PARTICULATE MATTER CHARACTERISTICS AND ATMOSPHERIC BOUNDARY LAYER HEIGHT OVER SOFIA

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Abstract: The paper presents results from aerosol experimental campaigns performed in the urban environment of Sofia. Laser Particle Counter data of 2 summer days (June, 7 and 8) and 4 winter days (December, 18, 19, 20, 21) of 2019 are discussed. Aerosol particle concentrations (number/l and mass µg/m^3) in channels 0-2.5 µm and 2.5-10 µm are measured at the open green area near Pliska (at 30 m distance from boulevard Tsarigradsko shose). The combined effect of the daily development of atmospheric boundary layer height, meteorological parameters, and hourly variations in the concentrations of the aerosol fractions is discussed. WRF-GDAS and HYSPLIT models are used for determination of the atmospheric boundary layer height and to follow the transport of air masses. BSC dust model is used as an additional source of information to assess the long-range intrusion of dust.

Key words: *air quality, aerosol concentration, atmospheric boundary layer, particle number concentrations, WRF-GDAS, HYSPLIT, NMMB-BSC-Dust*

INTRODUCTION

The Atmospheric Boundary Layer (ABL) height determines the volume in which different gaseous and aerosol pollutants are mixed due to turbulent processes within the atmosphere. To model the ABL height in urban environments is additional challenge due to the specific physical and chemical characteristics which play important role for pollutant dispersion, climate comfort, and weather forecasting (Chen et al., 2011; Batchvarova & Gryning, 2006; Batchvarova et al., 2006; Batchvarova et al., 2011; Rotach et al., 2005; Avolio et al., 2017). Specific studies on the city of Sofia including remote sensing measurements are presented by Kirova & Batchvarova, 2017; Kolev et al., 2016; Savov et al., 2016; Kolev et al., 2019. The combination of models and particle counter measurements provides comprehensive information on both the aerosols concentration characteristics in the urban atmosphere as well as about the vertical structure of aerosol layers and meteorological parameters determining the transport of air mass (Ngan et al., 2015; Stein et al.,. 2015; Lin Su et al., 2015).

METHODOLOGY AND EQUIPMENT

Experimental site and instruments

A two-channel BQ20 (TROTEC, Germany) laser particle counter (LPC) with channel 1 (0 - 2.5 µm) and channel 2 (2.5 - 10 µm) denoted further in the paper as PM2.5 and PM10, respectively, was used to measure instantly the number of particles and their mass with time step 10 or 15 minutes. The sampling rate is 0.9 l/min. The accuracy of the devices is in the range of 15-20%. Measurements were performed near bus stop Pliska in a green area 30 m North of Blvd. "Tsarigradsko shose", one of the largest boulevards in Sofia with heavy traffic. Only cars and busses are allowed with speed limit of 80 km/h.

Meteorological data were obtained from an automatic weather station located at Sofia airport with time resolution 30 minutes.

Experimental days

Measurements were performed during two typical summer days (7-8 June 2019), characterized by relatively calm anticyclone weather, and four winter days of (18 – 21 December 2019) characterised with high level of pollution and occurrence of fog in the morning hours. Particular behaviour of the aerosol concentrations was noted on December 21, a day with foehn wind.

Application of models

The Weather Research and Forecasting Model (WRF) is numerical weather forecasting and atmospheric simulation system designed for both research and operational applications across scales from tens to thousands of kilometres. The purpose of applying the WRF-GDAS model is to produce new atmospheric analyses using historical data (available from 2004 to present) and to analyze current atmospheric conditions by using Global Data Assimilation System (GDAS). The simulation results (GDAS meteorological data) in this paper are obtained from READY Web Server of NOAA ARL (https://www.ready.noaa.gov/).

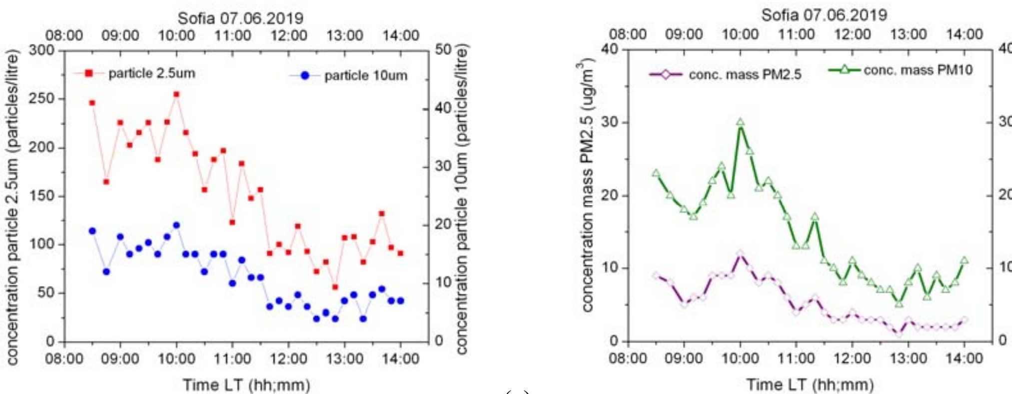
The Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT, http://www.arl.noaa.gov/ ready/hysplit4.htm), a Lagrangian dispersion model, has been coupled (online) to the Weather Research and Forecasting (WRF) meteorological model in such a way that the HYSPLIT calculation is run as part of the WRF-ARW prediction calculation (Ngan et al., 2015; Lin Su et al., 2015) . The embedded HYSPLIT includes dispersion, trajectories, deposition (dry and wet), etc. (Chen et al., 2011; Stein et al., 2015; Rolph et al., 2017).

The NMMB/BSC-Dust model (https://ess.bsc.es/bsc-dust-daily-forecast), developed in the Earth Sciences Department to simulate and/or predict the atmospheric cycle of mineral dust at BSC is used to assess the long-range transport of dust over the area of Sofia.

RESULTS AND DISCUSSIONS

Summer 2019

Anticyclone synoptic conditions prevailed on 7 and 8 June 2019 causing sunny weather and development of cumulus clouds in the afternoon mostly on the first day. Measured maximal temperatures were 25-30^{o}C and minimal - 13^{o}C.



(a) (b)

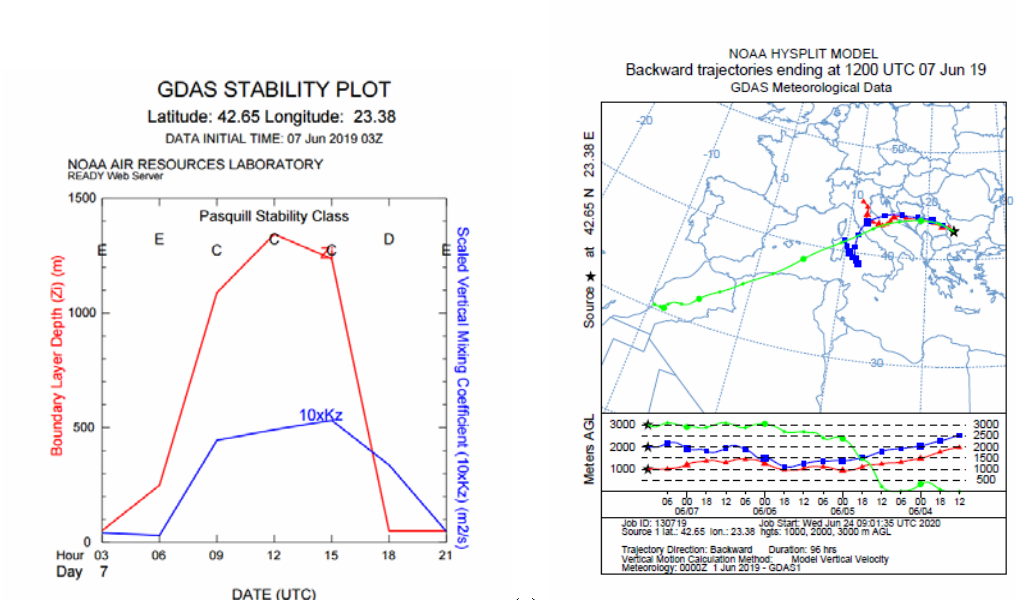
Figure 1. Daily variations in PM2.5 and PM10 on 7 June 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (μg/m^3)

The number of PM10 changes from 20 N/l in the morning hours to 10 N/l in the afternoon, and of PM2.5 from 250 N/l to 100 N/l (Fig. 1a). The corresponding mass concentrations for PM10 are from 25-30 μg/m^3 to 5 μg/m^3 in the afternoon and for PM2.5 from 10-12 μg/m^3 to 5 μg/m^3 (Fig. 1b).

WRF-GDAS model forecast for Boundary Layer Depth (Zi) over Sofia is 1200 - 1300 m (Fig. 2a). The model suggests prevailing wind from N (1-4 m/s) from 9 to 15 LT. HYSPLIT Backward trajectories of 1000, 2000 and 3000 m ending in Sofia at 12UTC on June, 7 2019 are shown in Fig. 2b. Transport of air masses from Morocco and Sahara desert at altitude of 3 km can be noted.

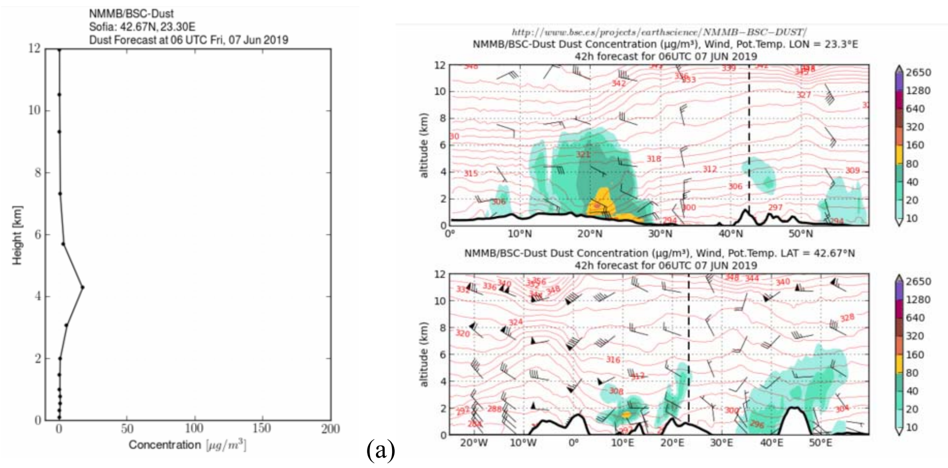
NMMB/BSC Dust (Dust Forecast at 06UTC Friday 07 June) gives a higher concentration in the layer between 3 and 6 km height with maximum of about 20 μg/m^3 at 4 km over Sofia (Fig. 3a). This intrusion of dust likely does not influence the measured aerosol concentrations in the urban surface layer. LON-

Height cross-section and LAT-Height cross-section present the distribution of dust concentration across North Africa and Europe (Fig. 3b). The dashed line indicates the position of Sofia.



(a) (b)

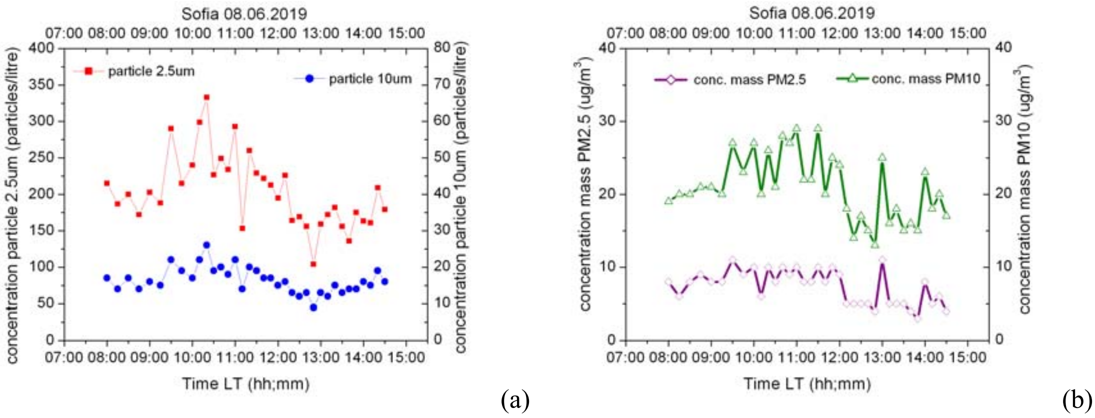
Figure 2. Model results for Sofia (LAT 42.65; LON 23.38) on 7 June (a) GDAS Stability plot and (b) HYSPLIT Backward trajectories



(a) (b)

Figure 3. NMMB/BSC Dust Forecast Concentrations (μg/m^3) at 06 UTC on 7 June (a) vertical profile and (b) LON&LAT-Height cross-section

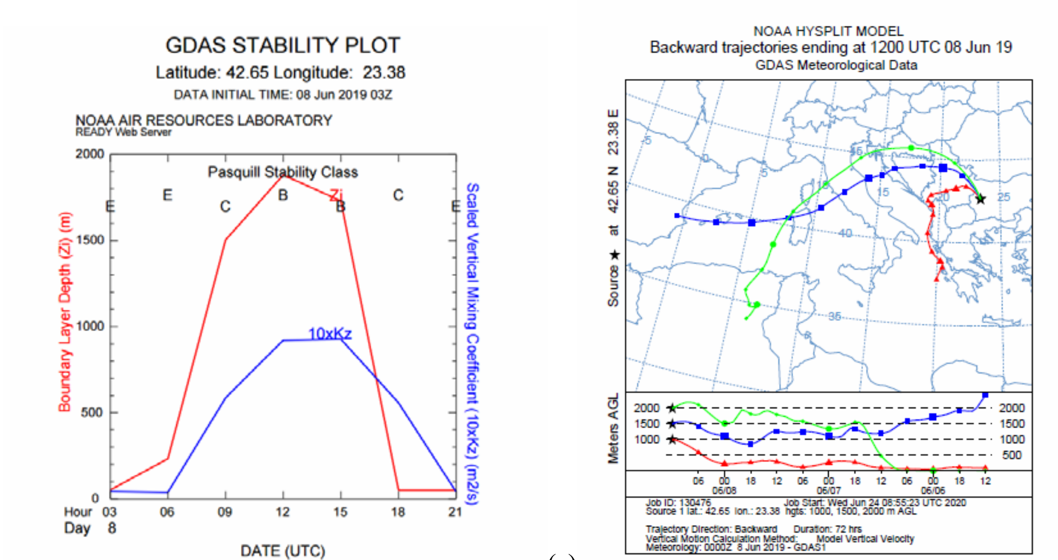
Measurements on 8 June show that the number of PM10 is around 20 N/l with max of 25 N/l from 9:30 to 10:30 LT and for PM2.5 the numbers are 220 N/l in the early morning hours and increase to 300-350 N/l from 9:30 to 10:30 LT, then fall to 175 N/l after 12 LT (Fig. 4 a). The corresponding mass concentrations for PM10 are from 15 to 30 μg/m^3. For PM2.5 the concentrations are around 10 μg/m^3 before 12 LT and around 5 μg/m^3 in the early afternoon (Fig. 4 b).



(a) (b)

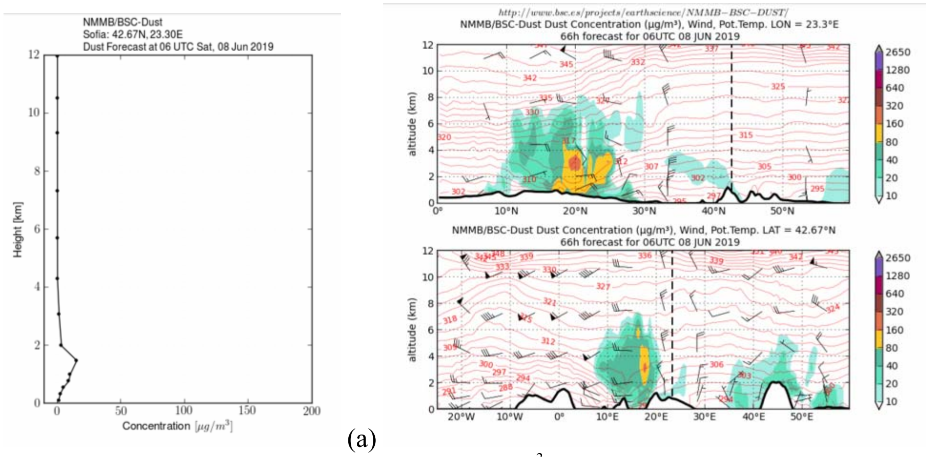
Figure 4. Daily variations in PM2.5 and PM10 on 8 June 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (µg/m^3)

WRF-GDAS forecast for ABL height for Sofia reaches maximum of 1900 m at 12 UTC. Pasquill Stability Class ranges from stable (E) in the morning to unstable (B-C) at 12 UTC (Fig. 5a). GDAS wind speed for Sofia on July 8 is 7 m/s in the morning hours and 1-4 m/s after 11 LT from NW. The HYSPLIT Backward trajectories of 1000, 1500 and 2000 m ending in Sofia at 12 UTC on June, 8 2019 are shown in Fig. 5b. The transport of air masses at the three levels is from different areas. The 2000-metre trajectory starts from Algeria. NMMB/BSC Dust (Dust Forecast at 06 UTC Sat 08 June) shows a higher concentration of about 20 µg/m^3 in the layer below 2 km, Fig 6a. This suggests that long-range transport of dust may influence the surface PM concentrations in Sofia in the afternoon hours when ABL reaches the height of dust intrusion. The LON&LAT-Height cross-sections present different distribution of dust concentration compared to the previous day (Fig. 6b).



(a) (b)

Figure 5. Model results for Sofia on 8 June (a) GDAS Stability plot and (b) HYSPLIT Backward trajectories



(a) (b)

Figure 6. NMMB/BSC Dust Forecast Concentrations (μg/m^3) at 06 UTC on 8 June (a) vertical profile and (b) LON&LAT-Height cross-section

During these summer days, the measured concentrations are lower than the sanitary norms. The height of the convective ABL (ABLH) reaches 1350 and 1900 m, on 7 and 8 June respectively. On 7 June (Friday) the morning rush hour concentration peak is at 10 LT and is strongly pronounced (Fig. 1). On 8 June (Saturday), high concentrations remain between 9 and 12 LT. Secondary increase is noted at 13 and 14 LT. Summary of measured and modelled parameters for the these summer days is given in Table 1.

Table 1. PM10 and PM2.5 concentrations and meteorological parameters (modelled or observed)

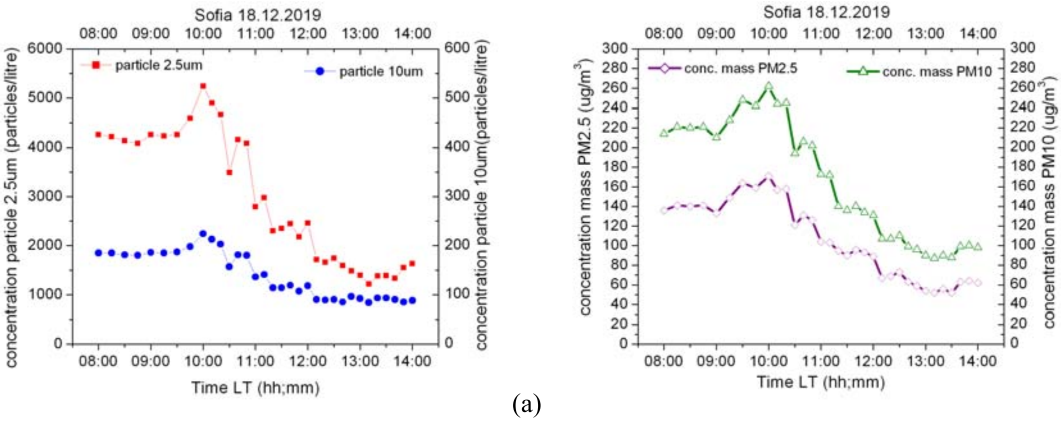
Day of experi-ment	PM10 mass min-max (μg/m^3) (obs.)	PM10 number min-max (N/l) (obs.)	PM2.5 conc. min-max (μg/m^3) (obs.)	PM2.5 number min-max (N/l) (obs.)	ABLH min-max (m) (model)	Wind dir/spee d (m/s) (model)	Tmax/ Tmin (^{o}C) (obs.)
7 June	5-30	5-20	2-12	50-250	250-1350	N/1-4	25-30/13
8 June	15-30	10-30	5-10	100-350	200-1900	NW/1-4	25-30/13

It can be noted that the measured PM2.5 particle number is higher on Saturday, 8 June, despite the expected lower traffic contribution during weekends and deeper ABL. Furthermore, the ratio highest/lowest values is smaller on 8 June (350/100 N/l), compared to the ratio (250/50 N/l) on 7 June. Possible reason for these differences is the long-range transport contribution according to Dust model (Fig. 6) to the surface particle concentrations on 8 June (Fig. 4).

Winter 2019

Anticyclone synoptic circulation prevailed in the period 18-20 December 2019 causing low wind speed from SW-S, morning fog conditions in valleys and low stratus clouds. Measured maximal temperatures were 10^{o}C and minimal 0^{o}C. No precipitation and no snow cover were measured in Sofia. Change of weather to cyclone circulation starts from 20 December, leading to strong feohn wind from S-SW in Sofia reaching 16 m/s, gusts up to 23 m/s and abnormally high temperatures of 15^{o}C.

Measurements on 18 December were performed from 8 to 14 LT under heavy fog conditions (observed relative humidity of 100 %) and show number of PM10 of 200 N/l until 10 LST and lower values (100 N/l) in the afternoon. Registration for PM2.5 shows 4500 N/l in the early morning hours, maximum of 5000-5500 N/l around 10 LT (related to morning rush hours and fog) and gradual decrease to 2500-2000 N/l after 12 LT (Fig. 7a). The corresponding mass concentration for PM10 (Fig. 7b) is from 220 μg/m^3 at 8 LT, with max of 250-260 μg/m^3 at 9:30-10:30 LT and 100 μg/m^3 in the early afternoon. The PM2.5 concentrations show similar behavior: around 140 μg/m^3 before 9 LT, 160-170 μg/m^3 at 10:30 LT and 60 μg/m^3 in the early afternoon. Summarized information of the winter experiment days is given in Table 2.



(a) (b)

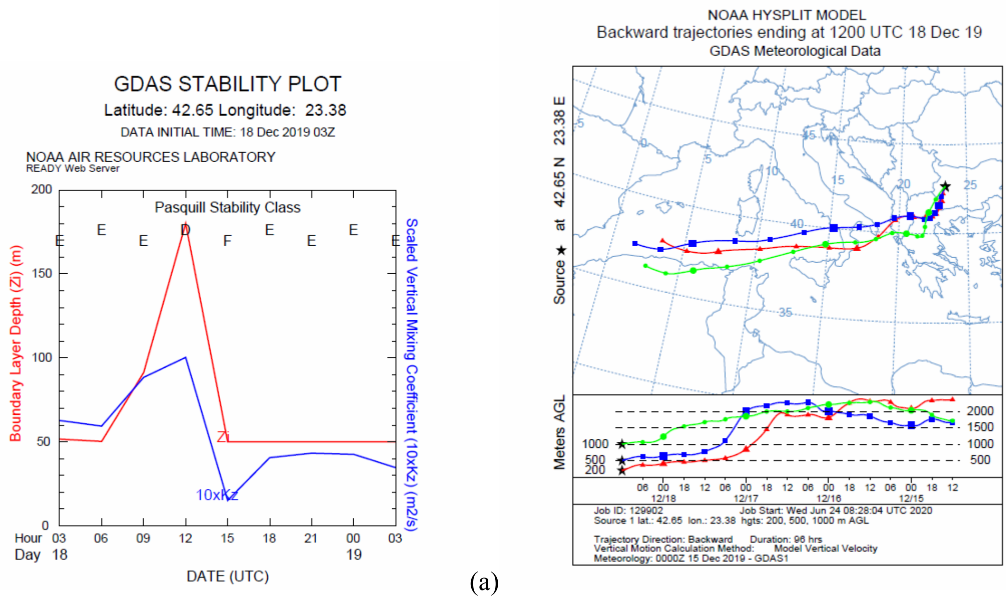
Figure 7. Daily variations in PM2.5 and PM10 on 18 December 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (μg/m^3)

GDAS gives ABL height of maximum 180 m and stable to neutral stratification over Sofia (Fig. 8a), constant SW-S wind of 1-4 m/s during the day. The 96-hours backward trajectories of height 200, 500 and 1000 m show constant SW flow (Fig. 8b).

Table 2. PM10 and PM2.5 concentrations and meteorological parameters (modelled or observed)

Day of experi-ment	PM10 mass min-max (μg/m^3) (obs.)	PM10 number min-max (N/l) (obs.)	PM2.5 mass min-max (μg/m^3) (obs.)	PM2.5 number min-max (N/l) (obs.)	ABLH min-max (m) (model)	Wind dir/speed (m/s) (model)	Tmax/ Tmin (°C) (obs.)
18 Dec.	80-260	100-200	50-170	2000-5500	50-180	SW-S/1-4	10/0 (fog)
19 Dec.	150-600	100-400	100-375	3000-11000	50-150	S-SE/1-4	10/0 (fog)
20 Dec.	70-120	50-100	30-70	1100-1700	450-150	S/1-4	10/0
21 Dec.*	10-100	20-90	10-40	300-1400	-	S-SW/16*	10-15/ >0

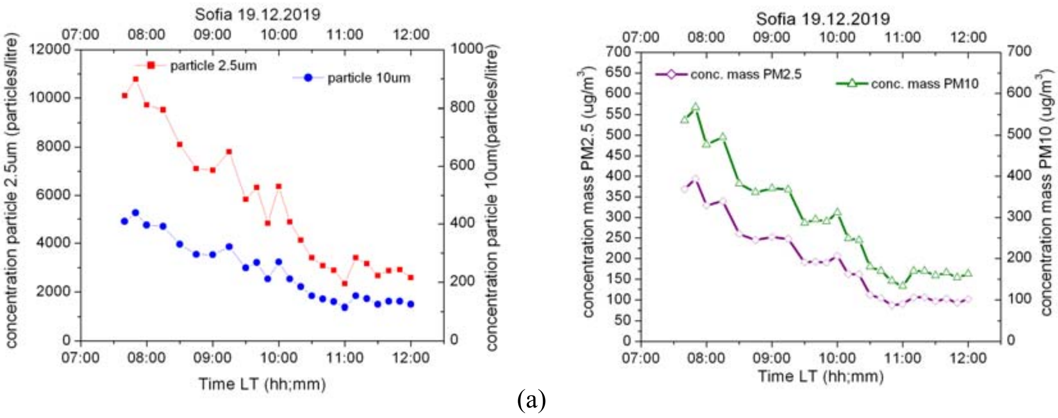
* on 21 December the wind data are from observations



(a) (b)

Figure 8. Model results for Sofia on 18 December (a) GDAS Stability plot and (b) HYSPLIT Backward trajectories

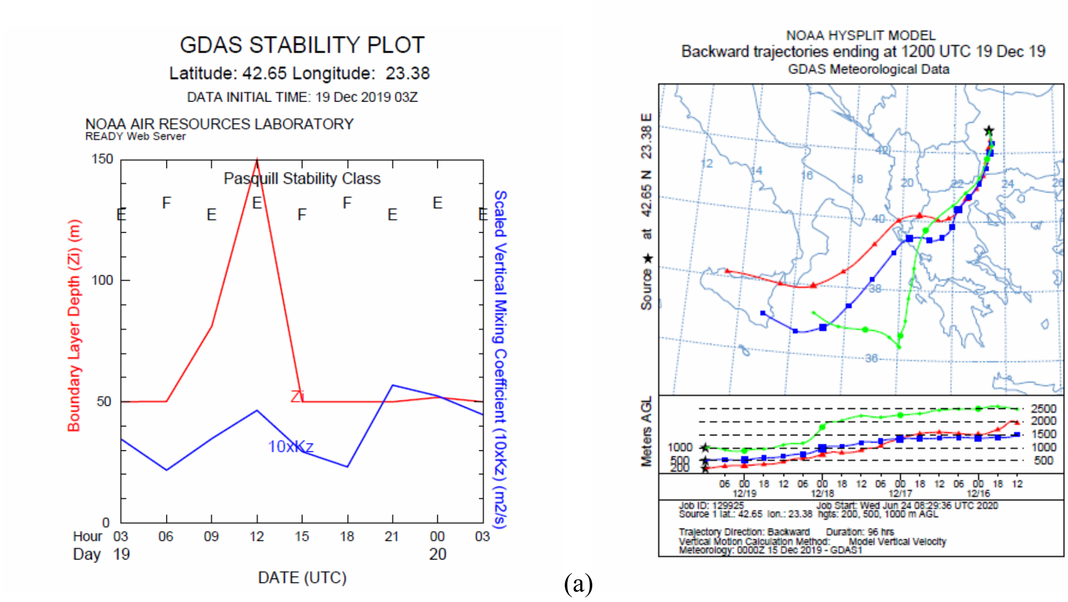
Measurements on 19 December were performed from 7 to 12 LT. The stable stratification and fog persisted leading to double increase of all maximal particle numbers and mass concentrations compared to the previous day (Fig. 9 and Table 2).



(a) (b)

Figure 9. Daily variations in PM2.5 and PM10 on 19 December 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (µg/m^3)

GDAS ABL height over Sofia is below 200 m, stratification is stable to very stable (Fig. 10a), and constant S-SE wind of 1-4 m/s during the day. The 96-hours backward trajectories of height 200, 500 and 1000 m show SW flow originating from Sicily (Fig. 10b).

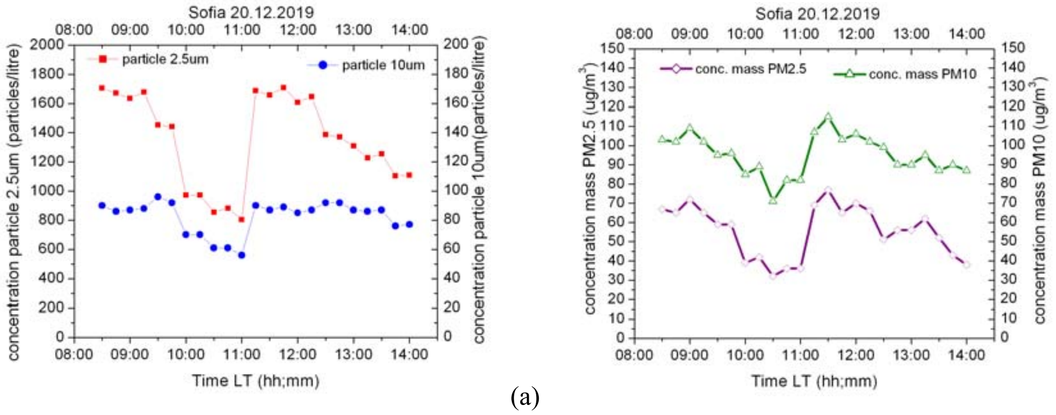


(a) (b)

Figure 10. Model results for Sofia on 19 December (a) GDAS Stability plot and (b) HYSPLIT Backward trajectories

On 20 December the synoptic conditions start to change to multi-centered low pressure structure over the Balkan Peninsula. The transport of warm air masses from SW causes increase of temperatures. NMMB/BSC Dust Forecast model indicates dust concentration of 50 µg/m^3 at 4000 m, showing long-range transport, which remains far above the ABL (maximal of 450 m) over Sofia.

The number and mass concentration measurements on 20 December show distinct decrease (two times in values) and different from the previous days changes with time. PM2.5 mass concentration starts from 70 µg/m^3 in the early morning (8:30 LT). A minimum of 30 µg/m^3 is recorded between 10 and 11 LT, related to the destruction of the fog. Higher values (80 µg/m^3) are recorded again between 11:30 and 12:30 LT, probably related with shorter working day and increased traffic of cars leaving Sofia for the following 6 days of Christmas holydays. PM10 concentrations are with similar to PM2.5 behavior, but with higher values starting from 100 µg/m^3 in the morning (8:30 LT), diminishing to 70 µg/m^3 and growing again to 120 μg/m^3 after 11 LT. After 12:30 LT the concentrations slowly decrease (Fig. 11 and Table 2).

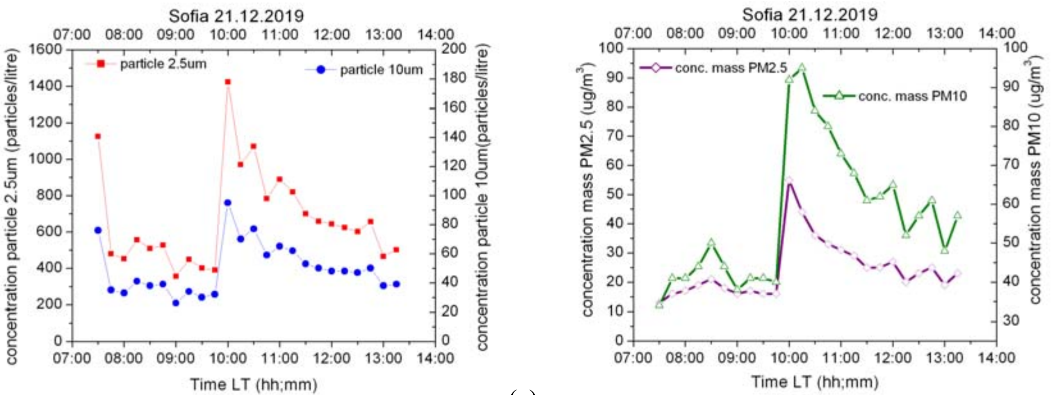


(a) (b)

Figure 11. Daily variations in PM2.5 and PM10 on 20 December 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (μg/m^3)

On 21 December the cyclone formed over Italy moved to NE above the Hungarian Plane. The southwesterly wind speed increased. Passing over Vitosha Mountain this flow was observed as feohn in Sofia, reaching wind speed of 16 m/s at Sofia airport and gusts of 23 m/s.

The measured PM10 and PM2.5 concentrations show peculiarities related to the new meteorological situation starting with low morning concentrations from 7 - 10 LT (PM2.5: 10 - 20 μg/m^3 and for PM10: 30 - 40 μg/m^3). Very rapidly the concentrations increase twice to values of 50 μg/m^3 and 90 μg/m^3, correspondingly (Fig. 12b). After 10:30 LT the concentrations decrease. This behavior is possibly related to short time wind gust situation during the peak period when large amounts of dust are lifted from the ground surface. It is interesting to note that PM10 number concentration increases twice and PM2.5 three times for the period 10-10:30 LT (Fig. 12a). This peak cannot be explained with high transport traffic, because of its very short duration.



(a) (b)

Figure 12. Daily variations in PM2.5 and PM10 on 21 December 2019, measured as (a) particles per liter (N/l) and (b) concentration mass (μg/m^3)

The last 2 days of the winter experimental campaign are peculiar in view of particle concentrations and show the dynamic interplay between meteorology and emission sources, which determines the air quality in the city.

CONCLUSIONS

This study presents experimental results concerning the daily distribution of the aerosol particles in the urban environment and the correlation to the synoptic situations, meteorological parameters and ABL height. The analysis is based on 2 summer and 4 winter days of aerosol particles measurements (mass concentration and number per liter) with laser aerosol particle counters.

In summer, the ABL is high and the observed concentration of aerosol particles is under the sanitary norms. On 8 June, the particles mass concentrations change two times from maximal to minimal values, while on 7 June this ratio is 6. The differences might be explained with the contribution of long range transport of dust. The observed maximums on both days are possibly related to intensive transport traffic along the Tsarigradsko shose in the morning hours.

In winter, the ABL height is low and the observed concentrations of aerosol particles are higher than the norms for 18 and 19 December. The maximal values are 3 times higher than the minimal and are related to fog conditions and intensive transport traffic along the Tsarigradsko shose in the morning hours. On 20 and 21 December the concentrations show peculiar changes with time probably related to the beginning of Christmas holidays and rare meteorological conditions due to feohn event.

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REFERENCES
Avolio, E., Federico, S., Miglietta, M., Lo Feudo, T., Calidonna, C., & Sempreviva, A. (2017). Sensitivity analysis of WRF model PBL schemes in simulating boundary layer variables in southern Italy: An experimental campaign. Atmospheric Research, 192, 58–71.

Batchvarova, E. & Gryning, S.-E. (2006). Progress in Urban Dispersion Studies. Theor. Appl. Climatol. 84, No. 1-3, 57-67.

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

Batchvarova E., Kolarova M., Veleva B., Neykov N., Neitchev P., Videnov P., Gamanov A., & Barantiev D. (2011). The atmospheric boundary layer – parameterizations, observations and applications. (2011) Bul. J. Meteo & Hydro, 16/1, 41-53.

Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmon, C.S.B., Grossman-Clarke, S., Loridan, T., Manning, K.W., Martilli, A., Miao, S., Sailor, D., Salamanca, F.P., Taha, H., Tewari, M., Wang, X., Wyszogrodzki, A.A., & Zhang, C. (2011). The integrated WRF/urban modelling system: development, evaluation, and applications to urban environmental problems. Int. J.Climatol. 31 (2), 273–288.

Kirova, H. & Batchvarova, E. (2017). Mesoscale simulation of meteorological profiles during the Sofia Experiment 2003. International Journal of Environment and Pollution, 61, 2, 2017, 134-147. DOI:10.1504/IJEP.10006760

Kolev, N., Savov, P., Evgenieva, Ts., Miloshev, N., Petkov, D., & Donev, E. (2016). Summer measurements of atmospheric boundary layer (ABL), aerosol optical depth (AOD) and water vapour content (WVC) over Sofia (Bulgaria) 2010–2014. Compt. rend. Acad. bulg. Sci., **69**, 4, 421-429.

Kolev, N., Savov, P., Evgenieva, Ts., Miloshev, N., Gueorguiev, O., Batchvarova, E., Kolarova, M. Danchovski, V., Ivanov, D. & Petkov, D. (2019). Investigation of the atmospheric boundary layer and optical characteristics of the atmospheric aerosols over Sofia in summer 2016, 10th Jubilee International Conference of the Balkan Physical Union, AIP Conference Proceedings 2075, 120004 (2019) https://doi.org/10.1063/1.5091262, Published Online: 26 February 2019.

Lin Su, Yuan, Z., Hung Fung, J. C., & Hon Lau, A. K. (2015). A comparison of HYSPLIT backward trajectories generated from two GDAS datasets, Science of the Total Environment, 506-507, 527-537.

Ngan, F., Stein, A., & Draxler, R. (2015). Inline coupling of WRF–HYSPLIT: Model development and evaluation using tracer experiments. J. Appl. Meteor. Climatol., 54, 1162–1176.

Rolph, G., Stein, A., & Stunder, B. (2017). Real-time Environmental Applications and Display sYstem: READY. Environmental Modelling & Software 95, 210-228.

Rotach, M. W., Vogt, R., Bernhofer, C., Batchvarova, E., Christen, A., Clappier, A., Feddersen, B., Gryning, S.-E., Martucci, G., Mayer, H., Mitev, V., Oke, T. R., Parlow, E., Richner, H., Roth, Roulet, M., Y.-A., Ruffieux, D., Salmond, J. A., Schatzmann, M. & Voogt, J. A. (2005). BUBBLE – an Urban Boundary Layer Meteorology Project, Theor. Appl. Climatol. 81, 231–261, DOI 10.1007/s00704-004-0117-9.

Savov, P., Kolev, N., Evgenieva, Ts., Vatzkitcheva, M., & Danchovski, V. (2016). Correlations between particle number concentrations, boundary layer height, meteorological parameters and urban environments. Compt. rend. Acad. bulg. Sci., 69, 1, 19-24.

Stein, A., Draxler, R., Rolph, G., Stunder, B., Cohen, M., & Ngan, F. (2015). NOAA'S HYSPLIT Atmospheric transport and dispersion modeling system. Bulletin of the American Meteorological Society, **96**, 12 (DEC. 2015), 2059-2078. Published by: American Meteorological Society.