Investigation of the aerosol optical characteristics in the planetary boundary layer over Sofia, Bulgaria by lidar, ceilometer and sun photometer

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The paper presents the results from atmospheric boundary layer height and aerosol optical depth measurements carried out in two different experimental sites in Sofia as well as from three-point measurements of aerosol number concentration. Four instruments (lidar, ceilometer, aerosol particle counter and sun photometer) were used in this study. Joint interpretation of sun photometer, aerosol lidar and ceilometer CHM 15k data allow the influence of the main part of the atmospheric aerosol in the planetary boundary layer to be accounted as well as the significant influence of aerosol layers and high clouds located in the area near to the tropopause on AOD values.

Introduction

The campaign was carried out in early summer 2009 (May 16 - May 23). This project is based on idea of comparing various air-quality aspects pertaining to the Sofia city "basin" with those pertaining to surrounding mountain areas [1]. The atmospheric aerosol is of fundamental importance to our understanding of climate change, ecological problems, ground-near ozone dynamics and human health. This paper presents some results of the planetary boundary layer (PBL) characteristics, obtained from the combined lidar-ceilometer-sunphotometer, aerosol particle counter and meteorological measurements made over Sofia (urban area, park zone and mountain). The main aim is determination of optical and microphysical characteristics of the atmospheric aerosol in three points of the valley and their variation during the planetary boundary layer formation over urban area, park zone and mountain.

The atmospheric boundary layer (ABL) climate may be considered as a component of the local climate. The height, structure and the processes taking place in the ABL depend directly on the solar radiation that reaches the earth surface. The structure and the processes taking place in the ABL are determined by the heat transfer between the earth surface and atmosphere. The height of the ABL determines the volume where the air pollutants are spread. Most of the aerosol is loaded within the first 2-3 km (by height) of the atmosphere over the urban area.

The paper presents the results from ABL height and aerosol optical depth measurements carried out in two different regions of Sofia.

Four instruments (lidar, ceilometer, aerosol particle counter and sun photometer) were used in this study.

The lidar measurements were accompanied by measurements of ceilometer CHM 15k, measurements of the aerosol optical depth in the visible and near infrared regions of the spectrum using Microtops II sun photometer and measurements of the aerosol size distribution by LPC (Laser-based particle-number concentration counter HHPC-6) in May 2009.

Instruments

In this paper measurements of the structure of aerosol layers, aerosol optical characteristics and aerosol number concentration performed using a ground based backscattering lidar, commercial five-channel hand-held Microtops II sun photometer, ceilometer CHM 15k and aerosol particle counter are presented. The ground based aerosol lidar is based in Laser–Radar Laboratory at the Institute of Electronics. The ceilometer CHM 15k, Microtops II sun photometer and aerosol particle counter HHPC-6 (MetOne) are based in Astronomical Observatory (AO) at the Sofia University "St. Kliment Ohridsky", Borisova gradina Park at a distance about 300m away from Tsarigradsko shosse Blvd. The main parameters of the four devices are:

Specifications of the lidar (developed in the Institute of Electronics): transmitter – a standard Nd - YAG laser (operational wavelength 532 nm, pulse duration and energy 15–20 ns and 10–15 mJ, repetition rate 12.5 Hz; receiving antenna – a Cassegrainian telescope (main mirror diameter 150 mm, equivalent focal length 2250 mm); photodetector – a PMT with an interference filter (1 nm FWHM); data acquisition and processing set – a 10 bit 20 MHz ADC and a PC [4].

Specifications of the sun photometers Microtops II: optical channels: λ=380nm, λ= 440nm, λ=500 nm, λ=675 nm, λ=936 nm and λ= 1020nm, viewing angle – 2.5°, dynamic range > 3x105, computer interface RS 232, data storage – 800 records, power source – 4 x AA alkaline batteries.

Specifications of the ceilometer-lidar: light source - laser protection class 1M under DIN EN 60825-1, measuring range 30-15000m, resolution 15m, measuring time 60s, measuring principle- optical (lidar), wavelength 1064 nm, pulse duration about 1ns, pulse repatition rate 5-7kHz, energy per pulse 8μJ.

Commercial ceilometer CHM 15k is manufactured in Germany by Jenoptic Laser, Optik, Systeme GmbH.

Specifications of the HHPC-6: This instrument samples and classifies aerosol particles into six particles-size ranges (geometric particle diameter 0.3-0.5 μm, 0.5-0.7 μm, 0.7-1 μm, 1-2 μm, 2-5 μm and >5 μm) giving output date in terms of number of particles per litre of air samples. The HHPC-6 used in the pilot campaigns is portable, has a sampling flow rate of 2.83 litres per minute and can be programmed in various manners [5].

Specifications of the meteorological station: Meteorological station is situated in the area of the AO, Borisova gradina Park. At the AO the total solar radiation, wind speed and direction sensors were located at a height of 10 m; those for determining of the air temperature and humidity − at 2 m height and those for measuring of the precipitation − at 0.5 m. The ground level ozone concentration was measured by TECO 49 UV photometer (determines the ozone concentration by measuring the attenuation of light due to ozone in the absorption cell at a wavelength of 254 nm). Due to the inherent stability of the UV adsorption technique used it could be considered that the ozone concentrations reported here to be within ± 5 ppb. The corresponding measuring equipment is summarized in Table I [3].

TABLE I Meteorological station equipment

Sensor	Parameter	Units
TECO 49	O3	ppb
05103 YOUNG wind monitor	Wind speed and wind direction	m/s
SP1110 Skye pyranometer	Total solar radiation	W/m2
MRI	Precipitation	mm
Vaisala HMP45C	Temperature	°C
Vaisala HMP45C	Relative humidity	%

Experimental results

Lidar data and ceilometer data

The ceilometer CHM 15k is located at AO, Borisova gradina Park at a distance of about 7km from the Institute of Electronics. The ceilometer data are obtained in the range between H=100m and H=15000m.

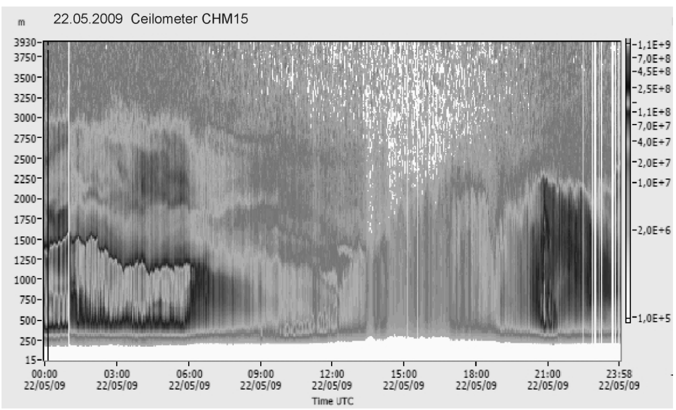

Fig.1. Height–time indicators constructed from the ceilometer CHM 15k data obtained on 22.05.2009

A few features (specifications) of the ceilometer should be pointed out, namely, the transmitter works at high repetition rate f = 4-5kHz at wavelength λ=1064nm, the receiver works in a photon counting mode and information is received from a quite higher height than from the lidar data. The device operates 24-hours continuously in automatic mode.

In this investigation we are going to discuss only the data at heights close to the ABL and no higher than H=4000m.

The longer wavelength ensures higher sensitivity to influence of humidity during the interaction with atmospheric aerosol.

Fig. 1 shows the ceilometer data obtained on 22.05.2009. The experiment started at 00:00 LST and finished at 23:58 LST. The development of the stable boundary layer (SBL), the residual layer (RL) and the CBL could be followed in time. In the first three hours period the SBL at height HSBL=200 m remained from the previous night is seen as well as RL divided in two parts, the first one at height HRL1=1000m and second one at height HRL2=2000m. The RL height decreased constantly and the RL is fully destroyed at 13:30 LST. The new ML starts to form around 09:30 LST and gradually and constantly increases up to height of about HML=1000 m at 12:00 LST and at 15:00 LST the ML height is about 2000m.

In the ceilometer data a layer is observed which is located above the RL and reaches height of about H=3000m and in particular cases up to H=4000m. During the experiments the height of the SBL reaches H=200m but is not very will-defined. The RL height is in the range of HRL=1500-2000m. The ML height reaches HML=2000-2250m around 15:00LST, i.e. about 1-1.5 hours later than the lidar data show. The ceilometer CHM 15k enables observation of formation of the atmospheric nocturnal stratification after sun set.

The lidar is located in the building of the Institute of Electronics at BAS.

On the next graphic (Fig. 2) lidar data obtained on 21.05.2009 are shown. The experiment started at 07:25 LST and finished at 13:30 LST. On the first lidar image at 07:25 LST aerosol layer at height of about H=200 m is observed, this is SBL, and the second layer at height of about 1200-1400 m is the RL remained from the previous day. On the second image two layers can be seen. At 10:30 LST the mixing layer reached height HML=1000 m and destroyed the residual layer at this height.

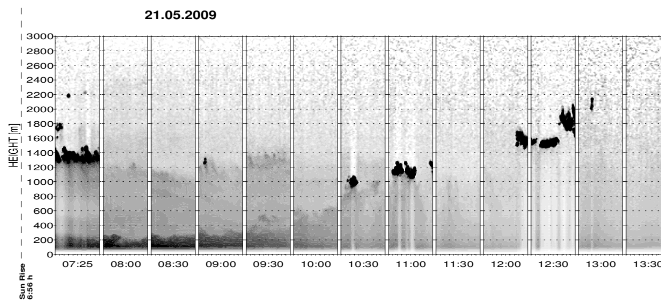

Fig.2. Height–time indicators constructed from the lidar data obtained on 21.05.2009

According to the lidar data aerosol layer with higher humidity is observed at height of about H=1200 m at 11:00 LST. Later this can be seen on the image at 12:00 LST, where a layer at height 1600m is observed above the ML. At 12:30 LST the ML reaches H=1600 m. At 13:00 LST the upper border of the mixing layer is about H≈2000 m.

In summary, the lidar data for the whole period of experiments from 12.05.2009 to 26.05.2009 show that: during all days the height of SBL is in the range of HSBL=200-300 m and it exists until 08:30-09:30 LST. The height of RL varies from HRL=1400 m on 21.05.2009 to HRL=2000-2200m on 12.05.2009 and 19.05.2009. The RL is fully destroyed in the period between 11:00LST and 13:00LST.

The ML starts to gradually increase between 08:30 LST and 11:30 LST. A rapid increase in the ML height is seen after that time and around 13:00 LST ML reaches height of about HML=1800-2200 m. The rapid increase in the ML height is usually in the range of ΔH=400-600m.

Sun photometer data

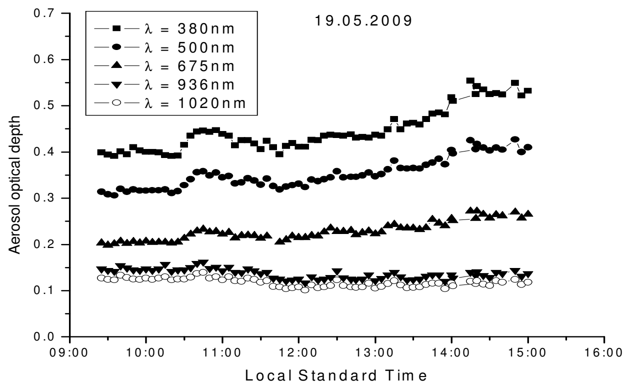

Fig.3. Daily variation in the aerosol optical depth at five wavelengths (λ=380nm, λ=500nm λ=675nm λ=936nm λ=1020nm) obtained by sun photometer on 19.05.2009

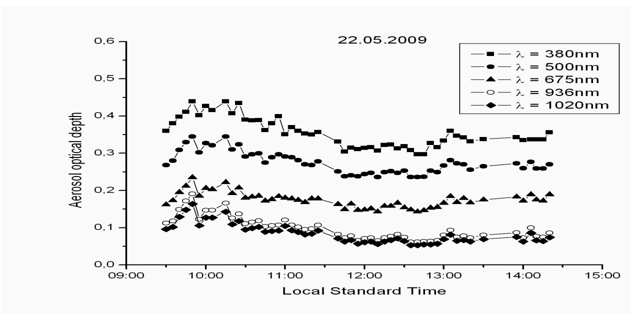

Fig.4. Daily variation in the aerosol optical depth at five wavelengths (λ=380nm, λ=500nm λ=675nm λ=936nm λ=1020nm) obtained by sun photometer on: 22.05.2009

Microtops II sun photometer has been located right next to the ceilometer CHM 15k at Astronomical Observatory, Borisova gradina Park in the period from 19.05.2009 to 22.05.2009 (Fig.3 and Fig.4). The experimental AOD data obtained at λ=500 nm can be summarized as follows: The AOD varied in the range from 0.22 to 0.41 in clear atmosphere for the period of measurements. When clouds are presented, AOD reached 0.74 (0.8). The height of the cloud base according to ceilometer data is in the range 8-11 km.

Two main areas can be separated in the AOD behavior obtained from the sun photometer data: the first one is from the beginning of the experiment at 09:00 (09:30) LST until 11:00 (11:30) LST when variations in the AOD values are seen and the second one in the period between 12:00 LST and 15:00 LST when AOD is almost constant. The only case when AOD gradually increased after 12:00 LST from 0.3 to 0.41 is during the experiment on 19.05.2009 which could be due to advection from other pollutant source (from different region).

HHPC-6 particle counter data for aerosol concentration in the range from 0.3-1μm

Fig.5 shows the data from the aerosol particle counter measurements carried out at three experimental sites in the period between 16.05.2009 and 23.05.2009: urban area (next to Tsarigradsko Shossee Blvd.), Astronomical observatory at

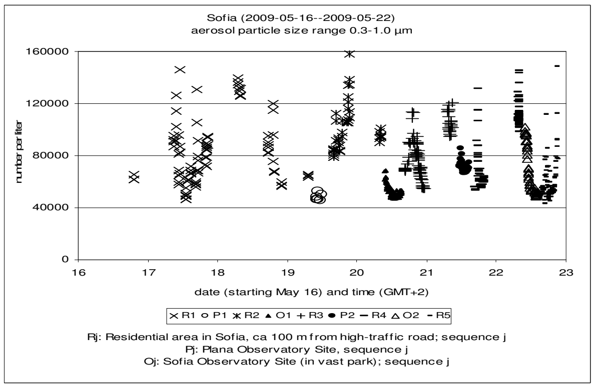

Fig.5. Daily variation in the aerosol size (ranges 0.3-1.0 μm) obtained by aerosol particle counter on16- 22.05 2009

Borisova gradina Park and in the Central Geophysical Station at Plana Mountain. The data can be summarized as follows: The aerosol concentration in the range 0.3-1μm varies from 4000 to 15 000 per liter. Lowest concentrations usually are seen at noon (when ML is developed) for the three experimental sites. Highest concentrations are measured in the urban area in morning and afternoon during traffic jam hours.

Meteorology during the experiments

Astronomical observatory (Borisova Gradina Park)

The temperature varied from 100C in the morning to 300C in the afternoon. The relative humidity varied from 98% in the morning to 30% in the afternoon. The variations were in opposite direction of the temperature one. The wind speed was from 0.1m/s to 0.6m/s. The maximum of solar radiation in that period slowly varied in the range of 900-980W/m2. (Fig.6.)

The ground ozone concentration varied from C=10ppb in the morning hours to C=45ppb at noon.

Central Geophysical Station – Plana Mountain

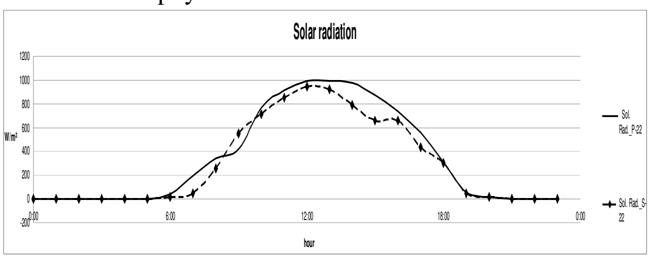

Fig.6. Daily variation of solar radiation obtained by meteorological station on 22.05.2009.

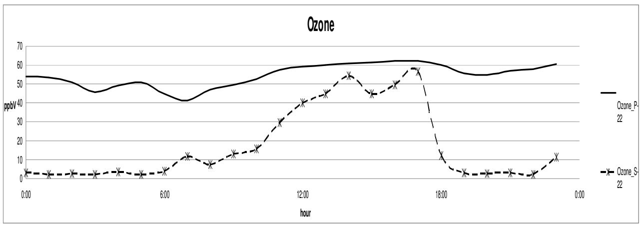

Fig.7. Daily variation of ozone concentration obtained by meteorological station on 22.05.2009.

The temperature varied from 8^0C in the morning to 21-25^0C in the afternoon. The relative humidity varied from 98% in the morning to 38% in the afternoon. The wind speed was from 0.8m/s to 3m/s and a few maxima are observed during the day. The maximum of solar radiation varied in the range from 600W/m2 to 1000W/m2 and the variations were higher that the one at AO. The ground ozone concentration varied slowly than the one at AO and it changed in the range from C=40ppb to C=60ppb. (Fig. 7)

Discussion

In the beginning of the analysis we shall pay attention on the new instruments used for the first time in Bulgaria during this complex experiment. First of all, the inclusion of ceilometer CHM 15k should be mentioned. The device allows observation of the aerosol structure of the atmosphere up to the tropopause which is important when accounting the influence of high clouds on PBL development.

The second aspect of our investigation is the use of LPC to obtain the size distribution of the aerosol particles which take part in processes taking place in the PBL of the atmosphere over urban area situated in a mountain valley.

The third aspect of this study is the three-point measurements carried out in the valley of Sofia for the first time: IE (lidar and ozonemeter), AO, Borisova gradina Park (ceilometer, meteostation, sunphotometer and LPC) and Central Geophysical Station at Plana Mountain (meteostation, ozonemeter and LPC).

The data from the different devices will be discussed separately as well as the options for their joint interpretation. Our long-term lidar observations on aerosol structure of the PBL in the valley of Sofia are one of the bases of these investigations. The second one is the long-term meteorological observations, including ground ozone concentration, in the regions of Rozhen, Ahtopol, Sofia and Plana. Lidar data provide detailed picture of the processes taking place in the PBL (up to 2000m) and the structure of the different layers in the ABL: height and life time of the SBL, RL and ML.

The celiometer CHM 15k data allow estimation of the influence of the whole atmospheric layer up to tropopause on the PBL development in the valley of Sofia (for example the experimental data on 15.05.2009).

Joint interpretation of sun photometer, aerosol lidar and ceilometer CHM 15k data allow the influence of the main part of the atmospheric aerosol in the PBL to be accounted as well as the significant influence of aerosol layers and high clouds located in the area near to the tropopause on AOD values.

The first comparison of the lidar data for the aerosol structure of ABL and ground measurements of the aerosol size distribution in time and space show the perspective (potential) and direction for future development of these investigations for scientific, ecological, biological (medical) purposes.

In conclusion, the main aim of this experiment will be discussed, namely, the hypothesis for homogeneity of the atmospheric pollution in horizontal and vertical direction in case of fully developed ML over an urban area in a mountain valley [2].

Summary

The comparison between the lidar data for the ML height in the region of IE and the ceilometer CHM 15k data for the ML height in the region of AO show: the ML in the region of AO develops with delay of about 1-1.5 hours compared to the formation of the ML in the region of IE, particularly, the time when ML reaches its maximum height. The maximum height of the ML in the region of AO in some cases is 100(200) m higher than the one measured in the region of IE.

When the maximum height of ML is reached, all of the conservative atmospheric components should be the same in whole layer. On fig. 7 is clearly seen that ground ozone concentration in the region of AO approaches the values obtained in the Central Geophysical Station at Plana Mountain around noon. The Central Geophysical Station is located at altitude approximately 600m higher than the altitude of AO. There is similar relation between the ground ozone concentration measured in AO and the one measured at “Kopitoto” Station, which is located at altitude 1350m a.s.l.

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