THE ROLE OF WIND IN THE CONFIGURATION OF THE AMBIENT AIR QUALITY IN ATHENS, GREECE

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ABSTRACT

It is well-known that natural and anthropogenic emissions of ambient pollutants affect air quality, and as a consequence the public health. Air pollution indices are commonly used to indicate the level of severity of air pollution to the public. The objective of this study is the assessment of the air quality levels in the urban environment of Athens, Greece using the Air Quality Index (AQI), which presents advantages as an administrative tool for early warning in the context of public health protection. The AQI is a complex index and calculated by compounding appropriately the concentrations of surface ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and particles with aerodynamic diameter less than 10 μm (PM_{10}). For this purpose, available hourly data of the above ambient pollutants recorded by the Athens air pollution monitoring network, during the period 2001-2006, were analyzed for the development of the proposed index.

The temporal and spatial distribution of the mean annual AQI values within greater Athens area (GAA) is examined, and the results are analyzed in terms of the meteorological conditions. The effect of wind speed and direction on AQI levels is found to be significant, among the other meteorological parameters such as air temperature, relative humidity, sunshine and total solar radiation. The analysis revealed that the higher values of AQI, during the warm period of the year, are strongly associated with sea breeze than with northern wind flow. The knowledge of the sea breeze characteristics over GAA contributes to the comprehension of the local air quality formation levels.

KEYWORDS: Ambient air quality; public health; air quality index; greater Athens area; Greece.

INTRODUCTION

Air pollution has become a major environmental issue and the deterioration of environmental quality in megacities is one of the most important problems inherited from the mid 70's. The increased industrialization and the simultaneous growth of the metropolitan areas are strongly related with their air quality degradation. Since the early 80's, it has become clear that atmospheric emissions of various air pollutants affect the health of human beings and animals, damage vegetation, soils and deteriorate materials, and, generally, affect not only the large metropolitan areas but also the medium-size urban areas. Yet measuring environmental quality remains a difficult task as it lies at the interface of epidemiology, public health, and economics. Providing emissions, or concentration information alone, is insufficient. It is not only meaningless to the non-expert, but also does not facilitate an easy comparison of different pollutants which might have very different impacts on population health and quality of materials.

Athens, a city of about 4 million inhabitants, faces serious air pollution problems like the vast majority of megacities worldwide. In that instance, human activities play an enormous impact on its quality of life and public health. Concerning the air quality, there are many sources and types such as photochemical smog, ozone and its precursors, and suspended aerosol particles. The concentrations of ambient air pollutants, which prevail in GAA, are sufficiently high to cause increased frequency to the hospital admissions for cardiovascular and respiratory problems [1-4]. More specifically, several studies indicated that ambient air pollution correlated with children's respiratory morbidity [5-7]. In recent years, European Union's (EU) air quality standards are frequently exceeded in the GAA, especially concerning O_3 and PM_{10} [8-10]. These findings in combination with human health adverse effects make clear that availability of reliable environmental information is crucial.

Air is the prime resource, in addition to the land and water, for sustenance of life. Air pollution problems can be defined as the increase of the concentration of air pollutants in the ambient air, which adversely affect the human health and others exposed to these pollutants. The correct measure of air pollution is a very important parameter that qualifies the possibility of a reply to queries such as whether a region is polluted or not, or how high the pollution level is. One way of assessing the air quality in an area is the use of environmental indices [11-15]. The main objective of these indices is to measure air quality with respect to its effects on human health. Development of a proper index and a mechanism to disseminate the index values to general public are essential for a successful index system. Such an environmental index is the so-called Air Quality Index (AQI) [16]. In this way, a characterization of the pollution level apart from the pollutant taken into account is obtained.

MATERIALS AND METHODS

Study area - data

The city of Athens is located in an area of complex topography within the Athens basin (~ 450 km^2). Mountains surround the city with heights ranging from 400 to 1500 m (Fig. 1). Openings between these mountains exist at the northeast and the west of the basin, while to the south there is the sea (Saronikos Gulf). The Athens basin has a southwest to northeast major axis and is bisected by a cluster of small hills. The prevailing winds in the Athens basin blow from N and NE in late summer, fall and winter, but from SSW and SW in the spring and early summer. These NE and SW directions coincide with the major geographical axis of the basin. The ventilation of the basin is poor during the prevalence of local circulation systems, such as sea/land-breezes along the major NE-SW geographical axis of the basin.

The GAA, like most metropolitan areas in the world, has significant air pollution problems. These problems are the result of high population density and the accumulation of major economic activities in this region, while the intense sunshine contributes to the high levels of photochemical air pollution, especially during the summer months. The air pollution problems are often exacerbated by factors that favour the accumulation of air pollutants over the city, such as topography (basin surrounded by mountains), narrow and deep street canyons, and adverse meteorological conditions such as temperature inversions, low wind speed, high temperature, or extensive periods of dryness [17].

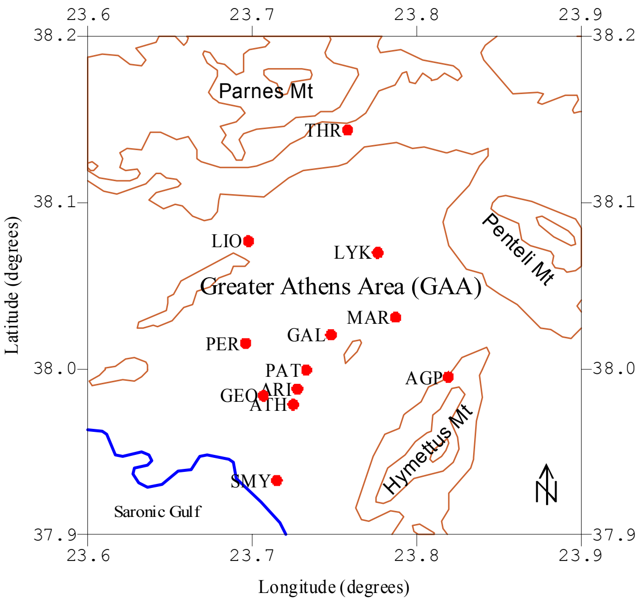

FIGURE 1 – Network of the sampling stations.

The air pollution episodes appear in Athens during all the seasons of the year, but the maximum is strongly associated with the development of sea-breeze [18]. Typically, during summer-months, the sea-breeze over Athens is relatively strong [19]. Except the great frequency of sea-breeze, the main factors that form air pollution episodes are the local topography with mountains surrounding the basin of Athens and preventing the ventilation of the urban area, as well as the wind flow field, which in the boundary layer is mainly of NE direction during the warm period of the year, and the existing sunshine [20].

TABLE 1 - List of stations and related information.

ID	Station	Abbreviated station name	Area	Longitude	Latitude
1	Agia Paraskevi	AGP	S - BG	37º 59´ 42´´	23º 49´ 10´´
2	Aristotelous	ARI	CC - T	37º 59´ 16´´	23º 43´ 39´´
3	Athinas	ATH	CC - T	37º 58´ 42´´	23º 43´ 30´´
4	Galatsi	GAL	CC - BG	38º 01´ 13´´	23º 44´ 53´´
5	Geoponiki	GEO	S - I	37º 59´ 01´´	23º 42´ 25´´
6	Liossia	LIO	S - BG	38º 04´ 36´´	23º 41´ 52´´
7	Lykovrissi	LYK	S	38º 04´ 11´´	23º 46´ 35´´
8	Maroussi	MAR	S - T	38º 01´ 51´´	23º 47´ 14´´
9	Patission	PAT	CC - T	37º 59´ 57´´	23º 43´ 59´´
10	Peristeri	PER	CC - BG	38º 00´ 55´´	23º 41´ 46´´
11	N. Smirni	SMY	CC - BG	37º 55´ 58´´	23º 42´ 54´´
12	Thrakomakedones	THR	S - BG	38º 08´ 37´´	23º 45´ 29´´

The objective of this work is the use of AQI, as a tool, to provide information on GAA's air quality and associated health concerns for the public, especially within the warm period of the year (April-September), when strong air pollution episodes appear because of the appropriate meteorological conditions (high values of air temperature, sunshine and solar radiation, but also the sea-breeze development). For this reason, the air pollution data used in the research consist of the hourly concentrations of ambient air pollutants: CO, NO_2, SO_2, O_3 and PM_{10} recorded by the network of the Greek Ministry of the Environment, Energy and Climatic Change (GMEECC). A detailed description of the GMEECC network is found in relevant publication [17]. In the current work, the hourly concentrations of ambient air pollutants in 7 of the GMEECC's network stations are examined, during the 5-year period 2001-2006. Monitoring stations are classified as centre city (CC) or suburban (S) ones, by their location, and also as traffic (T), industrial (I) or back-ground (BG) ones, by their categorization (Table 1).

Description of the air quality index

The AQI is a complex index and calculated by compounding appropriately the concentrations of ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), and particles with aerodynamic diameter less than 10 μm (PM_{10}). It converts the air pollutant concentrations into simple arithmetic values on a scale of 0-500. These arithmetic values correspond to various air quality categories. Intervals on the AQI scale are related to the potential health effects of the daily measured concentrations of the above-mentioned air pollutants.

The purpose of the AQI is to help people understand what local air quality means to their health. To make it easier to understand, the AQI is divided into 6 categories (Table 2). Each category corresponds to a different level of health concern [16].

Deductively, the AQI constitutes an improvement of the air pollution index PSI [21-24] and includes an additional intermediate category described as "unhealthy for sensitive groups" as well as an individual index for PM_{10} concentrations [16]. In the interests of this additional intermediate category, when AQI values are between 101 and 150, members of sensitive groups may experience health effects. This means they are likely to be affected at lower levels than the general public [16].

The air quality index is a piecewise linear function of the pollutant concentration. At the boundary between AQI categories, there is a discontinuous jump of one AQI unit. To convert from concentration to AQI, the following equation:

$$I = \frac{I_{high} - I_{low}}{C_{high} - C_{low}}(C - C_{low}) + I_{low} \qquad (1)$$

is used, where I is the (Air Quality) sub-index, C is the pollutant concentration, C_{low} is the concentration breakpoint that is ≤C, C_{high} is the concentration breakpoint that is ≥C, I_{low} is the index breakpoint corresponding to C_{low}, and I_{high} is the index breakpoint corresponding to C_{high}.

For each area, the daily AQI value is given by the worst registered condition among the 5 pollutants [25]:

$$AQI = \max[I_{O_3}; I_{PM_{10}}; I_{CO}; I_{SO_2}; I_{NO_2}] \qquad (2)$$

Given the pollutants' concentration data and the breakpoints in Table 3, every AQI sub-index is calculated using equation (1) (linear interpolation).

The values of the individual indices, together with the corresponding concentrations of air pollutants forming them, are shown in Table 3. In Table 3, for each pollutant, the breakpoint concentrations, corresponding to each category, are not on a linear scale. Breakpoint concentrations have been defined by EPA [16] on the basis National Ambient Air Quality Standards, and on the results of epidemiological studies of the effects of single air pollutants on human health [26]. A serious problem is that the evaluation of the AQI referred to a measuring site and not to a single air pollutant. In the atmosphere, several air pollutants are present simultaneously and the effects on human health due to the simultaneous presence of different pollutants in the atmosphere should be considered. In the evaluation of the AQI corresponding to a measuring site, where more than one

TABLE 2 - AQI scales of assessment for air quality, the corresponding AQI values and the possible effects to human health.

AQI Values	Levels of Health Concern	Health effects
0 - 50	Good	Air quality is considered satisfactory, and air pollution poses little or no risk.
51 - 100	Moderate	Air quality is acceptable; however, for some pollutants there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution.
101 - 150	Unhealthy for Sensitive Groups	Members of sensitive groups may experience health effects. The general public is not likely to be affected.
151 - 200	Unhealthy	Everyone may begin to experience health effects; members of sensitive groups may experience more serious health effects.
201 - 300	Very Unhealthy	Health alert: everyone may experience more serious health effects.
301 - 500	Hazardous	Health warnings of emergency conditions. The entire population is more likely to be affected.

TABLE 3 - Breakpoints for the AQI individual indices [16].

Sub -index value	O_3 8 h ppm	O_3 (*) 1 h ppm	PM_{10} 24 h μg/m^3	SO_2 24 h ppm	CO 8 h ppm	NO_2 1 h ppm
0-50	0.000-0.064	-	0-54	0.000-0.034	0-4.4	(**)
51-100	0.065-0.084	-	55-154	0.035-0.144	4.5-9.4	(**)
101-150	0.085-0.104	0.125-0.164	155-254	0.145-0.224	9.5-12.4	(**)
151-200	0.105-0.124	0.165-0.204	255-354	0.225-0.304	12.5-15.4	(**)
201-300	0.125-0.374	0.205-0.404	355-424	0.305-0.604	15.5-30.4	0.65-1.24
301-500	(***)	0.405-0.604	425-604	0.605-1.004	30.5-50.4	1.25-2.04

(*) The AQI for ozone is based on the 8-h average ozone concentrations. However, there are some regions where an AQI based on 1-h ozone concentrations may be more helpful.
(**) Due to the absence of national standards for NO_2 concentration levels, the determination of AQI is only allowed for values greater than 201.
(***) When the 8-h average ozone concentrations exceed the value of 0.374 ppm, then the AQI determination should be based on 1-h concentrations.

pollutant is monitored, the used procedure assumes the maximum individual index among those for the air pollutants monitored [16]. Actually, the category corresponding to the pollutants with the highest individual index value would be assumed at least as that corresponding to that location. Triantafyllou et al. [27] gave a detailed description of the developed AQI.

RESULTS AND DISCUSSION

The AQI values are calculated for the selected 12 representative monitoring sites, located in the GAA. Fig. 2 shows the statistical characteristics of the mean monthly AQI values for each of the 12 measuring sites from 2001-2006.

As seen in Fig. 2, during the examined 6-years period 2001-2006, the higher range appears in the measuring site AGP that is located 10 km to the NE of the Athens centre [9]. Consequently, AGP appears to be the most downgrading average air quality value. For almost the rest of the 11 monitoring stations, the air quality oscillates in lower value levels, indicating a more upgraded air quality.

The spatial distribution of the mean annual AQI values within GAA is presented in Fig. 3. It is depicted that in the eastern sector of GAA, limited by the Penteli and Hymettus mountains, air quality appears “moderate” (light grey color), while, in the western part of the studied area, air quality remains “good” (grey color).

During the cold period of the year (October-March), the air pollution episodes are less frequent, with the only exception of high CO concentrations appearing downtown due to central heating and heavy traffic [17, 23, 28]. The cold period is related to unstable atmospheric conditions caused by the passage of the depressions having tracks over Greece [29]. This pronounced instability contributes to the dispersion of the air pollutants and, for this reason, the role of the wind in the configuration of AQI values is diminished. On the contrary, the contribution of the prevailing wind during the warm period of the year to the spatial distribution of the air pollution within the GAA is significant and, therefore, it is analyzed in details in the process.

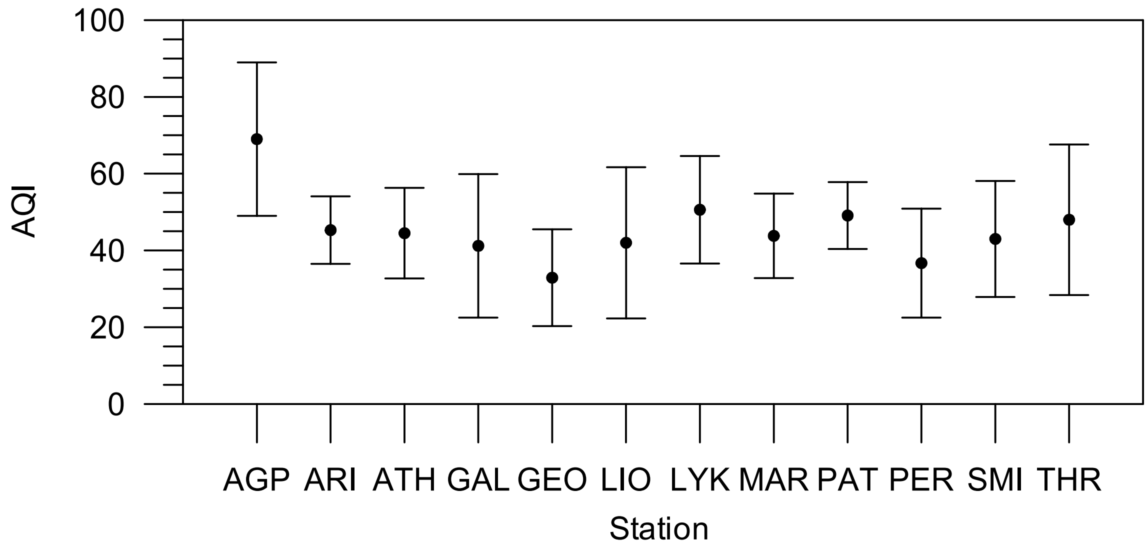

FIGURE 2 - Mean (± SD) monthly values of AQI at all measuring sites of GAA (2001-2006).

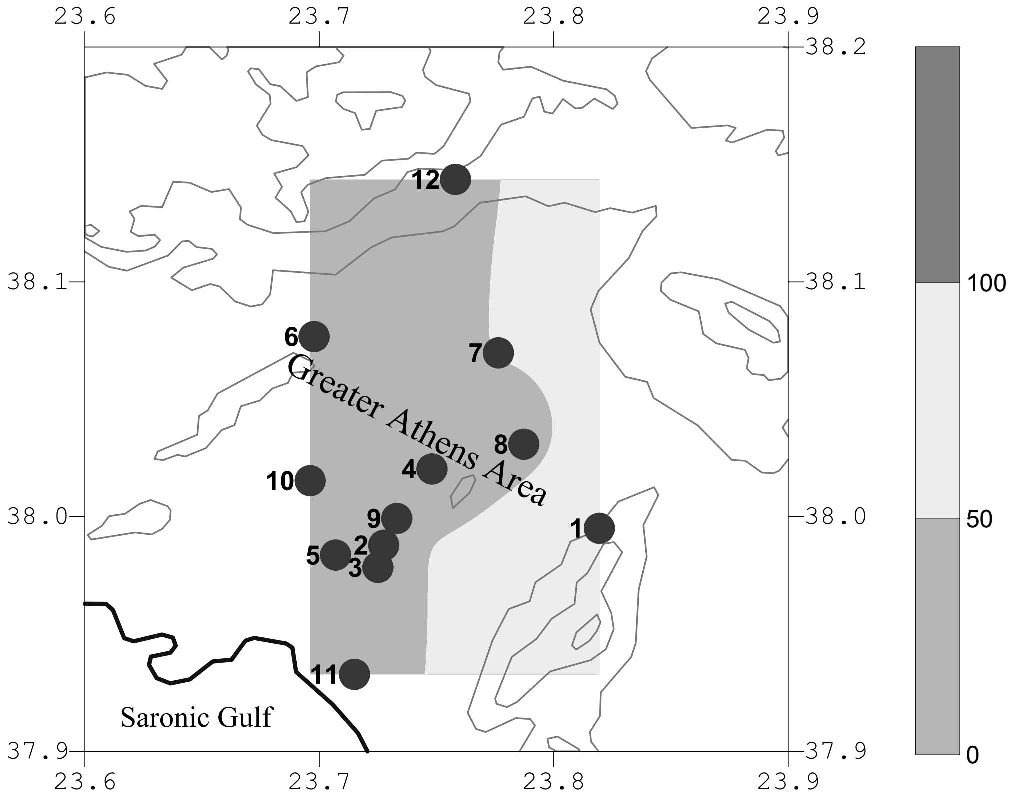

FIGURE 3 - Spatial distribution of the annual AQI within GAA.

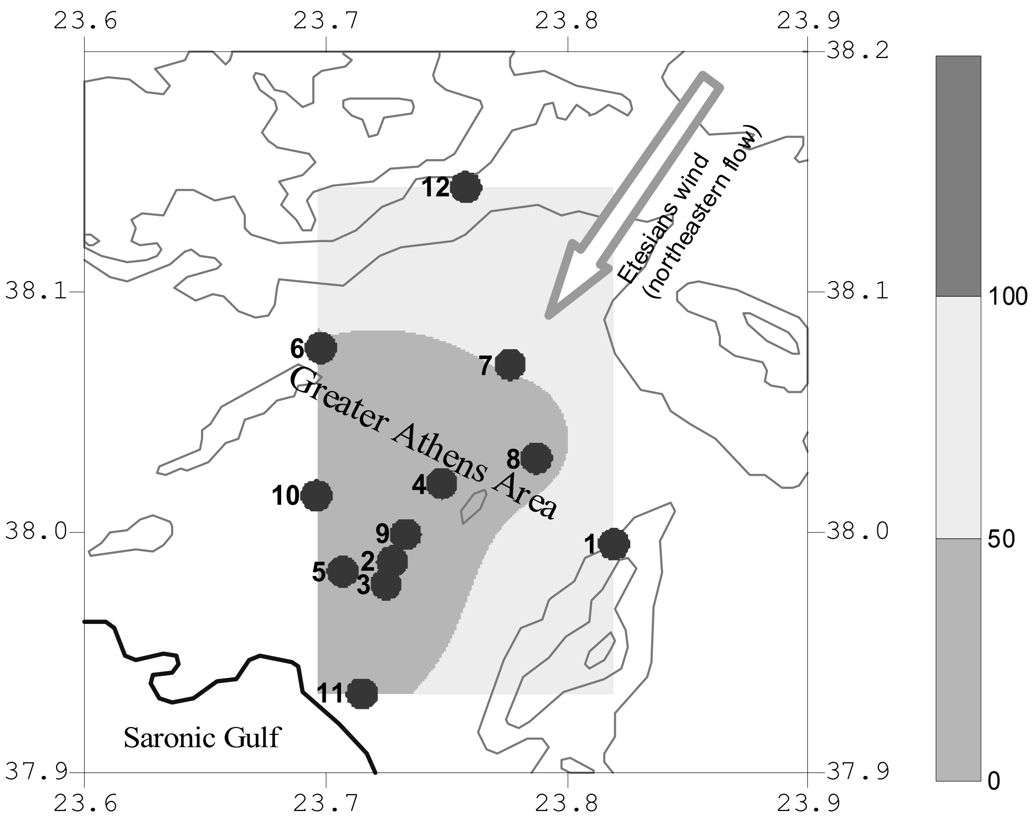

FIGURE 4 - Spatial distribution of the AQI within GAA during the warm period with northern wind-flow.

The warm period of the year (April-September) is associated with strong and frequent air pollution episodes (mainly photochemical), because of the appropriate meteorological conditions such as high values of air temperature, sunshine and solar radiation, and the development of sea breeze. Especially, the role of sea-breeze (southeastern flow) is significant in the configuration of the air quality. Nastos et al. [20] have concluded that the exacerbation of air pollution, mainly concerning NO_x pollutants, appeared in late spring or early summer, and is due to sea breeze, which is more often for that period of the year. The sea-breeze tends to stratify the atmosphere above the city, with the result of temperature inversion that traps the pollutants near the ground. On the contrary, during the warm period of the year, a northeastern flow opposes the sea breeze, resulting in a cleaner atmosphere within GAA. In the process, we analyze the spatial distribution of AQI for these two opposite wind regimes, which predominate during the warm period of the year.

The spatial distribution of the AQI within GAA during the warm period (April-September) with northern wind-flow is depicted in Fig. 4. This northern wind-flow is the well-known "Etesians" wind referred by Aristotle (5th century B.C.). This type is established in Greece, when a North Atlantic anticyclone, extended over Europe covering the Balkans, is combined with the Indian low over Asia Minor and the Eastern Mediterranean Sea. The blow of Etesians winds transfers polar continental (cP) air masses to Northern Greece, and the result is the appearance of precipitation and frontal thunderstorms. Another effect of the Etesians regime is the summer drought and the uniform weather conditions in Greece [29].

The mean AQI values during the warm period of the year with northern wind-flow decreases towards the sea, and almost the major part of GAA is characterized by "good" (grey color) air quality, while the surroundings by "moderate" (light grey color) air quality. The beneficial action of the northern flow which prevails the sea-breeze is to clean the atmosphere of the GAA by dispersing the air pollutants towards the sea. On the contrary, when sea breeze dominates, almost the whole GAA is under "moderate" (light grey color) air quality, with an exception of a small southwestern sector with "good" (grey color) air quality (Fig. 5). When sea-breeze is established, the air pollutants are pushed towards inland and, because of the existing topography with surrounded mountains, they are assembled within the basin limits. The maximum appeared in late spring or early summer, and is due to sea-breeze, which is more often for that period of the year. It is well-known that the circulation of sea-breeze appeared during warm days, with weak pressure patterns. The sea breeze tends to stratify the atmosphere above the city, with the result of temperature inversion that traps the pollutants near the ground.

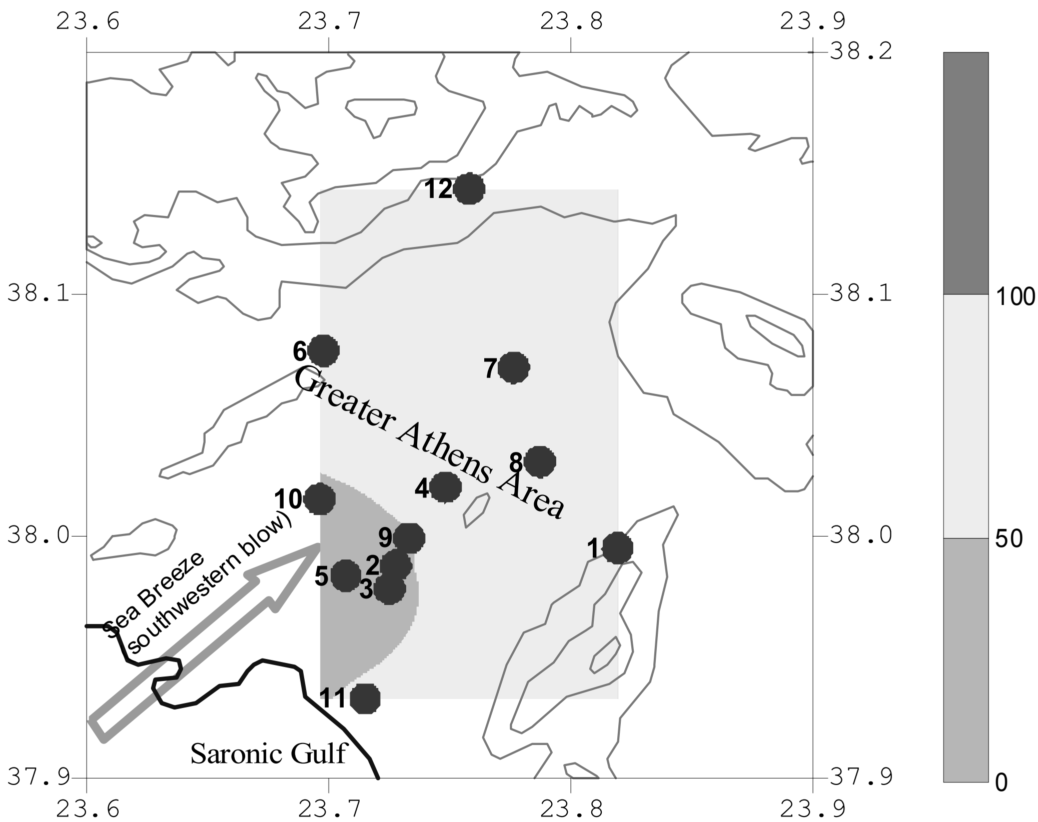

FIGURE 5 - Spatial distribution of the AQI within GAA during the warm period with sea breeze flow.

CONCLUSIONS

The assessment of the air quality in the greater Athens area (GAA) was performed by the use of air quality index (AQI). During the examined 6-year period 2001-2006, air quality was considered to be satisfactory, and air pollution posed little or no risk for almost all the sampling sites, with an exception of AGP site that is located 10 km to the NE of the Athens centre, where air quality was acceptable. However, for some pollutants, there may be a moderate health concern for a very small number of people who are unusually sensitive to air pollution. The role of the wind was proven to be significant in the configuration of AQI, especially within the warm period of the year. The north-eastern wind-flow, the so-called Etesians winds, is beneficial for cleaning the atmosphere of the GAA by dispersing the air pollutants towards the sea, and almost the major part of GAA, with an exception of the surrounding area at the foot of the encircled mountains, is characterized by "good" air quality. On the contrary, the development of the sea-breeze and the consequent air temperature inversion trapped the air pollutants within the boundary layer, and almost the whole GAA was under "moderate" air quality.

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