

A case of nighttime high ozone concentration over the greater Athens area

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Abstract

A case of abrupt and significant increase of surface ozone was examined, which is recorded during the night of October 9th, 2003, over the area of the Thriassion Plain – Greece, being accompanied by the occurrence of a wind outbreak during the same period. As this increase cannot be explained by the ordinary diurnal evolution of tropospheric ozone concentration, the possibility of downward stratospheric ozone transport was investigated. It was indeed found that the case is associated with tropopause folding and subsequent stratospheric air intrusion in the upper troposphere over Greece. With the aid of mesoscale modeling, being also supported by the hydraulic theory, it was found that the intense wind outbreak is associated with the development of disturbances in the lee side of the neighbouring mountain ranges. These disturbances contribute to the free troposphere – atmospheric boundary layer interaction, facilitating the transportation of stratospheric air close to the surface, thus resulting to the observed tropospheric ozone increase.

Zusammenfassung

Diese Arbeit analysiert die plötzliche und signifikante Zunahme der bodennahen Ozonmischungsverhältnisse bei gleichzeitigem Auftreten eines Sturms im Gebiet der Thriassion-Ebene (Griechenland, nahe Athen) in der Nacht vom 8. auf den 9. Oktober 2003. Da diese Zunahme des bodennahen Ozons nicht durch den üblichen Ozon-Tagesgang erklärt werden kann, wurde untersucht, ob ein Ozon-Transport aus der Stratosphäre möglich war. Tatsächlich wurde in diesem Zeitraum ein Einfalten der Tropopause mit nachfolgendem Eindringen stratosphärischer Luft in die obere Troposphäre über Griechenland gefunden. Mit Hilfe von mesoskaligen Modellrechnungen, unterstützt durch die Aussagen der hydraulischen Theorie kann man zu der Schlussfolgerung kommen, dass der intensive Windausbruch mit der Entwicklung von Wellen im Lee der benachbarten Gebirgszüge verbunden ist (Durrán, 1990). Diese tragen zur gegenseitigen Beeinflussung der freien Troposphäre mit der obersten atmosphärischen Grenzschicht bei und ermöglichen einen Transport von stratosphärischer Luft bis zur Oberfläche. Das wiederum führt zur Erhöhung der troposphärischen Ozonmischungsverhältnisse.

1 Introduction

The Greater Athens Area (GAA) is situated in a small peninsula in the south-eastern edge of the Greek mainland. Like other densely populated areas, it is a region of well-known air pollution problems, mostly photochemical. The central part of the GAA is the Athens Basin, while Thriassion Plain is located in the north-west, at a distance of 20 km with a total population of 78000 inhabitants (Figure 1). Air pollution in the Thriassion Plain is related with industrial activities as well as traffic.

Thriassion Plain is a closed basin, with a gentle slope towards the sea, not exceeding 3 %, being surrounded by mountains (see Figure 1): Parnis mountain (1413 m,

indicated by number 5) in the north, Geraneia mountain (1351 m, number 1) in the west-southwest, Pateras mountain (1191 m, number 2) in the west and Pas-tra mountain (1016 m, number 4) northwest, while it is open to the sea from the south (Elefsis Gulf). There is an exit to the north and two exits to the east, leading to the Athens Basin. Thriassion Plain extends in 15 km along the sea, while 12 km of the coastline is covered by industrial and harbour activities, where the main national highway towards southern Greece extends. The presence of mountains, in close proximity with the sea, produces local atmospheric circulation patterns that greatly affect the spatial distribution of ozone in the Thriassion Plain (LALAS et al., 1983; ASIMAKOPOULOS et al., 1992; HELMIS et al., 1995; HELMIS et al., 1997; GROSSI et al., 2000). More specifically, during the daytime two sea breeze cells form, the Saronicos and Elefsis gulf cells, that penetrate inland carrying polluted air

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Table 1: The stations of Thriassion Plain used in the study with topographical details. Also the measured parameters are summarised (WD = wind direction, WS = wind speed, P = atmospheric pressure, T = air temperature, Td = dew point, RH=relative humidity).

Station Abbreviation	Location	Distance from seashore (m)	Altitude (m)	Measured parameters
EL-1	Elefsis (city-centre)	1000	20	O ₃ , WS, WD
EL-2	Elefsis (peripheral)	1600	20	O ₃ , WS, WD
EKM	Mandra	600	50	O ₃ , WS, WD
P.As	Paralia Aspropyrgou	400	5	O ₃ , WS, WD
MAG	Magoula	5000	100	O ₃ , WS, WD
LGEL	Elefsis Airport	2000	30	WS, WD, P, T, Td, RH

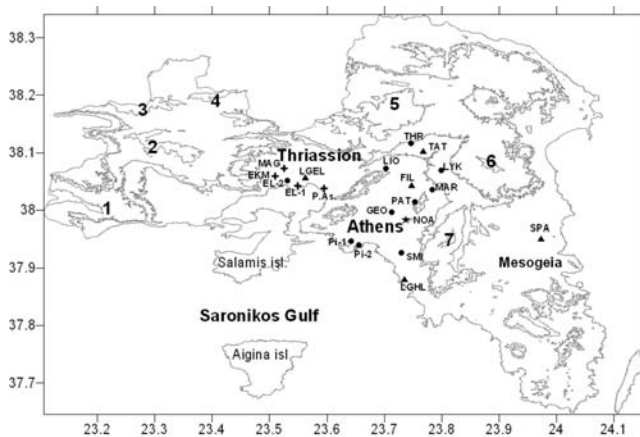


Figure 1: Topographical map of Attica - Greece, showing the Thriassion Plain and Athens Basin locations. The surrounding mountains are indicated by numbers: 1 represents Geraneia Mt; 2: Pateras Mt; 3: Kithaironas Mt; 4: Pastra Mt; 5: Parnis Mt; 6: Penteli Mt and 7: Hymettos Mt. The locations of the stations mentioned in the text are also displayed. The stations operated by the Bureau of Pollution Control and Environmental Quality are indicated by a cross, the stations operated by the Ministry of Environment are indicated by a dot, the stations operated by the Hellenic National Meteorological Service and the station NOA operated by the National Observatory of Athens is indicated by a star.

masses from the Athens Basin and the Thriassion Plain, respectively, northwards. The two cells converge in the foothill of Parnis mountain (number 5, see Figure 1), where high ozone concentrations are found. These polluted air masses are advected by the upslope flow and fed the re-circulation current of the sea breeze aloft towards the sea. In addition, during the nighttime, the land breeze advects the polluted masses offshore back to the sea, forming a reservoir ozone layer over the Saronikos gulf, that plays an important role in the above mentioned ozone distribution on the following day over the GAA under sea breeze conditions.

Although surface ozone concentrations have increased in Mediterranean urban areas, due to emissions of ozone precursors, the contribution of horizontal and vertical transport of ozone is also significant. Ozone plumes can travel long distances over the Mediterranean Sea in the lower troposphere and affect the air quality in urban remote locations in a time scale of 2–3 days (KALLOS et al., 2007). A main path of this transport reaches Greater Athens Area, starting from southern Italy and Sicily.

The stratosphere-troposphere exchange is an important process that controls the budget of ozone in the troposphere through its vertical transport (BONASONI et al., 2000; ZANIS et al., 2003a). Stratospheric intrusions occur during tropopause folding, being characterized by tongues of very dry and anomalously high potential vorticity (PV) air, extending equatorward (ZANIS et al., 2003a and 2003b; HSU et al., 2005; GERASOPOULOS et al., 2006; CRISTOFANELLI et al., 2009). Under deep and intense intrusions, this ozone rich stratospheric air descends into the middle troposphere and can reach the lower levels, even the ground, via turbulent mixing, causing composition changes of the tropospheric air and ozone episodes (DAVIES and SCHUEPBACH, 1994; STOHL et al., 2000; GHEUSI and CAMMAS, 2004).

A case of an abrupt nocturnal increase of ozone occurred on the 9th of October 2003, in the Thriassion Plain, which was accompanied by an intense windstorm along the lee side of the mountains. Since this increase cannot be explained by the ordinary diurnal evolution of tropospheric ozone concentration, in this study, an attempt is made to investigate this case and to further interpret the nighttime ozone increase in relation to the downward transport of stratospheric ozone within the troposphere, being supported by the formation of lee disturbances near the ground.

Table 2: Summary of the horizontal and vertical grid configuration parameters for the three RAMS grids. The model parameters include the number of grid points in the three directions (nx, ny, nz), the horizontal grid spacing (dx,dy) and the minimum and maximum vertical resolutions (dzmin and dzmax).

Grid	nx	ny	nz	dx, dy (km)	dzmin (m)	dzmax (m)
1	128	86	30	36	48	1000
2	122	114	30	9	48	1000
3	95	86	30	3	48	1000

2 Data

The ozone data used in this study were obtained from: a) four stations in the Thriassion Plain (EL-1, EKM, P.As, MAG) – operated by the Bureau of Pollution Control and Environmental Quality (GERPPE) of the Development Association of Thriassion Plain – providing 10 minutes data and b) one station (EL-2), providing hourly data under the responsibility of the Ministry of the Environment. Details on these stations are presented in Table 1.

More specifically, EL-1 station is located at Elefsis city center, inside the municipal parking area, away from large constructions. Station EKM operates near the large housing complexes of Mandra, neighboring the Industrial Zone of Elefsis to the south and the Industrial Zone of Mandra to the north-northeast while station MAG lies in the center of the urban area of Magoula. P.As is located in the center of Paralia Aspropyrgos, surrounded by a legislated industrial area of 3000 acres housing some large heavy industry units. Finally, station EL-2 is located at a distance of 600 m northwest of EL-1 station and 400 m of a main interchange of the new Athens-Korinthos National Highway.

Additionally, in this study ozone concentrations are employed from 20 monitoring stations in the Athens Basin, operated by the Ministry of Environment. All air monitoring stations provide measurements of wind speed and direction at 10 m. Meteorological data were obtained from the stations at Elefsis airport (LGEL), National Observatory of Athens at Thission (NOA) and Hellenikon (LGHL), including wind speed and direction, air temperature, relative humidity and pressure every 30 min. Supplementary, wind data from the other meteorological stations of the Greater Athens Area Filadelfia (FIL), Tatoi (TAT) and Spata (SPA) were employed. Except of NOA, the other meteorological stations are operated by the Hellenic National Meteorological Service. The location of all above mentioned stations is displayed in Figure 1.

Radiosonde data from Hellenikon (LGHL) (see Figure 1) were used at 02:00 and 14:00 LST (Local Standard Time) for the examined period. The surface charts along with their frontal analysis are obtained from the UK Meteorological Office (www.weathercharts.org). Daily maps of total ozone and deviation from the climatological mean were obtained from the Ozone Mapping Centre of WMO website (<http://lap.phys.auth.gr/>

ozonemaps). The PV plots and vertical cross sections were constructed with the aid of ECMWF ERA-Interim data. Backward trajectories were calculated with the aid of the HYSPLIT model (DRAXLER, 2003) at 3000 and 5000 m above the ground, up to 5 days before the case study.

3 Model simulations

In order to investigate the synoptic-scale and meso-scale circulation over the examined area, the Regional Atmospheric Modeling System (RAMS-6.0) was employed (PIELKE et al., 1992). The system allows simulations of the atmospheric processes on the scales of a few tens of meters to several thousands of kilometers. COTTON et al. (2003) provide an overview of the model's current status, focusing on new developments in the RAMS physics and computational algorithms since 1992.

For the examined case study, a 24-hour simulation was performed starting at 14:00 LST, on the 8th of October 2003, with a time step of 40 sec. The RAMS model was run on three nested grids with a horizontal grid spacing of 36, 9 and 3 km (Fig. 2) and used a stretched vertical coordinate (30 levels) from 48 m near the ground up to 18.5 km at the top of the domain. A summary of the horizontal and vertical grid parameters is provided in Table 2. The physical parameterization schemes used in the model simulation included the microphysics scheme, following WALKO et al. (1995) and MEYERS et al. (1997), the modified Kuo cumulus parameterization scheme (TREMBACK, 1990), the CHEN and COTTON (1983) radiation scheme and a 10-layer soil/vegetation/snow parameterization-LEAF-3 (WALKO et al., 2000). The convective parameterization scheme was run on the outer grid, while in the inner grids 2 and 3 explicit convection only were utilized only. In addition, the mixed phase microphysics scheme was run on all three grids.

The ECMWF (European Center of Medium Range Weather Forecasts) 0.5° gridded objective analysis fields were used for initial and lateral boundary conditions, every 6 hours intervals for the whole length of the simulation. Average monthly 1°-gridded sea-surface temperature data set (SST) was used for the water body, whereas the topography used for all grids derived from 30" resolution terrain data (USGS data set). Finally, gridded vegetation type data of 30" resolution was used to derive vegetation cover at each grid cell.

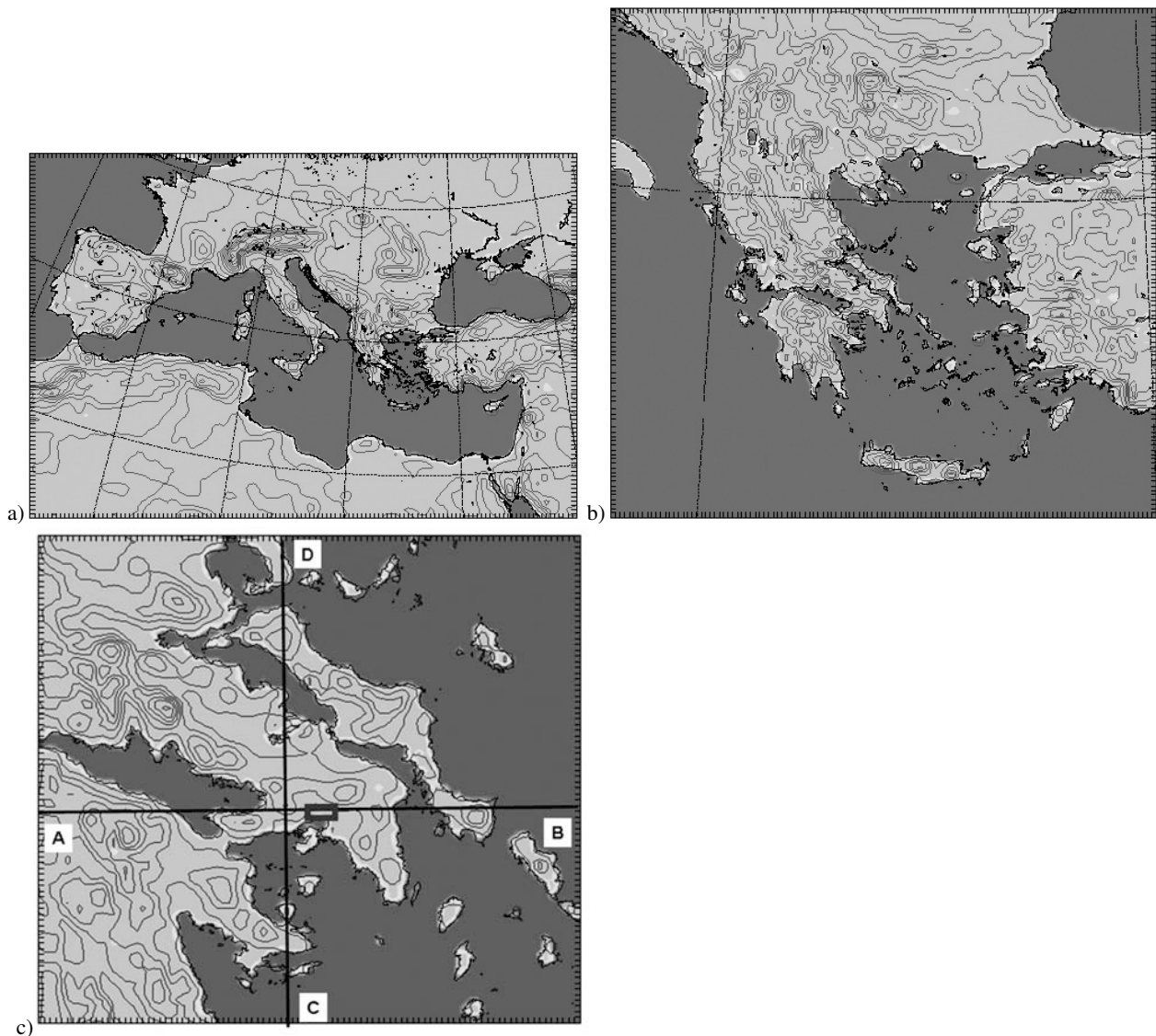


Figure 2: Figure 2: Areas covered by the three nested grids used for the model simulation: a) the outer grid with 36 km horizontal grid spacing, b) the second with 9 km horizontal grid spacing and c) the third grid with 3 km horizontal grid spacing. The lines AB and CD indicate the axes where vertical cross sections are taken. The examined area of Thriassion plain is represented by the square.

4 Meteorological analysis

On the 9th of October 2003 at 02:00 LST an upper level deep trough extends from Scandinavia southwards to Eastern Mediterranean (Figure 3a). The polar front jet is situated on the western flank of the trough. This synoptic situation results in strong westerly flow over Greece. At the surface, a cold front is observed over southern Greece, which has just passed over the Greater Athens Area, establishing synoptic-scale northwesterly winds of 5–6 m/s (Figure 3b). The passage of the cold front was associated with weak rainfall in the Thriassion Plain from 19:50 to 20:50 LST, on the 8th of October, without any convective activity and lightning, as was recorded at LGEL.

At about 01:00 LST, the wind suddenly shifted to the northwesterly/northerly sector (Figure 4a) and intensi-

fied remarkably at all stations of Thriassion (see Figure 4b). It is characteristic that gust winds of 29 m/s and 22.1 m/s were observed at LGEL and EL-1, respectively, at 02:20 LST. As can be seen in Figure 4b, the wind increase is mostly evident at these stations because they are located at a plain and open area, while the wind intensity was lower at the stations EKM and MAG which are located near the foot of the mountains, peaking at 13.4 and 12.4 m/s, respectively. Station P.As (not shown in Figure 4b) was the least influenced by the windstorm, since it is surrounded by large industrial units. At the same time the wind gust was accompanied by a sudden drop of the atmospheric pressure (see Figure 4b). The windstorm lasted until 06:20 LST, with another peak at around 04:30 LST (Figure 4b).

Exceptionally high winds were also reported at the stations of LGHL (northwesterly winds of 16 m/s at

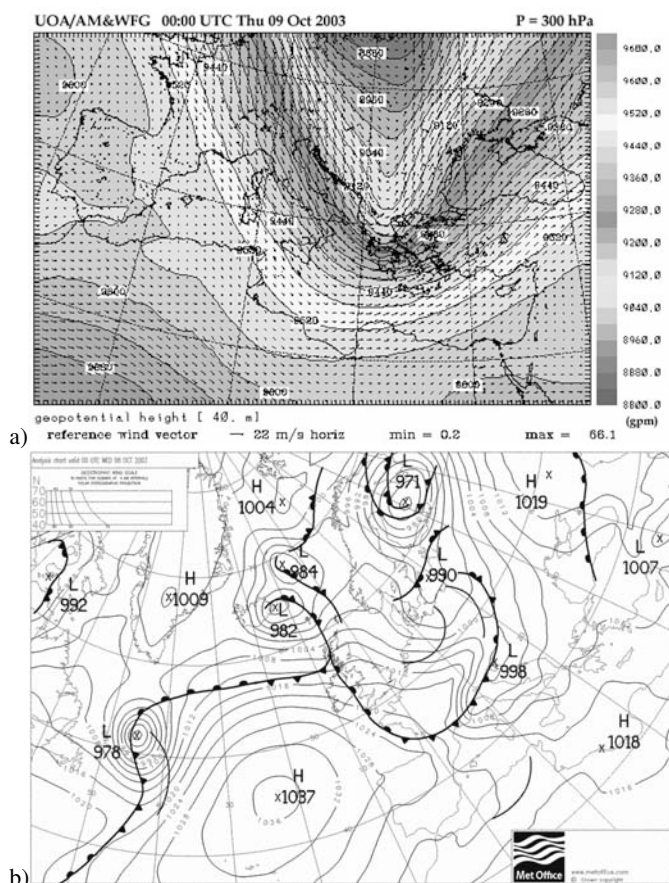


Figure 3: Analysis on the 9th of October 2003 at 02:00 LST of: a) geopotential height in color (at 40 gpm intervals) and wind field (vectors) at 300 hPa isobaric surface (as derived from RAMS model), b) mean sea level pressure along with frontal analysis (source: www.weathercharts.or).

02:00 LST) and NOA (westerly winds of 16.8 m/s at 02:00 LST). The sounding at LGHL at 02:00 LST has also verified the high surface winds that increase with height, appearing a localized peak of 30 m/s, at the level of 850 hPa (see Figure 4c). On the contrary, the wind speed was ranging at very low levels, 2–3 m/s at the other meteorological stations of the Greater Athens Area (not shown). Therefore, it is indicated that the windstorm moved southeastwards, influencing the Saronic coast and the Athens Basin.

5 Development of downstream disturbances

The intensity and duration of the windstorm during the nighttime drove our research towards the development of strong downslope winds that occurred in the lee side of Pateras mountain (number 2 in Figure 1) in the western part of the Thriassion Plain (see Figure 1a). DURAN (1990) has found that under certain wind and temperature profiles in the upstream side of a mountain, the low level accelerated flow rebounds downstream

through a turbulent jump, that is characterized by very intense downdrafts and horizontal winds, which become noticeable at the ground. In our case, this is supported by the westerly component of the background flow that is normal to the barrier and the intense wind speed (of 24 m/s) at the height of 990 m that represents the top of the mountain ranges.

Furthermore, following the hydraulic theory, the diagram of the non-dimensional mountain height versus the upstream Froude number provides a classification scheme of the form of the downstream disturbances, according to the upstream atmospheric profiles (HELMIS et al., 2000). In our case, the upstream profile of temperature and wind, as obtained from the RAMS model simulations on 9 October 2003, 02:00 LST at the nearest grid point at the ground, demonstrated the formation of a height inversion layer, with cross mountain component wind speed of $U = 19$ m/s, leading to an estimation of the depth of the stable layer of 3000 m, with corresponding stability of 0.0113 s^{-1} . Therefore, the value of non-dimensional mountain height is 0.66 and of the Froude number 0.79, being attributed to the regime II of the diagram, suggesting that the formation of a downstream disturbance, in the form of a jump, during the period of the windstorm that can propagate away from the mountain.

Indeed, the formation of intense downdrafts was verified in the model analysis. More specifically, the cross section of vertical velocity (Figure 5a) along the line CD (see Figure 2c) demonstrated that at 00:00 LST weak ascending motion is observed along the slope of mountain (not shown). In the following two hours (at 02:00 LST), intense descending motion appears to extend from the upper troposphere downwards to the top of the mountain, reaching the value of 3 m/s, and then downdrafts form along the slope, being characterized by lower values (Figure 5a). Similarly, the horizontal wind has intensified significantly between 00:00 and 02:00 LST (Figure 5b), reaching the value of 26 m/s at the top of the mountain and 14–16 m/s at the ground, near the foot of the mountain, which is consistent with observations at the stations EKM and MAG. Also, the model simulation revealed the southeastward propagation of these disturbances, as was stated in the previous paragraph, since the profile of vertical velocity at about the locations of EL-1, LGHL and Pi-1 (see Figure 1) was characterized by similar downdrafts in the first 1200 m above the ground, during the period 02:00–03:00 LST (not shown). This pattern is also consistent with the sounding at LGHL (see Figure 4c).

6 Analysis of surface ozone

The typical diurnal cycle of ozone under clear-air conditions indicates a maximum during the early afternoon due to photochemical production, a sharp decrease during the late afternoon as the stable nocturnal boundary layer develops while at night, a minimum value is

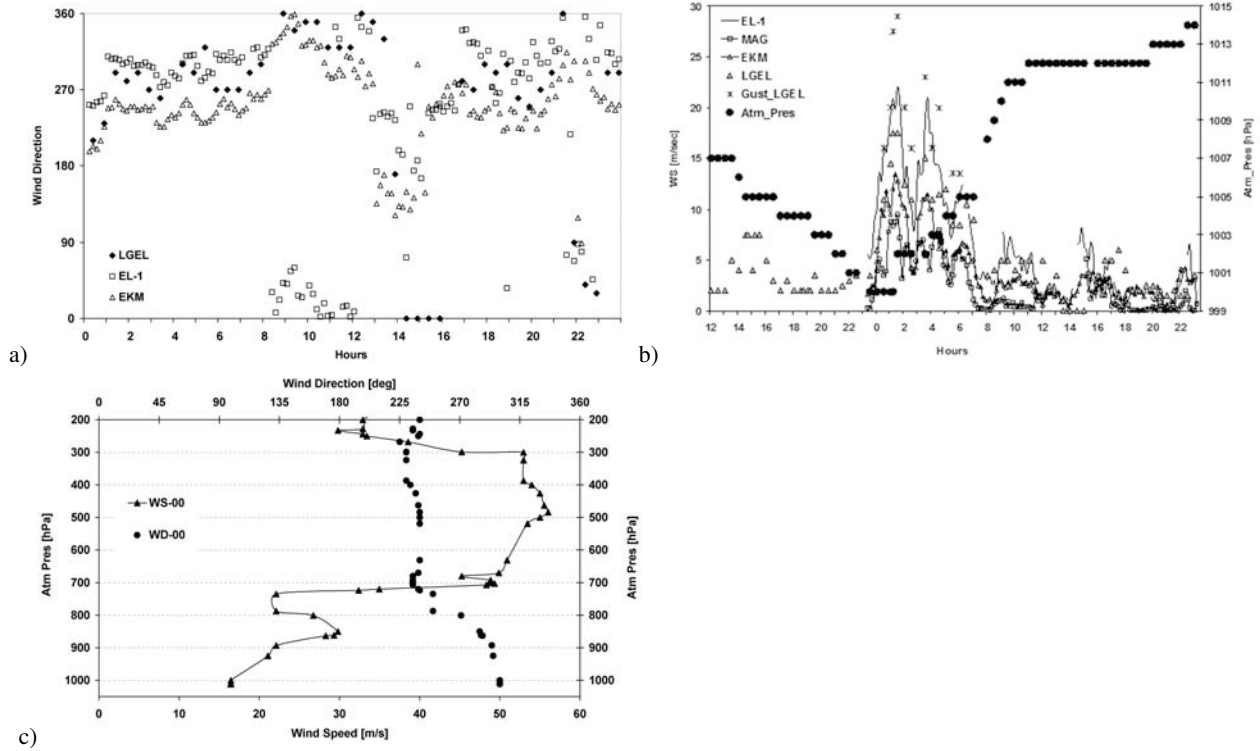


Figure 4: Variations from 12:00 LST (8 October) to 23:00 LST (9 October) at examined stations of: a) wind direction b) wind speed and atmospheric pressure at LGEL. The wind gusts at LGEL are also displayed from 00:00 to 06:00 LST. c) The sounding at LGHL at 02:00 LST of wind speed and wind direction.

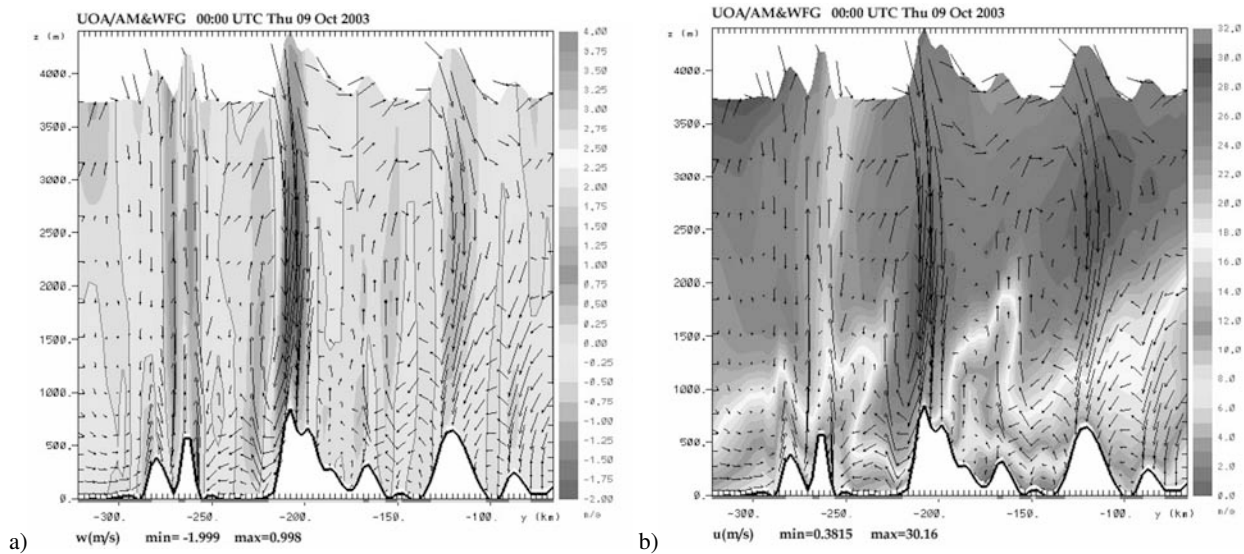


Figure 5: Vertical cross sections along the line CD shown in Figure 2c from the surface up to about 4000 m (as derived from RAMS model), on the 9th of October 2003, at 02:00 LST of: a) vertical component of wind (*w*) (at 0.25 m/s intervals) and wind field (vectors) and b) west-east axis (*u*) component of wind (at 1 m/s intervals) and wind field in arrows.

measured, due to deposition and chemical destruction (SEINFELD and PANDIS, 1998). Within the stable stratified nocturnal boundary layer the vertical ozone profile shows an increase from the surface to the top of the surface inversion. Above the inversion and within the residual layer the ozone concentration remains in-

creased, forming an ozone reservoir at a nearly constant level throughout the night (NEU et al., 1994).

Figure 6a presents the ozone evolution during the episode, at selected stations from 20:00 LST on the 8th of October to 22:00 LST on the 9th of October. While the daytime ozone peak on the 8th of October is of 60–

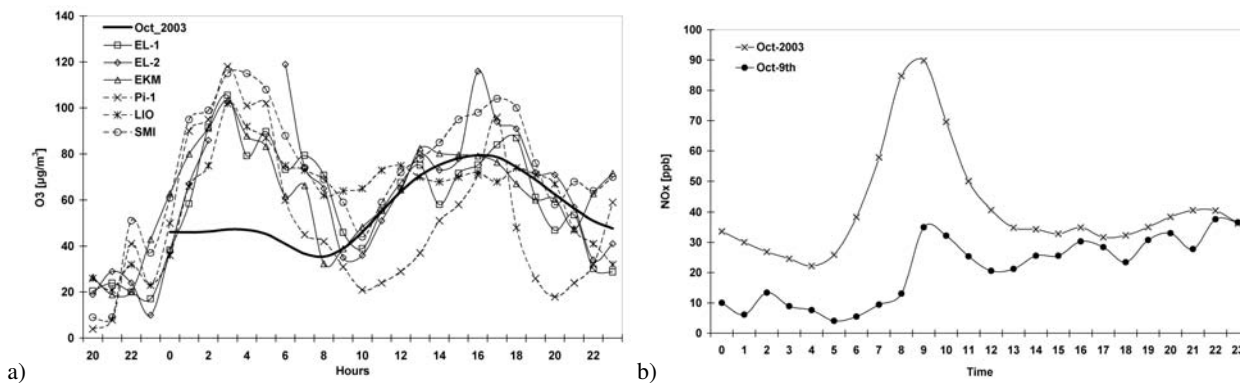


Figure 6: a) Ozone concentration variations from 20:00 LST (8 October) to 23:00 LST (9 October) at examined stations along with the October average hourly distribution of ozone over Thriassion for 2003. b) Hourly values of NO_x mixing ratio during the 9th of October averaged for all stations in the Thriassion Plain, along with the corresponding average distribution for October 2003. The time is LST.

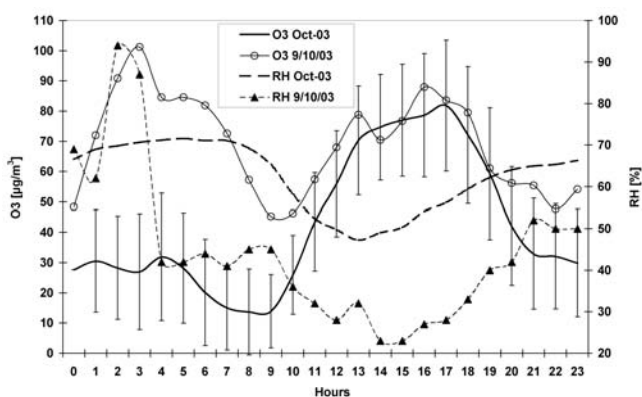


Figure 7: Hourly ozone concentration values at station EL-1 and relative humidity variation at station LGEL during October 9 2003, along with the corresponding average hourly distributions for October 2003. The bars represent the standard deviation of the mean hourly measurements of ozone concentration for October 2003.

70 $\mu\text{g}/\text{m}^3$ (not shown), during the windstorm episode and 30 min after maxima, the surface ozone concentration increased dramatically during the night at all stations of the Thriassion Plain and the Athens' stations along the path of the disturbance (EL-1, EL-2, MAG, EKM, Pi-1, Pi-2, SMI) up to 90–100 $\mu\text{g}/\text{m}^3$ (stations MAG and Pi-2 are not shown in Figure 6a). The peak values at EL-1, EL-2, MAG and EKM were as high as 109, 119, 97.4 and 108.1 $\mu\text{g}/\text{m}^3$, respectively, comparing well the daytime values. It is noteworthy that the corresponding mean hourly values at EL-1 station for October 2003 between 02:00 and 06:00 LST do not exceed the value of 30 $\mu\text{g}/\text{m}^3$ (see Figure 6a). These short lived spikes of ozone concentration during the night, equivalent or higher to peak values produced during the daytime, are not consistent with the above mentioned evolution of tropospheric ozone concentration.

The stations of the Athens Basin experienced similar behaviour during the examined period (see Figure 6a): at Pi-1, LIO, SMI the peak values were 118, 102 and

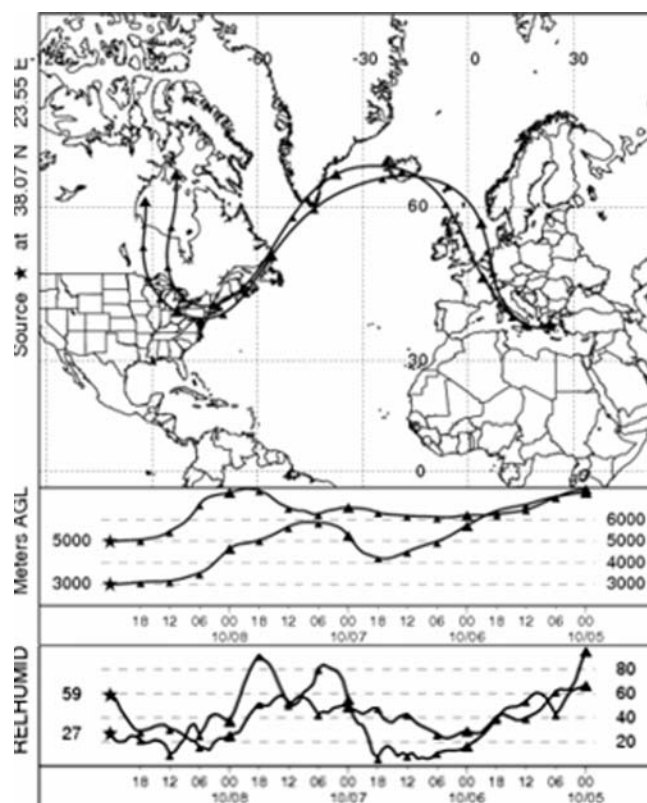


Figure 8: Backward trajectories starting from 00:00 UTC (02:00 LST) on the 5th of October 2003 ending to 00:00 UTC (02:00 LST) on 9th of October 2003, at the point LGEL (38,07 N and 23,55 E) at two heights in the troposphere 3000 and 5000 m above ground level, as derived by the HYSPLIT model. In the bottom, the 6 hours variation of relative humidity is presented for the two different heights. The presented hours are in UTC.

115 $\mu\text{g}/\text{m}^3$, respectively, while an unusually increase was also evident at stations with very low ozone values, such as PAT (not shown). However, this increase was not evident in the stations located in the north (such as MAR, LYK and THR) and east of the Athens Basin (Mesogeia Plain). The ozone increase in all above men-

tioned stations was not accompanied by a respective change in the concentration of NO_x , as can be seen by the average hourly variation of NO_x mixing ratio during the examined period for all available stations (EL-1, EL-2, MAG, P.As) in the Thriassion Plain – in relation to the corresponding average plot for October 2003 – (see Figure 6b), possibly suggesting that this increase is not related to horizontal transport of primary pollutants.

A possible explanation of the nighttime ozone peak is the vertical mixing of ozone from the residual layer to the ground, which is caused by a nocturnal low level jet (CORSMEIER et al., 1997). More specifically, when a Low Level Jet (LLJ) forms with the core just above the surface inversion, e.g. at about 200–300 m, while vertical wind shear is confined in the surface layer, below the jet core, the produced mechanical turbulence can lead to downward mixing of ozone from the residual layer to the ground. A decrease of surface humidity is also observed. The produced nocturnal ozone peak is typically in the order of one half or one third of the daytime peak (CORSMEIER et al., 1997).

In our case, as can be seen from model results a LLJ is evident at higher altitudes of 600–700 m (Figure 5a), that, however, is not likely associated with turbulent mixing, rather with a larger scale factor, such as the passage of a front (SGOUROS and HELMIS, in press). Wind shear indeed exists in the layer below the LLJ, however, it is not confined near the surface. In addition, according to the experimental data, the ozone increase is comparable with the daytime peak being accompanied by an abrupt decrease of relative humidity (Figure 7) in the examined area. Therefore, it is suggested that the nocturnal ozone peak is not associated with vertical transport of ozone from the residual layer.

On the contrary, the relative humidity drop (Figure 7) provides strong evidence of vertical transport of ozone-enriched air, resulting from stratospheric intrusions into middle troposphere and then to the lower levels via the development of hydraulic jumps. As a first attempt to examine this possible cause, the backward trajectories at the upper troposphere, ending at 02:00 LST, 9 October 2003, along with the relative humidity variation are examined. As can be seen in Figure 8, at the height of 3000 m, the air masses over the examined area seem to originate from higher altitudes, more specifically from the height of 7000 m two days before (6th of October 2003), from the stratosphere (HOINKA, 1998; NAGURNY, 1998), being characterised by a remarkable decrease of relative humidity, with values lower than 20 %. This possibility is further examined in the following section.

7 Stratospheric ozone intrusion

Potential Vorticity (PV), as a conservative tracer on isentropic surfaces, is a useful tool in identifying stratospheric air within the troposphere (HOSKINS et al.,

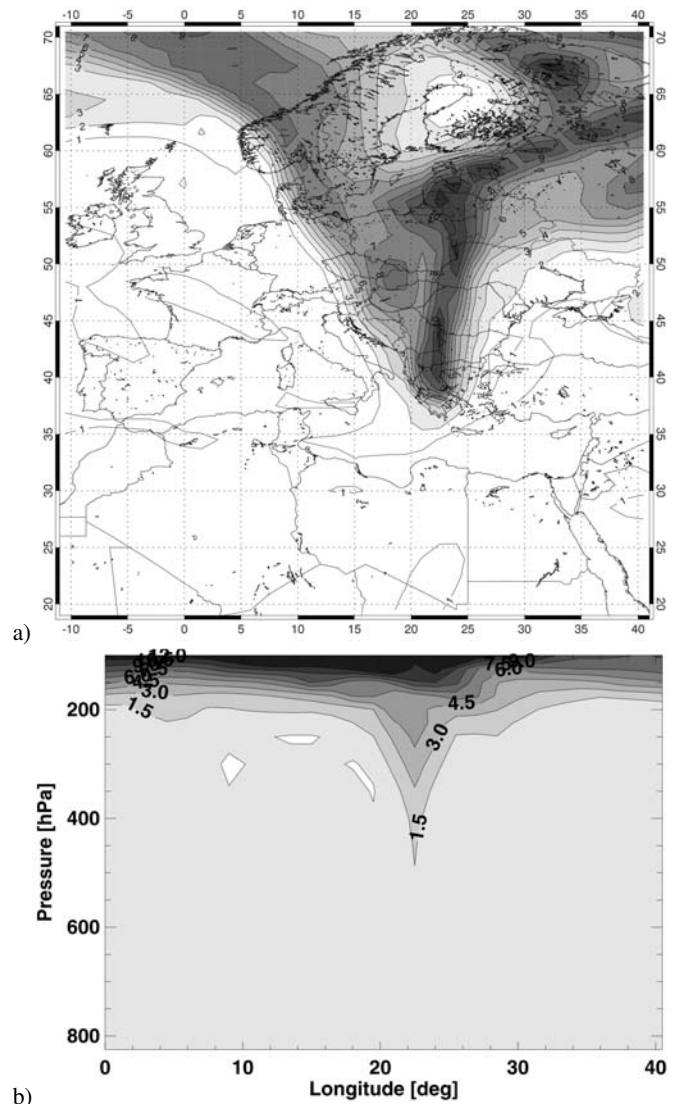


Figure 9: a) Potential vorticity distribution on the isentropic surface 330 K at 02:00 LST, 9 October 2003. b) Vertical cross section of potential vorticity along constant latitude = 38° at 02:00 LST, 9 October 2003.

1985). According to CRISTOFANELLI et al. (2004a, 2004b, 2009) a stratospheric intrusion in southern Europe is defined when the daily minimum of relative humidity is lower than 40 % and one of the 8 daily back-trajectories to show PV values of air masses higher than 1.6 PVU at altitudes higher than 5000 m (PV-RH criterion).

In our case, the upper level synoptic conditions, being characterized by a deep trough, and the polar jet entrance in its upstream side (see Figure 3a) are indeed favorable for the occurrence of stratospheric ozone intrusions (DAVIES and SCHUEPBACH, 1994; MOODY et al., 1996, KENTARCHOS et al., 1998). Furthermore, the PV analysis on the 330 K isentropic surface (Figure 9a) at 02:00 LST on 9 October 2003 shows a hook shaped streamer of high PV values, originating over Scandi-

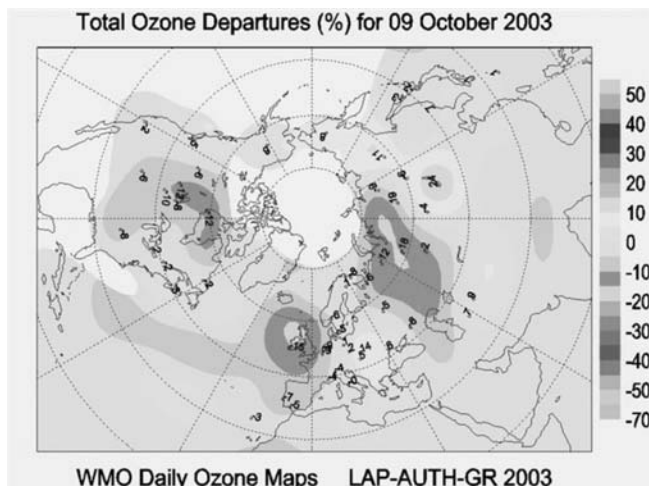


Figure 10: Departure of daily total ozone (%) for October 9, 2003 representing deviation from the mean total ozone for the period 1978–1988 (source: <http://lap.phys.auth.gr/ozonemaps>).

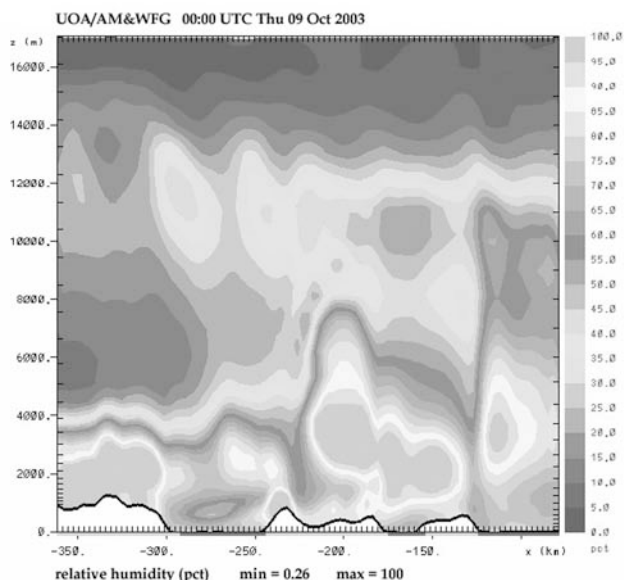


Figure 11: Vertical cross section of relative humidity field along the line AB shown in Figure 2c from the surface up to about 16 km (as derived from RAMS model), at 02:00 LST, 9 October 2003.

navia and extends southwards over southern Greece, with values reaching up to 7 PVU. This high PV air descends through the tropopause down to approximately 600 hPa (Figure 9b), where the isopleth of 1.5 PVU is found, representative of tropopause level in the Mediterranean (FLOCAS, 2000). These PV values satisfy the PV criterion for stratospheric intrusion over the Greek area (CRISTOFANELLI et al., 2009). In accordance with the PV analysis, the WMO daily ozone map verified the existence of high total ozone values over Greece (of 300 DBU), with positive departure up to 5 % (Figure 10).

The vertical cross section of relative humidity along the AB line (Figure 11), in relation to Figure 5a, supports the intrusion of very dry air within the troposphere sub-

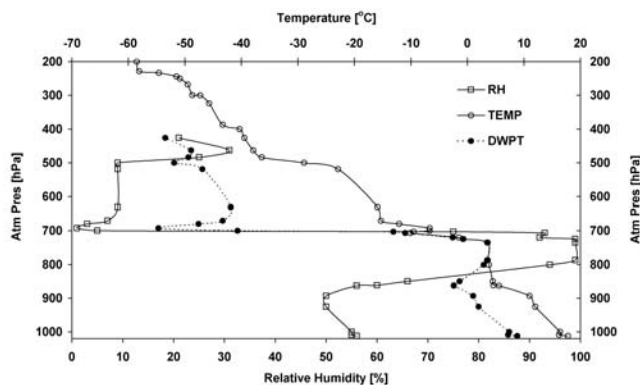


Figure 12: The sounding at LGHL of Temperature, Dew point and Relative Humidity at 02:00 LST, 9 October 2003.

siding over the top of the mountains. This is also corroborated by the sounding at LGHL at 02:00 LST, showing a stable dry layer between 500 and 700 hPa (Figure 12). It is characteristic that relative humidity and dew point jump to very low values, at the level of 700 hPa, being related with a corresponding wind maximum of 50 m/s (see Figure 4c).

The intrusion of dry stratospheric air can explain the abrupt drop of relative humidity (RH) at LGEL, that was mentioned in section 5 (see Figure 7). More specifically, the relative humidity dropped from 94 % to 42 % within an interval of less than two hours, while continues decreasing in the following hours down to 20 % at 14:00 and 15:00 LST. This minimum daily value of relative humidity value satisfies the threshold set by CRISTOFANELLI et al. (2009) to characterize an episode of stratospheric ozone intrusion. It is worth noting that these low values of relative humidity during the 9th of October are not typical of the examined area, in comparison with the average diurnal variation during October 2003 (Figure 7).

Therefore, it is suggested that the stratospheric ozone that descended down to mid troposphere is then possibly transported to the surface via the disturbances developed in the lee side of Pateras mountain (number 2 in Figure 1). Also, the descending motion behind the south-eastward moving cold front could also have contributed to this mechanism (DAVIES, 1994).

8 Concluding remarks

In this paper an attempt was made to investigate a case of abrupt and significant ozone increase in the Thriasion Plain during nighttime, with the aid of routine observations and model simulations in the examined area. It was found that this ozone increase could be caused by transport of stratospheric air masses down to the surface, more likely associated with an enhanced vertical stratosphere/troposphere air exchange and then with a free troposphere/atmospheric boundary layer air exchange. More specifically, stratospheric ozone could be intruded

into the middle troposphere through a tropopause folding over Greece. Over the Thriassion Plain, this ozone rich air has transported downwards to the ground, being facilitated by strong disturbances that developed in the lee side of the mountain ranges in the west side of the plain.

In the absence of any observations to examine the development and structure of such disturbances, the hydraulic-like theory was first employed and predicted the formation of jump-like disturbances in the lee side that can propagate horizontally away from the mountains. This prediction was based on the characteristics of wind and temperature profile in the upstream side. The RAMS model simulations have further examined and help understanding the relevant three dimensional dynamic processes that lead to the occurrence of the windstorm and the exceptional ozone increase during the night. Indeed, the simulations verified the formation of these disturbances in the Thriassion Plain, in the first 1000 m above the ground, as suggested by the theory.

The intrusion of stratospheric air into the troposphere during the examined period was favored by the upper level synoptic conditions and is documented by both isentropic PV distribution, total ozone maps and profiles of humidity and vertical velocity. This ozone rich air more likely descended down to the height of 3000 m and then reached the ground by the lee disturbances that developed in the lee side of the mountains of the Thriassion Plain.

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