Study of the Extreme Thermal Conditions for the Sofia Region—Preliminary Results

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Abstract The environmental thermal comfort is one of the issues not only these days, but also in the future, concerning the results from the climate projections. The objective of this paper is to study the human discomfort in winter and summer in Sofia and its surroundings. Weather Research and Forecasting (WRF) model numerical simulations were used to calculate two characteristics called indexes, of the thermal environmental properties from the human point of view. They estimate the deviation of the environmental conditions from the human thermal comfort. The first one—Wind Chill index describes the thermal discomfort in low temperatures (winter), depending on air temperature and wind speed. The second one—Heat Index describes the deviation from the summer thermal comfort in high air temperatures (summer), depending on the air temperature and relative humidity. Numerical experiments with combination of different parameterization schemes for atmospheric boundary layer and microphysical processes were carried out. Model performance for the temperature, wind speed and relative humidity were used for estimation of the best model options for calculation of the Wind Chill and Heat Index in the corresponding conditions when they are applicable.

Keywords Wind chill index modelling · Heat index modelling · WRF model performance estimation

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N. Dobrinkova and G. Gadzhev (eds.), *Environmental Protection and Disaster Risks*, Studies in Systems, Decision and Control 361,
https://doi.org/10.1007/978-3-030-70190-1_9

1 Introduction

The environmental thermal comfort is one of the issues not only these days, but also in the future, concerning the results for the projected thermal environmental conditions [26] and related air pollution [6–10]. The increasing population of the cities entails their growth through the gradual amplification of urbanizing. That strengthen the urban heat island effect [21], change the surroundings modifying the local circulations [11], and the precipitation distribution [4], etc. Therefore, the implications from the increasing or decreasing of the air temperature become of bigger importance. The degree of thermal discomfort is expressed as a single number, and depends mainly on air temperature, humidity, wind speed and possibly other parameters. That dependence is categorized in ordinal scale for deviation from the environmental thermal comfort for human beings [3]. The problem of thermal comfort for the territory of Bulgaria and the Balkan Peninsula is addressed in several studies. Some of them dealing with observations [14, 15], show that the deviations from the thermal comfort in Bulgaria become significant from the human perspective in both cold and warm seasons. Others, calculated from regional climate model, also show that the Balkan Peninsula is subjected to heat-related risk [16].

The objective of this paper is to study the human discomfort in Sofia and its surroundings in typically winter and summer conditions. The Weather Research and Forecasting Model (WRF) model was used for simulation of temperature, humidity and wind fields. Different parameterization schemes for atmospheric boundary layer and microphysical processes were compared for estimation of the best model options for modelling the Wind Chill index and Heat Index in typical winter/summer month. The paper is structured as follows. Section 1 consists of two subsections. The first subsection provides description of the numerical modelling experiment. The second subsection describes the calculation procedure of the degree of thermal discomfort. Section 2 gives results of the model validation. Section 3 describes the modelling results of the thermal discomfort in two subsection—the first is for the winter season, and the second one is for the summer season. The conclusions are made in Sect. 4.

2 Methodology

2.1 Meteorological Fields Modelling

WRF is a mesoscale numerical simulation system for research and operational forecasting of the atmospheric environment (WRFv3.9; [23]). Five nested domains in Lambert projection, with D1 at 9 km, D2 at 3 km, and three at 1 km horizontal resolution (D3, D4, D5) were selected for modelling with hourly output. The map with domains is shown in Fig. 1. The bigger domain D1 covers the north and central parts of the Balkan Peninsula, the inner domain D2—mainly the territory of Bulgaria, the innermost domains: D3—the Sofia valley, D4—Plovdiv region, D5—Varna region.

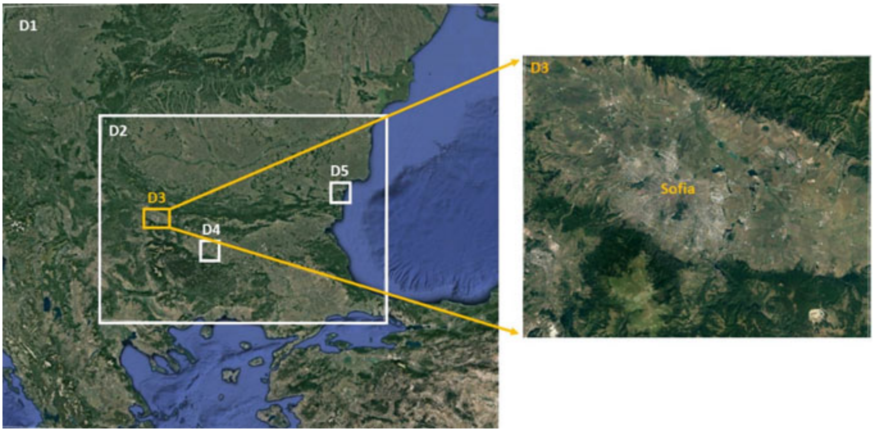

Fig. 1 Modelling domains with an enlarged view of the innermost domain D4 and Sofia city

The study considers only the innermost domain D3, which includes geographically the city of Sofia and its surroundings with complex terrain. The model was implemented with 50 pressure-based terrain-following vertical levels from the surface to 50 hPa. The initial and boundary conditions were derived from the 0.25° NCEP Final Operational Model Global Tropospheric Analyses (http://rda.ucar.edu/datasets/ds083.2/) datasets available every 6 h. Data assimilation (fdda model option) was used for the outermost domains D1 for all vertical levels and for domain D2 for the first 10 model levels above the ground. A detailed representation of the orography (NASA Digital Elevation Data—SRTM1Arc with ~30 m resolution; https://lta.cr.usgs.gov/SRTM1Arc), and utilized land cover (CORINE2018 Land Cover with ~90 m resolution; https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=download) after reclassifying procedure, described in [30], is applied in this study.

The atmospheric physics options are responsible for the including of the sub-grid atmospheric and surface processes, which cannot be solved explicitly by the model—the planetary boundary layer (PBL), microphysical processes, convection, shortwave, and longwave radiation processes, land-air interaction. The WRF physics package included: the new version of Radiative Transfer Model—RRTMG parameterization [13]—for longwave and shortwave radiation to compute radiation at every 10 min; Noah land surface model [2]; and Kain cumulus parameterization, for D1 domain only [17]. For this specific study, the most important was to calculate properly surface temperature, humidity and wind speed to ensure reliable calculation of the Wind Chill and Heat indexes. The model sensitivity was evaluated using three PBL schemes—Yonsei University scheme (YSU; [12]), Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2.5; [19]), the Quasi-Normal Scale Elimination scheme (QNSE; [27]), and two microphysical schemes—Thompson [29], and Lin [18]. The YSU PBL is a non-local K scheme, first-order; the MYNN2.5—turbulent kinetic energy, second-order scheme with level 2.5, and QNSE uses a self-consistent, quasi-normal scale elimination algorithm and spectral space representation. The Lin microphysics is a single-moment sophisticated scheme that has ice, snow, and graupel processes, suitable for real-data high-resolution simulations; Thompson also is a single-moment for cloud water, ice, snow, rain, graupel, hail, but calculate also the rain number concentration. The selections were made after laborious inspection process of various schemes in previous studies for the same domain ([5, 30, 31]). Six experiments were performed in this study with all possible combinations of options, described later by the names of the using schemes.

2.2 *Wind Chill Index Calculation*

The index applicable for calculation the discomfort in low temperature conditions, which are typical for the winter, is called Wind Chill index [20]. It describes the cooling power of the wind in cold weather, and depends mainly on the air temperature and the wind speed. The colder temperatures and higher wind speeds makes the human body cool stronger, deteriorating the thermoregulation system, and possibly the tone and the health [24]. For study the cold season discomfort conditions, a typical winter month (January 2016) was selected. For more intuitive perception by the people, it is given in temperature dimension [20]. It is defined as the temperature that the human individual feel in calm weather, with heat losses from the body equal to ones for the given air temperature and wind speed. The body reactions to different combinations of the air temperature and wind speed is categorized in a six-grade linguistic scale (Table 1) used by the Canadian government (Wind chill index, 2020/09/25). The wind chill temperature is calculated using simple relation:

$$T_{\_WindChill} = 13.12 + 0.6215T + 11.37V^{0.16} + 0.3965TV^{0.16}$$

The “T” is the air temperature at 2 m in °C. The “V” is wind speed at 10 m in kmh^{-1}.

Table 1 Wind Chill index severity categorization

Wind chill temperature (°C)	Wind chill category	Environment risk
0 ÷ −9	Low risk	Slight increase in discomfort
−10 ÷ −27	Moderate risk	Increased discomfort, with risk of hypothermia and frostbite
−28 ÷ −39	High risk	Exposed skin can freeze in 10–30 min
−40 ÷ −47	Very high risk	Exposed skin can freeze in 5–10 min
−48 ÷ −54	Severe risk	Exposed skin can freeze in 2–5 min
< −55	Extreme risk	Exposed skin can freeze in less than 2 min.

2.3 Heat Index Calculation

The summer bio-meteorological conditions are studied for a typical month for the summer season (August 2015). The discomfort in warm/hot weather depends mainly on the temperature and the relative humidity [24]. Higher temperatures make human body sweating more intense. The main mechanism for cooling of the body in these conditions is the evaporation from perspiration. If the relative humidity is high enough, that evaporation is suppressed, and the body starts warming, which could lead to dangerous health conditions. The degree of danger for the human beings in high temperatures can be modelled by the so-called Heat Index [1, 22, 25]. It is the temperature in reference values of humidity, wind speed and solar radiation, which provoke the human thermoregulation system to react in the same way, as in the current environment conditions. The index values are separated in categories, each corresponding to some physiological reactions of the human body (Table 2). It is calculated by multiple linear regression formula embedded in the procedure in NCAR command language [28].

3 WRF Model Validation

The output from all described above model configurations was validated against observations in winter and summer conditions. Data for air temperature and wind speed (for winter) and temperature and relative humidity (for summer) from the stations of the National Environment Agency at four locations in the Sofia city (Druzhba, Nadezhda, Pavlovo, Hipodruma) were used. Standard statistics—the Mean Bias (MB) and the Root Mean Square Error (RMSE) were calculated and applied as criteria for model performance.

The calculated MB are given in Table 3, and the RMSE in Table 4. The MB of the temperature at Druzhba, Hipodruma, and Pavlovo is lower for the MYNN2.5_Thompson configuration. The best model options for simulation of the temperature at Nadezhda is MYNN2.5_Lin. The smallest wind speed MB at Druzhba is for the MYNN2_Lin simulation. The best simulation for the wind speed at Hipodruma is MYNN2.5_Thompson, and at Nadezhda—QNSE_Lin. The wind speed at

Table 2 Heat Index severity categorization

Heat index (°C)	Heat index category	Environment risk
27 ÷ 32	Caution	Fatigue and cramps possible with prolonged exposure and activity
32 ÷ 41	Extreme Caution	Cramps, heat exhaustion and heat stroke
41 ÷ 54	Danger	Cramps, heat exhaustion are likely; heat stroke is probable
54 ÷	Extreme danger	Heat stroke is imminent

Table 3 Mean Bias of the model configurations of the temperature at 2 m (T in °C) and wind speed at 10 m (WS in ms^{-1}) for January 2016

Stations		Model configuration					
		MYNN2.5	MYNN2.5	QNSE	QNSE	YSU	YSU
		Lin	Thompson	Lin	Thompson	Lin	Thompson
Druzhba	T	−0.54	0.05	−3.06	−1.02	−0.84	−0.21
	WS	0.25	0.37	0.37	0.65	0.54	0.56
Hipodruma	T	−0.96	−0.68	−3.61	−1.82	−1.62	−1.13
	WS	1.1	1.13	1.14	1.27	1.32	1.36
Nadezhda	T	−0.09	0.4	−2.93	−1.19	−0.59	−0.23
	WS	1.13	1.17	1.09	1.29	1.43	1.48
Pavlovo	T	−1.07	−0.66	−3	−1.73	−1.68	−1.1
	WS	0.84	0.86	0.87	1.02	0.86	0.91

Table 4 Root Mean Square Error of the model configurations of the temperature at 2 m (T in °C) and wind speed at 10 m (WS in ms^{-1}) for January 2016

Stations		Model configuration					
		MYNN2.5	MYNN2.5	QNSE	QNSE	YSU	YSU
		Lin	Thompson	Lin	Thompson	Lin	Thompson
Druzhba	T	3.02	2.93	4.99	3.11	3.16	3.05
	WS	1.04	1.07	1.66	1.76	1.33	1.38
Hipodruma	T	3.21	3.35	5.44	3.67	3.54	3.57
	WS	1.46	1.5	1.92	2.01	1.79	1.86
Nadezhda	T	3.07	2.89	4.93	3.32	3.21	3.04
	WS	1.52	1.58	1.84	1.97	1.88	1.97
Pavlovo	T	3.4	3.36	4.51	3.31	3.6	3.25
	WS	1.35	1.43	1.78	1.86	1.5	1.51

Pavlovo is in the best agreement with observations for the MYNN2.5_Lin simulation. Overall, the results of the model validation by the MB suggest that the MYNN2.5_Thompson simulates temperature the best. On the other hand, the wind speed is simulated with the lowest MB by the MYNN2.5_Lin configuration.

The smallest model RMSE for the temperature at Druzhba and Nadejda is MYNN2.5_Thompson, at Hipodruma is MYNN2.5_Lin, and at Pavlovo is the YSU_Thompson. The smallest RMSE of the wind speed at all stations is the MYNN2_Lin. The results of the RMSE lead to the same conclusions as for the MB. Therefore, the MYNN2_Thompson model set-up simulates the air temperature with smaller error, and the MYNN2_Lin simulates in the best way the wind speed. In general, all configurations underestimate the temperature with less than 2 °C (except QNSE_Lin) and overestimate the wind speed with approximately 1 ms^{-1} or less.

Overall, the model validation shows that the configuration with MYNN2.5 PBL scheme and Thompson microphysics have better behaviour in comparison to the others, concerning these two meteorological parameters. Moreover, the model configuration using the Thompson scheme for microphysical parameterization presents better results than Lin.

The calculated MB of air temperature and relative humidity for the summer month are given in Table 5. The smallest values for temperature at Druzhba, Hipodruma and Nadezhda correspond to the model configurations MYNN2.5_Thompson, and QNSE_Lin for RH. The MB at Pavlovo is best for the QNSE_Lin simulation. Therefore, the MYNN2.5_Thompson gives better results than others for the simulation of the air temperature at 2 m, and the QNSE_Lin for the relative humidity at 2 m.

Table 5 Mean Bias of the model configurations of the temperature (T in °C) and relative humidity (RH in %) at 2 m for August 2015

Stations		Model configuration					
		MYNN2.5	MYNN2.5	QNSE	QNSE	YSU	YSU
		Lin	Thompson	Lin	Thompson	Lin	Thompson
Druzhba	T	0.18	−0.04	−0.53	−0.46	0.37	0.36
	RH	−3.55	−2.79	−0.02	−0.1	−5.29	−5.38
Hipodruma	T	0.29	0.01	−0.59	−0.45	0.36	0.34
	RH	−7.62	−6.99	−3.55	−3.9	−8.91	−8.91
Nadezhda	T	0.41	0.17	−0.47	−0.32	0.61	0.63
	RH	−7.3	−6.71	−3.32	−3.62	−9.21	−9.47
Pavlovo	T	1.33	1.08	0.42	0.58	1.35	1.37
	RH	−7.55	−7.04	−3.39	−3.84	−8.7	−8.72

Table 6 Root Mean Square Error of the model configurations of the temperature (T in °C) and relative humidity (RH in %) at 2 m for August 2015

Stations		Model configuration					
		MYNN2.5	MYNN2.5	QNSE	QNSE	YSU	YSU
		Lin	Thompson	Lin	Thompson	Lin	Thompson
Druzhba	T	2.36	2.31	2.35	2.73	2.23	2.23
	RH	11.88	11.72	11.7	12.63	12.27	12.27
Hipodruma	T	2.42	2.38	2.77	2.74	2.36	2.28
	RH	13.71	13.15	13	13.09	14.5	14.09
Nadezhda	T	3.04	3.07	3.51	3.48	2.89	2.91
	RH	14.13	13.92	14.3	14.44	14.96	15.09
Pavlovo	T	2.87	2.78	3.01	3.01	2.76	2.73
	RH	14.35	14.07	14.15	14.25	14.96	14.59

The calculated RMSE are given in the Table 6. The simulation YSU_Thompson has the smallest values for the air temperature at Druzhba, Hipodruma and Pavlovo. The model configuration that provides the lowest RMSE for the relative humidity in Druzhba and Hipodruma is QNSE_Lin, and in Nadezhda and Pavlovo is MYNN2.5_Thompson. We can note that the MYNN2.5_Thompson have almost equal RMSE values in comparison with MYNN2.5_Lin for both temperature and relative humidity in all stations. The same applies for the YSU_Lin and YSU_Thompson.

Overall, we see that the MYNN2.5_Thompson and QNSE_Lin have better behavior from the other model configurations concerning the summer conditions. The differences are probably linked to the way the boundary layer parameterization schemes simulate the heat and radiation flows in the summer. As only the MYNN2.5_Thompson configuration provide the best results for the simulations in both winter and the summer months, we can conclude that it is the best combination for simulation the extreme thermal conditions in the Sofia valley among the other parameterization schemes.

Sofia city is located in complex topography with mountain Vitosha nearby, and most likely, the differences in the result are coming from the ability of the parametrization schemes to capture the local modifications of the large-scale weather. Therefore, reasons could be the roughness and/or topography characteristics surrounding the city, proximity to the mountain areas, terrain height, and the station exposure to the solar radiation. Note that building structures are not presented explicitly in these types of models, and shadow as well as the building wake effects can affect the temperature and wind fields significantly.

4 Thermal Comfort Modelling

4.1 Wind Chill Modelling

The results from the Wind Chill modelling show that different cases belong mainly to the categories—Low Risk, Moderate Risk, and High Risk. The number of Low Risk cases in the different domain locations is shown in Fig. 2. There are between 210 and 360 Low Risk cases in many areas of the domain, and in Sofia city are somewhere from 210 to 300 cases, except at the foot of the Vitosha Mountain. The number of Low Risk cases in the endpoints of the domain is higher. The number in the north-eastern near-city areas for MYNN2.5_Lin, YSU_Lin, and YSU_Thompson, is smaller than for the other model configurations. We can note that, the YSU_Thompson has a relatively smaller number of Low Risk cases in the whole domain. The Low Risk count distribution at the Vitosha Mountain cover from above 390 in the lowest terrain heights to below 150 cases at the highest ones. Figure shows also, that the north-west and western slopes have more Low Risk cases more likely due to the wind speed reduction of the synoptic flow in close proximity to Vitosha Mountain.

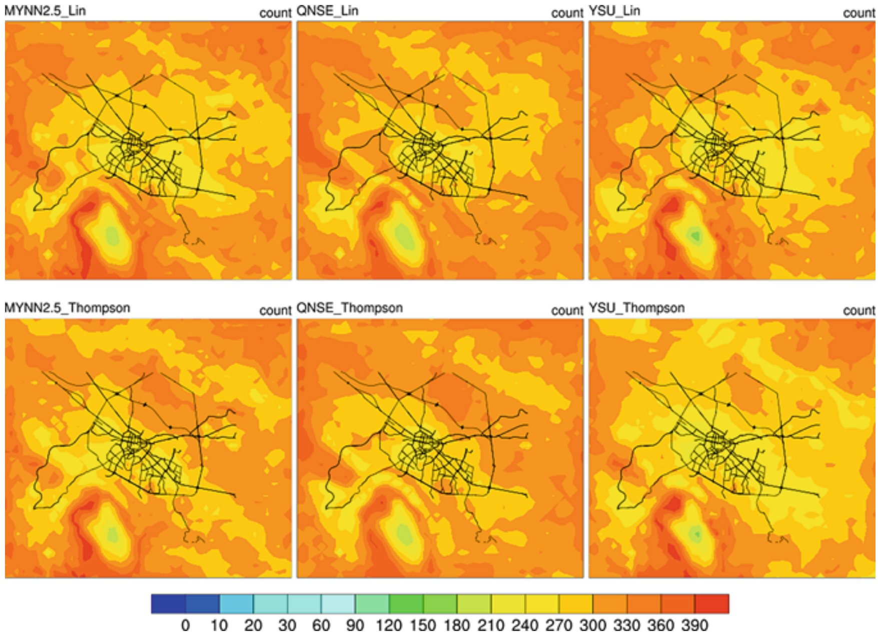

Fig. 2 Number of cases for Low Risk conditions from WRF simulations with different model options for January 2016

The spatial distribution of the Moderate Risk cases (Fig. 3) shows the following patterns. The number of cases varies from below 150 in the Sofia city area to above 300 in some of the end points of the domain. There are more than 240 cases in the Vitosha Mountain, and over large area, they are above 390. The QNSE_Lin model configuration has more Moderate Risk cases in Sofia city area than anyone else does. The spatial distribution of that one, QNSE_Thompson and YSU_Thompson, is more homogenous than in the other model configurations.

The plots for the High Risk cases (Fig. 4) are very similar for all model configurations, except the QNSE_Lin, which shows some spots of above 10 cases in the eastern and northwestern parts of the domain, similar to the Vitosha Mountain. The entire domain area has up to 10 cases. Only for the area of the Vitosha Mountain the number of cases increases from 10 to about 90 at the elevated areas.

Overall, the model configurations with QNSE_Lin boundary layer scheme have relatively bigger number of Moderate Risk cases, but not for the Low Risk conditions. Therefore, the application of that set-up in winter leads to more Moderate Risk wind chill conditions. Most likely one of the reasons is the stronger underestimation of temperature with approximately 3 °C in all stations at Sofia city in comparisons with other model set-ups.

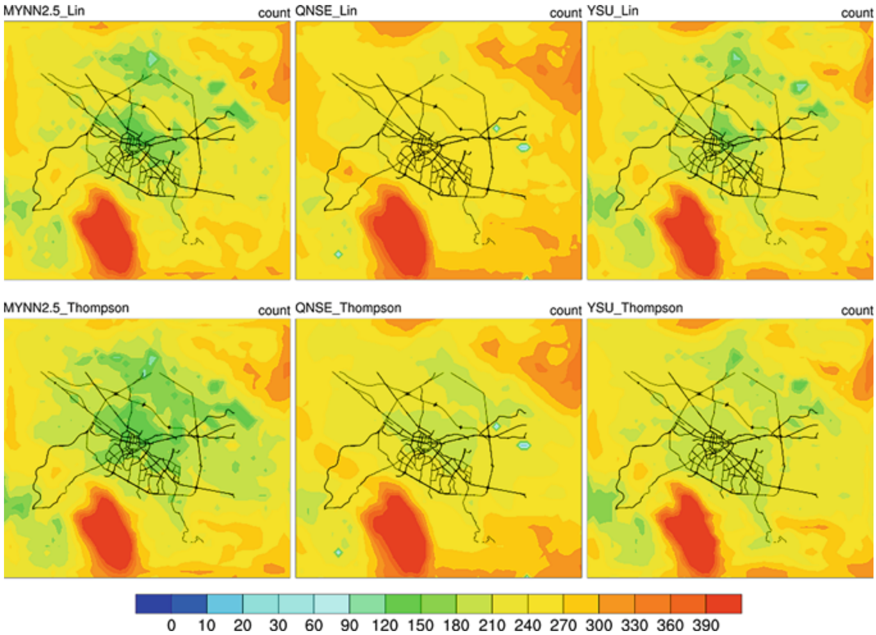

Fig. 3 Number of cases for Moderate Risk conditions from WRF simulations with different model options for January 2016

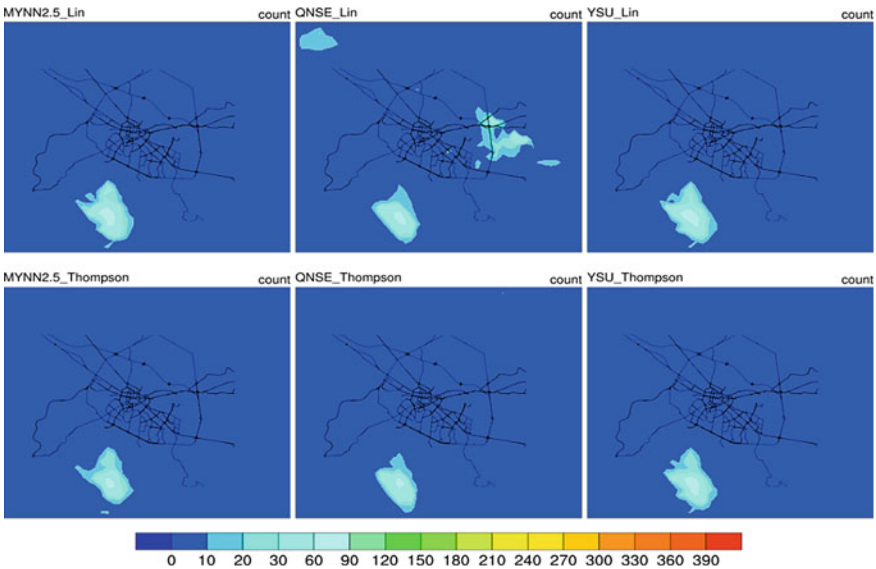

Fig. 4 Number of cases for High Risk conditions from WRF simulations with different model options for January 2016

4.2 Heat Index Modelling

The model results for the Heat Index reveal, that different cases belong mainly to two categories—Caution and Extreme Caution (see Table 2). The spatial distribution of the number of Caution is shown in Fig. 5. The distribution of the Caution category follows the topography of the domain. Normally, the higher terrain parts are characterized by smaller recurrence of the Caution conditions, relative to the lower terrains. The southern areas have up to ten cases. The case number increases in the more populated areas, especially the in Sofia, where the count of Caution reach between 210 and 240. Most of the vicinities around Sofia city have more than 90 cases. The YSU_Thompson configuration gives the biggest number of Caution conditions, above 210 in the Sofia city. The YSU_Lin and MYNN2.5_Thompson and MYNN2.5_Lin have similar spatial distribution of the number of Caution conditions. The simulations with QNSE boundary layer scheme differ with smaller counts. Therefore, the configuration with more places with extreme weather in August 2015 is YSU_Thompson, and the ones with mildest heat conditions are with QNSE boundary layer scheme.

The number of cases with Extreme Caution conditions (Fig. 6) has much fewer cases than with Caution. They are up to 20, and the locations with more than five have the smallest areas in comparison with the other count intervals. The configuration

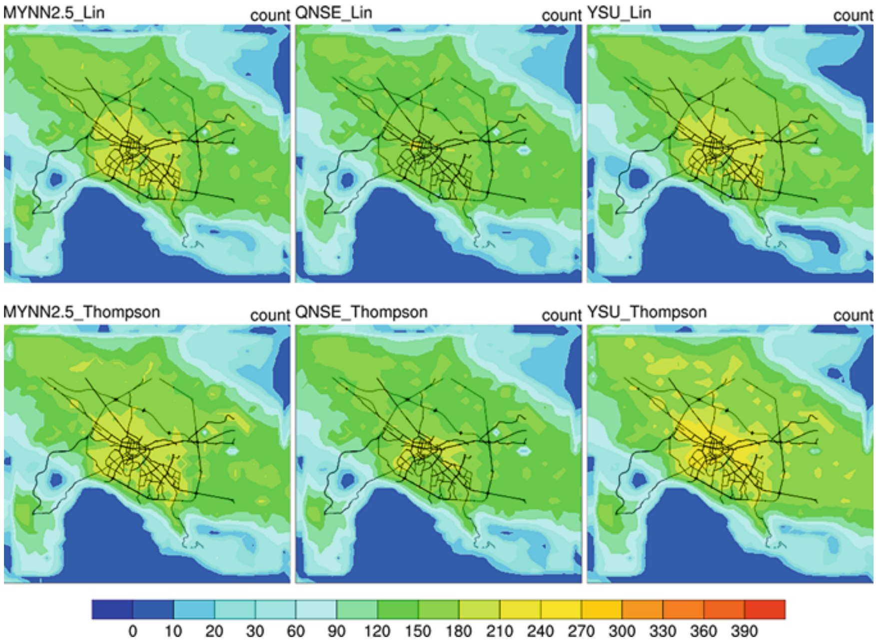

Fig. 5 Number of cases for Extreme Caution conditions from WRF simulations with different model options for August 2015

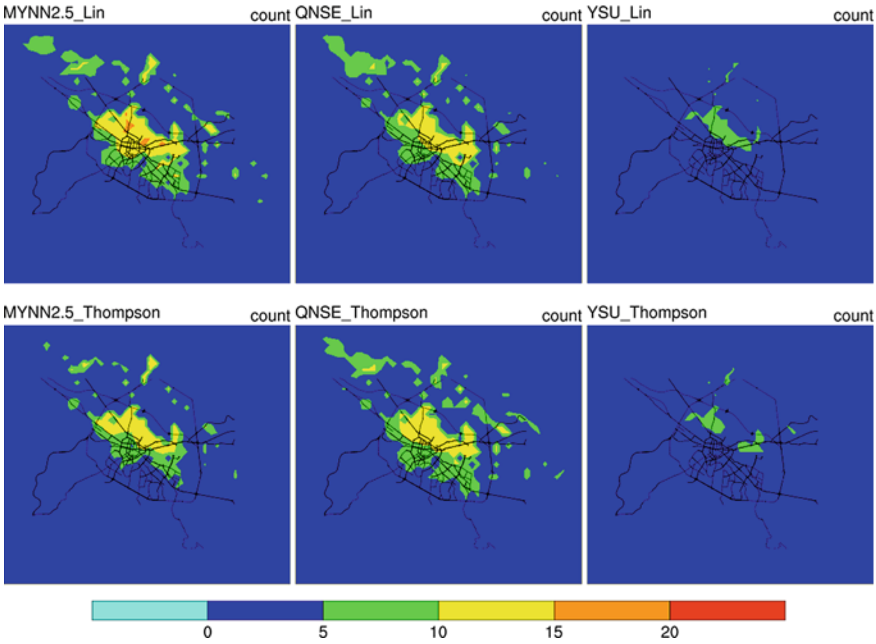

Fig. 6 Number of cases for Caution conditions from WRF simulations with different model options for August 2015

MYNN2.5_Lin is the only one with number of cases above 15. It has similar spatial distribution with simulations with QNSE boundary layer scheme, and to a lesser extent with the one with MYNN2_Thompson run. The YSU_Thompson is the milder one, with the most locations having at most five Extreme Caution conditions.

The differences reveal that the application of the YSU boundary layer scheme parameterization scheme brings to milder conditions in comparison to the other ones. But, as the cases are too small amount, we cannot make such a strong statement as for the Caution cases, about that. Therefore, we can conclude that the WRF model simulate milder conditions when use the QNSE boundary layer scheme.

Most likely, one of the reasons for these differences related to how well different microphysics schemes describe the humidity. The differences in simulation of the turbulence regime by the boundary layer parameterization schemes also could change the heat index values, respectively its categories frequency.

5 Conclusion

Overall, the model configurations with MYNN2.5 show better results than the other (QNSE or YSU) PBL schemes. It is very likely that some PBL schemes do not succeed to simulate the turbulence regime in the low atmospheric levels due to the location of Sofia city in complex topography, a valley surrounded by mountains and highland terrain, the most challenging conditions for numerical modelling. The local turbulent kinetic energy scheme MYNN2.5 is suitable not only for the stable winter conditions but also for the summer ones, although the QNSE scheme also shows good behavior in August 2015. Furthermore, the model configuration with Thompson microphysics gives a little better results than Lin microphysics.

The spatial distribution of the number of Moderate Risk cases of the Wind Chill index, calculated from the WRF output for the region of Sofia, in the winter depends mainly from the wind speed provided by PBL parameterization scheme. The model simulations with the MYNN2.5 PBL scheme have more heterogeneous spatial pattern of the Wind Chill index than the other ones for the Moderate Risk categories. The Low Risk distribution also varies between the model simulations. There are a few High Risk cases, which does not imply significant differences between the model configurations.

The type of boundary layer and microphysics parameterization schemes ensures the dependency of the spatial distribution of the number of Caution cases of the Heat Index in the summer. The number of Extreme Caution index conditions is very small in all configurations, especially in the ones with YSU PBL, and that cannot imply significant differences between the model configurations.

This study can recommend MYNN2.5 PBL and Thompson microphysics for both Wind Chill and Heat indexes modelling at the Sofia region. However, a more comprehensive study for longer period is needed to strengthen these preliminary conclusions.

Acknowledgements This work has been carried out in the framework of the National Science Program "Environmental Protection and Reduction of Risks of Adverse Events and Natural Disasters", approved by the Resolution of the Council of Ministers № 577/17.08.2018 and supported by the Ministry of Education and Science (MES) of Bulgaria (Agreement № Д01-322/18.12.2019).

We want to acknowledge the Bulgarian National Science Fund (grant DN-04/2/13.12.2016).

Special thanks to the Faculty of Physics at the University of Sofia "St. Kl. Ohridski" for the access to the supercomputing facilities (NESTUM cluster http://hpc-lab.sofiatech.bg/home/, funded by the ERDF Project BG161PO003-1.2.05-0001-C0001) at Sofia Tech Park, Sofia, Bulgaria and to US NCEP for providing free-of-charge data and software.

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