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ORIGINAL PAPER

Statistical analysis of boundary layer heights in a suburban environment

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Abstract The atmospheric boundary layer (ABL) is characterized by the turbulence eddies that transport heat, momentum, gaseous constituents and particulate matter from Earth's surface to the atmosphere and vice versa. Thus, the determination of its height has a great importance in a wide range of applications like air quality forecasting and management. This study aims at estimating the height of the ABL in a suburban environment and at investigating its temporal variation and its relationship with meteorological variables, like temperature and wind. For this purpose, radiosonde data from the suburban area of Thessaloniki, Greece, are analyzed. The data analysis reveals that ABL height is usually below 200 m in the morning hours during all seasons of the year and that is also low when near-surface temperature and wind speed are low too. Additionally, noon ABL height exhibits a strong seasonal variation, reaching higher values during summer than during winter. Very high values of ABL height, of the order of $\sim$3,000 m, are occasionally observed in Thessaloniki during summer. Moreover, sea breeze development during summer is related to a slight reduction of the ABL height.

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1 Introduction

The atmospheric boundary layer (ABL), also known as the planetary boundary layer (PBL), is the lowest part of the atmosphere, where physical quantities such as flow velocity, temperature, moisture etc., display rapid fluctuations (turbulence) and vertical mixing is strong. During daytime, the ABL height is usually defined to coincide with the base of the first inversion in potential temperature and a corresponding decrease in specific humidity (Johansson et al. 2001). This definition is equivalent to the height at which the vertical heat flux gradient changes sign. However, in both cases the height of the boundary layer should define the top of the turbulent layer.

Surface as well as large-scale synoptic influences determine the structure of the ABL. The ABL is incessantly changing both in space and time depending on orography, surface cover, season, daytime and weather. The vertical extent of the ABL may vary from less than one hundred to a few thousand metres. Heat, momentum, gaseous constituents and aerosols are transported by turbulence from and to the Earth's surface. In the morning, the vertical diffusion of pollutants is not favoured as ABL is shallow. Additionally, a typical diurnal profile of wind speed shows that the minimum values of wind speed are generally observed in the morning hours, as they are induced by the prevailing atmospheric stability in the early morning. Moreover, the concentration levels of some pollutants such as aerosols and ozone's precursors are elevated during the morning rush hours. Consequently, the accumulation of pollutants is more likely to occur in the morning hours, mainly attributed to the aforementioned meteorological conditions (Papanastasiou and Melas 2009). Furthermore, the control of emissions, the forecast of air quality and the implementation and assessment of legislation can be carried out by applying atmospheric flow models that require meteorological data in order to estimate the transport, dispersion and removal of pollutants. Since the dispersion of pollutants depends mostly on atmospheric turbulence, ABL height is considered as a crucial input variable for the computations. Thus, the accurate determination of ABL's height is crucial for many aspects of air quality management and forecasting (Prodanova et al. 2008), assisting the environmental managers to plan and apply policies towards the improvement of air quality.

Several techniques are suggested in literature for the determination of the ABL height, but none of them is successful for all conditions. The most important operational methods are reviewed and intercompared by Seibert et al. (2000), including direct measuring techniques (radiosonde, tethered balloon, mast) and remote sensing techniques (Doppler radar, lidar, sodar). The most common method to estimate ABL's height is to analyze potential temperature profiles in combination with humidity profiles, based on data collected by radiosondes, since routine soundings of temperature, humidity and wind are available all over the world (Norris 1998; Sempreviva and Gryning 2000; Joffre et al. 2001; Johansson et al. 2001; Gryning and Batchvarova 2002). However, radiosondes are launched only a few times per day; therefore, they do not provide continuous temporal vertical profiles in order to conduct a thorough analysis of ABL's time evolution. Remote sensing systems are also utilized for the same purpose (Lammert and Bösenberg 2006; Schwiesow 1986; Davis et al. 2000; Steyn et al. 1999; Cohn and Angevine 1999; Menut et al. 1999). They have the advantage of providing high temporal and spatial resolution information of the ABL; however their operation is much more complex and expensive.

The objectives of this study are to investigate the main temporal characteristics of the ABL's height in a suburban environment and to find out its relationship with basic meteorological variables, namely the near-surface temperature and the near-surface wind speed. For this purpose, radiosonde data from the suburban are of Thessaloniki, Greece are analyzed.

2 Materials and methods

2.1 Study area and data used

As mentioned earlier, this work aims at studying the main characteristics of the ABL in the suburban area of Thessaloniki, Greece, (40.63°N, 22.96°E). Thessaloniki is a coastal city in northern Greece where almost 1 million inhabitants live, constituting a typical Mediterranean urban environment. It is located at the north coast of Thermaikos Gulf where there is a smaller gulf, the gulf of Thessaloniki. The greater urban area covers a $\sim$62 km^2 area extending approximately 17 km along the coast of Thermaikos Gulf (Fig. 1).

In order to determine the ABL height, data recorded by radiosondes are analyzed. The radiosondes (Vaisala RS80) are routinely carried out twice a day at "Macedonia" airport, on behalf of the Greek National Meteorological Service. The launching site ("Macedonia" airport) is located at a 16-km distance to the south from the city centre (Fig. 1). Due to the fact that radiosondes from all wind sectors are used, the paper aims at studying the ABL in the suburban area of Thessaloniki. The balloons are launched at 05:37 $\pm$ 26 min UTC (morning) and 11:37 $\pm$ 34 min UTC (noon), respectively. 05:37 and 11:37 UTC correspond to mean launching time, while 26 and 34 are the corresponding standard deviations. During the period November–March, balloons are launched only once a day (noon). The sonde equipment takes approximately 1 measurement every 2–4 s that corresponds to an elevation of 10–25 m, while lifting from the ground to $\sim$30 km height, depending on the balloon's vertical velocity. The data set includes morning and noon vertical profiles of atmospheric pressure, temperature, relative humidity, wind speed, wind direction as well as near surface temperature and near-surface wind speed, covering the 2-year period 2000–2001.

Due to the variation in sunrise time, the morning radiosondes either represent a stable boundary layer or they are performed during the morning transition, according to the launching season. However, the identification of the stability conditions is not included in the present paper's objectives, so relevant research is not carried out.

2.2 Estimation of the ABL height

In this study, the ABL height is estimated through a Bulk Richarsdon Number (BRN) method. Seibert et al. (2000) state that this technique can be applied satisfactorily in situations where turbulence is produced either convectively or mechanically. The BRN, R_B, is calculated for each height level by applying the following equation (Stull 1988)

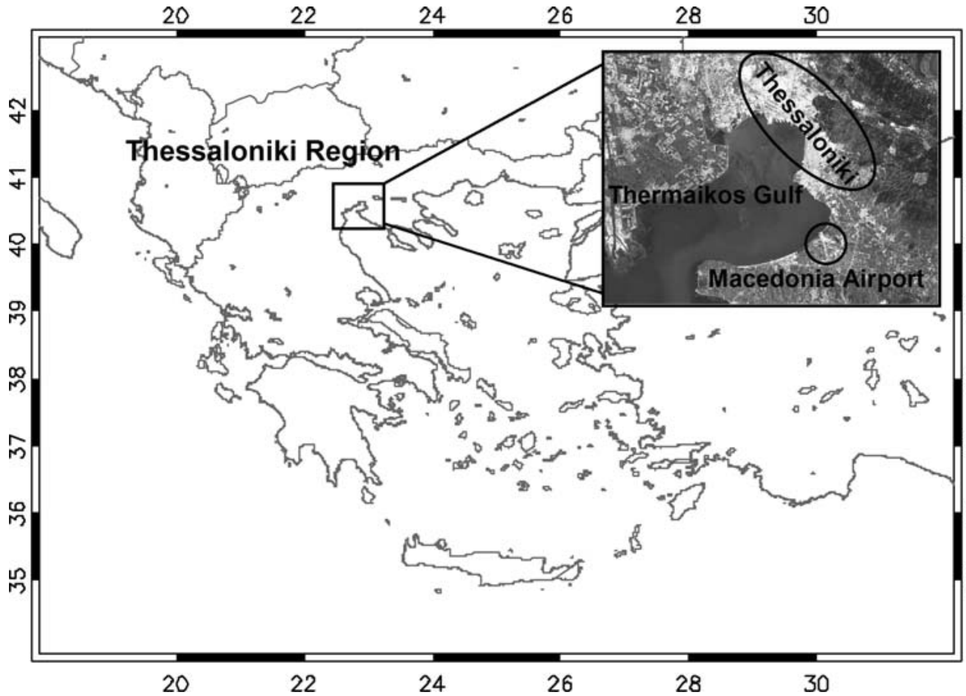


Fig. 1 The study area. The radiosondes are launched from "Macedonia" airport

$$R_B = \left(g\Delta\overline{\theta_v}\Delta z\right)/\left\{\overline{\theta_v}[(\Delta\bar{U})^2 + (\Delta\bar{V})^2]\right\} \qquad (1)$$

Assuming an atmospheric layer between z_1 and z_2 ($z_1 < z_2$) height levels, $\overline{\theta_v}$ is the mean potential temperature between z_1 and z_2, $\bar{U}$ and $\bar{V}$ are the mean horizontal wind components, $\Delta\overline{\theta_v}$ expresses the difference $\overline{\theta_{v2}} - \overline{\theta_{v1}}$ while $\Delta\bar{U}$ and $\Delta\bar{V}$ express the $\bar{U}_2 - \bar{U}_1$ and $\bar{V}_2 - \bar{V}_1$ differences, respectively. R_B is calculated for each height level. The actual value of ABL is chosen as the first height where R_B exceeds the BRN critical value, R_{Bcrit}, which is equal to 0.25 (Sorensen 1998; Hennemuth and Lammert 2006). When $R_B < R_{Bcrit}$, it is assumed that turbulent flow dominates in the atmosphere, while, when $R_B > R_{Bcrit}$ the prevailing flow is laminar. This technique is applied to estimate ABL height for each individual set of observations (morning/noon), referring to the 2-year time period 2000–2001. Although the data that are recorded by the radiosondes have sufficient vertical resolution, the estimation of ABL heights below 200 m could be regarded as less confident.

3 Results and discussion

3.1 Frequency distribution of ABL heights

Frequency distributions of the ABL height estimated from data collected by noon and morning radiosondes during the 2-year period 2000–2001 are presented in this section. As mentioned earlier, there are no morning radiosondes for the period November–March. ABL height values are classified into 200-m classes from ground up to 4,200 m. Figure 2a shows the frequency distribution of the ABL height for the morning measurements. The first (0–200 m) and the second (200–400 m) class include 42 and 22% of the values, respectively, while the vast majority of the values are distributed to the first four classes (0–800 m). The fact that almost half of the morning ABL heights are included in the first class (0–200 m) could be attributed to the low solar radiation budget that generally reaches the earth during the morning (05:06 ± 27 min UTC) in middle latitudes. Only a few values are distributed to classes over 800 m, which mainly refer to summer ABL heights. Since, ABL typically extends from the ground to 2–3 km (Garratt 1992), ABL heights greater than 3,000 m for the city of Thessaloniki should be treated with caution. Such values could be attributed either to extreme atmospheric conditions or measurement errors.

The frequency distribution of the ABL height for the noon measurements is presented in Fig. 2b. ABL height values shift to higher classes being distributed more uniformly. This structure is attributed to the relatively high solar radiation budget that generally reaches the earth during the noon in middle latitudes leading to convective conditions. Despite the absence of a sharp maximum, the most frequent class of ABL heights is 200–400 m AGL.

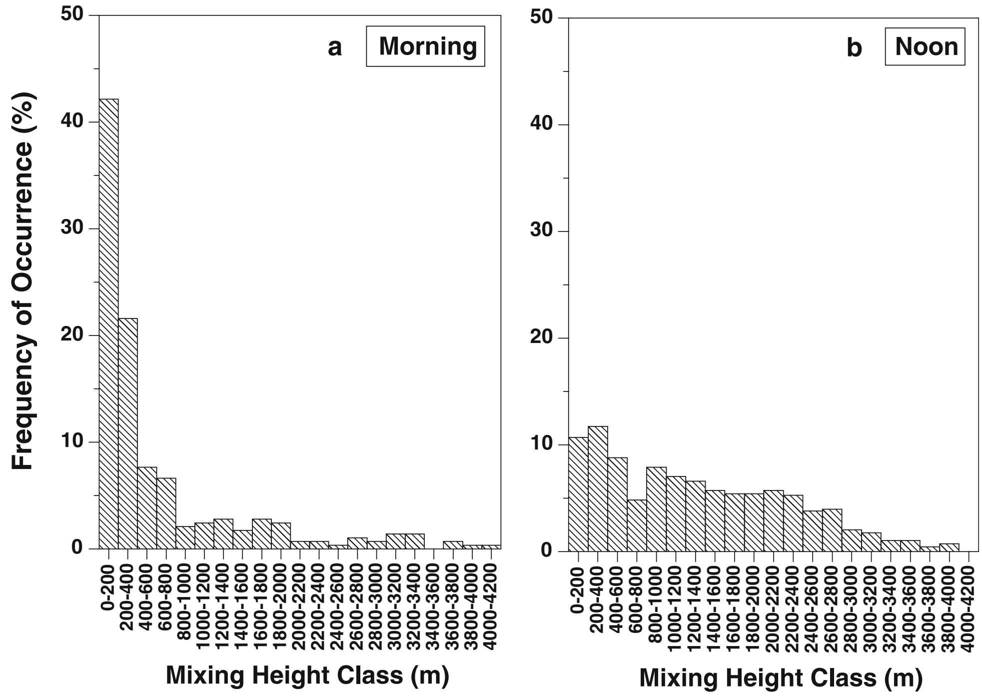


Fig. 2 Frequency distribution of morning (**a**) and noon (**b**) ABL heights over Thessaloniki area

3.2 Relating ABL height to meteorological variables

3.2.1 Near-surface air temperature

This section investigates the relationship between ABL's height and near-surface temperature. Air temperature can be used as a proxy for the sensible heat flux that is one of the factors that determines the ABL's growth. However, uncertainty could be induced in calculations if the estimation of the ABL's height is based solely on the air temperature neglecting the effect of soil moisture. The available energy is partitioned into sensible and latent flux; when the surface is not dry, part of the available energy tends to be used as latent heat on the expense of sensible heat (King et al. 2006). However, the near-surface air temperature can be used as a proxy of the ABL height as higher temperatures statistically indicate an increase of the available energy. Additionally, the daily and annual temperature variation is well correlated to the corresponding ABL's height variations.

ABL height values are classified into 200 m classes as mentioned above, while temperature is divided in four classes ($T \leq 280$ K, 280 K $\leq T \leq 290$ T, 290 K $\leq T \leq 300$ K, 300 K $\leq T$) which have been selected in accordance with the mean seasonal temperatures that are observed in the city of Thessaloniki.

The morning frequency distributions of the ABL height for the different temperature classes are presented in Fig. 3a–c. It is worth mentioning that the first temperature class ($T \leq 280$) is not shown separately in these figures as there were no radiosonde profiles during the cold period of the year. When temperature is less than 290 K (Fig. 3a), the vast majority of the ABL height values is distributed to the first three height classes (0–600 m) while 61% of those values are included in the first 200 m class. Figure 3b reveals that a shift to higher classes occurs when temperature is in the interval 290–300 K. The ABL height values that are in the first 200 m is reduced to 40.8%. A shift to even higher ABL heights is also observed in Fig. 3c which corresponds to temperatures higher than 300 K. Figure 3c shows that when the temperature exceeds 300 K, the most frequent class of ABL heights is 200–400 m AGL. Studying the above-mentioned shift, it could be estimated that an increase of 10 K in the near-surface temperature leads to an increase of the mean morning ABL height in the average by $\sim$430 m.

Figure 3d–g refers to the noon frequency distributions of the ABL height. Now, temperature is divided into four classes. When temperature is less than 280 K (Fig. 3d), the vast majority ($\sim$98.3%) of the ABL height values are within the range 0–1,400 m; 19% and 21% of the values are included in the first two classes, respectively. A shift to higher classes is observed in Fig. 3e–g. It is very interesting to point out the occurrence of a relatively high percentage of ABL heights in classes even around 2,500 m. ABL height values over 2,500 m are observed in the region of Thessaloniki especially during the hot Greek summer when the mean summer surface temperature equals to 299 K (source: Hellenic National Meteorological Service). Generally, it is noticeable that an increase of 10 K in the

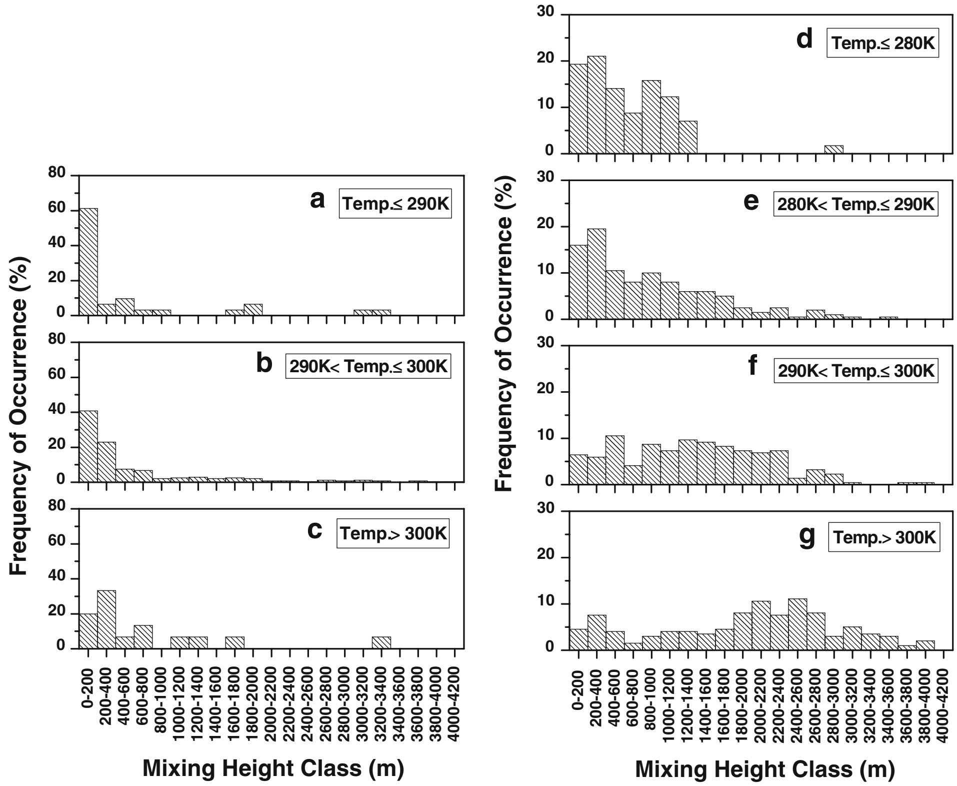


Fig. 3 Frequency distribution of morning (**a–c**) and noon (**d–g**) ABL heights over Thessaloniki area, for several near surface temperature (Temp.) classes

near surface temperature leads in the average to an increase of nearly 440 m in the mean noon ABL height. Higher temperatures are likely to be associated with stronger convective activity in the ABL which contributes to the development of large energetic eddies that penetrate into the free atmosphere and lead to the rapid development of the ABL. This is likely to have the same effect on the ABL development during morning and midday hours.

3.2.2 Near-surface wind speed

In this paragraph, the relationship between ABL height and near-surface wind speed is investigated. Wind speed is used as a proxy for the momentum flux that is another factor that drives the ABL's growth. ABL height values are classified into 200 m classes as above, while the selected wind speed classes are those that are used to define Pasquill's stability classes (Pasquill 1961).

The morning frequency distributions of the ABL height for the different wind speed classes are presented in Fig. 4a–e. Figure 4a reveals that when wind speeds are very low (<2 m s^{-1}), the vast majority of the ABL height values are less than 400 m (44 and 33% in the first and second height class, respectively). When wind speeds are in the interval 2–3 m s^{-1} the ABL heights are lower than 200 m in the 58% of the examined days (Fig. 4b). The distribution of the ABL height values shifts to higher classes as the wind speed becomes stronger, a fact that is clear in Fig. 4d (46% of the ABL height values correspond to the 600–800 m class, Fig. 4e). Moreover, Fig. 4e reveals that when wind speed exceeds 6 m s^{-1} the ABL height is never lower than 400 m.

The noon frequency distributions of the ABL height for the different wind speed classes are quoted in Fig. 4f–j. When wind speed is less than 2 m s^{-1} (Fig. 4f), 80% of the ABL height values are distributed to the first five classes, being less then 400 m in 60% of the cases. As wind speed increases, the ABL height elevates and its distribution becomes more uniform (Fig. 4g–i). When wind speed becomes greater than 6 m s^{-1} the distribution of the ABL height values seems to be almost random (Fig. 4j). In general, higher surface wind speed classes lead to greater mean noon ABL height values with an average rate of 272 m from class to class. This is attributed to the enhanced production of mechanical turbulence which is related to the wind speed. Another likely explanation is related to the sea breezes that are frequently developing in Greece during the warm period of the year. Sea breezes are usually associated with relatively low wind speeds and lead to ABL heights that are considerably lower than the observed ABL heights during offshore flow (Kambezidis et al. 1995; Melas et al. 1998).

Fig. 4 Frequency distribution of morning (**a**–**e**) and noon (**f**–**j**) ABL heights over Thessaloniki area, for several near-surface wind speed (WS) classes

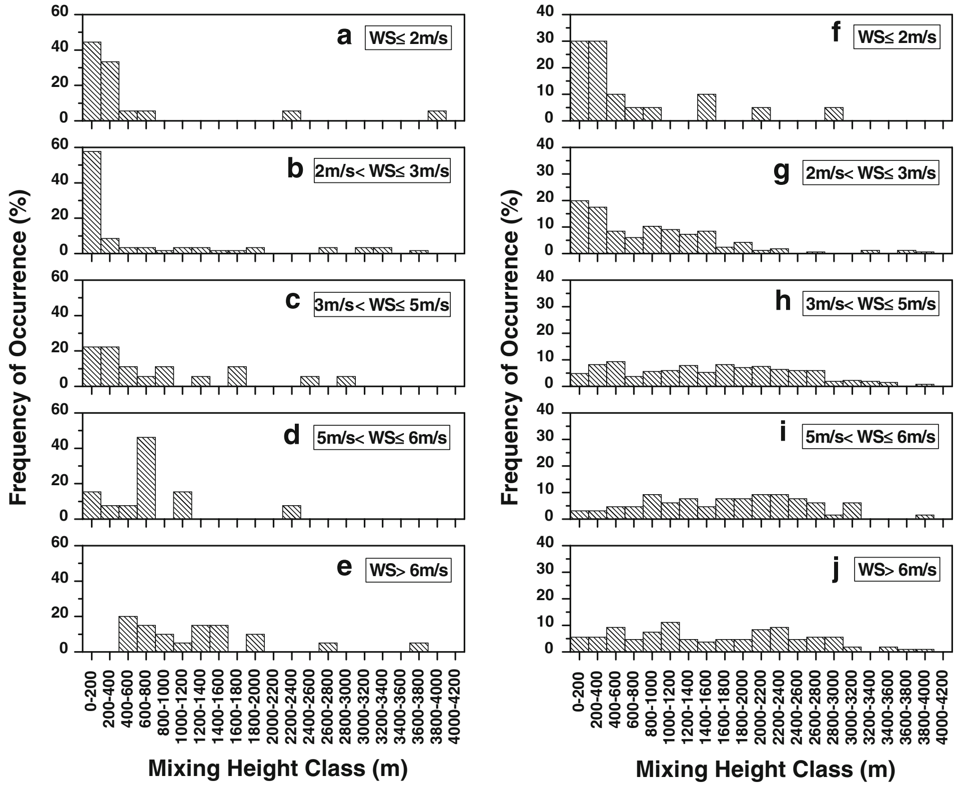
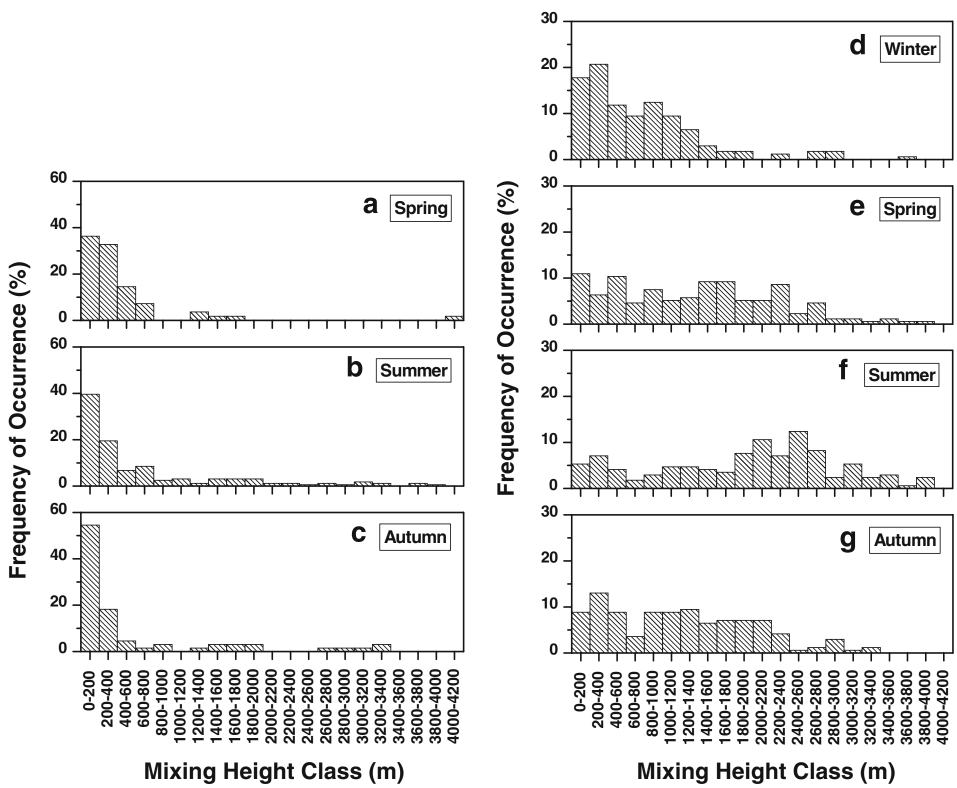


Fig. 5 Seasonal variation of the frequency distribution of morning (**a**–**c**) and noon (**d**–**g**) ABL heights over Thessaloniki



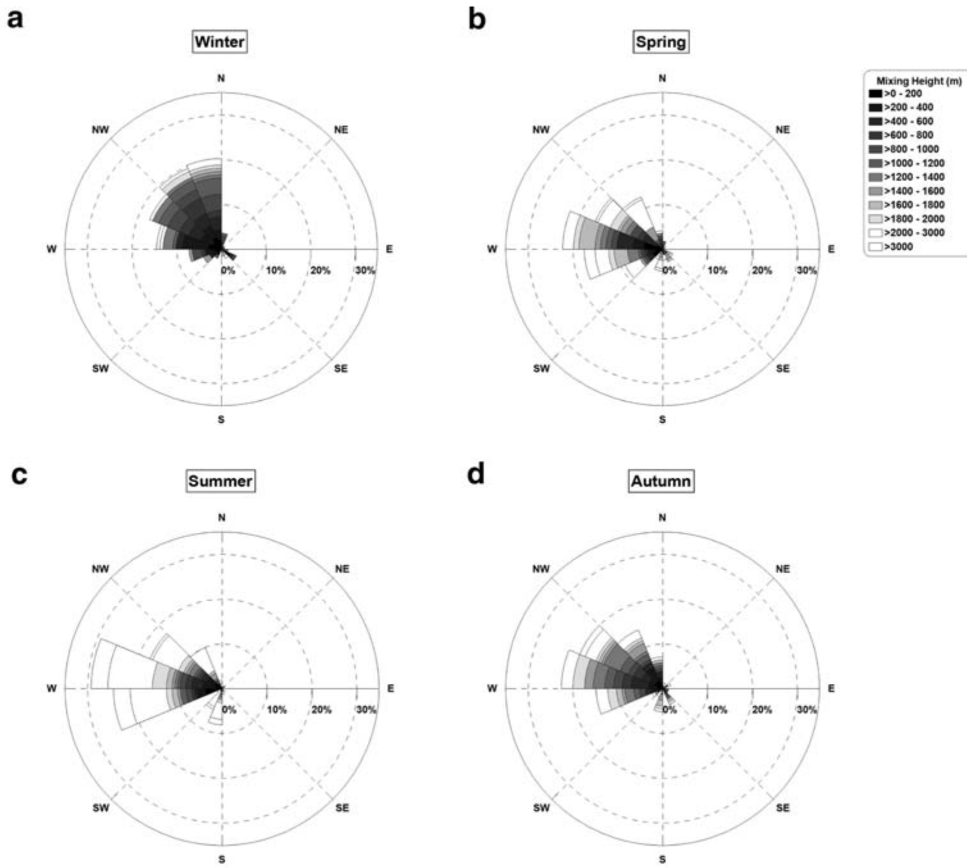


Fig. 6 Wind rose of noon ABL heights over Thessaloniki area

3.3 Seasonal variation of ABL height

The frequency distribution of morning spring, summer and autumn ABL height values are presented in Fig. 5a–c. In spring, morning ABL heights usually do not exceed 800 m with ~70% of the values being lower that 400 m (Fig. 5a). The summer morning ABL height values exhibit a spring-like structure, but the distribution has a longer tail towards higher classes (Fig. 5b). However, in autumn, morning ABL heights remain lower than 200 m in more than 50% of the examined days (Fig. 5c).

The frequency distribution of noon winter, spring, summer and autumn ABL height values are cited in Fig. 5d–g. The frequency of the winter noon ABL height values shows a maximum at the lowest classes (heights less than 400 m) and decreases with increasing height classes (Fig. 5d), while in spring, noon ABL height values are more uniform and exhibit an intense shift to higher classes (Fig. 5e). In summer (Fig. 5f), an additional shift to higher classes is observed, exhibiting a peak frequency of occurrence equal to 12% that corresponds to the 2,400–2,600 m class. The frequency of ABL heights during autumn shows a shift to lower classes again (Fig. 5g) which is generally higher than the respective observed during spring.

The above-described results are similar to those revealed by other studies conducted in Greece (Santacesaria et al. 1998; Tombrou et al. 2007) and at other European sites (Hennemuth and Lammert 2006; Lammert and Bösenberg 2006; Davies et al. 2007).

Figure 5a–c reveals that morning ABL heights do not exhibit a pronounced seasonal variation as it usually remains below 800 m. On the contrary, noon ABL height is lower during winter and becomes higher during the warm period of the year as solar radiation becomes more intense. It is worth investigating whether part of the seasonal variability could be attributed to the development of a sea breeze that is very frequently observed in the greater study area during the warm period of the year. "Macedonia" airport is located at the coastline (Fig. 1), so wind and temperature profiles are greatly influenced by the sea breeze circulation. Figure 6a–d presents the distribution of noon ABL heights for different wind direction classes. The utilized wind direction data are measured at 26 m AGL. Noon radiosondes correspond to the time when the sea breeze has almost reached its maximum strength, so they are considered to depict sea breeze's maximum impact. During summer the frequency of sea breeze occurrence is very high (>70%, Matsouka 2006) and the impact of the sea breeze on the ABL height is expected to be more clearly demonstrated in Fig. 6c. This figure reveals that during summer, the frequency of occurrence of wind directions associated with sea breezes (WSW–NW) (Melas et al. 1994) is very high. The average ABL height for the sea breeze sector is 1672.2 ± 1056.3 m, slightly lower than the average value for all wind sectors (1795.2 ± 1016 m). Melas et al. (2005) found that during sea breeze days the ABL height in Athens area is appreciably lower when compared to no sea breeze days. The present results can be explained by the fact that Thessaloniki bay is very closed and relatively shallow and the effect of the sea breeze on the ABL structure is not as pronounced as in the Athens case.

4 Conclusions

The objectives of the present study are to identify the statistical characteristics of the ABL height and to investigate its relationship with temperature and wind speed. For this purpose, radiosonde data from Thessaloniki area are analyzed. The following conclusions can be drawn:

(i) In the morning, the frequency of the ABL height values shows a pronounced maximum at the first class (heights less than 200 m), the vast majority of the heights being lower than 800 m, a fact that could be attributed to atmospheric stability that commonly prevails during the morning in middle latitudes. At noon, ABL heights shift to higher values, being distributed more uniformly.

(ii) The ABL heights are strongly associated to the surface temperature and wind speed. For high wind speeds (>6 ms^{-1}) or high temperatures (>300 K) the ABL heights show their maximum values and are relatively uniformly distributed without any pronounced maximum.

(iii) Noon ABL heights exhibit a strong seasonal variation, with the higher values observed in summer, when solar radiation becomes more intense. On the contrary, morning ABL heights show a less pronounced seasonal variation, usually being lower than 200 m.

(iv) Very high values of ABL height, of the order of ~3,000 m, are observed in Thessaloniki during summer.

(v) The mean ABL height during summer sea breeze days is found to be slightly lower than the average ABL height during all summer days.

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