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[1] Environmental Physics Laboratory, Technological Education Institute (TEI) of Kozani, Kozani, Greece
[2] Department of Applied Physics, University of Athens, Athens, Greece

Boundary Layer Evolution over a Large and Broad Mountain Basin

A. G. Triantafyllou[1], **C. G. Helmis**[2], **D. N. Asimakopoulos**[2], and **A. T. Soilemes**[2]

With 5 Figures

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Summary

In this study observations of the vertical structure of the Atmospheric Boundary Layer (ABL), recorded at a broad mountainous valley are presented. The vertical profiles of temperature, wind speed and direction up to a height of about 800 meters over the valley bottom have been measured and the temporal evolution of ABL structure of the area has been studied. Specifically, the mechanism of nocturnal inversion destruction during morning hours has been studied, which is of major importance in the study of the dispersion of air pollutants over the area. These observations suggest that the break up of nocturnal inversion during morning hours is mainly caused by a combined mechanism, the build up of the Convective Boundary Layer (CBL) and the presence of upslope winds, resulting to a continuous descent of the top of the nocturnal inversion.

1. Introduction

The ABL evolution over mountainous terrain and the formation of slope or valley wind systems is a subject of great interest in a variety of applications such as air quality modeling, diffusion of pollutants, wind energy etc. (Hanna et al., 1984; Banta, 1984).

In flat terrain ABL evolution is a result of the synoptic conditions and the radiation from and to the ground. In mountain valleys, since the height differences between the surrounding mountains and the valley is usually large, the local flow and the lapse rate are less influenced by the synoptic scale (Wooldridge and Ordill, 1978). In this respect local phenomena affect the formation of the local flow and the temporal evolution of the boundary layer.

Several studies concerning the interaction between the formation and structure of the mountainous ABL as well as the generation of slope and the valley wind systems have appeared (e.g., Defant, 1951; MacHattie, 1968; Kao et al., 1975; Lenschow et al., 1979; R. Banta et al., 1981). Whiteman (1982) studied the breakup of temperature inversions in the deep mountain valleys of western Colorado under different weather conditions. In this study they found that the nocturnal temperature inversion is destroyed mainly by the descent of the inversion top and the growth of a CBL. Helmis et al. (1990) in a study over a large and broad valley indicated that the growth of the CBL plays an important role on the destruction of the nocturnal temperature inversion. They also showed that a transient cross-valley circulation system transports the warmed air along the slope of the valley towards the middle of the stable core. This mechanism results in the local mixing and smoothing of the lapse rate and affects the growth of the CBL. Bader and McKee (1983, 1985) using a two dimensional cross-valley dynamic model examined the parameters of the valley that affect the structure of the developing ABL.

In the present work an attempt is made to investigate the temporal evolution of the ABL in the broad mountain valley of Kozani-Ptolemais by means of tethered balloon observations on clear weather days during different meteorological conditions. This is of major importance concerning the study of air pollutants dispersion since this vicinity is the largest lignite producing area of Balkan and the Greek Public Power Corporation (PPC) produces at this area about the 70% of electric power consumed in Greece (Triantafyllou et al., 1993).

2. Description of the Topography and Instrumentation

Ptolemais – Kozani greater area lies in the northern part of Greece, and particularly in the middle of Western Makedonia. This area is a broad, relatively flat bottomed basin surrounded by mountains. The map of the topography of the greater area is given in Fig. 1.

The valley runs from northwest to southeast and has a length of 50 km and a width which ranges from 10 to 25 km. The base site has a slight slope to the northwest of the order of 2/1000 and lies at a height of about 650 m above the mean sea level (MSL), while the top of the surrounding mountains are about 700 m higher than the bottom. The sides and the floor are covered by isolated trees, small bushes and rock outcroppings. In the bottom there are small hillocks, some of which has been created from deposits of the Public Power Corporation.

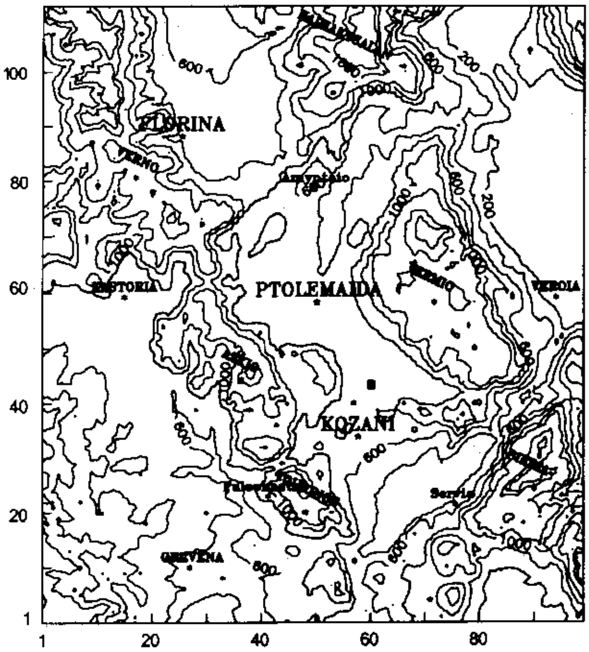


Fig. 1. Map of the topography of the greater Ptolemais area, showing the location of the tethered balloon system (■)

The tethered balloon system which was used consists of a tethered balloon, an electric winch, an airborne package, a laptop PC and the associated software. The system measures simultaneously dry and wet bulb temperature, wind speed, wind direction and relative pressure up to 1000 m. A tiny microcomputer on board collects the data and manages the system. The laptop PC is used as ground station to onload before each flight the program to the microcomputer and to collect and process the acquired data after the flight (Soilemes et al., 1993).

3. Results and Discussion

During the 1991–1992 experimental period tethered balloon soundings were performed under different meteorological weather conditions. However the obtained data are representative of a rather narrow range of synoptic weather conditions since they reffer to mainly high pressure systems which prevailed over the greater Balkan area.

Each experiment normally lasted 24 hours during which succesive soundings were made every one two hours.

The entire data set, which was eventually collected, consists of 11 days, which can be categorised into three general cases and are described as follows:

3.1 Winter Period

3.1.1 January 6, 1992

On the 6th January 1992, Greece was under the influence of a high-pressure system that covered all the South Europe and the Balkan without any pronounced gradients, and with weak northwesterly synoptic winds, which reached 7–8 m/s at 700 hPa. The sky was clear, the air temperature near the ground was −2.2 °C at 06:55 LST when the soundings started, while the ground was covered with hoar frost.

In Fig. 2 the potential temperature (θ) and the corresponding wind speed and direction profiles

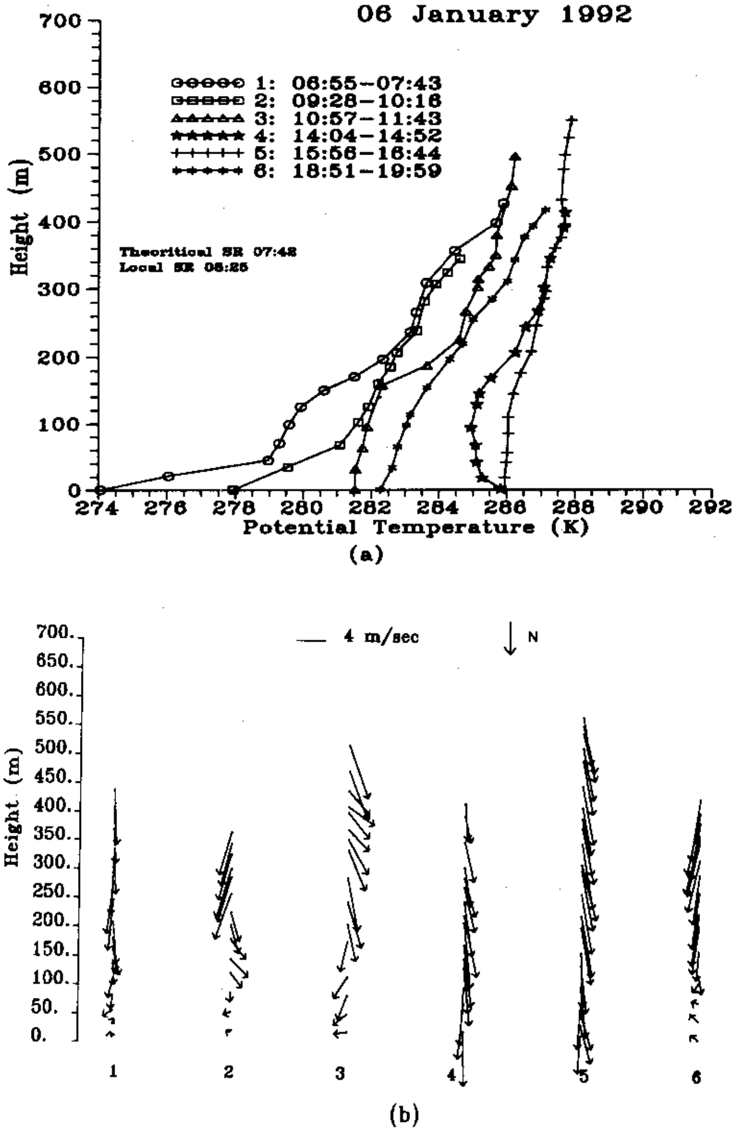


Fig. 2. (a) Potential Temperature θ(K) profiles from tethered balloon ascents. The time (LST) of the start and finish of the ascents are also indicated. (b) Corresponding wind speed and direction profiles

are shown. The profiles extend up to 500 m above ground level (AGL) and show a strong surface based inversion of 5 K/50 m which associated with a stable layer aloft (06:55–07:43 LST ascend). The second sounding, one hour after local sunrise, shows a stable layer with an intense surface based inversion at the first 70 m. From the corresponding wind data (Fig. 2b), it is clear that during the second sounding, a weak easterly flow appeared at the surface, which was reinforced during the next sounding. This local flow is attributed to the heating of the western side of the valley which caused a pressure gradient and the corresponding upslope flow. The upslope flow evacuates air masses from the bottom and results to a sinking of the stable layer thus a descent of the top of the inversion. This is evident in the third sounding at 10:57–11:43 LST where a neutral layer is evident up to 170 m AGL while the top of the nocturnal inversion has descended to the same height.

The next sounding at 14:04 LST shows the conservation of the nocturnal inversion at a height of about 170 m, while a shallow surface-based convective boundary layer was formed. Later on, the prevailling strong wind smooths the lapse rate and finally creates an almost neutral layer which then occupies the whole depth of the ABL. The subsequent sounding at 18:51 LST, that is about 2 hours after sunset, shows that a ground base inversion is created at all heights of the sounding. This is due to the down slope winds which are caused by the radiative cooling of the valley slopes, which create in turn a cold air stable layering (Whiteman, 1982).

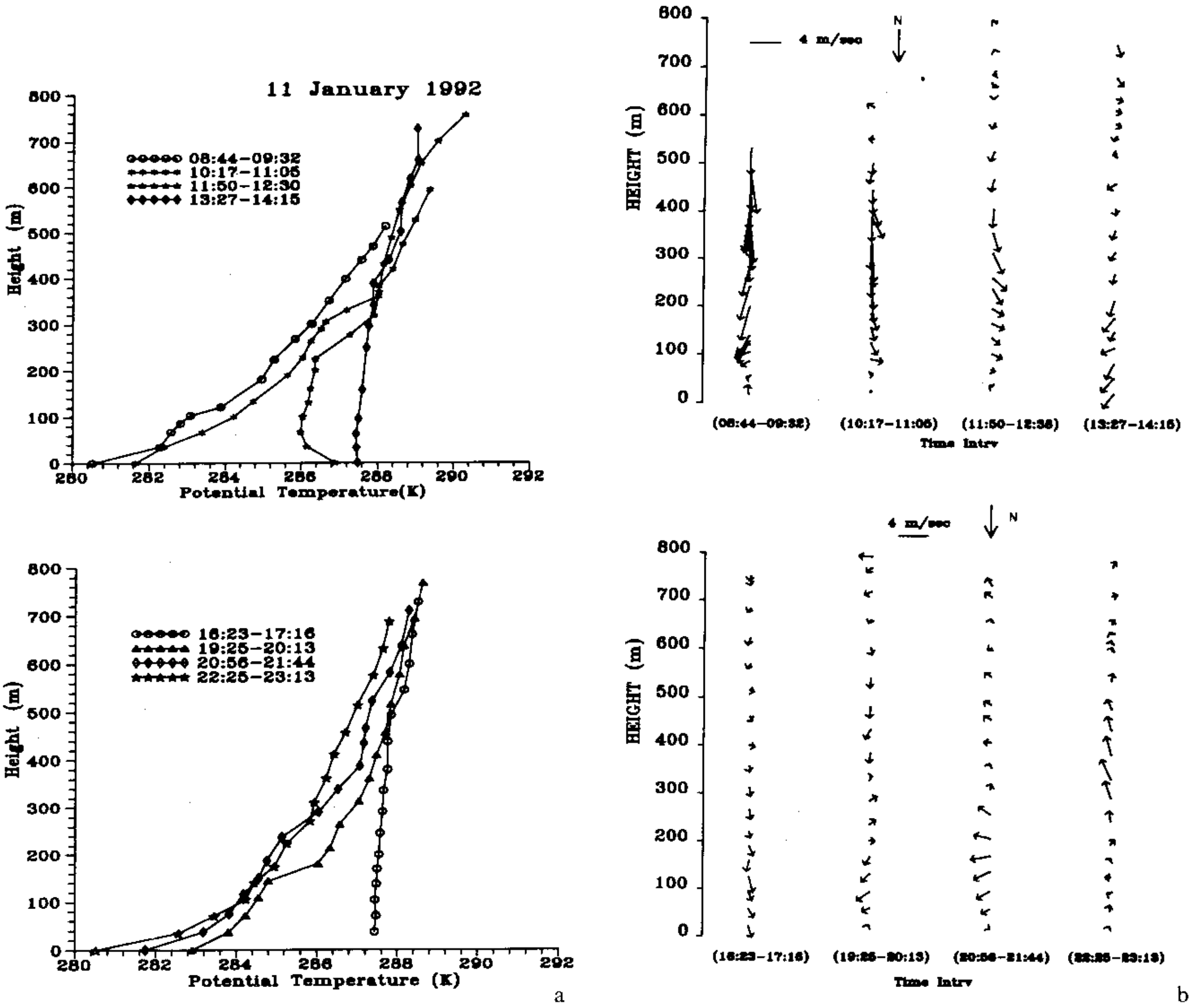
The delay of the nocturnal inversion destruction which has been observed during this winter day in this relatively wide valley is in agreement with Bader and McKee (1983, 1985), who examined the effects of valley width and surface heating rate in relation to the daytime evolution of the valley atmosphere. In our case, since the valley was covered with hoar frost, the available energy was reduced by the high latent heat and the initial sunrise stable layer was sustained throughout the day (Whiteman, 1982).

3.1.2 January 11, 1992

A second experimental case representative of the winter period is the one on the 11th of January 1992. A cold front was moving from North toward Greece and warm advection was observed in the lower troposphere. This was a day with the air temperature ranging at about 4 °C (06:00 LST).

The ABL structure is given through the potential temperature (θ) and the wind speed and direction profiles which are shown in Fig. 3a, b.

From the first sounding it is apparent that an inversion layer with a strength of 8 K/500 m was present extending up to a height of 500 m, close to the ridgetops of the surounding mountains. The second ascend indicated a slow heating of the air close to ground and sinking of the stable core, (the nocturnal stable layer up to about 350 m). The temperature of the air near the ground was increased significantly at 11:50 LST, as seen in



a b

Fig. 3. (a) Potential Temperature θ(K) profiles from tethered balloon ascents. The time (LST) of the start and finish of the ascents are also indicated. (b) Corresponding wind speed and direction profiles

Fig. 3a and an upward growth of the convective boundary layer began. This resulted to a descent of the inversion top and a growth of the convective ABL. Thus by 11:50 LST a 50 m deep superadiabatic layer was formed near the ground, while a height inversion at 300 m was maintained.

The subsequent sounding showed a neutral layer up to 400 m, where there was a weak elevated inversion, which in the next sounding was shifted at 500 m AGL.

At 19:25 LST, about 2.5 hours after local sunset, an inversion layer was created up to about 500 m. Within this stable layer a more intense surface based inversion layer (150 m) was present. Slope winds as reported before, resulted from radiative cooling of the valley slopes, assisted the valley floor filling with cold air and created a cold air stable layer. Furthermore, at 22:25 LST the ground based inversion riched 250 m, while higher up a less stable layer existed.

The daytime evolution of the ABL at 11th of January 1992 is seen in Fig. 4. In this figure the variation of the potential temperature during the day at different heights is shown. As seen from this figure, the potential temperature changes more quickly at lower altitudes as well as during sunrise and sunset time periods.

Considering both the wind and temperature observations it is obvious that the inversion destruction is caused by a combined process mechanism. On one hand the continuous growth of a convective ABL due to solar heating and on the other the continuous descent of the temperature inversion top due to the up slope winds. The later results in the evacuation of air masses from the bottom of the valley which are replaced by warmer air presumably leaving from above. Eventually the inversion is destroyed when the descending top of the inversion meets the ascending CBL without making apparent which of the two processes is predominant.

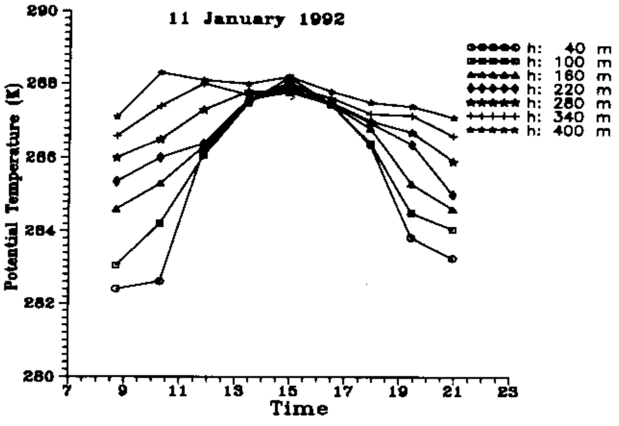


Fig. 4. Potential Temperature variation at different heights

This behaviour is characteristic of the recorded data in Ptolemais valley and is in agreement with the observations made by Whiteman (1982) in a less wider and deeper than the Ptolemais valley.

3.2 *Summer Period*

On 10th of August 1992 the high pressure system which covered the East part of the Mediterranean and Balkan area was weakened so that the thermal low over the Anatolian Plateau extended toward West. The kind of wind pattern across the Aegean during these days is called etesiens or meltemi (Carapiperis, 1951). These winds are stronger during the day and weaker during the night.

During this day the wind at 700 hPa was from E direction and reached 7–8 m/s.

In Fig. 5 the potential temperature profiles and the corresponding wind data of the 10th of August experimental day are shown.

The profiles extend up to 650 m AGL and indicate an inversion with a strength of 8.5 K within the first 250 m, during the 04:39–05:27 ascent. Within this stable layer a more intense surface based inversion of 5 K in the first 50 m layer was present. Higher up a neutral layer with constant potential temperature is formed.

With in the ground based inversion layer a weak south flow prevailed caused by the valley slope, while at the upper level an almost constant easterly flow blew.

A similar situation appears during the next sounding. After sunrise the heating of the western slope at the sides of the valley initially produced a pressure gradient favorable to upslope wind flow. The upslope winds drew air from the bottom of the valley and resulted in a sinking of the stable layer.

The subsequent profile of potential temperature at 08:32 LST showed a relatively rapid development of a shallow convective layer near the ground and a height inversion at an altitude of 160 m. This indicates that the top of the inversion descends, following the same pattern with the

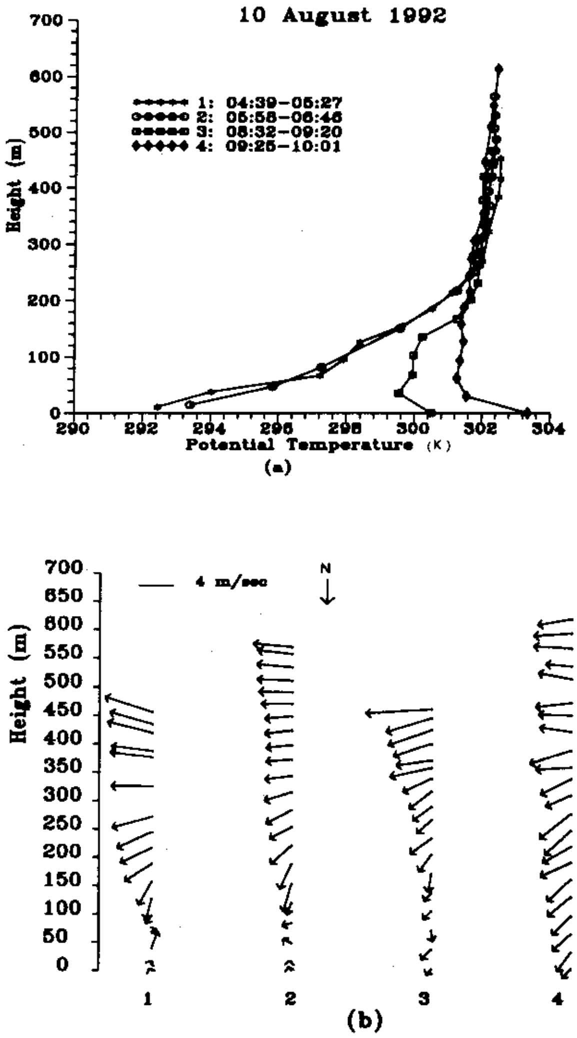


Fig. 5. (a) Potential Temperature θ(K) profiles from tethered balloon ascents. The time (LST) of the start and finish of the ascents are also indicated. (b) Corresponding wind speed and direction profiles

previously in the presented cases. Within the unstable layer NE upslope flow prevailed due to heating of the western slope of the valley sides. Within the neutral layer the winds are from Easterly directions.

At 09:25 LST the inversion was destructed, and at all heights the wind agreed with the synoptic patterns.

4. Discussion and Concluding Remarks

Eleven cases of boundary layer evolution were studied mainly during clear weather conditions. Most days were characterised by a lack of significant cloud cover, with light wind speed at 700 hPa of about 7 m/s.

Some basic information about the destruction of the inversion for the 11 cases studies is summarised in Table 1. In particular the initial depth of the inversion is depicted in column 2. The inversion strength, the potential temperature difference between the base of the sounding and the top of the inversion, is given in column 3, while the column 4 shows the time of the corresponding sounding. The mean temparature near the ground during this time is recorded in column 5. Column 6 indicates the time and the pattern of the inversion destruction, while column 7 and 8 give the surface and 700 hPa wind respectively. It is worth mentioning here that the wind speed and direction were deduced from the corresponding synoptic chart of 12 UTC.

For the 11 cases studied, the inversion depths ranged from 150 m (for a summer case) to 650 m (for a winter case) while the inversion strength averaged at 10.4 K and varied from 8 K to 16 K. It is worth noting here that the inversion depth had only a limited effect on inversion strength. Seasonal differences seemed to be large mainly due to the inversion depth which for the winter cases was deeper than the summer ones.

The time period after sunrise required for the inversion to be destroyed varied from 2.5 to 7 h. The inversions were destructed more rapidly during summer than during winter.

Table 1 indicates that, concerning the inversion destruction the combined mechanism of the growth of the CBL and the descend of the inversion top, is the most common pattern in this broad mountain basin. The inversion destruction due to the growth of a convective boundary layer was observed during 3 cases, while during two of the 11 selected cases the inversion was remained.

From the data presented in this paper some basic remarks can be made concerning the ABL evolution of the Ptolemais valley at least for the synoptic conditions studied.

- There is a strong ground base inversion during morning hours up to the ridgeline during the winter period, and at lower height during summer period.
- Inversion depth has only a limited effect on inversion strength. Seasonal differences seemed to be large mainly due to the inversion depth and the time period after sunrise required for the inversion to be destroyed.

Table 1. *Summary of Inversion Break up Data*

1 Date	2 Inversion Depth (m)	3 Inversion Strength (K)	4 Sounding time	5 Temperature (°C)	6 Destion time/ pattern	7 10 m* Wind deg/m.s^{-1}	8 700 hPa wind (m/s)
22/09/91	220	8	07:40–08:30	12	11:00/I	272/0.2	7.7 NNW
20/11/91	650	9	07:30–08:20	4.5	/III	203/0.4	7.7 SSW
04/01/92	440	16	08:00–08:50	−1.5	/III	202/1.4	5.1 WSW
05/01/92	250	8.5	07:05–07:50	−2	10:30/II	203/0.2	7.7 NW
06/01/92	400	12	06:50–07:40	−2.20	15:00/II	284/0.1	7.7 NNW
07/01/92	650	12	06:00–06:40	−2.20	16:00/I	209/0.2	7.7 NW
08/01/92	540	10	08:30–09:20	−0.10	13:00/II	217/0.9	7.7 NW
11/01/92	600	8.5	08:40–09:30	3.60	13:00/II	221/0.1	5.1 WSW
12/01/92	600	12	07:30–08:20	−1	14:00/II	230/0.2	10.3 WNW
09/08/92	150	9.5	05:30–06:20	14	09:15/I	182/0.1	7.7 NE
10/08/92	250	8.5	05:50–06:40	15.5	09:30/II	166/0.1	7.7 E

I. Growth from the ground of a CBL
II. Growth from the ground of a CBL and descend of the inversion top
III. As (I) and/or (II) but the inversion is not finally destroyed

* Mean value measurement of the sounding time interval.

- The destruction of the nocturnal inversion is made early in the morning or late noon in relation to the season of the year, following a pattern which combines two processes: a) The development of a surface based convective boundary layer, which erodes the inversion beneath and b) the continuous descent of the top of nocturnal inversion due to upslope winds, which evacuate air masses from the lower part of the stable core causing sinking of the stable core.

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Authors' addresses: A.G. Triantafyllou, Environmental Physics Laboratory, Technological Education Institute (TEI) of Kozani, GR-50100 Kozani, Greece; C. G. Helmis, D. N. Asimakopoulos and A. T. Soilemes, Department of Applied Physics, University of Athens, 33, Ippokratous Street, GR-10680 Athens, Greece.