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Experimental Results from a Ceilometer, a Sun Photometer, Particle Counters and Meteorological Measurements in the Valley of Sofia

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Abstract. This study is aimed at analyzing ground based observations of aerosol optical depth (AOD), water vapour content (WVC), total ozone content (TOC), particle number concentrations and height of atmospheric boundary layer (ABL) carried out over mountain valley – Sofia ($42^\circ 39'$N, $23^\circ 23''$E, 591 m a. s. l.) and mountain Vitosha (900 m and 1350 m a. s. l.). The present investigation is a complex experiment on atmospheric boundary layer formation in a mountain valley and atmospheric aerosol optical and microphysical characteristics implemented by means of remote sensing devices (active and passive) as well as *in situ* measurements in 2014, 2015 and 2016. The ABL height and its aerosol structure were determined by a ceilometer CHM 15k. A sun photometer Microtops II was used to measure aerosol optical depth (AOD) and water vapor content (WVC). Measurements of particle number concentrations were carried out at different altitudes by three laser particle counters that allow the dispersion of different aerosol size-ranges, due to the ABL formation and development in a mountain valley, to be followed. Additional information concerning the meteorological situation during the experiment was obtained from a ground-based meteorological station and aerological sounding.

1 Introduction

The atmospheric boundary layer (ABL) is the lowest part the atmosphere with a primary importance due to the human activities implementation in it. The processes taking place in the ABL control the energy, humidity and atmospheric pollutants during the interaction between earth's surface and free atmosphere [1]. Till now, the processes taking place in the ABL were considered to have a local character depending on the location of the experimental site, for example, a mountain-valley, a coastal area or above the sea surface. Researches on global weather conditions and global climate began to acquire an increasing importance with the development of the remote sensing devices, active and passive, especially when used in monitoring from space [2,3]. This is especially true in the presence of meteorological phenomena such as hurricanes forming over the oceans and causing damage to settlements, seasonal fires in various parts of the continent, desert storms contaminating large regions and rapidly developing industrial regions of countries such as China, India Brazil, etc. that seriously pollute the environment [4]. ABL investigation is also interesting due to its complex structure in height and dynamic in time. Different methods exist, theoretical and experimental, for determination of the height of the different layers in the ABL [5]. There are attempts to create models accounting the real processes in the ABL as well as to standardize the parameters/characteristics of the ABL determined by the different methods [6]. In the present complex investigation, active (a ceilometer) and passive (a sun photometer and an ozonometer) remote sensing devices were used as well as instruments for in-situ measurements such as ground-based meteorological station, laser particle counters and the nearest radio sounding data. In our previous investigations we have determined, by lidar, the height of the different layers in the ABL, namely, a sable boundary layer (SBL), a residual layer (RL) and a mixing layer (ML). Sun photometers were used to determine aerosol optical depth (AOD) and water vapor content (WVC). The ABL influence on AOD and WVC behavior is also studied [7-9]. In this study, an attempt to access the ML influence on aerosol particles dispersion will be done. A number of investigations [10,11] have shown that the mixing layer height (MLH) is inversely proportional to the aerosol mass concentration, i.e at low MLH, the aerosol mass concentration is higher. In other studies [12], the influence of the different meteorological conditions, such as fog/haze and clouds, on the aerosol mass concentration is investigated as in fog/haze the MLH is lower and, respectively, the aerosol mass concentration is higher that could lead to complex ecological situations and serious health problems of the population in the region of research. The present investigation is aimed at determining the relation between the MLH over an urban area, situated in a mountain valley, and the aerosol particle concentration. For this purpose, aerosol particle counters were located at different heights in the valley allowing determination of the aerosol particle concentration changes in different size ranges in height and time during the ML development.

2 Instruments

Specifications of the ceilometer-lidar: light source – a microchip Nd:YAG laser with a central wavelength of 1064 nm; measuring range 30–15000 m; resolution 15 m; measuring time 60 s; pulse duration about 1 ns; pulse repetition rate 5–7 kHz; energy per pulse 8 μJ.

Specifications of the sun photometer Microtops II: optical channels: $\lambda = 380$ nm, $\lambda = 500$ nm, $\lambda = 675$ nm, $\lambda = 936$ nm and $\lambda = 1020$ nm, viewing angle: 2.5°, dynamic range $> 3 \times 105$, data storage: 800 records, power source: 4 AA alkaline batteries.

Specifications of the ozonemeter Microtops II: optical channels: $\lambda = 305.5$ nm, $\lambda = 312.5$ nm, $\lambda = 320$ nm, $\lambda = 936$ nm and $\lambda = 1020$ nm, viewing angle: 2.5°, dynamic range $> 3 \times 105$, data storage: 800 records, power source: 4 AA alkaline batteries.

Specifications of the LPC: a portable laser particle counter PC200 (manufactured by TROTEC Germany) capable of measuring in six size channels: 0.3, 0.5, 1, 2.5, 5 and 10 μm.

3 Results

3.1 Ceilometer data

The height of the SBL on 23.06.2014 was $H_{\text{sbl}} = 500$ (600) m, the RL height was $H_{\text{rl}} = 2300$ m. The ML formation started at about 09:00h and gradually increased up to $H_{\text{ml}} = 1000$ m at 11:45h and destroyed the RL. In the period between 12:45h and 14:45h rapid increase is seen in the ML development and its height reached $H_{\text{ml}} = 2100$ m that is the maximal for the day. Fair weather clouds (FWC) formed in the period from 15:00h and 18:00h at the top of the ML. At about 19:00h the RL and SBL started to form.

The next day that we shall discuss here is 07.07.2015. The height of the SBL was $H_{\text{sbl}} = 500$ m. The RL height was $H_{\text{rl}} = 1600$ m evidencing the intrusion of Saharan dust that is conformed also from the air mass backward trajectories. The new ML started to form at 09:00h and gradually destroyed the SBL. The RL destruction from the rising ML started at about 11:45h and it is fully destroyed at 12:45h when MLH reached 2000m. In the period between 12:45h and 15:00h MLH continued to increase and reached $H_{\text{ml}} = 2150$ m.

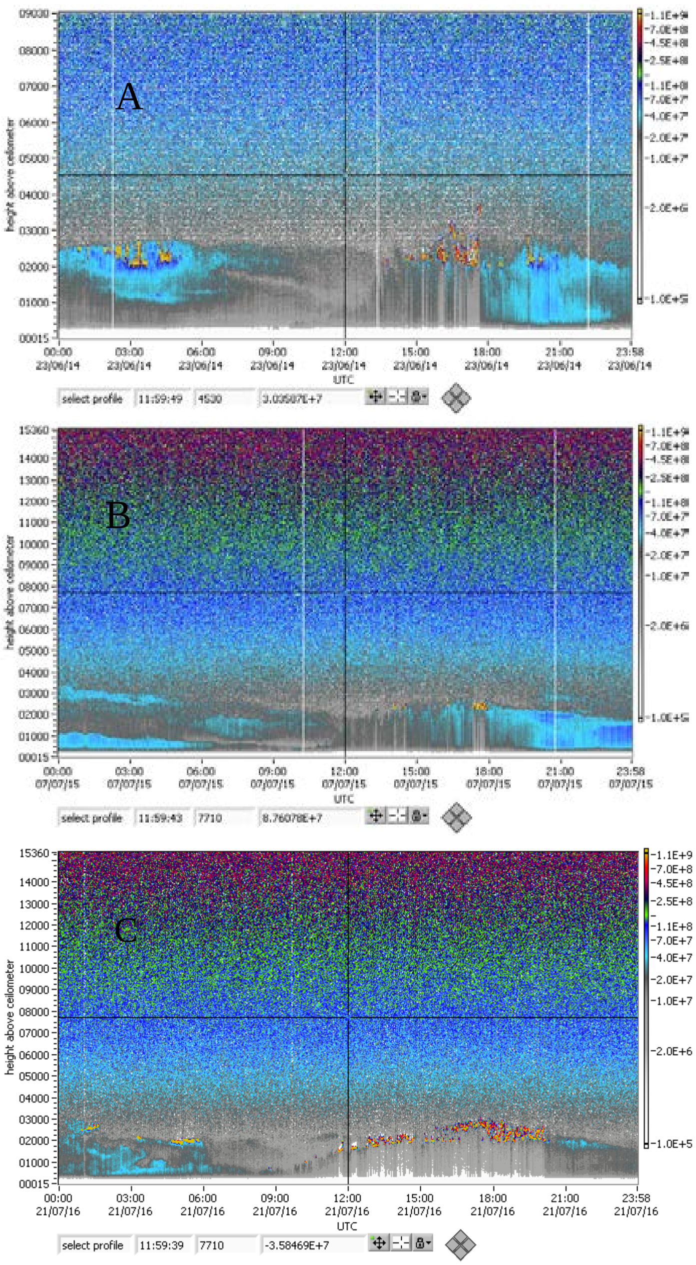

Figure 1: Height–time indicators constructed from the ceilometer CHM 15k data obtained on: A) 23.06.2014, B) 07.07.2015 and C) 21.07.2016.

The last day whose ABL development will be discussed is 21.07.2016. The SBL height was $H_{\text{sbl}} = 400$ m. The RL height was $H_{\text{rl}} = 1200$ m. ML formation started at 08:45h destroying SBL at about 09:30h. MLH reached $H_{\text{ml}} = 1500$ m at 12:00h. FWC formed after 12:45h when the MLH is 2000 (2200) m. The maximum MLH for the day including the clouds was $H + \text{ml} = 2800$ m. The RL formation started after 19:30 – 20:00h.

3.2 Aerosol optical depth, water vapor content and total ozone content data

The sun photometer and ozonometer Microtops II was used to measure aerosol optical depth and water vapor content and total ozone.

Three types of behavior were observed during the experiments: 1) AOD had highest values in the morning hours and decreased during the ABL formation (07.07.2015); 2) AOD had lower values in the beginning of the day and gradually increased (in some cases rapidly) during ABL development (23.06.2014); and 3) AOD increased around noon (or in the afternoon for about two hours, for example, from 11:30 to 12:30 LST) and decreased afterwards (21.07.2016). Higher morning AOD values (about 09:00 LST) could be related to the processes taking place in the ABL formation. Solar radiation reaches the earth's surface and heats it leading to evaporation and increase of the air humidity. Atmospheric aerosol is wetted and AOD increased. Higher AOD at the noon and early afternoon hours, when the ABL is developed could be related to high aerosol emission from dry surface or enhanced evaporation from wet surface uniformly dispersed in height due to the turbulence. The formation of scattered clouds on the top of the ABL is supposed to cause the gradual increase in AOD in some of the days. The rapid increase in AOD is usually caused by dense clouds that cover the Sun and in such cases the measurements were stopped. WVC exhibited also different behavior, but similar to the AOD one, during the three experimental campaigns: WVC was highest in the morning hours (about 09:00 LST) and gradually decreased. WVC was lower in the beginning of the experiment and gradually increased with the ABL formation (in some cases a rapid increase is observed). WVC increased in the afternoon (between 15:00 LST and 19:00 LST) and gradually decreased afterwards. The total ozone content (TOC) varied from 224 DU to 300 DU during the campaigns. A certain relation has been observed between the AOD behavior obtained at $\lambda = 500$ nm and total WVC, especially in the morning hours. Such relation is not observed in the TOC behavior.

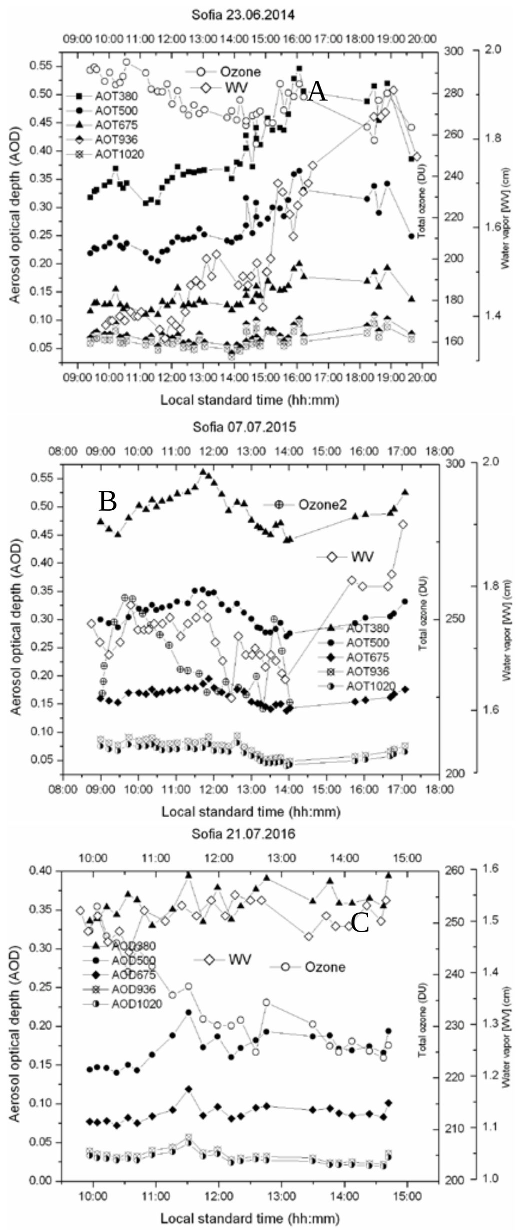

Figure 2: Daily variations in the aerosol optical depth values and water vapour column and total ozone values obtained over Sofia on: A) 23.06.2014, B) 07.07.2015 and C) 21.07.2016.

3.3 Meteorology data (radio sounding of the atmosphere over Sofia)

In the present investigation of the ABL development, we compare the ML height determined from the ceilometer's data with the one obtained by radiosounding. Usually, in such complex experiments is a tricky task to compare the data for a certain parameter obtained by different devices. The ML height determination by the ceilometer is based on the different aerosol concentrations in the ABL and the free atmosphere. When meteorological data are used, the MLH determination is based on the features of the potential temperature and specific humidity profiles [13]. Here the MLH is associated with the base of the elevated inversion in the potential temperature profile. The comparison shows that the obtained heights have different but close values and confirmed our assumptions when the two methods are used.

Figure 3 shows the aerological sounding data obtained on one of the experimental day considered in the paper. On 07.07.2015, the MLH was about 2000 m. The temperature was over 30°C. The wind had North-Eastern direction (not disturbed by the agglomeration). The air mass was relatively dry and almost insignificant cloudiness.

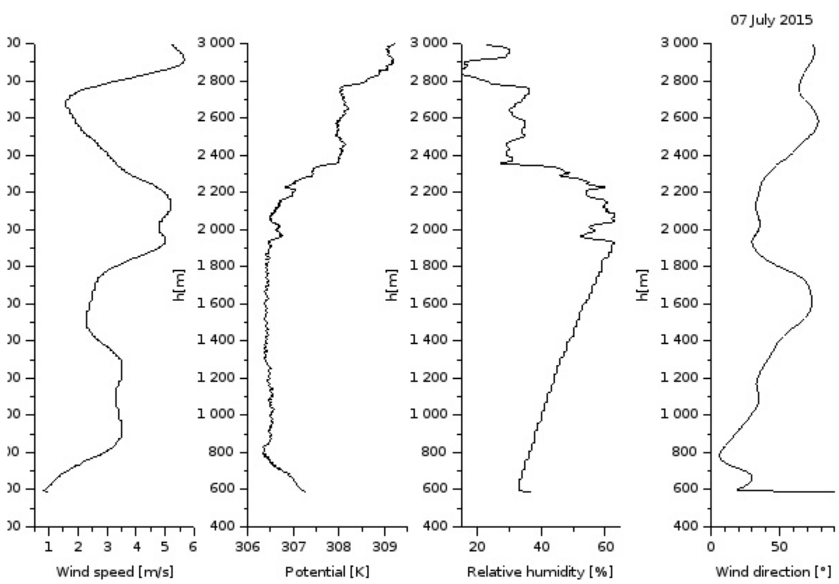

Figure 3: Wind direction and speed, temperature, and relative humidity over Sofia on 07.07.2015.

3.4 Aerosol particle number concentrations data at Sofia and Vitosha mountain

Present investigation is a complex experiment implemented by active and passive remote sensing devices and in-situ measurements of the aerosol particle number concentrations in different size ranges at three heights in the valley: 59 1m a.s.l. (Sofia), at 900 m and 1350 m (Vitosha mountain). This study is an extension of our previous investigations carried out from 2011 to now. The main task here is to determine the relation between the ABL height and the size and number concentrations of the particles at a certain height. Our goal is to identify which particle size is actively involved in the ABL formation and in some aspect will give guiding information about the ABL development and, in particular, its height supposed to best correlating with one or several particle sizes.

In the beginning of the measurements carried out on 07.07.2015, the maximum concentrations in all particle sizes ranges between 0.3 μm and 10 μm are observed in the period from 09:00 to 09:45h followed by a decrease influenced by the ABL development whose volume and, respectively, height increased after sunrise. The behavior of the particles of size $d = 0.3$ μm and $d = 0.5$ μm is similar. The shape of curves for the other measured sizes $d = 1$, 2.5 and 5 μm are also similar. The behavior of the particles of size $d = 10$ μm is different but closer to the one of particles of sizes $d = 1$, 2.5 and 5 μm (not shown here).

On 16.07.2015 a maximum in the particle number concentrations is observed at 10:00h due to the heavy vehicle traffic. The decrease of the concentrations of the particles of size 0.3 and 0.5 μm is a consequence from the ABL development and a minimum is observed at 12:30h (not shown here). The following three figures show the particle number concentrations behavior for sizes $d = 1$, 2.5 and 5 μm and minimum is observed around 12:30h but in the period between 11:00 and 12:00h the concentration increased due to the ML formation. Similar behavior but more fluctuating is observed for the particles of size 10 μm.

At height 900 m, on 07.07.2015 the behavior of particle number concentrations in size ranges $d = 0.3$, 0.5, 0.7, 1, 2.5 and 5.0 μm is similar with small differences. After 12:00h concentration of particles of sizes 0.7, 1.0, 2.5 μm increased. Fluctuations are observed in the particle number concentration for size 0.5 μm after 11:30h. The main difference between 591 m and 900 m is significantly higher concentration of particles of size 0.3 μm at the last one, namely, 42 000 p/L at 591 m at 09:15 – 10:00h and 125 000 p/L at 900 m at 09:00 – 09:45h. This difference shows the presence of temperature inversion. Other difference observed for all sizes is a local maximum about 11:00h evidencing that the ML reached height 900 m.

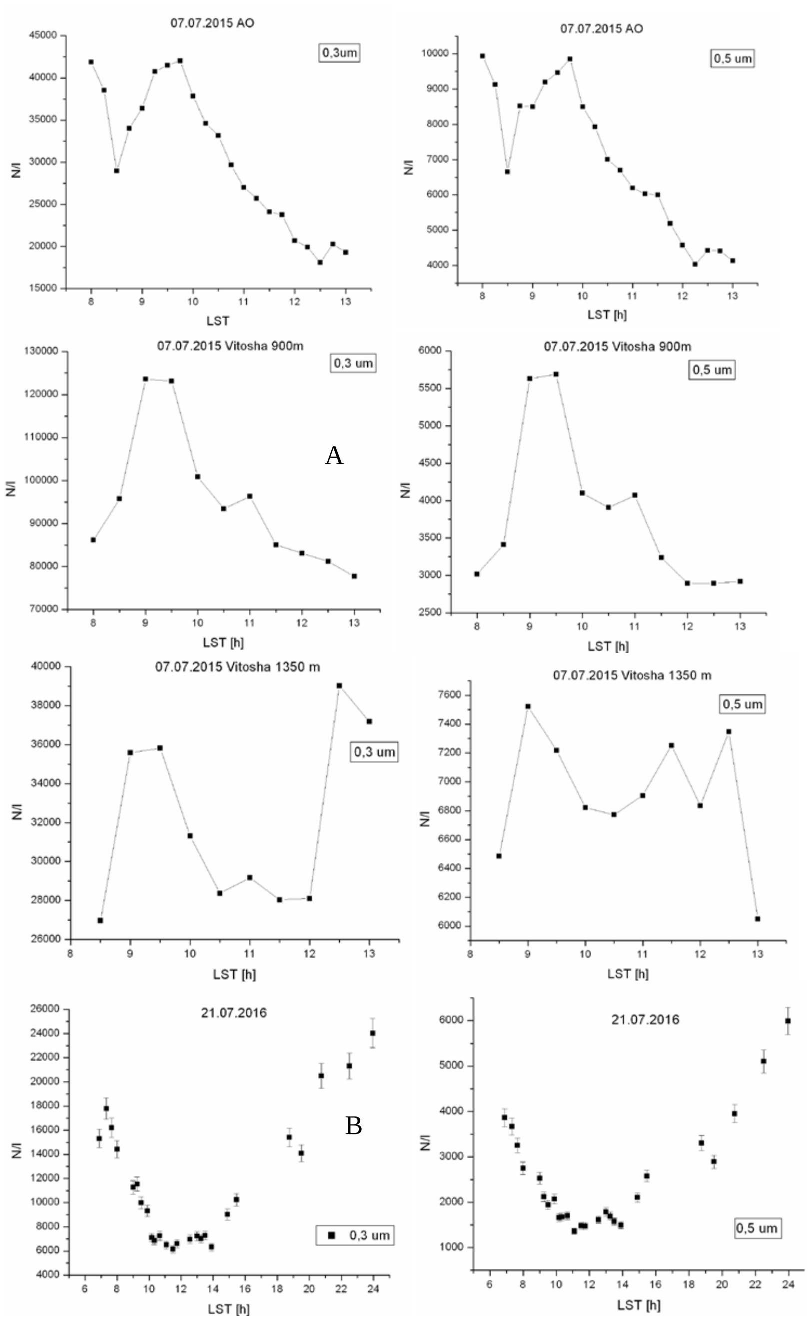

Figure 4: Evolution of fine particle number concentrations at Sofia (591 m), Vitosha1 (900 m) and Vitosha2 (1350 m) on: A) 07.07.2015, and B) 21.07.2016 at Sofia (591 m).

At height 1350 m, maximum in the particle number concentration in the morning hours is observed only for particles of size 0.3 and 0.5 μm. Particle number concentrations for the rest of the sizes ($d = 1$, 2.5, 5 and 10 μm) have similar behavior and low concentrations in the beginning of the measurements. A rapid increased in the concentration is seen after 12:00h in the frame of one hour up to 13:00h that is supposed to be due the ML reaching this height.

In the end of this sub-section, we shall point out that experiments with extended period of measurements were also carried out, for example, from 07:00 to 24:00h on 21.07.2016. The results obtained confirmed the statement that during the ML development and, respectively, the increase of its height, the aerosol particle number concentrations for sizes 0.3 and 0.5 μm decrease. Near the sunset when the sunshine is reduced, the aerosol particle concentrations increase as in this process the MLH decreases and two layers form – SBL at ground level and RL in height trapping mainly fine mode aerosol particles.

4 Discussion

The present investigation is a complex experiment on atmospheric boundary layer (ABL) formation in a mountain valley and atmospheric aerosol optical and microphysical characteristics implemented by means of remote sensing devices (active and passive) as well as *in situ* measurements in 2014, 2015 and 2016. The ABL height and its aerosol structure were determined by a ceilometer CHM 15k. A sun photometer Microtops II was used to measure aerosol optical depth (AOD) and water vapor content (WVC). Measurements of particle number concentrations were carried out at different altitudes by three laser particle counters.

The ceilometer data show that after sunrise the heating of the ground starts as well as the destruction of the SBL by the rising ML. The ML formation starts about 09:00h and ML reaches it maximum height at 12:00-13:00h in case of rapid development and at about 15:00-16:00h in case of slowly developing ML. The main role in AOD behavior in the morning have particles dispersed in the SBL and RL, during the day with the development of the ML, particles located in the ML and RL influenced the AOD values while after the RL destruction AOD behavior depends only on the particles in the ML. Aerosol particle number concentration in the beginning of the experiments depends mainly on the particles dispersed in the SBL and RL. During the formation of the ML, the particle concentration depends on its height. Particle number concentration decreases with the increase of the MLH, and is lowest when the MLH is maximal. These experiments were carried out in clear sunny days with relative humidity of about 50% so its influence is neglected.

According to the ceilometer data, the ABL height varied from 800 m to 2700 m in the observed period from 2014 to 2016. The AOD at $\lambda = 500$ nm changed between 0.14 and 0.26 in 2014. Mean AOD values were 0.35 ± 0.13 and 0.37 ± 0.16 in 2015 and 2016, respectively. The WVC ranged from 0.9 to 2.7 cm. Different types of AOD and WVC behavior were observed. The total ozone content (TOC) varied from 230 DU to 340 DU during the campaigns. Variations in the particle number concentrations at three altitudes were considered to be related to the daily ABL development. The present investigation is aimed at determining the size of the aerosols which participate most actively in ABL formation and the particle distribution in height in the different hours of the day which, in turn, determines the different states of the ABL as a stable boundary layer (SBL), a residual layer (RL) and a mixing layer (ML). Considering the data collected at Sofia on 07.07.2015, we could say that in the beginning of the experiment the concentration of all particles with diameter between $d = 0.3$ μm and $d = 10.0$ μm reached maximum value at 10:00LST and decreased afterwards due to the ABL development whose volume increases after sun rise. The maximum observed at 10:00LST is related to the vehicles traffic. The behavior of the concentration of the aerosol particle with diameters $d = 0.3$ μm and $d = 0.5$ μm is similar while the one of the bigger particles with $d = 10.0$ μm is closer to the behavior of the concentrations of the particles with diameters $d = 1.0$ μm, $d = 2.5$ μm и $d = 5.0$ μm. At height of about $= 900$ m the concentration of the aerosol particles with diameter $d = 0.3$ μm is significantly higher than at Sofia showing an existence of a temperature inversion. The second feature at this height is observed for all aerosol particle sizes at about 11:00LST (a local maximum) that could be due to the uplifted aerosol particles during the ABL development. At the third height considered here $H = 1350$ m, the data obtained for all size-ranges exhibit different behavior even for the close size-ranges as $d = 0.3$ μm and $d = 0.5$ μm. The common feature is the increase of the aerosol particle concentrations after 12:00LST that could be due to the ABL that reaches this height whose thermals uplift the aerosol particles.

5 Conclusion

In this study, the results obtained during three experimental campaigns carried out in the summers of 2014 – 2016 are presented. The main investigations were pointed at determining of the diurnal variations in the heights of the different layers in the ABL, and the AOD and WVC values in an atmospheric column. The interactions between ABL, AOD and WVC and particle number concentrations data are discussed. The main results can be summarized as follows: (1) The mean values of the heights of the different layers in the ABL were 150 – 400 m for the SBL, 1600 m for the

RL and 1700 – 2500 m for the ML; (2) Two kinds of ABL behavior were observed: ML rapidly increased and reached its maximum height about 12:30 LST and ML gradually increased and reached its maximum height about 15:00 LST; (3) Different types of aerosol optical depth and water vapor content behavior were observed, and (4) With the growth of mixing layer height, the consentration of aerosol particles decreased and when the ML height was maximal, the concentration was minimal. In our future work, an attempt will be done to use the results obtained to access the atmospheric aerosol influence on ecology and human health in the region of research.

Acknowledgements

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