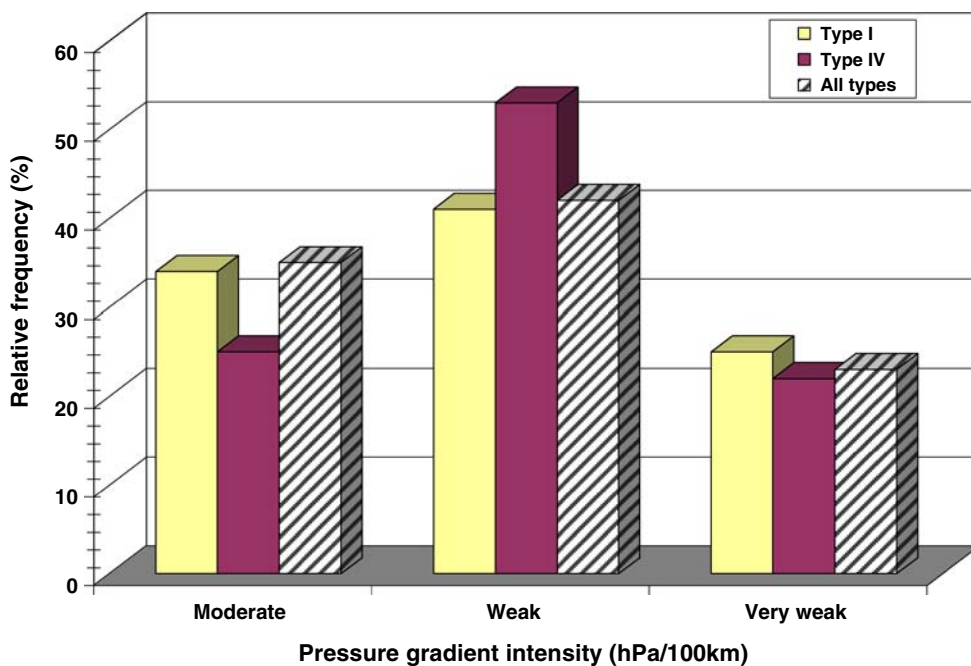
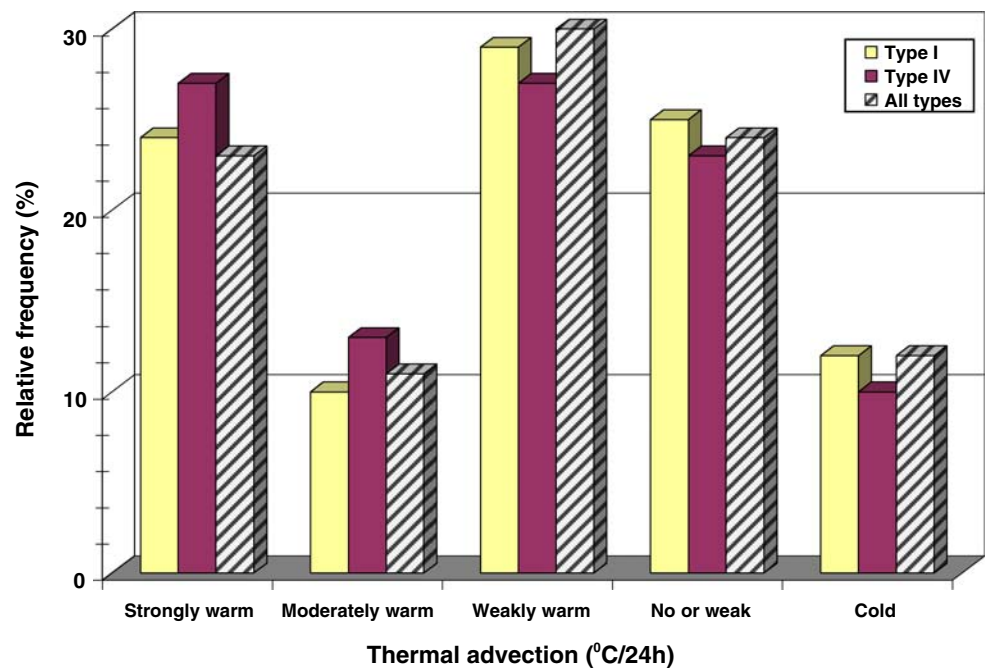


Fig. 7 Relative frequency (%) distribution of the air pollution episodes (all types) and types I and IV according to the thermal advection at 850 hPa



air masses facilitates the formation of poor air-quality conditions. It should be noted that in our case, the warm air advection was found to occur mainly in the cold period, in agreement with the maximum number of warm invasions in Thessaloniki (Flocas 1972), accounting partly for the occurrence of episodes during this season.

From Fig. 7, it becomes evident that the most frequent types I and IV are mainly associated with warm advection. Only a respective percentage of 10 and 12% occur along with weak cold advection (temperature decrease ranges between -1.1 and 2°C in 24 h), resulting in very low temperatures in the city. In these cases, the deterioration of air quality in the city is signified by transport of air pollutants from the north and increased emissions due to excessive central heating operation (Sindosi et al. 2003).

Strong warm advection occurs in 24 and 27% under types I and IV, respectively, despite the different synoptic origin of the two types: the former type is characterized by a prolonged anticyclone being characterized by generally warmer air masses while the latter by an anticyclone combined with a low-pressure system that can easily shift to other synoptic patterns, depending on the position and extension of the anticyclone.

Table 3 presents the cross-classification of the episode days according to the pressure gradient intensity and thermal advection. It becomes evident that the occurrence of episodes in Thessaloniki mainly requires weak pressure gradient, being accompanied by warm advection, implying that the horizontal mixing is mostly coupled with vertical mixing and consequently the importance of the interaction between the synoptic scale and local scale circulation. The greatest frequency of the episodes is characterized by a temperature change of $1\text{--}3^{\circ}\text{C}$ in 24 h, which is independent of the prevailing pressure gradient.

Furthermore, strongly warm advection or cold advection is associated with stronger pressure gradient.

The results of Table 3 have been statistically checked with respect to the null hypothesis that the two classification criteria (namely, pressure gradient and thermal advection) act independently of one another. After calculating the expected cell frequencies and comparing them with the corresponding observed frequencies, with the aid of a χ^2 -test this hypothesis has been accepted at confidence level 0.01 (NIST/SEMANTECH 2006).

4.2 Local scale classification

For each episode day, the observed surface wind daily variations at two stations (M1 and M3) were carefully inspected, in combination with the radiosonde data, with emphasis on the background wind direction/intensity and development of local flows. The periods of calms have

Table 3 Contingency table classifying air pollution episodes according to the large-scale pressure gradient and the thermal advection at 850 hPa in the lower troposphere during the examined period

Temperature advection ($^{\circ}\text{C}/24\text{ h}$)	Pressure gradient intensity (hPa/100 km)		
	Moderate (1–5)	Weak (0.5–1)	Very weak (<0.5)
Strongly warm (>4)	30	31	17
Moderately warm (3–4)	16	12	12
Weakly warm (1–3)	34	47	20
No or weak advection ($-1\text{--}1$)	22	35	25
Cold <-1	17	21	5

been excluded from our analysis. Following the methodology adopted by Helmis et al. (1997b) to classify the local scale circulation over the Mesogia Plain (Athens), five recurrent surface wind flow patterns were found to prevail during air pollution episodes in Thessaloniki, two of them being characterized by the predominance of local flows and three by the predominance of background flow:

- Pattern A1. Predominance of pure local flows
- Pattern A2. Interaction of local flows with background flow
- Pattern B1. Predominance of southerly background wind throughout the whole day
- Pattern B2. Predominance of northerly background wind throughout the whole day
- Pattern B3. Predominance of westerly background wind throughout the whole day

Therefore, each episode day is characterized by one of the above-mentioned local flow patterns. It was found that the vast majority (84%) of the episodes occur under sea breeze conditions: 73% are assigned to pattern A1 and 9% to pattern A2. The remaining episodes are associated with intense background flow: 6, 5 and 7% of the days are assigned to patterns B1, B2 and B3, respectively.

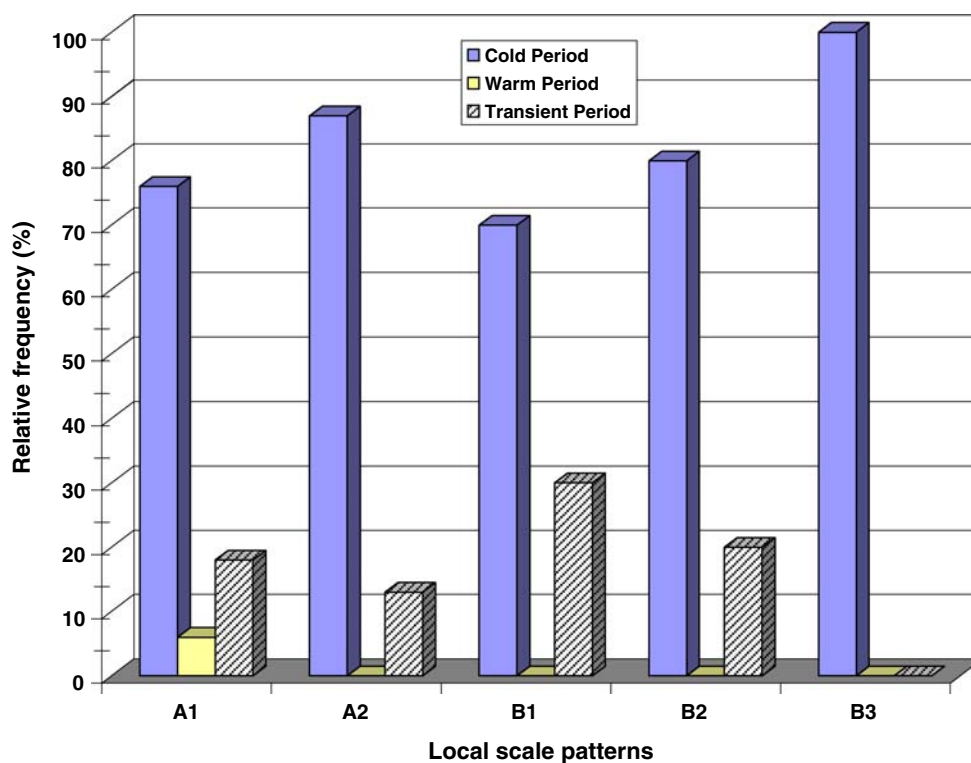
The comparison with the frequency distribution of the local-scale circulation (not shown) reveals that the sea-breeze conditions, favouring the air pollution episodes, represent a significant percentage of the circulation over

GTA (almost 29% for A1 and 3% for A2 on annual basis for the period 1989–2004). On the contrary, it was found that only a small percentage of episodes occurs under the most frequent pattern of northerly wind B2, being observed over GTA with a frequency of 40% throughout the whole period. Finally, no episodes are observed under easterly component wind, representing 12% for the whole examined period.

The frequency analysis of the local-scale patterns per season (Fig. 8) demonstrated that all types present their maximum occurrence in the cold period. More specifically, 76% of type A1 is observed in the cold period, 18% in the transient period and only 6% in the warm period, while type A2 presents a frequency of 87% in the cold period and 13% in the transient period. This implies that, although Thermaikos sea breeze mainly develops in the warm period and transient months, it certainly favours air pollution episodes in the cold period when it can still develop with smaller frequency and intensity (Livadas and Sahsamanglou 1973). It should be noted that this prominent role of sea breeze in the occurrence of air pollution episodes in Thessaloniki, especially in the cold period, does not seem to be the case for Athens (Kallós et al. 1991).

It is interesting to note that the only pattern that forms in the warm period is A1, suggesting that only pure sea-breeze conditions favour air pollution episodes during this season. When the background flow prevails (patterns B1, B2 and B3), the episodes occur in the cold and transient period, except of B3 that is only associated with cold period episodes.

Fig. 8 Relative frequency (%) of the local scale patterns for the cold, warm and transient period



5 Discussion on the combined synoptic and local flows

Since each air pollution episode day in Thessaloniki has been assigned to one synoptic type and one local scale pattern, a day-by-day cross tabulation has been performed in order to link the observed surface wind flow to the synoptic circulation and to further interpret the local flow variations according to the synoptic driving force. In this sense, a more detailed description of the flow patterns favouring the occurrence of air pollution episodes in Thessaloniki can be achieved.

According to Table 4, when air pollution occurs, the most frequent synoptic types greatly favour the formation of sea breeze conditions (local patterns A1 and A2), despite their different synoptic origin. Furthermore, types I and IV can be also associated with stronger background wind (patterns B1 and B2, respectively). While the pure sea-breeze pattern A1 is assigned to all synoptic types, the other local-scale patterns occur under certain synoptic types. In the following, each local-scale pattern that favours air pollution episodes in Thessaloniki is described in relation with the associated synoptic types, as derived by the previous analysis of both classification schemes.

5.1 Pattern A1

This pattern develops when an anticyclone prevails over Northern Greece for several days, under the synoptic types I (36%) and IV (27%). The anticyclone has tracked from Central Europe or southwest Russia or it originates over the Balkans, with highest frequency during winter (Makrogiannis and Giles 1980; Sahsamanoğlu et al. 1991). It is common that in winter the synoptic type I is related to sunny, dry and calm spells, the so-called “Halkyon days” (Makrogiannis and Goutsidou 1984). Under these weather conditions, the air is relatively cool near the ground and warmer aloft, resulting in the formation of strong temperature inversions during the night, which retain in the following day hours keeping the whole amount of pollutants near the ground (Lalas et al. 1983). This mechanism is supported by the high frequency of calms in the nocturnal hours in the Thessaloniki city during

winter, especially in December and January (Livadas and Sahsamanoğlu 1973).

Furthermore, the weak background flow allows the development of the undisturbed Thermaikos Bay breeze early in the morning at around 09:00 LST with SW direction and intensity of 2–3 m/s at station M1. Later, after 1400 LST the Thermaikos Gulf breeze develops, being associated with shift to southerly direction and intensification to about 4–5 m/s, and remains until 19:00–20:00 LST. It should be noted that the sea breeze is weaker during winter. The sea breeze is also observed in the inland station M3 at around 1200–1300 LST with southerly direction. The sea breeze remains until 19:00–20:00 LST. During the night, a weak land breeze develops (1–2 m/s) with northeasterly direction.

5.2 Pattern A2

This pattern is favoured by type I (5%) as well as to type IV (3%), being associated with stronger background wind that interacts with the local flows. More specifically, pattern A2 occurs when an anticyclone prevails over the northern Greece (Livadas and Sahsamanoğlu 1973), but combined with a low-pressure system in the east. These synoptic conditions result in strengthening of the northerly component synoptic wind and are observed from October to May, when a depression appears over the area of Cyprus or Turkey (Kallos and Metaxas 1980) or from June to September when the Pakistan thermal low extends over Eastern Mediterranean (Arseni-Papdimitriou et al. 1988).

Since the background flow has strong offshore component (northerly), the sea breeze develops with a delay. For this reason, at M1, a sudden shift in the wind direction is observed from the northern to southern sector at about 11:00–12:00 LST. Depending on the intensity of the background flow, the sea breeze can be suppressed, while it does not always reach the inland station M3. Similarly to pattern A1, the development of the sea breeze under this pattern facilitates the accumulation of air pollutants in Thessaloniki. After 18:00 LST, the background wind again predominates, disrupting the formation of nocturnal local circulations.

5.3 Pattern B1

This pattern mainly forms over GTA when the synoptic type II (4%) prevails, implying that GTA is found in the warm sector of a shallow frontal depression, frequently following a track from western Mediterranean or northern Europe towards northern Greece in winter (Flocas 1988). Also, B1 pattern is associated with pattern I. Contrary to the previous two patterns, in this case, the pressure gradient intensity is stronger, establishing a moderate synoptic flow

Table 4 Frequency distribution (%) of the air pollution episodes according to the synoptic types and local scale patterns

	I	II	III	IV	Total
A1	36	7	3	27	73
A2	5	1	0	3	9
B1	2	4	0	0	6
B2	0	0	1	4	5
B3	2	3	1	1	7
Total	45	15	5	35	100

from the southern sector. GTA is influenced by moderate southwesterly synoptic flow and clear sky conditions, preventing the development of the sea breeze. Warm-air advection plays an important role in the formation of poor dispersion conditions. The distinct difference with pattern A1 is that at both M1 and M3 stations the wind is southeasterly with intensity more than 3 m/s since early in the morning and it continues blowing from the southerly/southeasterly sector, without significant intensity variations throughout daytime and night time.

5.4 Pattern B2

This pattern is mostly related with type IV (4%), when the anticyclone over the Balkan becomes reduced with an accompanied intensification of the low-pressure system in the east. Under these conditions, the pressure gradient over the Aegean sea strengthens and the northerly component background flow intensifies. Also, a significant percentage (1%) is associated with the type III, that is almost unfavourable for other patterns (B2 and A1). According to type III, a cold front has passed over northern Greece, as it has moved from the north, causing weak to moderate northwesterly flow over GTA. The passage of cold fronts over northern Greece appears maximum frequency in winter (Flocas 1984), being associated with the frequent southeastward movement of the so-called Balkan front over Northern Greece (Flocas and Karacostas 1996).

The advection of cool air masses and the clear sky conditions support the formation of surface temperature inversion that consequently limits the vertical ventilation of the city, especially during the morning hours. Furthermore, the northerly background wind supports the transport of air pollution from the industrial area of Thessaloniki, which is located in the northwest of the city of Thessaloniki. Contrary to pattern A2, this pattern totally suppresses the local flows. At both stations M1 and M3, the pattern B2 is recognized by the northerly component wind that constantly persists throughout the whole 24-h period.

5.5 Pattern B3

This pattern forms mainly under the synoptic type II (50%), when the GTA is located in the warm sector of a frontal depression. However, in this case, the background wind has strong westerly component, due to the position and intensity of the frontal depression. When the background wind is strong, it favours the transport of polluted air masses from the industrial area of Eordea (Koloutsou-Vakakis et al. 2001), where four lignite plants and lignite mines are located and 70% of the electric power consumed in Greece is produced. The transport is performed alongside the mountain Vermion (see Fig. 1a) above the Thermaikos

gulf and then towards the city via the sea breeze circulation (Asimakopoulos et al. 2000). Besides, it was demonstrated that the high concentrations in Eordaia (see Fig. 1a) are mostly favoured during winter, due to the topographically induced boundary layer evolution (Triantafyllou et al. 1995). Moreover, the B3 pattern is related to type I with lower frequency (38%), implying that the presence of an anticyclone over the GTA can produce westerly component background wind.

In this case, the background wind is weaker compared to the previous case while it is parallel to the coastline. For this reason, it does not allow the development of a strong sea breeze system by eroding its vertical structure (Helmis et al. 1995). When this pattern occurs, at stations M1 and M2, the wind direction is southwesterly in the morning with intensity greater than 3 m/s, then a more westerly component (WSW) becomes prominent that retains during the following day hours while in the night the wind shifts again to the southwestern sector. The wind intensity does not present significant diurnal variation.

6 Conclusions

In this study, the synoptic and local scale atmospheric circulation was examined that prevails during the air pollution episodes in the urban coastal area of Thessaloniki for a period of 15 years (1989–2004). Four types of synoptic scale circulation were recognized (I, II, III, IV) and five patterns of the local scale circulation (A1, A2, B1, B2 and B3).

The episodes occur mainly during the cold period (October to March), while a very small percentage of episodes appear in the warm period. After 1998, the frequency is clearly reduced, while it does not exceed the value of 9 days on an annual basis. The 50% of pollution episodes last only 1 day. During the cold period, the episodes are attributed to CO and PM₁₀ exceedances, while smoke is an important contributor, as well.

It was worth mentioning that the air-pollution episodes and the associated local flow in coastal urban areas with different terrain characteristics, although they appear similarities, have substantial differences. Due to this fact, important differences have been identified in the forcing of the air pollution episodes between the two major cities in Greece (Athens and Thessaloniki). Therefore, it is very interesting to present the characteristics of air pollution meteorology patterns for different areas.

More specifically, for the city of Thessaloniki, it was found that the sea/land breeze favours the occurrence of the air pollution episodes, as was demonstrated in other urban coastal areas. More specifically, the highest percentage (almost 73%) of air pollution episodes is characterized by the development of Thermaikos sea-breeze circulation.

However, for Thessaloniki, the most interesting finding is that this mechanism is active even in the cold period of the year, when the sea breeze can still develop with smaller frequency and intensity.

During the episode days, the development of the sea breeze is supported by the prevalence of a large-scale anticyclone over northern Greece, which is the most frequent synoptic type during air pollution episodes (in a percentage of 80%). Depending on the position of the anticyclone and the presence of a low-pressure system to the east, the sea breeze develops undisturbed (A1 pattern) or can interact with offshore background wind and appears with delay (A2 pattern).

The warm advection seems to play an important role in the occurrence of air pollution episodes, since 64% of the episodes require a temperature increase of at least 1°C/24 h during the previous 3 days. The stronger warm advection occurs when southerly background wind prevails (pattern B1), being mainly associated with the warm sector of a weak frontal depression (type II). In addition to the warm advection, the episodes mainly occur under weak pressure gradient, implying that the horizontal mixing is mostly coupled with thermal mixing.

However, there is a small number of episodes that are associated with stronger background wind, either northerly (pattern B2) or westerly (pattern B3) with frequencies of 5 and 7%, respectively, signifying the transport of air-polluted masses over the city. In the first case, the transport occurs directly from the industrial area which is located in the northwest of the city. In the second case, the transport is performed from the industrial area of Eordaia in the west of GTA, above the Thermaikos Gulf and then via the sea-breeze circulation above the city.

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