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MODELLED AND MEASURED ABL CHARACTERISTICS FOR THE CITY OF SOFIA

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Abstract: The Atmospheric Boundary Layer (ABL) over Sofia is studied based on Weather Research and Forecasting (WRF) model set on 4 nested domains of grid size 32, 8, 2 and 0.5 km, using high resolution terrain (1 arcsec) data and Corine adopted to USGS classes land-use (3 arcsec). The innermost domain includes the urban area and surrounding valley and mountains and is spread on a horizontal grid of 157x129 nodes and 100 vertical levels, 27 of which below 600 m. NCEP Final Analysis 0.25 deg is used for initial conditions. Several boundary layer parameterization schemes are tested for the vertical profiles of wind, temperature and turbulent kinetic energy by comparison with sodar data. Two SCINTEC sodars (MFAS) are located within the innermost model domain – one (Sofia sodar) at the eastern part of Sofia and the other (Vakarel sodar) at 27 km in ESE direction. The Vakarel sodar, is equipped with RASS extension. The study covers several 2-week periods and here two days of late summer are given as example. Synoptic cases of weak atmospheric pressure gradients above the Balkan Peninsula are chosen for the analyses. The simulations capture closely the observed wind direction changes. The values of wind speed and temperature are slightly underestimated. The highest correlation between model and measurements is found for the air temperature and lowest for the vertical wind velocity profiles.

Key words: *ARW-WRF evaluation, Atmospheric Boundary Layer, sodar observations, case studies, RASS profiles*

INTRODUCTION

Sofia city is a challenging for meteorological modelling complex urban system, because of its geographical setting in a mountain valley and the urban development with variety of residential, sports and industrial buildings, parks, etc., as well as the growing urban road infrastructure. The city is spread at a mean altitude of about 550 m above sea level (a.s.l.) and is surrounded by several mountains, namely Lyulin, Vitosha, Lozen and Viskyar (to the southwest and south), the Vakarel Mountain to the southeast, the low Slivnitsa Heights to the northwest and the Balkan Mountains to the north. The main objective of this study is to understand in further detail the processes within Sofia urban area and the effect of Vitosha Mountain on large-scale flows comparing the wind and turbulence behavior at urban and rural sites. Sodar data of high space and temporal resolution within and outside the city allow extensive evaluation of vertical profiles in the simulated flow, wind and turbulence characteristics. Measurements and discussion of turbulence characteristics in the area are performed by Batchvarova et al. (2007), but only for the surface layer. Concerning the ABL height and vertical profiles of meteorological parameters in the valley, until 5-6 years ago only radiosoundings (regular or experimental) were the source of information, Batchvarova et al. (2011), Kirova and Batchvarova (2017).

SODAR OBSERVATION AND SITES

The study is based on observations with two mono-static multi-beam Doppler acoustic remote sensing systems - Flat Array Sodar MFAS (SCINTEC), one in the eastern part of the city and the other in a rural area at 27 km in south-east direction (Figure 1). The vertical resolution of the data is of 10 m and the temporal resolution 10 minutes. The Vakarel sodar operated continuously, while the Sofia sodar only during day time (between 9 a.m. – 6 p.m. local summer time). A RASS extension for temperature profiles measurements is installed at the rural site. The operating frequency range of the sodars is 1650 - 2750 Hz, and 9 emission/reception angles (0°, ± 9.3°, ± 15.6°, ± 22.1°, ± 29°), a vertical range from 150 m to 1000 m. The wind speed (WS) is measured with accuracy of 0.1 - 0.3 ms^{-1} and wind direction (WD) of 2 - 3 degrees (Scintec AG, 2011). The sodar data output is saved every 10 min with averaging period of 30 min. The first measurement level is at 30 m and the maximum vertical range is 73 levels (i.e. up to 750 m at the chosen resolution).

METEOROLOGY

Synoptic charts of Europe reveal weak atmospheric pressure gradients above the Balkan Peninsula during the selected periods for model data validation. The meteorological observations at NIMH show sunshine duration of 5 hours on 3rd September and 10 h on 4th September; precipitation of 18 mm in late afternoon on the second day; and cloud cover of about 6/10 during the regular soundings performed at 12 UTC at on both days. The sounding system MW41 with RS-41SG radiosonde allows vertical resolution of 5 - 6 m. The ABL height is estimated about 1600 m and 1400 m above ground on first and second day, correspondingly. The prevailing wind direction is south-easterly on the first day and westerly on the second. The wind speed within the ABL reaches maximum of 4-5 ms^{-1}.

MODEL SETUP

WRF (WRF-ARW V3, 2017), a state-of-the-art atmospheric non-hydrostatic model, is used for numerical experiments in this study. Four nested domains in Lambert projection are selected, with the outermost D1 at 32 km covering the Balkan Peninsula, D2 at 8 km covering Bulgaria, D3 at 2 km covering the western part of Bulgaria, and the innermost D4 at 500 m covering the Sofia Valley and part of surrounding mountains (Figure 1). D4 is set to 157 x 129 cells with area approximately of 79 x 65 km. The model is implemented with 99 pressure-based terrain-following vertical levels from the surface to 50 hPa, 27 levels up to 600 m above the ground level (a.g.l.) and 40 levels up to 1000 m a.g.l. The initial and boundary conditions are derived from the 0.25-degree NCEP Final Operational Model Global Tropospheric Analyses, available every 6 hours. Data assimilation is used only for the outermost D1 for all vertical levels and for D2 above the first 10 model levels. NASA dataset with 1-arc-second (~30 m) resolution (SRTM1Arc; https://www.usgs.gov/centers/eros/science/) and CORINE 2012 database for land cover with 3-arc-second resolution (CLC2012, https://www.eea.europa.eu/data-and-maps/data/clc-2012-raster) are applied. Complete description of the methodology of data processing and remapping CLC2012 to the existing into the model surface properties of USGS are described in (Vladimirov et al., 2018; Dimitrova et al., 2019). The WRF physics package includes the new version of Radiative Transfer Model parameterization for longwave and shortwave radiation; Noah land surface model; and Grell-Freitas cumulus parameterization, for D1 and D2 domains only. The same domain has been tested with different planetary boundary layer (PBL) and microphysics schemes (Egova et al., 2017; Vladimirov et al., 2018; Danchovski et al., 2019 Kirova et al., 2020). Based on these results the BouLac scheme (with prognostic TKE prediction, local vertical mixing, eddy viscosities depend on TKE and length scale) is considered for the simulation of 3-4 September. Different schemes are described in WRF-ARW V3 (2017).

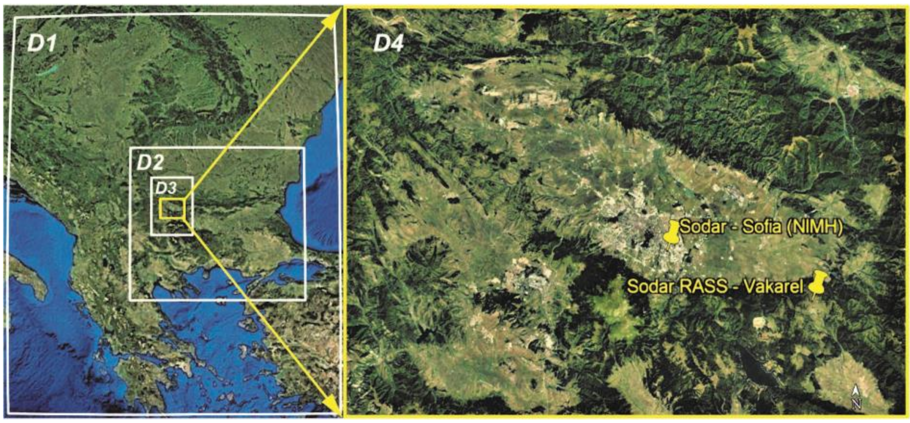


Figure 1. Modelling domains (D1-D4) and the location of the sodars within D4

RESULTS AND DISCUSSIONS

Sodar measurements

Sodar observations in Sofia and Vakarel for 3rd and 4th September 2018 are presented in Figure 2. The period is characterized by reversing of the WD from SE on the first day to NW on the second day at both sites (Figure 2 - a, d). During the first day higher values of the WS are observed reaching up to about 10 ms^{-1} (Figure 2 - b, e). The continuous observations at Vakarel site allow to observe a significant decrease in the WS (Figure 2 - e) in the entire vertical range of the sodar during the transition between these two days at the night of 3rd to 4th September. This period is also characterized with frequent changes in WD (Figure 2 - d). Higher values of TKE are registered by Vakarel sodar on 3rd September (1.13 m^2s^{-2} between 6 a.m. and 3 p.m. UTC) compared to Sofia sodar (0.44 m^2s^{-2}), Figure 2 (c, f). On 4th September the TKE values at both sites are close. About 3 °C higher values are registered for the temperature profiles of 3rd September compared to those of 4th September in Vakarel (Figure 2, g).

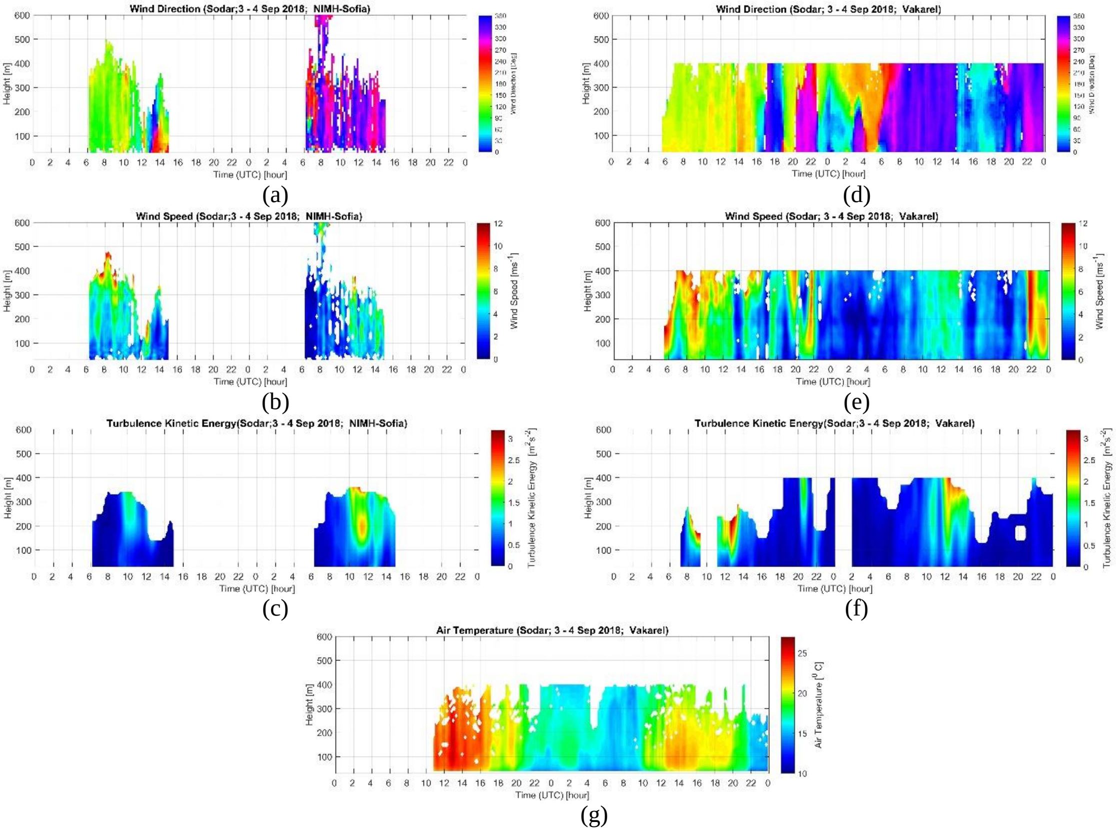


Figure 2. Sodar measurements of WD (a, d), WS (b, e), TKE (c, f) and T (g) in Sofia (a, b, c) and in Vakarel (d, e, f, g) for 3 - 4 September 2018

Model evaluation

In order to compare model profiles and sodar observations, the model output is linearly interpolated to the levels at which the sodar performed measurements (a total of 58 levels from 30 to 600 m at every 10 m). The analysed parameters at both sites are wind speed (WD), wind direction (WD), wind components (U, U, W), turbulent kinetic energy (TKE), and temperature (T) only at Vakarel. The statistical indicators which are used are model mean, observation mean, standard deviations (SD), bias and correlation coefficient (r). All estimations for WD are computed using the circular statistics. The linear r is calculated for two data sets to represent changes of r with height and changes of r in time. The results for TKE and T are shown in Figure 3.

The spatial values of r in Sofia are 34 (blue lines and blue axes) for TKE calculated from 108 time pairs (Figure 3-a). The 34 values of r for the TKE at Vakarel (Figure 3-b) are computed from 223 time pairs.

The r for temperature are calculated at 37 levels, based on 225 time pairs (Figure 3-c). The TKE correlation is significant for most of the levels (79 %). At Vakarel for entire profiles of TKE and T (Figure 3-b, c) a positive correlation is calculated with $|r| > 0.5$ in more than 97 %. Strong correlation is observed for T (Figure 3-c) for all measurement levels and for TKE in 84 % of the cases.

The temporal values of r (the red lines and axes in Figure 3) are composed from 34 levels for TKE and 37 levels for T. The TKE temporal r set for Vakarel contains 255 values and for Sofia - 108 values. At Sofia a positive correlation is observed in 32 % for TKE. Values of $|r| > 0.5$ are calculated in 81 % for TKE. Very strong and strong correlations are observed for TKE respectively in 37 % and 32% of the time series. At Vakarel positive correlation is observed in 53 % of the pairs for TKE and in 50 % for T. Values of $|r|>0.5$ are calculated in 64 % for TKE and 56 % for T. A strong correlation is observed for the air temperature (in 28 % for T) and very strong for TKE (27 %).

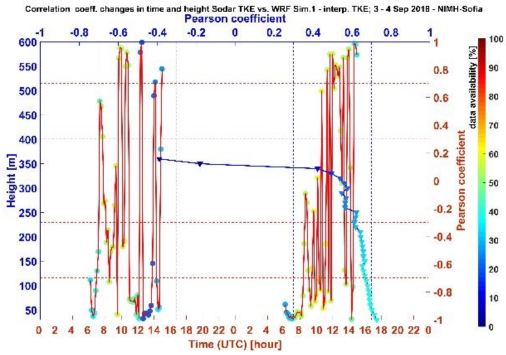
The statistical indicators are presented in Table 1. The highest r is calculated for WD (0.85) at the urban site, and for the same variable r is lowest (0.11) at the rural site. Higher bias of the WD is calculated for Vakarel compared to Sofia. Better statistical indicators (higher r, smaller difference of SD obs and SD mod as well as lower bias by absolute values) are obtained for U component at the rural site. Significant correlations for V component are calculated for both sites. The TKE is simulated with strong correlation coefficient and very small overestimation of 0.1 m^2s^{-2} in Vakarel compared to Sofia where significant correlation and higher bias of 1 m^2s^{-2} are obtained. Strong correlation is observed for T and it is overestimated only by 0.1 °C. The vertical structure in rural site is reproduced with lower values of errors and high values of r except for the WD.

Table 1. Statistical indicators for Sofia and Vakarel, Simulation 1, BouLac ABL scheme, 3 - 4 September 2018

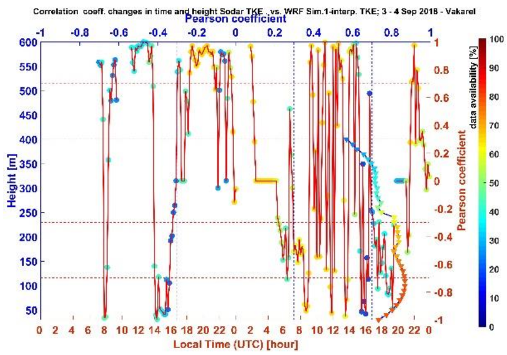
	Indicators/ Parameters	**WD (degrees)**	**U (ms^{-1})**	**V (ms^{-1})**	**TKE** (m^2s^{-2})	**T** (°C)
Sofia	count	3251	3251	3251	2869	
	r	0.85	0.74	0.66	0.59	
	SD mod	66.6	2.3	1.6	0.9	
	SD obs	77	3.4	2.7	0.5	
	bias	-7.4	0.4	-0.7	1	
	mean mod	358.9	-0.1	-0.8	1.7	
	mean obs	6.3	-0.5	-0.1	0.7	
Vakarel	count	9291	9291	9291	6361	6975
	r	0.11	0.74	0.58	0.74	0.79
	SD mod	76.9	1.9	2.7	1	2.3
	SD obs	74.2	3.1	3.5	0.5	2.7
	bias	102.8	-0.1	0.3	0.1	0.1
	mean mod	130.2	-0.4	0.1	0.7	18.9
	mean obs	27.4	-0.3	-0.2	0.6	18.8

The differences between observed and modelled TKE and T are shown in Figure 4. During the simulated period the TKE is mostly overestimated by the model in Sofia and Vakarel (blue colour) around midday, and underestimated at night in Vakarel (red colour). The overestimation of the TKE in Sofia for both days is bigger than in Vakarel. The averaged difference between observed and modelled TKE is -1.1 m^2s^{-2} for the first day and -1 m^2s^{-2} for the second day in Sofia and -0.75 m^2s^{-2} and -0.67 m^2s^{-2}, respectively, in Vakarel. Almost equal largest TKE differences are registered for both sites for both dates (-2.86 m^2s^{-2} in Sofia and -2.69 m^2s^{-2} in Vakarel) for the first day, and (-2.79 m^2s^{-2}) and (-2.61 m^2s^{-2}), respectively, for the second day.

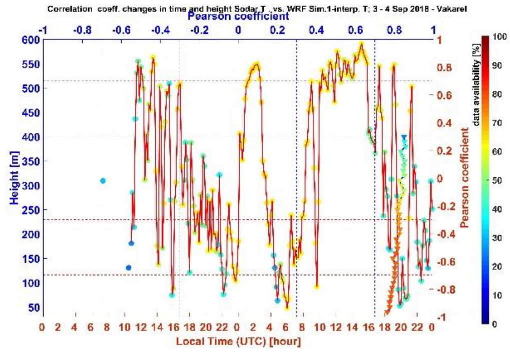
The model underestimated the observed TKE values at Vakarel site starting from 14:40 UTC of 3rd September until 5:20 UTC on 4th September with average value of the difference about 0.3 m^2s^{-2} and maximum of 1.7 m^2s^{-2} between 20:20 – 20:50 UTC.



(a)

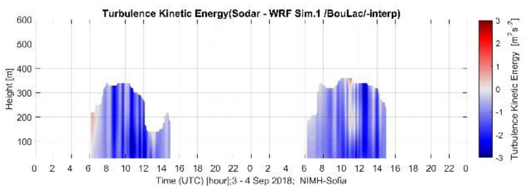


(b)

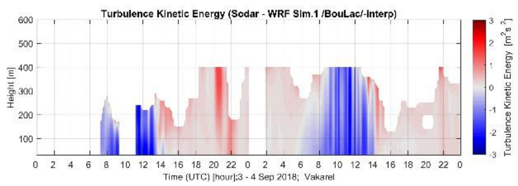


(c)

Figure 3. Spatial (top and left blue axes and blue line with coloured triangles) and temporal (botom and right red axes and red line with coloured dots) values of r for TKE at Sofia (a) and Vakarel (b) and T at Vakarel (c). The availability of data is presented by the colour of the symbols (colour bar on the right)



(a)



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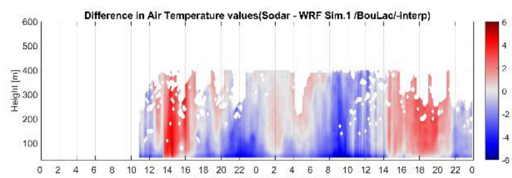

(c)

Figure 4. Difference between observed and modelled TKE at Sofia (a) and Vakarel (b) and T at Vakarel (c) for the period 3 - 4 September 2018

The second period with underestimation with average difference of 0.25 m^2s^{-2} at Vakarel site starts at 14:20 UTC on 4th September and continues till the end of simulation. The maximum is again of 1.7 m^2s^{-2} and is observed between 21:30-21:50 UTC in the highest layer of observation.

DISCUSSION AND CONCLUSIONS

Both Sofia and Vakarel sodars are of middle range which defines the availability of data up to 600 m elevation with high vertical resolution of 10 m, thus not providing profiles within the entire convective boundary layer. Still, the information on wind and turbulence parameters profiles is unique for the area and will be analyzed further. The studies cover two-week periods of late summer and winter of 2018 and early spring of 2019. Synoptic cases of weak atmospheric pressure gradients above the Balkan Peninsula are chosen for the analyses. Just one example of the methods used for analyses is presented here for a 2-day period in September 2018, when convective ABL reached height of 1400-1600 m above ground. It is found that the simulations capture closely the observed wind direction changes, slightly underestimate the horizontal wind speed components and temperature. The TKE is overestimated during midday hours and underestimated during the other parts of the day. The highest correlation between model and measurements is found for the air temperature.

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