MODELLING THE IMPACT OF VANISH GREEN AREAS ON LOCAL METEOROLOGICAL CONDITIONSIN SOFIA, BULGARIA

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Abstract - The rapid and unprecedented growth of the Bulgarian capital, Sofia city, brought serious challenges, including environmental degradation and increased human health risks associated with heat, noise, pollution and crowding. Approximately a quarter of the Bulgarian population (1,600,000) live in Sofia city at present. A significant part of the open space has vanished as result of building construction during last couple of decades. The expansion of the city impacted the agricultural land and green areas, reaching the foothills of the mountains Vitosha and StaraPlanina. It is widely known that urban green spaces such as parks and urban forests help reducing heat accumulation and improve air quality. The goal of this study is to investigate the impact of disappearing green areas in Sofia and its suburbs on local meteorological conditions. The Advanced Research version of the Weather Research and Forecasting model (ARW-WRFv3.9) is employed to simulate the local meteorological conditions using fine horizontal grid that is 500 meters of the most inner domain. Very high resolution of orography (1 arcsec) and land cover data (3 arcsec) are used. Three experiments were performed including substitution of the urban area with most representative rural land cover, replacement of existing urban area with high-density urban area in whole city, and extension of high-density urban area with parks and city forests are performed. The existing local meteorological conditions are compared with results from the hypothetic city development. The study aims to draw attention on the negative effects of losing green areas in our urban environment.

Index Terms -Heat Fluxes, Numerical Modelling, Urban Environment, Urban Green Areas.

I. INTRODUCTION

Most people live in cities and urbanization is continuing worldwide. Today, 55% of the world's population lives in urban areas, and a proportion is expected to increase to 68% by 2050 [1]. This trend is significant for Bulgaria also. Bulgarian population leaving in the urban areas has increased approximately 2.7 times, from 27.6% in 1950, up to 74% in 2015 [2]. According to the official statistics, Sofia has now about 1,238,438 inhabitants [3]. The problem with the lack of compulsory address registration, however, makes the city's management believe that there are between 1,600,000 and 1,800,000 people in the capital, which makes up about a quarter of the country's population of 7,050,034 according to the National Statistical Institute [3]. The rapid growth of Sofia city brought serious challenges, including environmental degradation and increased human health risks associated with heat, noise, pollution and crowding. The unprecedented inhabitantgrowth and constantly increasing flow of job seekers in the capital city, dynamically changed the socio-economic conditions. This trend become even stronger after Bulgaria accession to the European Union, due to increased investments and new stringent regulations.

Many studies have shown that buildings and urban land use significantly modify the flow fields in micro and mesoscale [4, 5, 6, 7, 8, 9, 10]. The build-up areas cause significant changes in the fields of meteorological parameters and affect considerably local microclimate [10, 11]. The differences in energy balance, temperature, humidity, and storm runoff between urban areas and rural surfaces are substantial. Urban ecosystems are formed by the biological population of organisms (vegetation, animals, and people) and the abiotic environments of cities [10].An urban area includesremnant ecosystems (e.g. undisturbed ponds, lakes, ravines, escarpments, forests and other parkland), managed ecosystems (e.g. fields, tended parks, gardens, cemeteries, golf courses and other open ground) and totally anthropogenic systems (those dominated by the built system, such as roads, buildings parking lots, industrial tips and ponds) [10].

It is widely known that urban green spaces such as parks and urban forests can help reduce anthropogenic heatflux and improve air quality. A significant part of Sofia's open green space has vanished as result of building construction in recent years. The expansion of the city has modified the agricultural land and green areas, reaching the foothills of the mountains Vitosha and StaraPlanina.

The goal of this study is to investigate the direct effect of urbanization on local meteorological conditions, and the impact of disappearing green areas in Sofia and suburban.The Advanced Research version of the Weather Research and Forecasting model (ARW-WRFv3.9) is employed with fine horizontal (500 meters) resolution for the most inner domain. Three experimentsare carried out: 1) substitution of the urban area with most representative rural land cover; 2) replacement of existing build-up area (4 categories) with high-density residential land cover throughout the whole city; 3) extension of high-density urban residential area overthe parks and city forests. These hypothetic most extreme land cover changes, which are due to human activities, provide a quantitative base to alarm the authorities about possible irreversible harmful effects on urban ecosystem and quality of life in Sofia.

II. MODEL SET-UP

The well-known Weather Research and Forecasting (WRF) model, version 3.8.1 is used for the numerical experiments. WRF is a state-of-the-art atmospheric modelling system, designed for broad range of applications [12]. These include idealized simulations for investigation of specific physical processes in the atmosphere, data assimilation, and operational forecast.

2.1. Modeling domain and initialization

High resolution numerical modelling,withhorizontal (500 meters) resolution and 100 irregular stretched vertical levels, with greater density in planetary boundary layer (PBL), is exploited for this study. Four nested domains are used based on a Lambert Projection (Fig. 1), which essentially covers Balkan Peninsula (Domain 1, D1), Bulgaria (Domain 2, D2), Western part of Bulgaria (Domain 3, D3) and Sofia Valley (Domain 4, D4). D1 has 36 x 44 horizontal grid points with 32-km grid-point spacing; D2 – 73 x 65 with 8-km cells respectively; D3 – 69 x 97 with 2-km cells, and D4 cover Sofia Valley with 157 x 129 cells.

The initial and boundary conditions are derived from the 0.25 degree NCEP Final Operational Model Global Tropospheric Analyses [13] prepared operationally every 6 hours. Data assimilation (fdda model option) is used for domain D1 (the parent domain) at all vertical levels and for domains D3 andD2 only above the closest to the ground 10 modellevels. The fdda option did not apply for the most inner domain (Sofia valley).

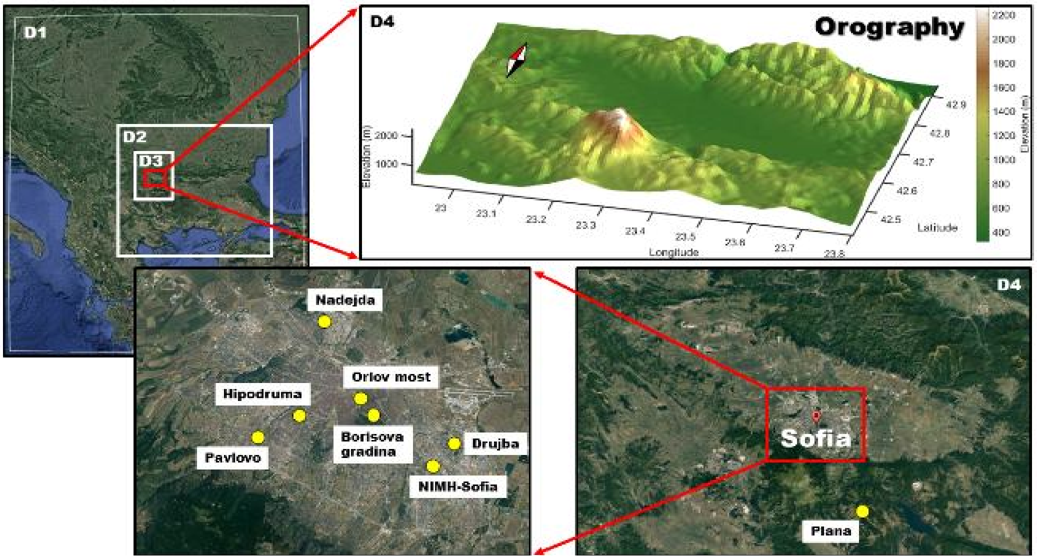

Fig.1.Modelling domains with enlarged view of the most inner domain D4 and Sofia city; the location of observational sites used for model validation are also shown.

Two major changes are introduced into WRF by the input static fields, in order to improve the model performance. With increasing grid resolution, small-scale terrain features can be better resolved in the model and a more realistic representation of the terrain is achieved [14, 15]. Two new datasets have been implemented and adapted to the study domain - high resolution topography data [16] with resolution 1 arcsec (approximately 30 m), and the Corine land-cover dataset [17], with resolution 3 arcsec (approximately 90 m), which have been revisedto US Geological Survey landuse (USGS) classes. More details regarding the procedure and new datasets implementation can be found in [18].

2.2. Model options

The WRF physics package includes: the Rapid Radiative Transfer Model longwave radiation parameterization [19], Dudhia shortwave radiation parameterization [20], which computes radiation at fine time scales (every 10 min), and Noah land surface model [21]. Grell-Freitas (GF) cumulus scheme [22] is used only for the coarse meso-scale simulation D1 with 32 and D2 with 8 km grid spacing). The same exact domain has been tested already with different PBL and microphysics schemes [18, 23]. A sophisticated microphysics scheme [24], suitable for real-data high-resolution simulations, and

Yonsei University planetary boundary layer turbulence scheme [25] are used in this study.

III. CASE STUDY

The selected case study covers 11 days (25 August – 4 September, 2016) with considering 24 hours of spin-up. The case study is characterized with anticyclonic fair weather, dry (low humidity, the mixing ratio 7 g/kg less than50 % relative humidity, averaged for the all stations in Sofia) and quiescent (wind speed < 5 m/s at 850-hPa) conditions.

3.1. Observations

Observations for temperature and relative humidity at 2 m at six automatic stations (Borisova Gradina, Orlov most, Druzhba, Hipodruma, Nadezhda, Pavlovo) and one synoptic station (NIMH) located in Sofia city (see Fig.1), are used for model validation. Near surface data from outside the urban area site (Plana) and vertical profiles (NIMH) are also available and comparison have been done, however these results will be discussed in a future article.

3.2. Model validation

Standard statistical measures - the mean bias (MB),mean absolute error (MAE), root mean square error (RMSE), and correlation coefficient (r) for temperature and mixing ratio are shown together with the mean values and standard deviation in table I. The indexes of agreement (IA) parameter, developed by Willmott [26], is a standardized method to determine the degree of the model prediction error(eq. 1).

$$IA = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}\left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} \quad (1)$$

Here P_i and O_i are the predicted and observed values, respectively, and $\overline{O}$ is the mean observed value.The IA values range between zero and 1, with 1 indicating a perfect match. WRF delivers results with an excellent performance for temperatureat 2 m with IA and r 0.98, MAE in reasonable range less than 1.5 °C. Thenegative bias -0.7°C indicatesslight underestimation of the registered temperature.The mixing ratio has not so good agreement with observations as the temperature, but still shows reasonable rates of 0.71 for IA and 0.64 for r. The MAE is 1 g/kg or approximately 14% from the mean value 7.1 g/kg.

Statistical Measures For Temperature And Mixing Ratio (All Stations Located In Sofia)

	TEMPERATURE		MIXING RATIO	
	Observations	Modelling	Observations	Modelling
Mean	23.9	23.2	7.1	6.8
St. Dev.	5.6	5.3	1.0	1.2
MB		-0.7		-0.3
MAE		1.4		1.0
RMSE		1.6		1.2
IA		0.98		0.71
r		0.98		0.64

IV. RESULTS AND DISCUSSION

The interaction at the bottom model boundary between the surface and the atmosphere, that is, the coupling through surface fluxes of heat, moisture, and momentum, is performed by the Land Surface Model

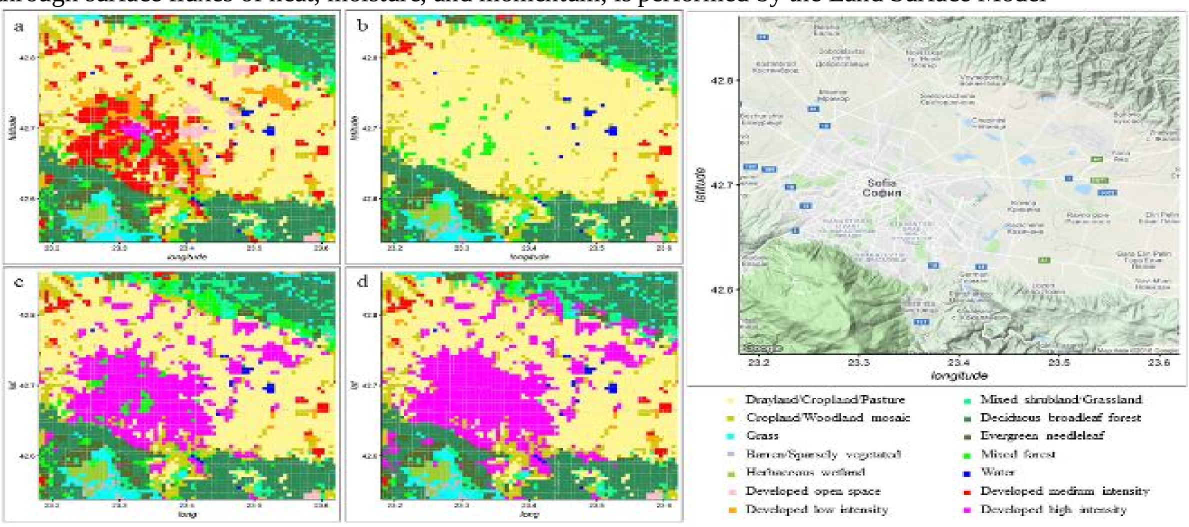

Fig. 2.Maps of different classes used in adapted CORINE land cover base case (a) and with different experiments – non-urban (b), urban-high-intensity (c), urban-no-parks (d). Sofia city municipality map and legend with different land-use classes are also shown.(figure should be in color)

(LSM) module in WRF. In addition to the computation of surface fluxes, LSMs also compute soil and land cover properties, such as soil temperature and moisture. WRF provides output for main fluxes at the ground – surface sensible, latent heat and ground heat fluxes that balance the total net radiation (incoming and outgoing shortwave and longwave radiation). These fluxes strongly depend on different land categories, which have diverse surface thermal properties such as thermal inertia, surface heat capacity, surface emissivity and albedo.

Four different build-up categories are considered for the urban area in this study - high and low intensity residential areas, medium or industrial areas, and developed open space – roads, parkings,etc). Results from this case (called further base urban case; see Fig. 2a) are validated in section 3.2 as this case corresponds to the present conditions. Three numerical experiment were conducted, with corresponding abbreviation used further: 1) non-urban - all urban categories in Sofia municipality area were replaced with the surrounding the city most common land cover category - Dryland Cropland and Pasture (Fig. 2b); 2) urban-high-intensity –all four build-up categories were replaced with high intensity residential areas (Fig. 2c); 3)urban-no-parks - all four build-up categories and parks were replaced with high intensity residential areas (Fig. 2d). The first experiment provides useful information on the effect of urbanization on local meteorological conditions bymodifying the agricultural land to build-up area. The difference between base and non-urban case are investigated. Second and third experiments describe the hypothetic city development expansion, the worst scenario.

We realize, that the modeled scenarios are exaggerated to some extent, but the goal of this study is to draw attention on possible very negative effectson our urban environment due to losing green and open areas. The expansive building construction in Sofia city municipality during the past couple of decades, transformed the city, producing many very densely built-up spots.

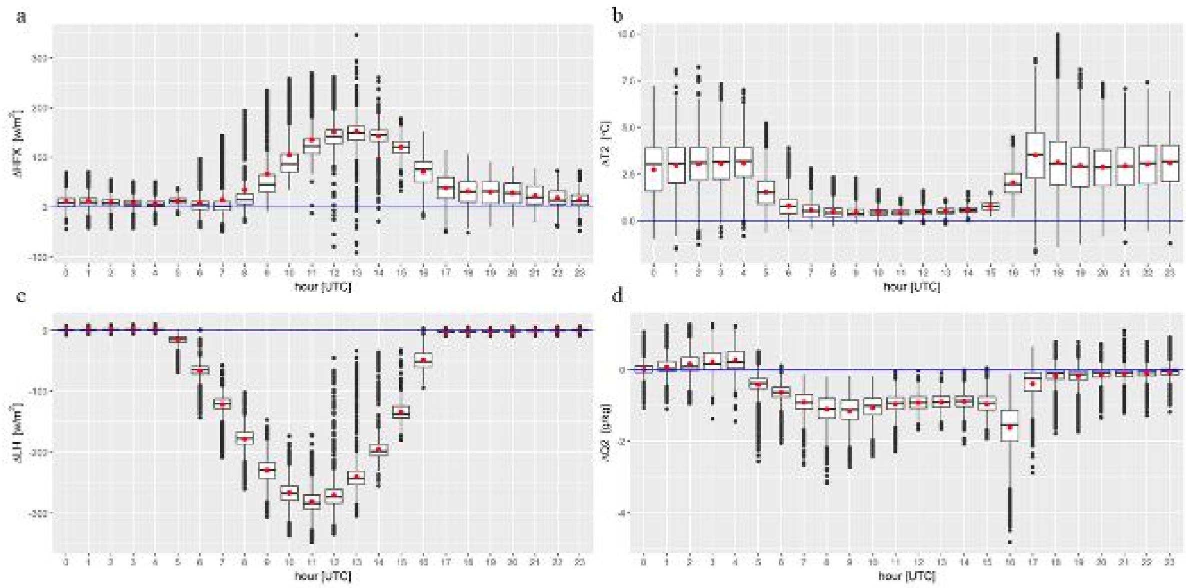

Fig. 3.Box plots presenting differences between: base urban and non-urban scenarios for sensible (a) and latent (c) heatfluxes, temperature (b) and water vapor mixing ratio (d). Presented data are extracted from all grids with build-up land use and cover the entire considering period).

A box-and-whisker diagram is a descriptivemethod for graphically depicting groups of numerical data through their quartiles.Fig. 3 presents differences between base urban and non-urban scenarios.Plots present the mean (red dot inside the box), the median (black line inside the box), the vertical lines correspond to the lowest datum still within 1.5IQR (interquartile range) of the lower quartile (base of the box) and the highest datum still within 1.5IQR of the upper quartile (top of the box).All data outside adopted criterion are presented by dots.Data, extracted from all grids with build-up land cover, considering the entire period are used.

The effect of urbanization (the expansion of the urban landscape) leads to significant disturbance of the surface geometry and properties. Natural materials are removed, replaced or modified and the new environment often dominated by impermeable manufactured materials.The large volume of asphalt, brick, concrete and other materials give urban areas a low thermal inertia and high surface heat capacity than rural areas. Thermal inertia is a physical parameter representing the ability of a material to conduct and store heat during the day and reradiate it during the night. Materials with high thermal inertia value show less temperature amplitude during a full heating and cooling cycle (day heating and night cooling process) than those with lower thermal inertia. Surface heat capacity is the measure of the increase in thermal energy content or heat per degree of temperature rise. Surfaces with more heat capacity like mixed forest will need more time and more energy from the sun in order to increase their temperature during the day. The difference in sensible heat flux, result from the modifications to the surface cover, has maximum mean value more than 250 W/m^2around noon (Fig.3a). The urbanization leads to an increase of temperature with approximately 2.5°C during the night, when the materials emit the stored heat during the day,well known heat island effect (Fig.3b).The densely built urban landscapes are the predominant impervious surface cover and the relative lack of vegetation means there is relatively little water available for 'natural' evaporation so the daytime latent heat flux is significantly reduced.Significant decrease in the latent heat flux mean value more than 250 W/m^2 (Fig.3c) affect the moisture content in the atmosphere, and the water vapor mixing ratio drops with approximately 1g/kg (Fig.3d). The effect of denser build-up and urban landscape extension in Sofiacity municipality are shown in Fig.4.The growth of building density and height leads to an increasein near surface temperature with approximately 2 °C and decrease in nocturnal temperature with approximately 5 °Cat Druzhba site (the categorywas changed from lowto high intensity). This finding can be result of cavity effect of the surface which increase both surface absorptivity and emissivity.The general effect is an increase of the diurnal amplitude change. The expansion of the urban landscape over the parks and green areas in the city leads to an increase in temperature in the late afternoon and night time with approximately 5°C at Borisova Gradina site. Great amount of radiationgets accumulated in the human-manufactured materials and that is emitted to the atmosphere during night-time.

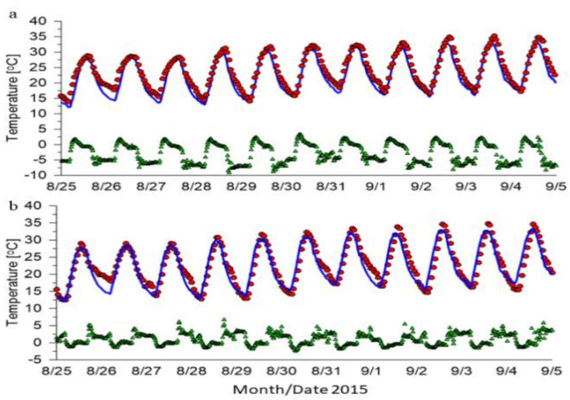

Fig. 4. Temperaturetimeseriesforthebaseurbanscenarios, comparedwithobservations (theupperplot) andthetemperaturedifferenceafterreplacementofurban-low-intensitycategoryat Druzhba site (a) andparkareacategoryat BorisovaGradinasite (b) withurban-high-intensitycategory

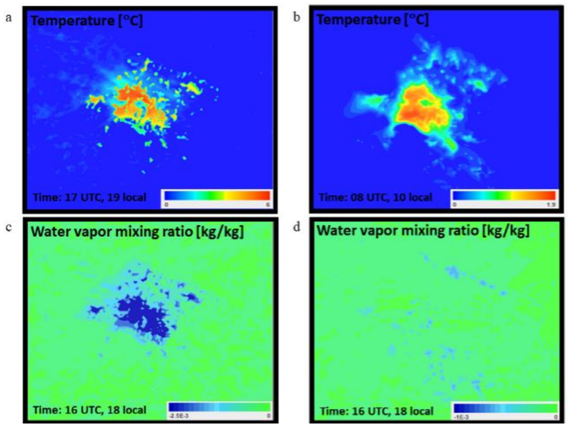

Fig. 5.Spatial distribution of differences in average field of temperature and water vapor mixing ratio, from particular experiments: base urban caseminusnon-urban (a, c) and urban-no-parksminusbase urban case (b, d)

All experiments cover the entire 11 day study and the mean fields represent an hourly average over all days. As this study case covers days with similar conditions, averaging by hour will result in smoothing the random errors within the numerical modeling. Examples of spatial distribution of differences in average field of temperature and water vapor mixing ratio, from particular experiments, are shown in Fig. 5. Maximum effect from the land use replacement in the fields of temperature and humidity occur at different time. The urban landscape increases temperature with 6 °C and decrease moisture with 1.5 g/kg in comparison with the rural area. High intensity residential areas, that describe higher buildings and denser build-up, strengthen the effect adding approximately 2 °C more and reducing moisture with approximately 1g/kg for the specific areas, where parks and open green areas has vanished.

CONCLUSIONS

Most of the earth's resources are consumed in the mega cities of today, where most people live. Urban environmental challenges need to be solved promptly and in parallel with the cities development to ensure a sustainable future and healthy and happy population. An integral approach that considers both the environment problems related to human activity, and the health and comfort of the city inhabitants, is the only way to avoid costly and harmful mistakes due to wrong assumptions and lack of proper expansion planning. The numerical modelling techniques that are discussed in this paper deal with the challenges of future city development scenarios. These are extremely powerful tools that deliver critical data to the city planners, authorities and decision makers.

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