Bulgarian Journal of Meteorology and Hydrology

Национален институт по метеорология и хидрология

National Institute of Meteorology and Hydrology

Bul. J. Meteo & Hydro 28/2 (2024)

Application of radio sounding data in atmospheric boundary layer study related to PM_{10} pollution in Sofia

Orlin Gueorguiev[1], BlagorodkaVeleva[1*], Elena Hristova[1], Ekaterina Batchvarova[2], Maria Kolarova[1]

[1] National Institute of Meteorology and Hydrology, 66, Tzarigradsko Shose, Sofia 1784, Bulgaria
[2] Climate, Atmosphere and Water Research Institute, Bulgarian Academy of Sciences

Abstract: Sofia valley is characterized by specific meteorological conditions because of its complex terrain, surrounding mountains and the presence of different industrial, traffic and domestic pollutant sources. Particulate matter is a serious problem of urban air pollution in many Bulgarian cities, including Sofia. Therefore, it is important to study in greater detail the impact of the meteorological factors on PM_{10} mass concentration. The vertical profiles from radio sounding and the meteorological parameters from the synoptic station are analysed in relation to PM_{10} mass concentration. Wind, humidity and potential temperature profiles are used to determine the Atmospheric Boundary Layer (ABL) height from the radio sounding data, special attention being paid to the days with exceedances of PM_{10} daily limit value of 50 $\mu g.m^{-3}$. PM_{10} concentrations from five urban and one high altitude automatic monitoring stations (AMS) are used to study the daily and seasonal variations of PM_{10} during the period 2012-2014. High correlations of PM_{10} daily concentrations (0.8 - 0.95) are obtained between the data from the different urban stations. The effect of precipitation, mean wind velocity, prevailing wind direction on PM_{10} pollution levels is considered. Well distinguished seasonal pattern is revealed, with maximum during the cold period of the year, corresponding to the minimal values of ABL height. The lowest concentrations are measured during summer, when intensive turbulent mixing is present. The opposite seasonal variation is registered at station “Kopitoto”, situated at 1350m a.s.l. on the slope of the Vitosha Mountain, suggesting that in winter the station is often above the urban mixing layer, while in summer the urban ABL may incorporate the entire slope. Stagnant weather conditions and inversions are the major factor contributing to the high PM_{10} values registered during the cold period

[*] blagorodka.veleva@meteo.bg

in Sofia. PM_{10} concentrations 3-5 times higher than the daily limit values are observed in winter days and anticyclone synoptic situation, when the estimated ABL height is below 150-200 m.

Keywords: PM_{10}, urban air pollution, ABL, radio sounding

1. INTRODUCTION

The mixing conditions in the ABL are an important meteorological factor for the dispersion of air pollutants, in particular in urban areas. The Mixing Layer Height (MLH) is an important parameter of the ABL, influencing strongly the level of air pollution. The MLH varies with local relief and climate, synoptic situation, meteorological conditions, thermodynamic stratification, land cover and exchange processes between surface and atmosphere. The methods applied to study MLH using different techniques, such as meteorological radio-sounding, ground-based remote sensing, comparing their advantages and disadvantages are discussed in Caicedo et al (2017); Danchovski (2019); Emeis et al. (2008); Fearon et al. (2015); Stull (1988); Seibert et al. (2000).

There are no remote sensing systems for vertical sounding of the atmosphere in Sofia at the NIMH, but only aerological observations, performed daily at 12:00 UTC at the Central Aerological Observatory of Sofia. The data from the radio-soundings are used in many tasks related to air quality problems in Sofia (Batchvarova et al., 2006, 2008, 2011; Danchovski, 2016; Veleva et al., 2010). This kind of studies are important for understanding the processes leading to elevated levels of air pollutants, in particular for the urbanized area of the Sofia city, with population of 1.26 million, situated in a deep valley (Sofia Valley).

Sofia valley has a floor elevation in the range of 500-600 meters (mean altitude of about 550 m). It is surrounded by the Vitosha mountain to the south with its highest peak Cherni Vrah of 2290 m and the Lyulin mountain to south-west. The Balkan mountain (Murgash peak,1687 m) is situated to the north and northeast, and, parts of the Sredna Gora and Lozen mountain – to the south-east (1226 m height). The Vakarel mountain is to the east (700-900 m). Sofia valley is 75 km long (in NW to SE direction) and between 5 and 20 km wide.

The unfavourable meteorological conditions (Andreev et al., 2004; Batchvarova et al., 1994; Bluskova et al., 1983) in the city, which is the most densely populated area in the country, and diverse urban pollution sources (industrial, traffic and domestic) require enhanced monitoring programs and more effective measures to improve air quality, specifically for PM_{10} and $PM_{2.5}$ (Nat. Rep. MoEW, 2016).

The air pollution with particulate matter in Sofia is characterized by a distinguished seasonal pattern with peaks during the cold period of the year (Hristova and Veleva, 2013; Veleva, 2006). The relation between air quality and mixing layer height is known, but the details vary with location. Recent studies in different regions and cities are presented in (Guarnieri et al., 2015; Pal et al. 2012; Tang et al. 2016).

The main objective of the current work is to evaluate the relation of PM_{10} pollution to the mixing conditions characterized by Mixing Layer Height (MLH), precipitation and other meteorological parameters.

2. METHODOLOGY

2.1. The study area and particulate matter data

The PM_{10} daily concentrations are used to study the impact of mixing height on the daily and seasonal variations of PM_{10}. The PM_{10} data were obtained from experimental campaigns at the NIMH and from the Executive Environmental Agency (ExEA) automatic monitoring stations (AMSs), covering the territory of Sofia.

PM_{10} sampling was carried out at the Central Meteorological Observatory (CMO) in Sofia (42.655 N, 23.384 E, at 586 m a.s.l) of the NIMH, which is situated in the south-east part of the city (Figure 1, blue dot). 24-hour PM_{10} samples were collected during the winter and summer experimental campaigns (2012–2014) using TECORA low-volume air sampler on 47 mm quartz fiber filters according to the EN-12341 standard.

PM_{10} daily concentration data were provided by ExEA for 6 AMSs: AMS “Pavlovo”, AMS “Hipodruma”, AMS “Orlov Most”, AMS “Nadejda”, AMS “Drujba” and background AMS “Kopitoto” (Figure 1). The urban AMS stations are positioned at altitude of 550-600 m a.s.l. AMS “Kopitoto” is situated on the northern slope of the Vitosha mountain at 1350 m a.s.l., (south-westward of the Sofia city). AMS “Drujba” is located closest to the NIMH CMO and the PM_{10} sampling station.

During the period 2012-2014, no significant change in the sources of particulate matter in the Sofia region was reported by the environmental authorities.

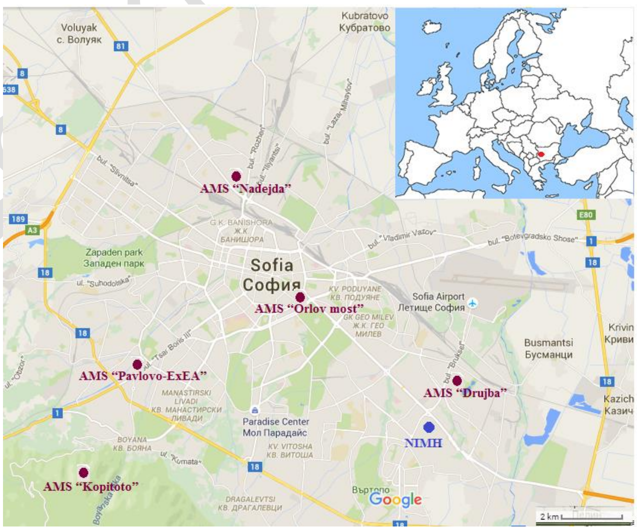

Fig. 1. Map with Central Meteorological Observatory (blue dot) and the automatic monitoring stations of the ExEA at the MoEW (red dots).

2.2. Meteorological data

Synoptic and aerological data from the NIMH and processed information from the NIMH Monthly Bulletin were used to describe the local meteorological conditions.

The aerological soundings were performed daily at 12:00 UTC with high vertical resolution of 5- 6m by Vaisala MW41 sounding system since July 2013 at the Central Aerological Observatory (CAO) WMO 15614. Before that, for 2012 and the beginning of 2013, the data were obtained by MW21 with vertical resolution of 10-12 m. Vertical profiles from 588 to 3000 m a.s.l. were extracted for the analysis to incorporate the ABL and overpass the highest mountain top.

The mixing layer height (MLH) was determined from the noon vertical profiles of potential temperature (θ), wind speed (WS) and wind direction (WD), and relative humidity (RH), based on expert assessment.

3. RESULTS AND DISCUSSIONS

3.1. Seasonal and inter-annual variation of PM_{10} in Sofia

Particulate matter concentrations are known to vary across broad temporal scales: diurnal, weekly, synoptic, intra-seasonal, seasonal and inter-annual. In addition, short- and long-term trends resulting from imposition of control strategies can be registered (EEA Report, 2020; EEA, 2024). In this study, the mean daily concentrations are the basis to analyze PM_{10} pollution in the Sofia region.

The EU (EU Directive 2008/50/EC) and the national limit value for PM_{10} daily concentration is 50 $\mu g.m^{-3}$, not to be exceeded more than 35 times per calendar year, and for the mean annual PM_{10} concentration it is 40 $\mu g.m^{-3}$. During 2012, 2013 and 2014, the years of this experimental study, the mean annual PM_{10} concentrations were above the limit value of 40 $\mu g.m^{-3}$ at all Sofia urban stations. The number of days with exceedances at 4 urban Automatic Monitoring Stations (AMSs) varied between 59-108 days in 2012, 62-110 days in 2013 and 55-105 days in 2014 (Report RIEW 2014; Nat. Rep. MoEW 2016). To demonstrate the seasonal pattern, the PM_{10} mean quarterly concentrations from 4 AMSs urban monitoring stations and 1 high altitude station, "Kopitoto", are plotted in Figure 2. The number of days with precipitation for every quarter is presented by bars, with highest impact during the cold period of the year. Well distinguished seasonal pattern is observed with maximums during the cold period of the year at all urban stations. Minimums are observed in the summer months when intensive turbulent mixing and high MLH are present, resulting in lower measured concentrations. The PM_{10} concentrations at the "Kopitoto" station are lower in winter in contrast to the urban stations. In summer, the "Kopitoto" station falls often within the well-developed summer ABL, so the PM_{10} concentrations are similar to those measured at the urban stations (third quarter of the year). A similar pattern with maximum in the winter months, is reported for TSP (Total Suspended Particulate), PM_{10} and $PM_{2.5}$ in Salt Lake City (Whiteman et al., 2014).

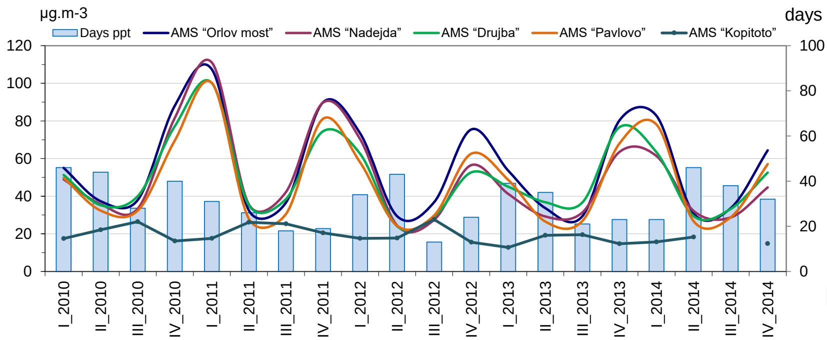

Fig. 2. Mean quarterly PM_{10} concentrations at 4 urban AMSs in Sofia and the mountain AMS "Kopitoto". The number of days with precipitation for every quarter is presented by bars.

The inter-annual variation shows that the highest PM_{10} values, as well as the highest mean annual value for the considered period are registered during the first quarter of 2011, which may be attributed to the role of precipitation.

When examining the variations of the PM_{10} daily values at the four urban stations, a synchronous change from day to day is noted. This feature points to a well-mixed ABL over the city. Thus, high coefficient of determination (R^2 between 0.81÷0.97) is calculated between all urban monitoring stations depending on the pair of stations and period of the year. No correlation (R^2~0.03) is found between the mountain AMS "Kopitoto" and the urban AMSs on an annual basis. Analyzing the daily values from the longer period 2011-2015, the correlation between AMS "Kopitoto" and the urban stations is estimated for summer, winter and transient seasons. In the winter months December, January and February, there is no correlation (Pearson correlation coefficient, r~0.12). Moderate correlation is obtained for the summer months June, July and August, r = 0.20 - 0.48 depending on the distance from the urban station to the "Kopitoto" station. Higher correlation is obtained for the transient months March, October and November, r~0.50-0.53; for April, May and September r increases from 0.51 (AMS "Nadejda") to 0.65 (AMS "Pavlovo"). This is a direct indication of more intensive mixing during these months. High correlation is also obtained between the PM_{10} daily values at the NIMH, AMS "Drujba" and the "Pavlovo" stations during the experimental campaigns.

Precipitation plays an important role in self-cleaning of the atmosphere and in improving air quality. To analyze how the precipitation events affect the PM_{10} concentrations in Sofia, the days of the 2012-2014 period were divided in several groups: (i) days without any precipitation, or with daily sum of precipitation less than 0.1mm; (ii) days with 0.1-1 mm precipitation; (iii) days with 1.1-3 mm precipitation; (iv) days with 3.1-7 mm precipitation; (5) days with 7.1-25 mm precipitation; (6) days with more than 25.1 mm precipitation. The mean PM_{10} concentrations for each group and each of AMS stations are shown in Figure 3. The difference between days without precipitation and days when precipitation occurs is clear for all stations.

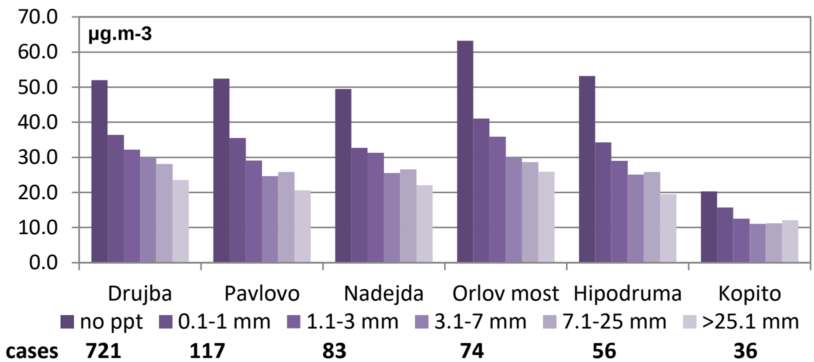

Fig. 3. Mean PM_{10} concentrations for days with different amount of precipitation for the 6 AMSs for the period 2012-2014

The number of cases for all AMSs for each precipitation gradation is given in Figure 3. Days without precipitation, noted as “no ppt”, are the most frequent (721 cases). These cases include days when the daily precipitation sum is < 0.1mm. The decreases in mean PM_{10} from group (i) to group (ii) vary from 23% for AMS “Kopitoto” to 32-36% for the urban stations. The tendency of decrease in PM_{10} concentration with increase of the daily precipitation sums persists in the next groups.

Comparing the inter–annual variations of PM_{10} to the precipitation regime during these 5 years, Table 1, reveals that the highest air pollution values correspond to the driest year of the studied period (2011). Thus, with the tendency for drier climate in the region, higher level of air pollution can be expected, if the emissions remain unchanged.

Table 1. Mean annual PM_{10} concentrations for AMS, annual sum of precipitation at the NIMH CMO station and number of days with daily precipitation ≥0.1mm

Year	Annual ppt sum [mm]	N days precip. ≥0.1mm	AMS Drujba	AMS Nadejda	AMS Orlov M.	AMS Hipodruma	AMS Pavlovo	AMS Kopitoto
2010	719.8	158	50.6	49.5	54.6	47.1	46.0	20.6
2011	405.6	94	61.9	70.0	66.3	62.8	59.7	22.4
2012	561	114	42.1	44.7	53.9	47.7	43.7	19.6
2013	501.4	118	49.0	41.3	52.4	41.5	43.2	16.6
2014	1063.4	139	44.7	41.6	53.0	46.5	47.7	

3.2. Mixing Layer Height (MLH)

The MLH is of prime importance for the dilution of pollutants emitted within the ABL. The elevated temperature inversion or entrainment zone that marks the top of constant potential temperature layer is called Mixing Layer Height and serves as a lid for the pollutants, keeping them within the ABL.

The MLH is estimated from radio-sounding data accounting for the biggest vertical gradient in the profile of the potential temperature (θ) (Seibert et al., 2000; Stull, 1988). For days when the θ profiles are changing very slowly with height, these gradients are not sufficient to estimate the MLH, so the gradients in the profiles of wind speed (WS), wind direction (WD) and relative humidity (RH) are used. The profiles of θ and RH are often in correlation and show clearly the ABL height.

The MLH is changing throughout the day due to the changing generation of mechanical and convective turbulence. This growth can be estimated based on the surface measurements of the meteorological parameters (variation in solar radiation, heat balance, temperature, wind direction and speed), on the potential temperature gradient in the free atmosphere, and on the synoptic situation (Batchvarova and Gryning, 1991). The atmosphere is well mixed around noon when radio-sounding is performed and the highest MLH is expected for Sofia in the range of 800 – 1800 m in summer, spring and autumn and 100 – 400 m above the ground in winter. During the night, the MLH has much lower values of about 50-100 m above the ground in winter and within 200 – 300 m during summer, because of the stable stratification of the nocturnal ABL. In this analysis, the MLH is determined from 12 UTC radio-sounding and is representative for the developed convective ABL.

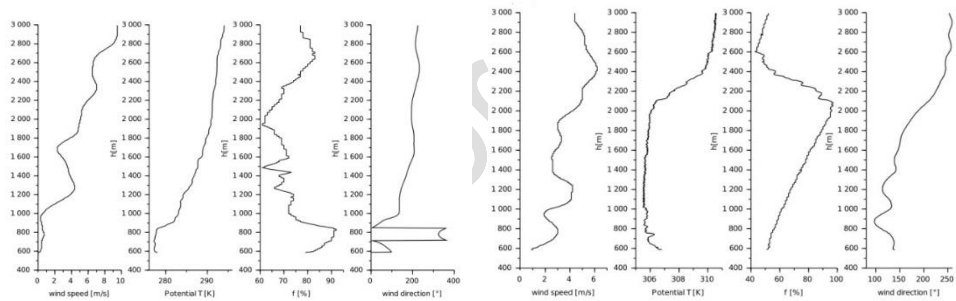

Fig.5. Vertical profiles of wind speed, potential temperature, relative humidity and wind direction for February 6, 2014 (left) and July 30, 2014 (right)

Examples of radio-sounding profiles from the 2014 experimental campaigns are presented in Figure 5. High PM_{10} concentration of 134.3 μg m^{-3} was observed at MLH of 260 m above the ground in the winter of 2014 and low PM_{10} of 23.9 μg.m^{-3} at the MLH of 1410 m above the ground in the summer.

Previous studies of modelling and derivation of MLH from operational and experimental radio-soundings in the Sofia region also show a distinguished seasonal pattern of the relation between MLH and air pollution during the years (Batchvarova et al., 2006, 2008, 2011; Veleva et al. 2010).

3.3. PM_{10} in experimental campaigns and relation to meteorological parameters

The experimental campaigns aimed to collect PM_{10} samples for elemental analyses at the CMO-NIMH station were organized during cold and warm period of the year, namely January-February and July-August for all three years of the period 2012-2014

(Veleva et al., 2014, Veleva et al., 2015). In 2012, additional measurements were also performed in October and December.

In total, 149 daily PM_{10} values were obtained and related to the mean (T_{avg}) and the minimal daily temperature (T_{min}), surface atmospheric pressure (P), relative humidity (RH), wind speed (WS), cloud cover, noon MLH, daily precipitation sum. The negative correlation coefficient is calculated as follows: to T_{avg} (r = -0.41); to T_{min} (r = -0.43); to WS (r = -0.37); to noon MLH (r = -0.31). Weak positive correlation is observed between PM_{10} concentrations and P and RH (r = 0.30). PM_{10} concentrations do not correlate to cloud cover.

3.4. PM_{10} mass concentration and MLH at Sofia

Stagnant weather conditions and inversions are the major factor for the high PM_{10} values registered during the cold period, not to forget the additional source from domestic heating. The negative correlation of PM_{10} and the mean daily, minimum and maximum T illustrates this. The correlation coefficient varies from - 0.32 in 2012 to - 0.45 for 2014 for all urban stations.

The comparison between the measured PM_{10} mass concentration and the corresponding MLH determined from 12 UTC aerological soundings at Sofia is presented for the periods of the winter and summer experimental campaigns of 2012, 2013 and 2014 (Figure 6). The daily precipitation sums are shown as well. The influence of precipitation on PM_{10} concentrations and MLH is clearly manifested, particularly in the winter of 2013 and the summer of 2014.

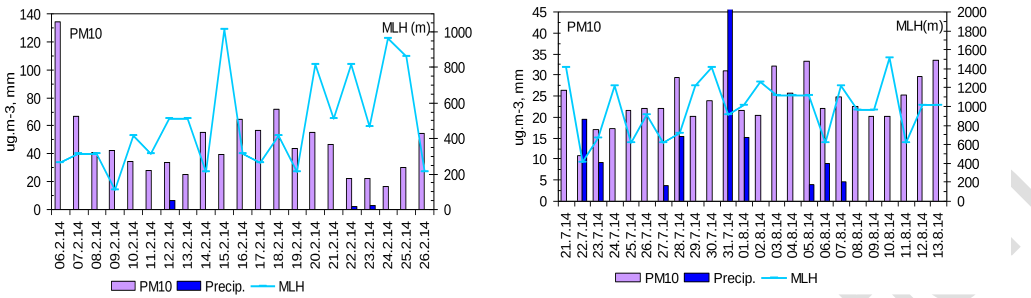

Fig.6. Estimated MLH, measured PM_{10} concentrations and days with precipitation during winter (left) and summer (right) experiments at CMO, NIMH

The results show that for days with low MLH, the concentration of PM_{10} is usually high while for days with high MLH, the PM_{10} mass concentration is below the limit values.

To quantify the correlation between high PM_{10} pollution and MLH for the 2012-2014 period, the days of exceedances were identified. This gave 264 days for AMS "Drujba" and 250 days for the other urban AMSs. In general, for the days with PM_{10} exceedances, negative correlation with r = – 0.354 between PM_{10} and MLH is registered. The decreases of the PM_{10} mean concentrations with the increase of MLH are presented on Table 2.

Table 2. MLH gradations and mean PM_{10} concentrations for the days of exceedances

MLH [m]	Mean PM_{10} [$\mu g.m^{-3}$]	Number of cases
60-210	127.55	81
260-410	78.80	83
460-660	71.81	43
>700	61.34	36

Further details of estimated MLH and registered PM_{10} concentrations for the days with exceedances of the daily limit value (50 $\mu g.m^{-3}$) for AMS "Drujba" are presented in Figure 7 for the years 2012, 2013 and 2014.

Low MLH values correspond to high PM_{10} concentrations, observed mainly in winter days. During the summer, high MLH values correspond to low PM_{10} levels.

The highest number of days with exceedances is registered in January, February and December of 2012; in January and December of 2013; and in January, November and December of 2014.

Only sporadic cases of exceedances are observed in the summer months at AMS "Drujba", which are possibly associated with local sources from construction works or fires, which do not affect the rest of the urban AMSs.

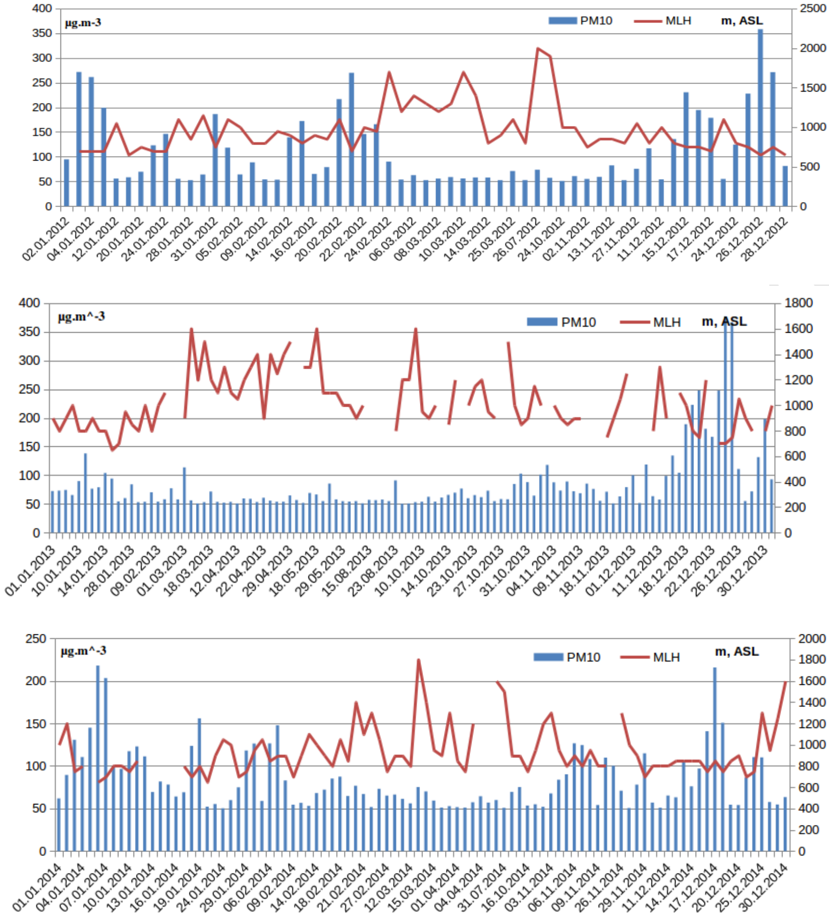

Fig.7. Estimated MLH and registered PM_{10} concentrations for days with exceedances of the daily limit value (50 µg.m^{-3}) for the years 2012, 2013 and 2014.

The missing red line (for MLH) segments in Figures 6 and 7 indicate a lack of aerological sounding data for those periods.

4. CONCLUSIONS

Stagnant weather conditions and inversions are the major factor for the high PM_{10} values registered during the cold period in Sofia. PM_{10} concentrations 3-5 times higher than daily limit values are observed in winter days and anticyclone synoptic situation, when the estimated MLH is below 250 m. High MLH values correspond to low PM_{10} concentrations. For days with precipitation, MLH is reduced due to the cooling effects and PM_{10} concentrations are lower due to the washout effect.

High coefficient of determination (R^2 between 0.81÷0.97) is observed for PM_{10} daily concentrations across all urban monitoring stations. No correlation (R^2~0.03) on an annual basis is found between AMS "Kopitoto" and the urban stations. When seasons/months are considered separately, moderate correlation coefficient (r~0.50-0.53) for March, October and November and (r ~ 0.51 - 0.65) for April, May and September is obtained.

The impact of daily precipitation on PM_{10} concentration is studied. Average PM_{10} concentrations exhibit a statistically significant reduction on days with precipitation compared to dry periods. The percentage of this decrease is from 23% for AMS "Kopitoto" to more than 32% for the urban stations.

ACKNOWLEDGMENT

This research was conducted within the Program for carrier development of young scientists of the Bulgarian Academy of Sciences, Contract DFNP 34/20.04.2016.

REFERENCES

Air Quality e-Reporting (AQ e-Reporting) https://www.eea.europa.eu/en/analysis/maps-and-charts/air-quality-statistics-dashboards

Andreev V., Branzov Ch., Koleva E., Tzenkova A., Ivancheva J. and Videnov P. (2004), Climate and human comfort of Sofia. Ecology of the City of Sofia, Species and Communities in an urban Environment, PENSOFT Publishers, Sofia-Moscow. pp. 25-54.

Batchvarova E, Pisoni, E. and Finzi G. (2011), Modelling and measurements of the atmospheric boundary layer in Sofia, Bulgaria, Int. J. Environment and Pollution, Vol. 46, Nos. 1/2, 61-68, 2011.

Batchvarova E., Gryning S.-E., Rotach M.W and Christen A. (2006), Comparison of modelled aggregated turbulent fluxes and measured turbulent fluxes at different heights in an urban area, Air pollution modelling and its application XVII, Borrego C. and Norman A. (Eds.), (Kluwer Academic/Plenum Publishers) (NATO Challenges of Modern Society series), 363-370.

Batchvarova E., Syrakov D. and Tzenkova A. (1994), Air pollution characteristics of a region of Sofia and data from field experiments (1992-1993) Urban Air Pollution. Monitoring and Control Strategies. Allegrini I. and De Santis F. (Eds.), NATO ASI Series, 2. Environment 8, 235-242.

Batchvarova E., Valkov N. and Veleva B. (2008), Study of long term air pollution and meteorological data in five Bulgarian towns, Proc. of 17th Int. Symp. 'Ecology & Safety' 2008, 9-13 June 2008, Sunny Beach Resort, Bulgaria, International Scientific Publications, publ. by INFO INVEST, Bulgaria 2 (1) 571-577.

Batchvarova E. and Gryning S.-E. (1991), Applied model for the growth of the daytime mixed layer, Boundary-Layer Meteorology 56, 261-274.

Bluskova D. Zlatkova L., Lingova S., Modeva, Zh.,Subev L., Teneva M. (1983), Climate and microclimate of Sofia, Publ. House of the Bulg.Acad. of Sciences, Sofia, 152 (in Bulgarian).

Caicedo, V., Rappenglück, B., Lefer, B., Morris, G., Toledo, D., Delgado, R. (2017), Comparison of aerosol lidar retrieval methods for boundary layer height detection using

ceilometer aerosol backscatter data. Atmos. Meas. Tech., 10, 1609–1622.
Danchovski V. (2016), Determination of the height of the mixing layer from radiosonde data in the city of Sofia - preliminary results, 3rd National Congress on Physical Sciences, 29 Sep. – 2 Oct. 2016, Sofia, Section: Physics of Earth, Atmosphere and Space, on CD
Danchovski V. (2019), Summertime Urban Mixing Layer Height over Sofia, Bulgaria, Atmosphere 10(1), 36; https://doi.org/10.3390/atmos10010036
EEA Report No 09/2020 Air quality in Europe - 2020 report, Publications Office of the European Union, 2020 ISBN 978-92-9480-292-7, ISSN 1977-8449, doi:10.2800/786656
EEA 2024, European Environment Agency, Environmental information systems https://www.eea.europa.eu/en/analysis/indicators
Emeis S., Schafer K. and Munkel C. (2008), Surface-based remote sensing of the mixing-layer height – a review, *Meteorologische Zeitschrift* , 17 (5) 621-630.
Fearon M., Brown T. and Curcio G. (2015), Establishing a national standard method for operational mixing height determination *J. Operational Meteorology* 3 (15) 172-189, http://dx.doi.org/10.15191/nwajom.2015.0315.
Guarnieri F., Calastrini F., Busillo C., Messeri G. and Gozzini B. (2015), A model chain application to estimate mixing layer height related to PM10 dispersion processes, Hindawi Publishing Corporation, *The Scientific World Journal*, Vol. 2015, p. 11, Article ID 298492, https://doi.org/10.1155/2015/298492
Hristova E., Veleva B. (2013), Variation of air particulate concentration in Sofia, 2005-2012', *Bulgarian Journal of Meteorology and Hydrology* (BJMH) 18 (1-2) 47-56.
Malandrino M., Martino M. Di, Ghiotta G., Geobaldo F., Grossa M., Giacomino A. and Abollino O. (2013), Inter-annual and seasonal variability in PM10 samples monitored monitored in the city of Turin (Italy) from 2002 to 2005, *Microchemical Journal*, 107, 76-85.
Nat. Rep. MoEW, (2016), National Report on the State and Protection of the Environment, MoEW, Sofia, http://eea.government.bg/bg/soer/2014 .
Pal S., Xueref-Remy I., Ammoura L., Chazette P., Gibert F., Royer P., Dieudonné E., Dupont J.-C., Haeffelin M., Lac C., Lopez M., Morille Y. and Ravetta F. (2012), Spatio-temporal variability of the atmospheric boundary layer depth over the Paris agglomeration: An assessment of the impact of the urban heat island Intensity, *Atmospheric Environment*, 63 261-275.
Report RIEW (2014) http://www.riew-sofia.org/index.php/2014-02-03-21-18-13
Seibert P., Beyrich F., Gryning S.-E., Jofre S., Rasmussen A. and Tercier P. (2000), Review and intercomparison of operational methods for the determination of the mixing height *Atmospheric Environment*, 34, 1001-1027.
Stull R. (1988), An introduction to boundary layer meteorology, Kluwer Academic Publishers, Dordrecht, pp 665.
Tang G., Zhang J., Zhu X., Song T., Münkel Ch., Hu B., Schäfer K., Liu Z., Zhang J., Wang L., Xin J., Suppan P. and Wang Y. (2016), Mixing layer height and its implications for air pollution over Beijing, China, *Atmospheric Chemistry and Physics*, 16, 2459–2475.
Veleva B., Hristova E., Nikolova E., Kolarova M. and Valcheva R. (2015), Statistical evaluation of elemental composition data of PM10 air particulate in Sofia, *International J. of Environment and Pollution* (IJEP), 57 (3-4) 175–188.
Veleva B., Hristova E., Nikolova E.¸ Kolarova M., and Valcheva R. (2014), Seasonal variation of PM10 elemental composition in urban environment, International Scientific Events, Sunny Beach, Bulgaria, *J. of International Scientific. Publications: Ecology & Safety*, Vol. 8, Part 1, 265-275 www.scientific-publications.net
Veleva B., Valkov N., Batchvarova E. and Kolarova M. (2010), Variation of Radon short lived

beta radionuclides (Radon progeny) and mixing processes in the atmospheric boundary layer, *Journal of Environmental Radioactivity*, 101, 538-543.

Veleva, B. (2006), Time variation of the dust concentration and deposition in Sofia during the period 1981-2002, Proc. of BALWOIS Conference, Ohrid, Macedonia, http://balwois.com/conference/balwois-2006/.

Whiteman D., Hoch S., Horel J. and Charland A. (2014), Relationship between particulate air pollution and meteorological variables in Utah's Salt Lake Valley, *Atmospheric Environment*, 94, 742-753.