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ANALYZING THE BASIC METEOROLOGICAL ASPECTS OF A PARTICULATE AIR POLLUTION EPISODE OVER THE INDUSTRIAL AREA OF NORTHWESTERN GREECE DURING THE NOVEMBER 2009

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ABSTRACT

The complex terrain basin of Amyntaio – Ptolemais – Kozani in Western Macedonia of Greece is an area characterized by increased industrial activity and therefore it demands continuous and assiduous environmental monitoring. A prolonged particulate matter air pollution episode was recorded in the area during November 2009. Basic meteorological aspects are analyzed, during the episode period. Daily and hourly PM10 and PM2.5 concentration measurements were used along with surface and lower atmosphere hourly meteorological parameters from 13 measuring stations. The observational data were supported by data produced by the meteorological component of an air pollution model.

The overall analysis showed that the episode was primarily the result of the synoptic setting of the middle and lower troposphere. An Omega blocking pattern which gradually transformed to a high-over-low pattern prevailed over central and southern Europe during the episode's period. The examination of the vertical wind field in the lower troposphere and appropriate stability indices, revealed a continuous absence of significant convection. The weak horizontal wind field near the surface and the reduced mixing height combined with the lack of synoptic forcing resulted in the trapping of the pollutants in the lower troposphere and the recording of increased airborne particulate matter concentrations. The radical change of the synoptic setting in the first days of December marked the end of the episode.

KEYWORDS: stability, particulate matter, Omega block, high-over-low.

INTRODUCTION

Western Macedonia in Greece and especially the complex terrain basin of Amyntaio – Ptolemais – Kozani (BAPK), hosts a considerable number of Power Stations (PS) facilities along with lignite mines that feed these PSs. As a result, the air quality of the area is significantly affected due to the large amounts of airborne particulate matter (PM) emitted by those facilities (Triantafyllou 2003). The thorough and precise analysis of any possible relations between the meteorological conditions and the atmospheric pollution may help to successfully forecast extreme air pollution episodes, providing the necessary time and information to prepare for, or even avoid them.

Significant work has been carried out in the subject around the globe. McKendry (2000) investigated the meteorological parameters affecting the PM10 levels in the Lower Fraser Valley, British Columbia in Canada, while Rodríguez *et al*. (2002) examined the origin of high summer PM10 and TSP (Total Suspended Particles) concentrations at rural sites in Eastern Spain, concluding amongst others, that breeze circulations are partly responsible for these extreme events. The dependence of urban air pollutants on meteorology in the area of Cairo was analyzed by Elminir (2005). It was shown that wind and humidity affected the concentration and speciation of the pollutants. Barbadimos *et al.* (2011) examined the possible influence of meteorology on PM10 trends and variability in Switzerland from 1991 to 2008 and indicated that wind and temperature are two of the most significant factors.

In Greece, many researchers have already addressed the problem. Kallos *et al.* (1993) studied a series of air pollution episodes in Athens during the period 1983-1990 concluding that “days with critical balance between synoptic and mesoscale circulations and/or days of warm advection in the lower troposphere” favor such episodes. Triantafyllou (2001) studied high PM10 concentration episodes in Eordea valley and showed that stagnant meteorological conditions are most frequently associated with these episodes. Flocas *et al.* (2009) concluded amongst others, that air pollution episodes in the Thessaloniki area are primarily associated with anticyclonic conditions, small temperature rise and sea breeze circulation. Larissi *et al.* (2010), studied the temporal and spatial distribution of the Air Quality Index (AQI) within greater Athens area (GAA) and showed that the higher values of the index (high AQI values are generally associated to high concentrations of specific pollutants) during the warm period of the year, are strongly associated with sea breeze. This association was also noted by Proias *et al.* (2012) in the Greek city of Volos.

The meteorological setting of a particulate air pollution episode during November 2009 is investigated in the present paper. The episode is identified by means of particulate matter concentration values in specific sites along the BAPK axis. The data used are: a) mean daily PM10 and PM2.5 concentrations from the atmospheric pollution stations network of the Greek Public Power Corporation (PPC) and the Laboratory of Atmospheric Pollution and Environmental Physics of the School of Technological Applications of TEI of Western Macedonia, b) operational ECMWF analyses data, c) soundings data and d) vertical profiles of the basic meteorological parameters, produced by a prognostic local scale meteorological model.

THE AREA

The BAPK is situated in a mountainous area of western Macedonia, Greece. It presents a NW to SE orientation, with Amyntaio at the north and Kozani at the south end. Figure 1 depicts a topographic map of the area, the 13 measuring stations (1. Kato Komi, 2. Petrana, 3. Kozani, 4. Koilada, 5. Oikismos B, 6. Pontokomi, 7. Mavropigi, 8. Oikismos A, 9. Pentavrisos, 10. Anargiroi, 11. Amyntaio, 12. Vevi, 13. Florina) and the 6 power plants sites (PS1. Agios Dimitrios, PS2. Kardia, PS3. Ptolemaida, PS4. Amyntaio, PS5. Meliti, PS6. Bitola).

DATA AND METHODOLOGY

Hourly observational data from stations belonging to the Greek Public Power Corporation (PPC) and to the Laboratory of Atmospheric Pollution and Environmental Physics of the School of Technological Applications of TEI of Western Macedonia are one of the primary data sets used. These data include surface wind speed and direction and PM10 and PM2.5 concentration measurements, extending from 1/11/2009 to 30/12/2009. Based on the hourly observations, mean daily values are also computed. Daily PM10 values for November and December from 2006 to 2009 have also been used. Operational ECMWF analysis data of horizontal resolution of 0.25x0.25 degrees and temporal resolution of 6 hours, at all the basic pressure levels, are used to produce the required synoptic charts by means of Grid Analysis and Display System (GrADS). The Mean Sea Level Pressure (MSLP) and the 500hPa geopotential height fields are examined to define the synoptic conditions of the episode. The vertical wind velocity at the 700hPa level is used to identify possible synoptic forcing in the area.

The meteorological component of The Air Pollution Model (TAPM) is also used to produce hourly vertical profiles of specific atmospheric parameters like temperature, potential temperature, wind speed and direction and other useful variables like the mixing height for selected sites of the area. The Air Pollution Model (TAPM) is a PC-based, nestable, prognostic meteorological and air pollution model driven by a Graphical User Interface (GUI). The GUI allows the user to configure inputs, run the model and analyze outputs generated by the model. It is linked to databases of terrain height, land use, and sea surface temperature information. Data sets of synoptic scale meteorology inputs needed for simulation accompany the model. More details on TAPM equations and parameterizations, including the numerical methods used to solve the model equations, can be found in Hurley (1997), Hurley (2002a), Hurley *et al*. (2001), Hurley *et al*. (2005), while the model application in W. Macedonia region in Zoras *et al*. (2007) and Triantafyllou *et al*. (2011). The meteorological component of TAPM is an incompressible, non-hydrostatic, primitive equation model with a terrain – following vertical coordinate for three-dimentional simulations. It includes parameterizations for cloud micro-physical process, turbulence closure, vegetative canopy and soil, and radiative fluxes. The mean horizontal wind components u and v are determined from the momentum equations and the terrain following vertical velocity from the continuity equation. Potential virtual temperature θ_v is determined from an equation combining conservation of heat and water vapor. Pressure is determined from the sum of hydrostatic and optional non-hydrostatic component. The boundary-layer height (Zmix) in convective conditions is defined as the first model level above the surface for which the updraft velocity decreases to zero, while in stable/neutral conditions it is defined as the first model level above the surface that has a vertical heat flux less than 5% of the surface value following Derbyshire (1990). More details about that can be found in Hurley (2008). Micro-physics is based on Katzfey and Ryan (1997) for warm rain, and include bulk parameterizations for condensation of water vapor, evaporation of cloud water and rain water, auto-conversion and collection of cloud water to form rain water and an expression for the rainfall terminal velocity. The meteorological component of the model is nested within synoptic-scale analyses/forecasts that drive the model at the boundaries of the outer grid. The model is initialized at each grid point values of u_s, v_s, θ_{vs}, q_s interpolated from the synoptic analyses. At the model top boundary, all variables are set at their synoptic values, while zero gradient boundary conditions are used for all variables at the lateral boundaries. The model run for a twenty days' period (15/11-5/12/2009) using 25 vertical model levels, and three nested domains of 35x35 horizontal grid points at 30, 10 and 3 Km spacing for the meteorology. NCEP synoptic analyses were used at the outer grid boundaries. Pontokomi was considered as the center (0,0,0).

Sounding data from the nearest sounding station (Thessaloniki) are used, mainly to determine the presence of vertical forcing through the examination of stability indices such as the Total Totals Index (TTI) (Miller, 1967), the Lifted Index (LI) (Galway, 1956; Blanchard, 1998), the K-Index (KI) (George, 1960) and the Showalter Index (SI) (Showalter, 1953). TTI values over 44 are associated with convective activity that increases as the index values increase. Values over 55 indicate very strong instability. LI values between -2 and -6 are indicative of convective potential while values below -6 are associated with very strong convection. SI values between 3 and -3 indicate possibility of showers and thunderstorms and values below -3 are indicative of very strong convective activity. Finally, KI values over 20 suggest possible convective activity, while values over 40 imply certainty of convection.

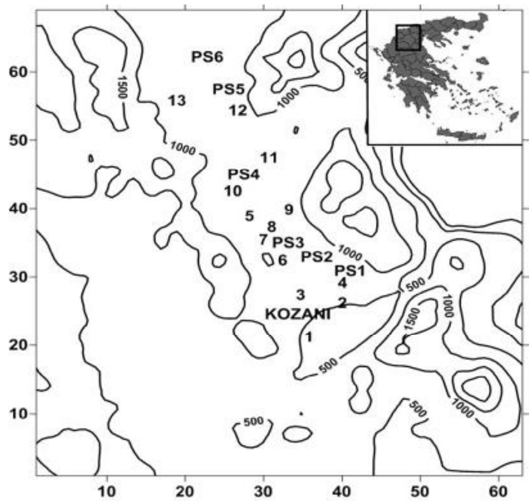

Figure 1. The study area. Measuring stations (1, 2, 3,…, 13) and power plants sites (PS1, PS2,…, PS6)

RESULTS

The definition of the exact time period of the episode is not a straightforward task, due to the diversity of the measuring sites. Daily PM10 mean values from November of 2006 to November of 2009 are used to calculate the November PM10 threshold daily value of the upper 25% of the distribution, for each measuring site. Any day with mean PM10 value exceeding this value is considered to be part of the episode.

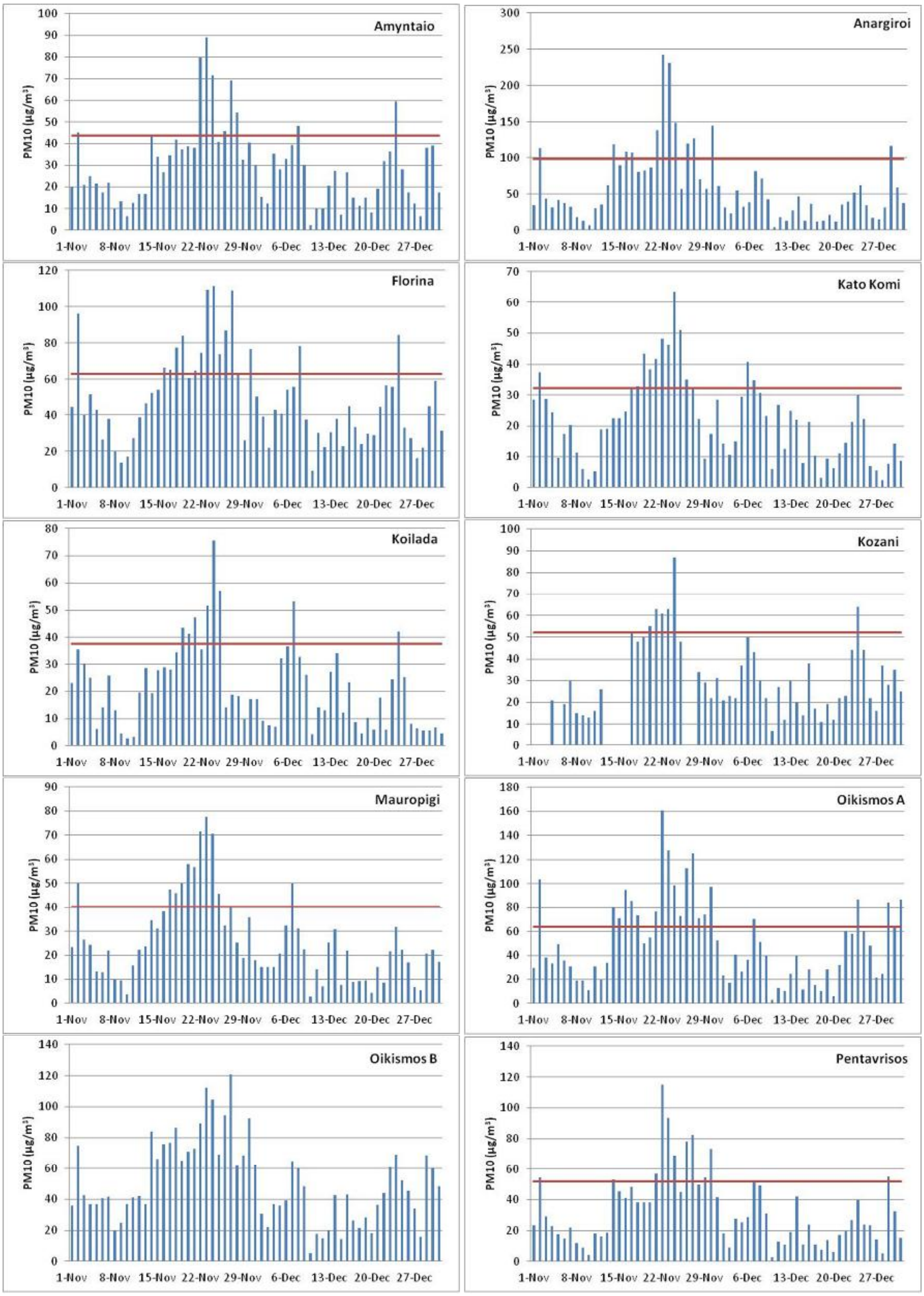

Figure 2. Daily PM10 concentration values, for all the available measuring stations. The red line indicates the PM10 threshold daily value of the upper 25% of the distribution

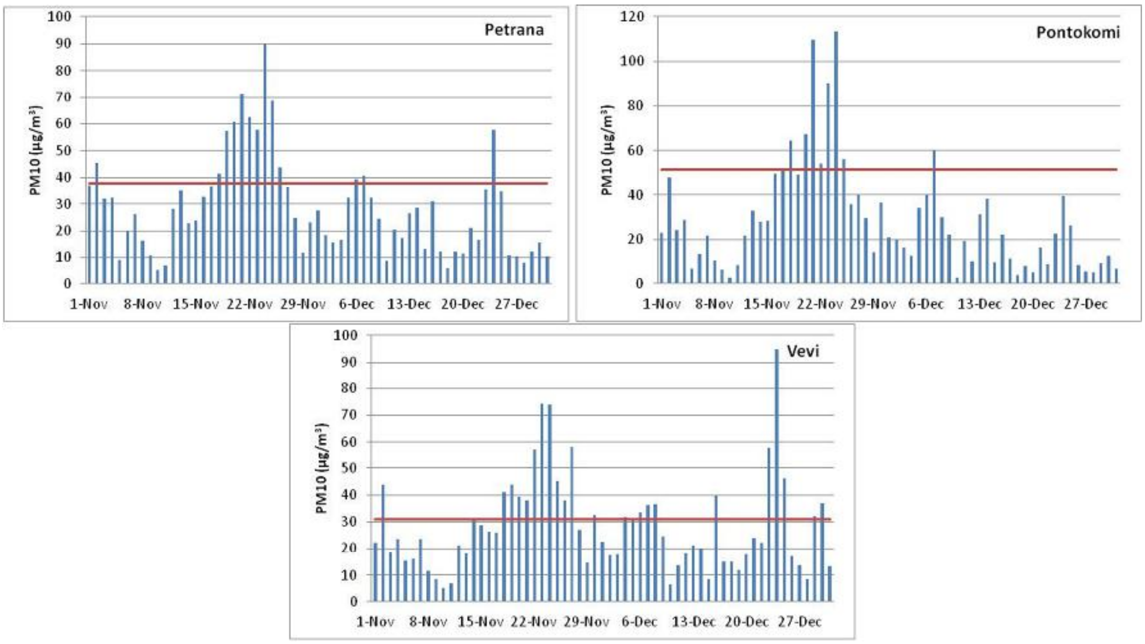

Figure 2 (continued). Daily PM10 concentration values, for all the available measuring stations. The red line indicates the PM10 threshold daily value of the upper 25% of the distribution

The studied episode starts at the 14th of November for some of the stations and ends after the 25th, showing a peak between the 22nd and the 24th of November. The exact length depends on the measuring station. This is illustrated in Figure 2, where the time evolution of the daily average PM10 concentration for all the measuring sites is depicted. The threshold value of the upper 25% of the distribution is also shown as a continuous horizontal line (daily values for the station of Oikismos B for the period 2006-2009 were not available). In order to avoid falsely excluding part of the episode, it is considered to extend from the 14th to the end of November of 2009.

The synoptic setting over the examined area is investigated based on MSLP and 500hPa synoptic charts. Southern Europe is dominated by an Omega block (Huschke 1959, Karacostas et al. 2006) from 17/11 to 20/11 as it can be seen in Figures 3a and 3b. During the 21st and 22nd the Omega block gradually transforms to a high-over-low pattern (Figure 3c) that lasts until the night of the 23rd of November. At the afternoon of the 24th (Figure 3d) a short wave embedded on the almost stagnant long wave passes over Western Macedonia and reinforces temporarily the surface wind field. Another short wave passes over the area during the afternoon of the 28th (Figure 3e) causing light rainfall. A trough associated to a deep depression, approaches Greece during the 1st of December (Figure 3f) establishing a strong southeasterly flow and producing significant rainfall in western Macedonia during the 1st and 2nd of December.

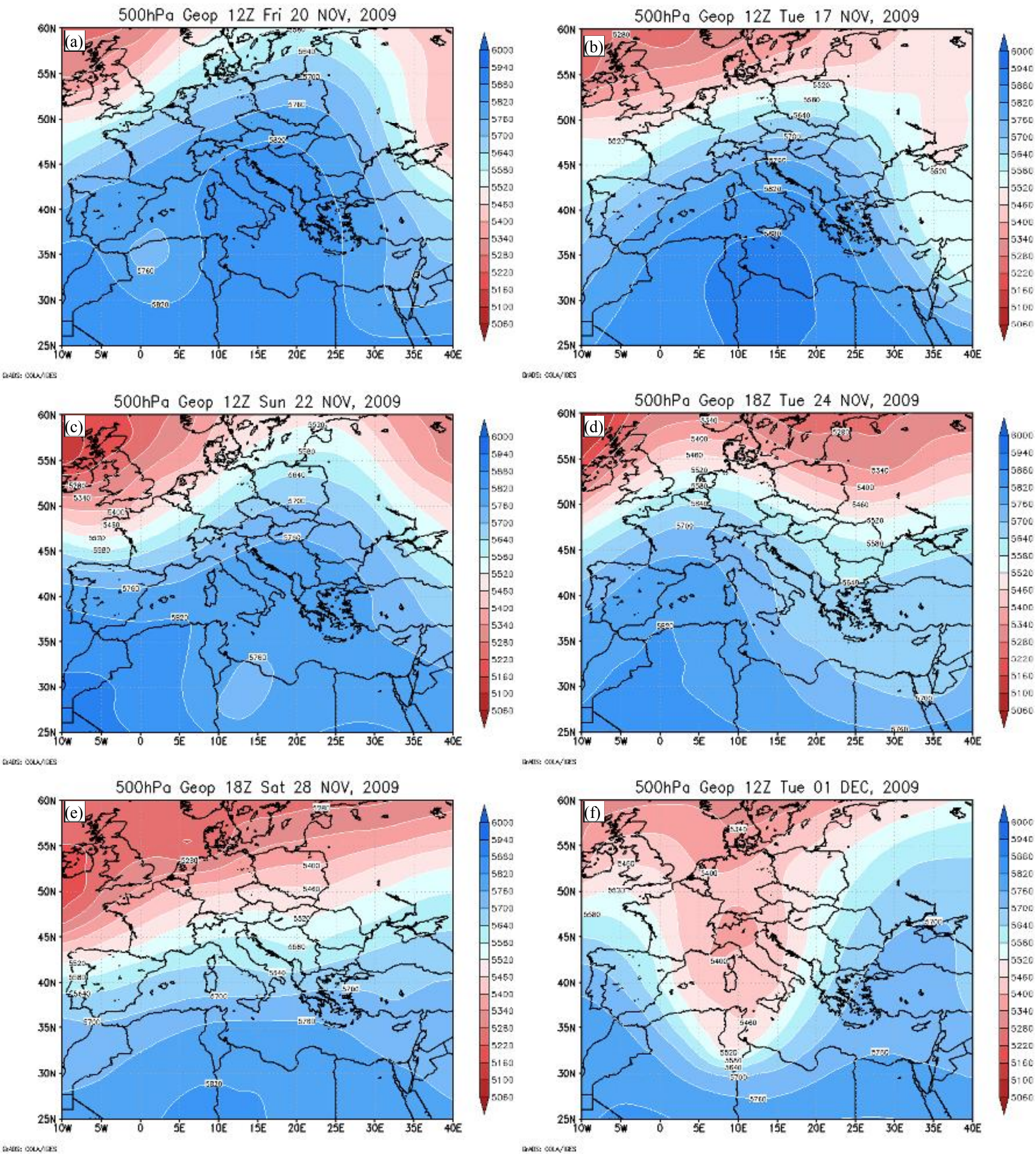

Figure 3. Geopotential height (in gpm) at the 500 hPa level during significant time instances of the episode

Due to the Omega block that dominates the area, MSLP and therefore the associated surface wind field, is quite weak (Figure 4a), strengthening during the passing of the first short wave on the 25th of November (Figure 4b). The horizontal wind field in the lower troposphere weakens again during the 26th of November (Figure 4c) and strengthens again due to the second short wave of the 28th (Figure 4d). The approach of the trough preserves the strong surface horizontal wind (Figure 4e) until the first days of December when the depression reaches the examined area (Figure 4f).

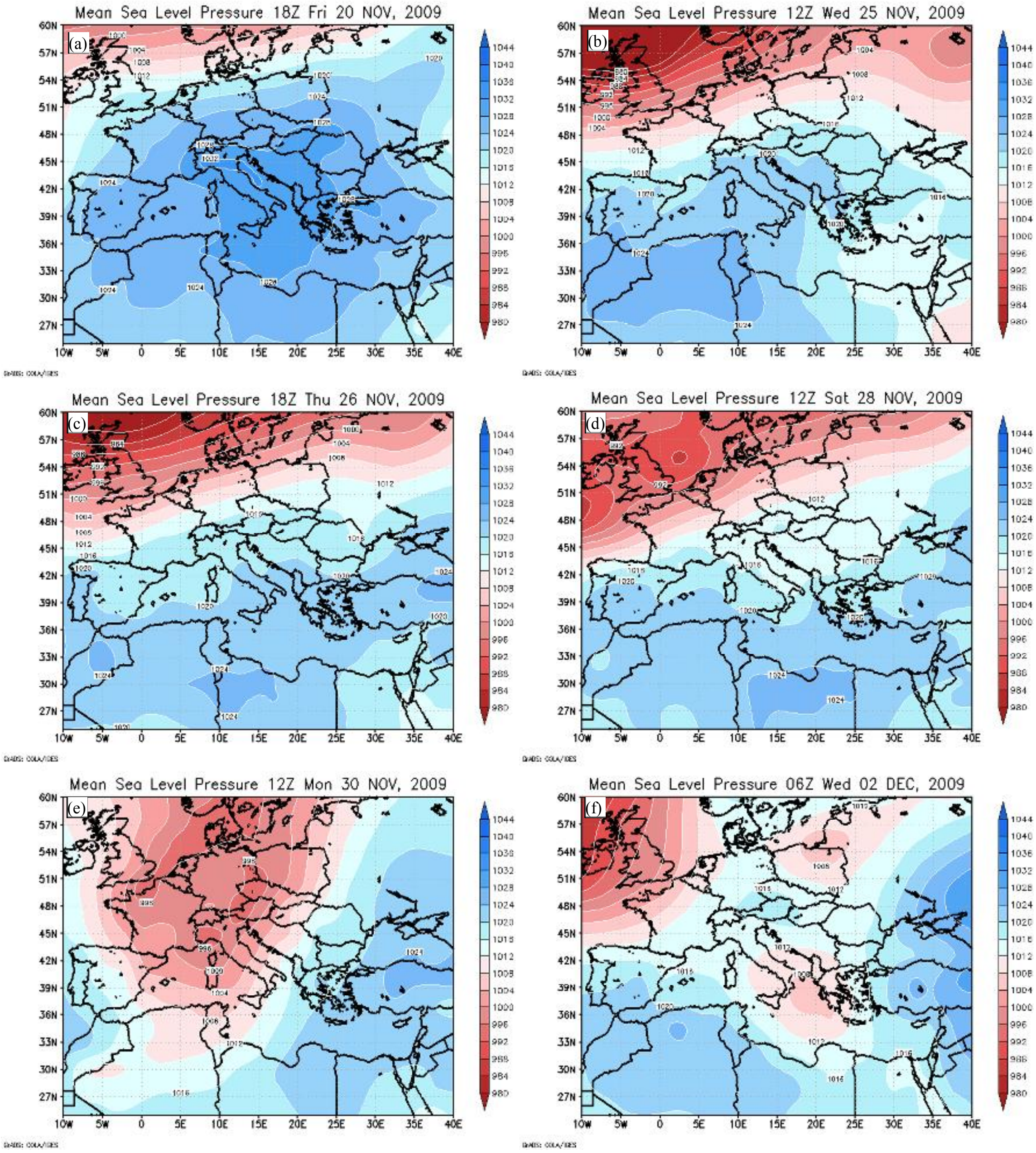

Figure 4. MSLP (in hPa) during significant time instances of the episode

The significant strengthening of the horizontal surface wind field, directly associated to the passing of the two shortwaves, is confirmed by the model's outputs, as can be seen in the Figure 5. During days of week synoptic surface pressure field like the 22th of November (Figure 5a and 5b), the horizontal surface wind is also very week and is formulated mainly by the local circulation patterns. The passing of the upper air shortwaves on the 25th and the 28th of November increases significantly the surface wind speed and homogenizes the surface wind direction (Figures 5c and 5d respectively).

Lack of significant synoptic forcing during the days of the episode is revealed through the investigation of the omega vertical velocity in the pressure level of 700 hPa. As can be seen in Figure 6a the area is dominated by week vertical motions that are usually less than 10 hPa h^{-1}, even in the warm hours of the day. The passing of the first short wave during the afternoon of the 24th does not change the situation significantly (Figure 6b), but the shortwave of the 28th strengthens the vertical motions (Figure 6c), resulting in light rainfall. The vertical wind field weakens again during the following hours (Figure 6d), until the arrival of the depression during the first days of December when increased vertical wind velocity is recorded in the area (Figure 6e).

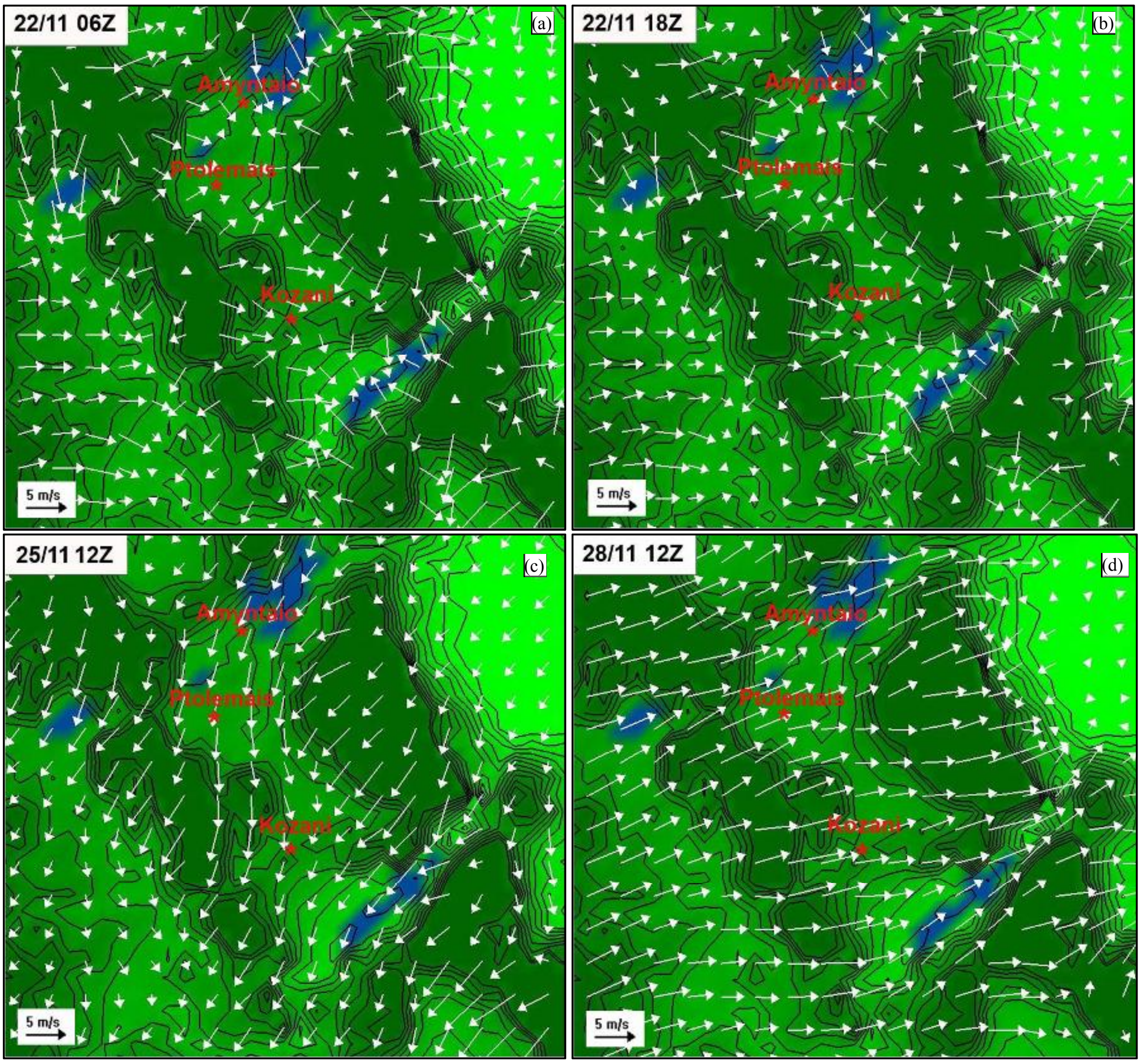

Figure 5. Surface wind field simulations during significant time instances of the episode

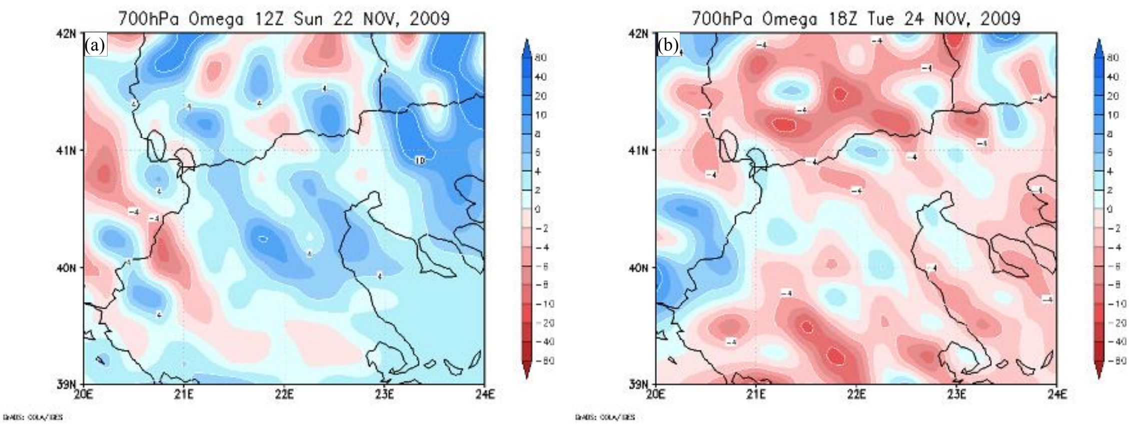

Figure 6. The vertical velocity field (in hPa h^{-1}) during significant time instances of the episode

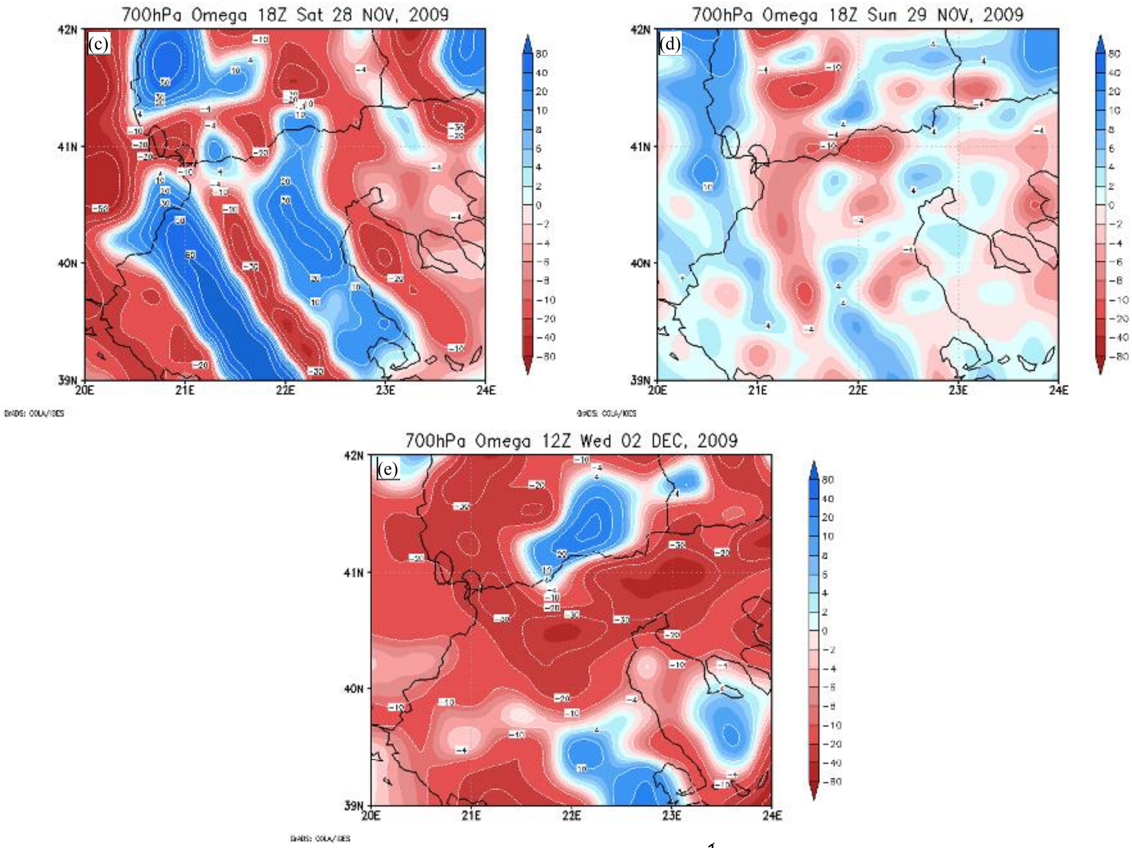

Figure 6 (continued). The vertical velocity field (in hPa h^{-1}) during significant time instances of the episode

An almost constant increase of PM10 and PM2.5 concentrations is recorded as the surface wind remains weak. During the 25th of November when the wind field strengthens temporarily, PM10 values at Pentavrisos drop significantly. The same pattern appears after the 28th of November when the wind field presents another significant increase (Figure 7a). An analogous decrease of PM2.5 concentrations values is recorded at Oikismos A, following the significant strengthening of surface wind after the 27th of November (Figure 7b).

Hourly mixing height values are calculated by TAPM at various sites. Figure 8 shows the diurnal variation of this parameter from 15th to 30th of November at Pentavrisos and Oikismos A. Low mixing height values are recorded during most hours of the days, increasing only around midday. Moreover, a gradual decrease of the top of the mixing height until 22nd of November is recorded. Another significant feature is the increased mixing height during the last hours of the 25th and the first ones of the 26th of November, that may be partially associated to the intensified vertical motions in the area.

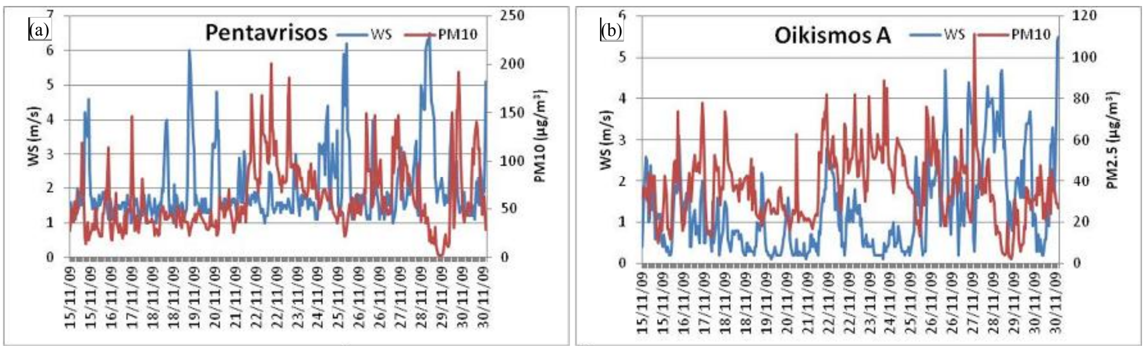

Figure 7. (a) Wind speed (m s^{-1}) and PM10 (μg m^{-3}) hourly values at Pentavrisos (Fig.1, measuring station 9) and, (b) Wind speed (m s^{-1}) and PM2.5 (μg m^{-3}) hourly values at Oikismos (Fig.1, measuring station 7) from 15th to 30th of November

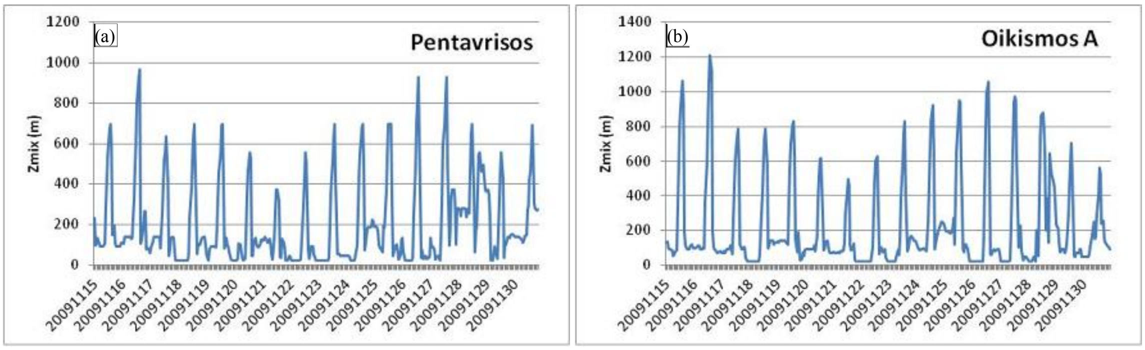

Figure 8. Mixing Height (m) hourly values at (a) Pentavrisos and (b) Oikismos A from 15th to 30th of November

The examination of the diurnal variation of the potential temperature vertical profiles produced by TAPM shows a strong surface temperature inversion existing during late afternoon, night and morning hours during most of the days of the episode. Figure 9 presents as examples the vertical profiles of potential temperature at Pentavrisos and Oikismos A stations, on the 21st of November, just before the peak days of the episode. As can be seen, the base of the inversion is lifted only around the warm hours of the day and in some cases a shallow convective boundary layer is formed. In general, it was found that the diurnal variation of the bottom of the inversion follows a pattern similar to that of the mixing height. It becomes evident that pollutants are practically trapped in the lower boundary layer.

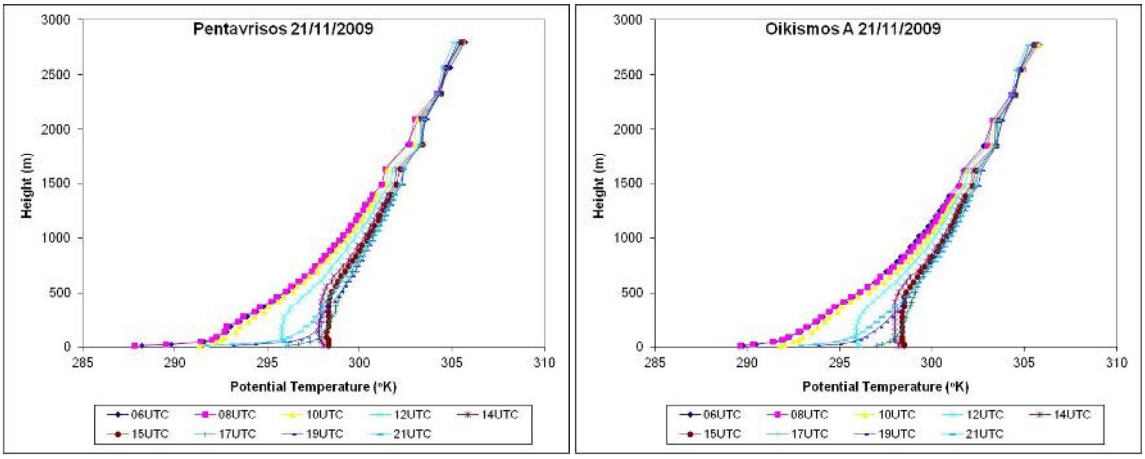

Figure 9. Vertical profiles of potential temperature at Pentavrisos and Oikimsos A

Finally, sounding data of the nearest station (Macedonia airport, Thessaloniki) were acquired from the University of Wyoming. Four of the most common and scientifically acknowledged indices (TTI, LI, SI and KI) were examined for the period from 14/11 to 3/12. Figure 10 presents the time evolution of these indices during this period. Relative stability is evident during the episode period, confirming the lack of significant synoptic forcing in the area. The only exception is an indication of week instability on the 24th and 25th expressed by the increased values of TTI. After the 29th of November the instability increases significantly due to the passing of the second shortwave and the arrival of the depression at the first days of December.

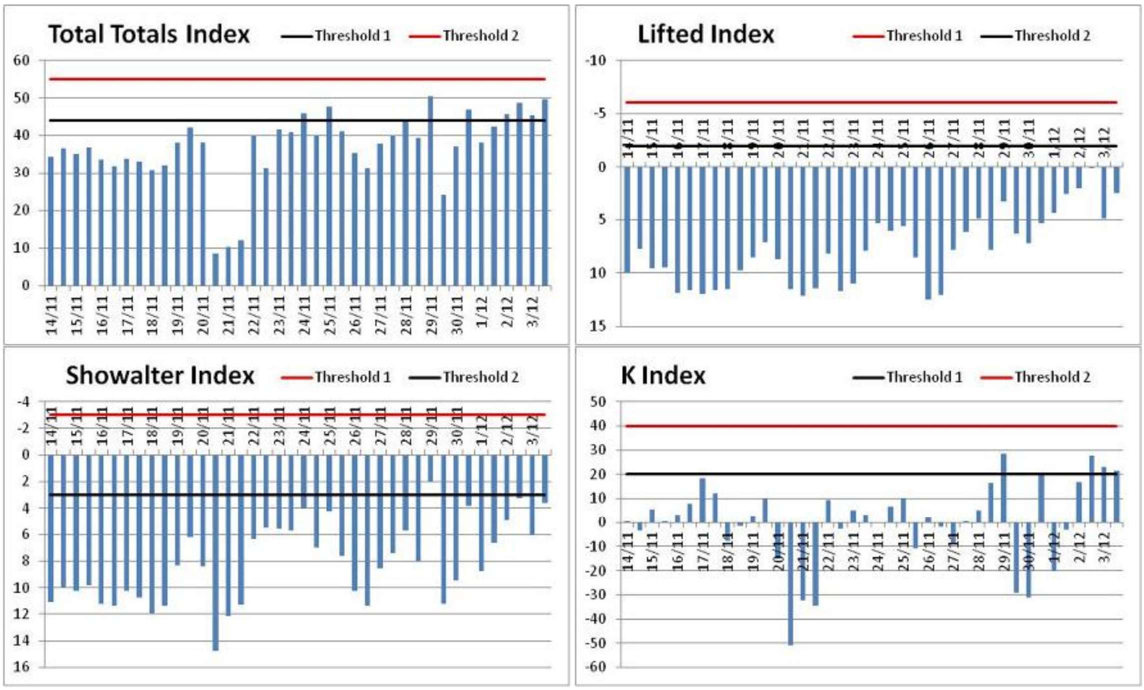

Figure 10. Time evolution of the four examined stability indices.
The black and red lines illustrate the threshold values of each index.
The vertical axis values are in reverse order for the two indices (LI and SI)
where instability increases with the decrease of the index values

CONCLUSIONS

The evaluation and synthesis of the results presented in the previous section can be summarized in the following:

- The airborne particulate matter intensive pollution episode that was recorded in the BAPK during the last 15 days of November 2009 is the result of the synoptic setting that prevailed in the middle and lower troposphere. An Omega block followed by a high-over-low pattern in the southern Europe formed such a boundary layer structure in the area of interest, which favored high PM10 and PM2.5 concentrations.
- A ground based temperature inversion persisted during most of the days, except the warm hours of the day, when a shallow convective layer was developed. The lack of significant synoptic forcing allowed the lingering of the pollutants inside the boundary layer.
- The wind field in the surface and lower troposphere was very weak and assisted the trapping of pollutants in the lowest part of the boundary layer increasing the airborne particulate matter concentrations values.
- The PM10 and PM2.5 values are associated to the mixing height variation in the area, during the episode period.
- The change of the synoptic setting during the last days of the episode caused the development of significant synoptic forcing and the strengthening of the horizontal wind field near the surface, resulting in a significant decrease of PM10 and PM2.5 concentration. The rainfall that followed marked the end of the episode.

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