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Sensitivity of Different Physics Schemes in the Simulation of Heat Wave Events over Bangladesh Using WRF-ARW Model

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Abstract

Heat waves (HWs) are an extreme temperature condition that has a direct impact on human lives. In recent years, a large number of people have died all over the world due to hot weather. The purpose of this study is to predict HWs accurately to mitigate the casualties caused by them. Two HW events are selected for this study (Event-1: 0000 UTC of 18 May to 0000 UTC of 25 May 2015, Event-2: 0000 UTC of 05 April to 2100 UTC of 08 April 2015). At first, sensitivity tests have been done using different combinations of physics schemes. Sensitivity of Planetary boundary layer (PBL) and surface layer (SL) schemes combinations (YSU-Revised MM5, YSU-MM5, MYJ-Eta, and ACM2-Revised MM5) and land surface models (RUC, Noah, Noah-MP, and CLM4) are investigated to predict Comfort Index (CI), which is identified by using Physiological Equivalent Temperature (PET). To simulate PET, the primary meteorological variables 2-m air temperature (T2), 2-m relative humidity (rh2), mean radiant temperature (TMRT), wind speed at 10 m (ws10), and cloud cover data have been used. These parameters were simulated by the WRF model using both single and nested domains. The experiments found that the combination of the YSU-MM5 scheme and the Noah land surface model predicted the WRF simulated variables very well. The study also found that the CI exists between the slight heat stress to extreme heat stress and the maximum PET values were found to be 47.6 ºC and 48.5 ºC for Rajshahi and Khulna event respectively.

Keywords: Heat waves, Climate change, Land surface model, Surface Layer, PET, CI.

I. Introduction

A Heat Wave (HW), a period of successive hot weather along with high humidity, affects both the natural and human environment. Their most life-threatening impacts are the degeneration of human thermal comfort conditions which consequently increase various heat related diseases. It is well established that extreme heat poses a serious health risk, causing many deaths each year[1]. Every year a large number of people die because of heatstroke and heat exhaustion from the excessive heat exposure in the various regions over the world. In 2021, more than 1,400 people died in western North America because of HW with more than 800 excess deaths than the expected in western Canada[2]. Nowadays, in Indian subcontinent HWs are increasing alarmingly because of climate change, influenced by human or various devastating hazards. HWs were ranked as 4th of the 10 deadliest natural disasters in South Asia in 2015[3]. In India, around 17000 people died due to extreme HW in between 1970 to 2019[4]. Bangladesh is also one of the world's most climate vulnerable countries, with HW frequency and severity expected to rise in future[5]. An eight day long HW in 2008 killed approximately 3800 people, mostly elderly, in Bangladesh[6]. Several cities in Bangladesh have experienced a significant increase in the surface urban heat island intensity (SUHII) over the past 20 years (2000–2019), with the highest rise of $1.9°C$ at night for Chattogram city[7]. The study of Meehl et al. showed that the intensity, frequency and duration of HWs will also increase in the second half of the 21st century[8]. At the end of the century, the maximum temperature is expected to increase by $2°C$ to 2.5°C under RCP4.5 (Representative Concentration Pathway) scenario, and by up to 4°C for the RCP8.5 scenario[9]. To mitigate the casualties early warning systems of HWs have already been placed in developed countries[10], which have been known to save lives[11]. According to Bangladesh Meteorological Department (BMD), four types of HWs are categorized in Bangladesh based on temperature. These are mild (36°-38°C), moderate (38°-40°C), severe (40°-42°C) and very severe HWs (>42°C)[12]. To develop HW warning system, WRF model is a valuable tool to compute primary meteorological variables. In this paper, the study investigated the variations of PBL, SL and LSMs schemes which are strongly related to the HWs. Afterwards, using the WRF model output parameters as the input to the Rayman model, the study calculated the PET and compared it to the observed PET to have a proper combination of schemes to predict the HWs.

II. Model and Methodology

Identification of Heat Wave Events

HW event is identified by using an extreme temperature criterion based on IPCC's (Intergovernmental Panel on Climate Change) definition of extreme temperature index, TX90p[13]. As stated by the index TX90p, a HW day is

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determined when the daily maximum temperature exceeds the 90th percentile of the average temperature of late twenty century reference period (1961-1990). Applying this index to the daily maximum temperature data we have selected two HW events, one in Rajshahi, event-1($23.8°N$ to $25.27°N$ and $88.01°E$ to $89.8°E$) and another in Khulna, event-2 ($21.68°N$ to $23.6°N$ and $88.57°E$ to $89.97°E$).

Table 1. WRF model setup for the study.

No. of domain	2
Domain Coordinates	D01 (for both events): 19.8° N to 26.7° N and 88° E to 93° E D02 (event-1): 23.4° N to 25.3° N and 88.05° E to 89.7° E, D02 (event-2): 21.6° N to 23.65° N and 88.55° E to 90.35° E
Resolution	9km (Parent), 3km (Nested).
Vertical co-ordinate	40 sigma levels
Number of grid points	X-direction (West-East) 100,85 points, Y-direction (South-North) 127,118 points
Run time	Event-1: 0000 UTC of 18 May to 0000 UTC of 25 May 2015 Event-2: 0000 UTC of 05 April to 2100 UTC of 08 April 2015
Horizontal grid distribution	Arakawa C-grid
Time integration	3rd order Runge-Kutta
Microphysics	WRF Single–moment 6–class Scheme.
Cumulus parameterization schemes	Kain-Fritsch (KF)
PBL parameterization	Yonsei University Scheme (YSU), Mellor–Yamada–Janjic Scheme (MYJ) and Asymmetric Convective Model 2 Scheme (ACM2)
Surface Layer	Revised MM5 Scheme, Eta and MM5 Similarity Scheme
Land surface parameterization	Unified Noah Land Surface Model, Noah–MP Land Surface Model, RUC and Community Land Model Version 4 (CLM4)
Radiation scheme	RRTM for long wave

WRF Model Description[14]

The Advanced Research of Weather Research and Forecasting (WRF-ARW, Version 4.0) developed by National Center for Atmospheric Research (NCAR) has been used for this study. Having various dynamical cores, the model has been used for both operational forecasting and research purpose. It's a fully compressible and Euler non-hydrostatic model including a run-time hydrostatic option. Its vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model top is a surface of constant pressure. The model also incorporates various lateral boundary condition options for real-data and idealized simulations, several physics options and positive-definite advection scheme. The model setup and domain configuration for this study are shown in Table 1 and Fig. 1.

Fig.1 (a,b) shows the domain configurations. The large domain (D01) covers whole over Bangladesh and nested domain (D02) covers Rajshahi for event-1 as well as Khulna regions for Event-2. Six hourly GFS datasets of $0.5° \times 0.5°$ grids are used for the simulations.

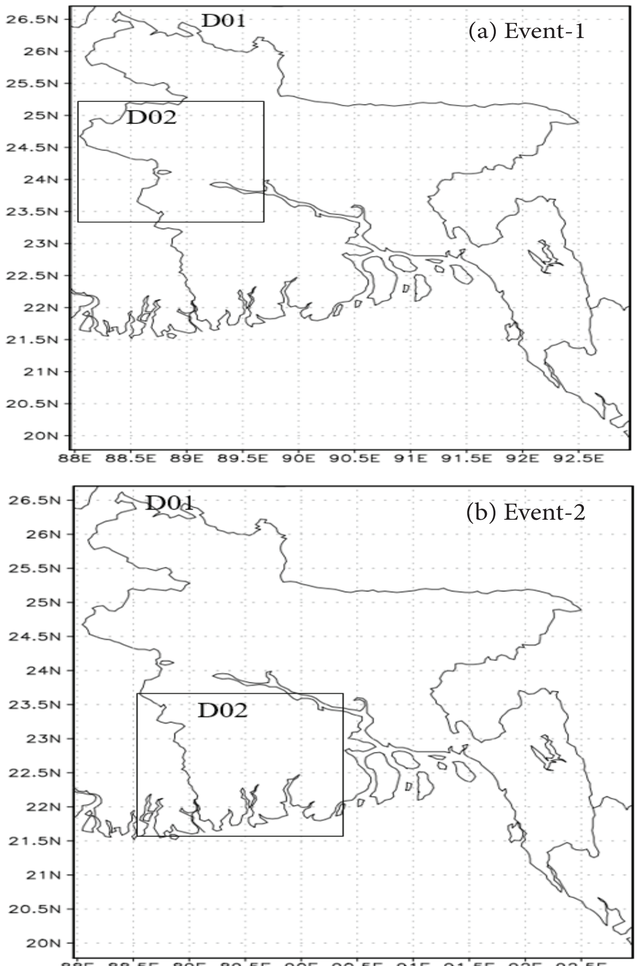

Fig. 1. Domain configurations.

Sensitivity Experiments

Frist we've performed four sensitivity experiments for the PBL-SL combinations (YSU-Revised MM5, YSU-MM5, MYJ-Eta, and ACM2-Revised MM5) keeping the LSM fixed to Noah as the study of M. N. Patil et. al. showed that in dry period the Noah-LSM performed well in comparison with the observation for different surface parameters[15]. Then the study varied LSMs (RUC, Noah, Noah-MP, and CLM4) keeping PBL-SL combination set to YSU-MM5. M. Mohan et. al. showed that the WRF model performed better for YSU-MM5 combination in the subtropical region of India[16]. Table 2 illustrates the combinations of the seven numerical experiments performed in this study.

Table 2. Combinations selected for the sensitivity experiments.

PBL Schemes	Surface Layer Scheme	Land surface models
YSU	Revised MM5	Noah
MYJ	Eta	Noah
ACM2	Revised MM5	Noah
YSU	MM5	Noah
YSU	MM5	CLM4
YSU	MM5	Noah-MP
YSU	MM5	RUC

Rayman Model[17] & PET[18]

Rayman version 1.2 is used in this study. PET is simulated by Rayman Model using WRF model simulated primary meteorological parameters such as 2-m air temperature (T2), relative humidity (rh2), wind speeds (WS10), and cloud cover. It calculates the heat load based on the Munich Energy Balance Model for Individuals (MEMI)[18]. The MEMI model includes the following energy balance equation, $M + W_0 + R + C + E_{sk} + E_{res} + E_{sw} + S = 0$. Where, M is the metabolic rate, W_0 the metabolic workload, R the radiation heat flux, C the sensible heat flux, S the heat storage, and E_{sw}, E_{res}, E_{sk} are latent heats by- sweat rate, respiratory system, and by skin respectively. Calculation of PET includes measuring of the thermal conditions of the body with MEMI for a given combination of meteorological parameters. Then the calculated values for mean skin temperature and core temperature are inserted into the model MEMI which solves the energy balance equation system for the air temperature T_a (with air velocity $v = 0.1 m/s$, vapor pressure $V_P = 12 hPa$, and mean radiant temperature $T_{mrt} = T_a$). This resulting air temperature is described as the PET. The following table shows the different grades of thermal perception and physiological stress based on the different ranges of PET.

Table 3. Different ranges of thermal bio-climate index (PET) of a human body 19

PET (°C)	Thermal perception	Grade of physiological stress
18.1-23.0	Comfortable	No thermal stress
23.1-29.0	Slightly warm	Slight heat stress
29.1-35.0	Warm	Moderate heat stress
35.1-41.0	Hot	Strong heat stress
>41.0	Very hot	Extreme heat stress

III. Result and Discussions

Temperature

Fig. 2(a, b) shows the temporal variations of temperature for different combinations of PBL-SL schemes (Fig. 2a) and for different LSMs schemes (Fig. 2b) for event-1 (Rajshahi). In both the cases all the simulations are quite able to capture the observed pattern in temperature. For PBL-SL combinations, the maximum temperature was found to be 42 $°C$ at 0300 UTC of 22 May for ACM2-Revised MM5 schemes. In case of LSMs variations the maximum temperature was found to be 42.8 $°C$ for CLM4 scheme. The observed maximum temperature of 39.4 °C was accurately captured (40.5 $°C$) by YSU-MM5 experiment. Again for Khulna event (Fig. 2c, 2d), the temperature pattern was similar and all the schemes were able to capture it. The observed maximum temperature was 36.6 °C which was again most accurately predicted by YSU-MM5 experiment. In table 4, we have calculated the RMSE for different combinations of PBL-SL and LSMs. The minimum RMSE is obtained for YSU-MM5 combination. The performance of this combination may corresponds to strong vertical mixing associated with YSU PBL and strong heat flux associated with MM5 surface layer scheme. YSU-Revised MM5 has shown a slight deviation from YSU-MM5. The maximum RMSE is found in ACM2-Revised MM5 scheme which may be due to the weakened vertical mixing and entrainment at the top of the PBL. From the comparisons of land surface (LSM) schemes, it can be observed that Noah LSM has given minimum RMSE and CLM4 has showed maximum RMSE. The better performance of Noah land surface may be associated with the strong heat flux near the land surface.

Table 4. RMSE of T2 and WS10.

Schemes	RMSE (°C) Event-1		RMSE (°C) Event-2	
	T2	WS10	T2	WS10
YSU-Revised MM5	1.513	2.305	2.218	2.314
ACM2-Revised MM5	1.811	2.642	2.581	2.430
MYJ-Eta	1.595	2.820	2.289	3.238
YSU-MM5	1.471	2.015	2.208	2.313
RUC	1.684	2.135	2.269	1.598
Noah-MP	1.818	2.440	2.507	3.482
CLM4	1.978	2.784	2.608	3.698

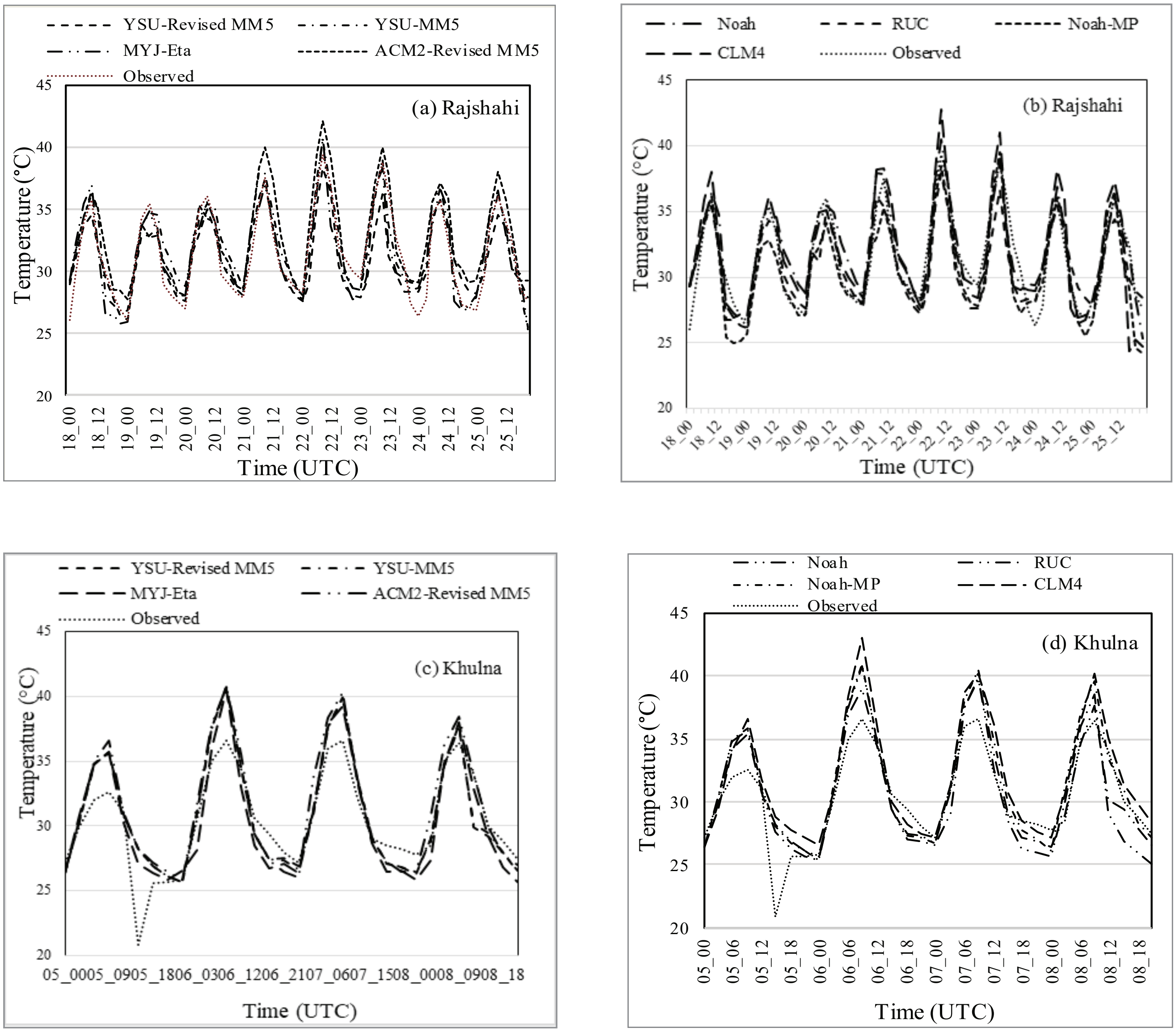

Fig. 2(a-d). Comparison of Model simulated and observed temperature (T2) using PBL-SL and LSMs schemes for Event-1 and Event-2.

Wind Speed

Fig. 3(a-d) illustrates that the most of the WRF model simulated ws10 for both events are deviated from the observed ones. In some cases the simulated ws10 is found maximum while the observed ws10 was the minimum. The study of Giannarosa et. al (2019) also showed the same aberrant behavior of wind speed associating this deviations to strong frictional velocity near the surface[20]. In this case, the deviation may also be due to the strong frictional velocity at the surface. The observed maximum ws10 (8 m/s) was recorded on 24th April. MYJ-Eta (7.89 m/s) for PBL-SL combination and CLM4 (7.76 m/s) for LSM schemes were found to be the closest to the observed maximum value. However, model captured the maximum ws10 36 hours and 12 hours earlier than the observed time for MYJ-ETA and CLM4 experiments respectively. In contrast, the minimum RMSE was found for YSU-MM5 and RUC experiments obtaining values of 2.015 m/s and 1.598 m/s respectively.

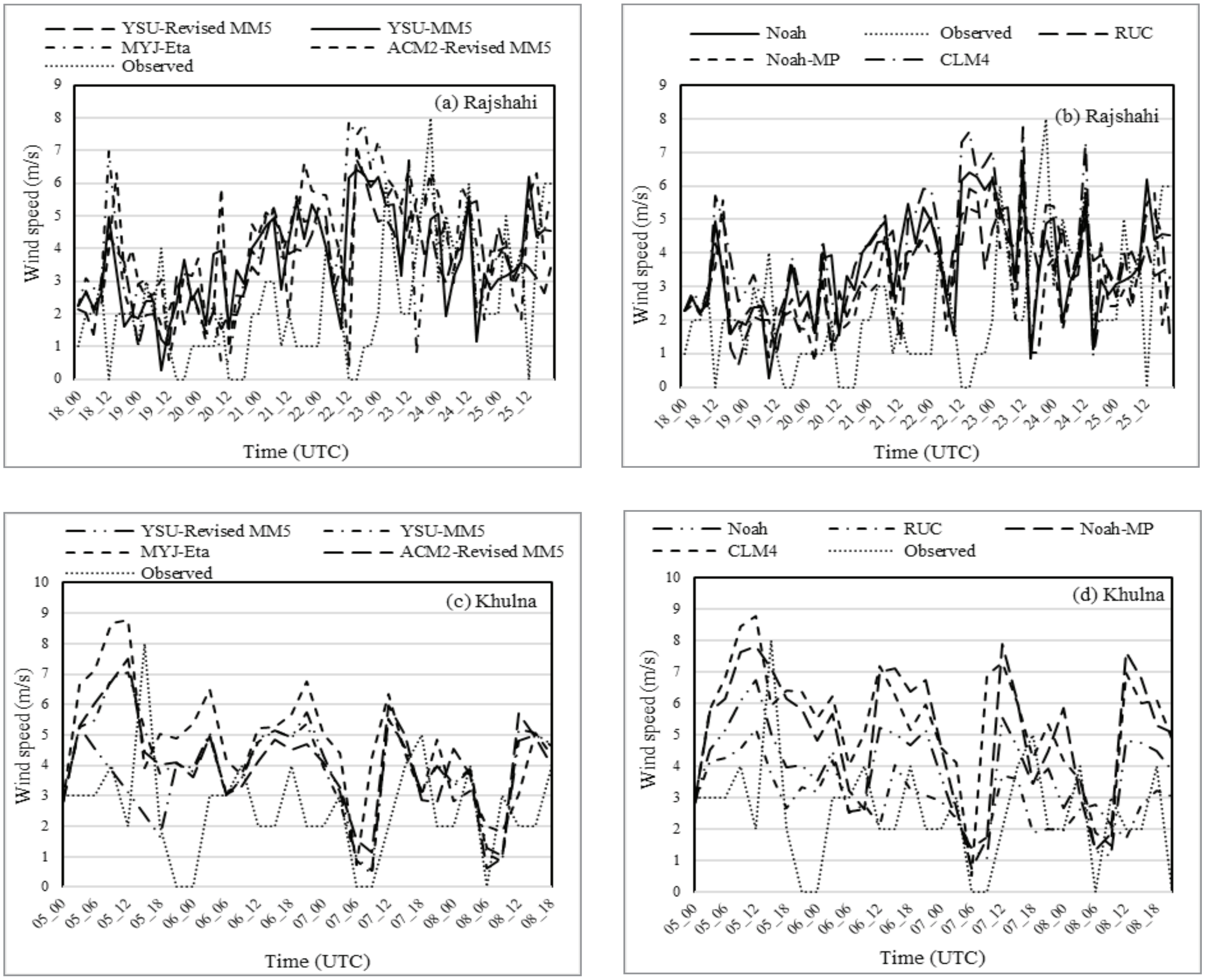

Fig. 3(a-d). Comparison of Model simulated and observed wind speeds (WS10) using PBL-SL and LSMs schemes of Event-1 and Event-2..

Relative humidity

Figure 4(a-d) shows that the model simulated rh2 for all the combinations matches with the pattern of the observed rh2. All of the combinations simulated very high humidity along with very high temperature, during the day sometimes greater than 90% which is very uncomfortable for a human body.

Comfort Index (PET)

PET strongly depends on the amount of downward solar radiation and heat flux at surface layer. The highest values of PET were found to be 43.2ºC, 46.1ºC, 46.5ºC and 47.6ºC at 0300 UTC of 22 May for YSU-Revised MM5, YSU-MM5, MYJ-Eta and ACM2-Revised MM5 schemes respectively, where the observed (calculated using observed meteorological variables) maximum value was 44.9°C for event-1 (Rajshahi). For event-2 (Khulna), highest predicted values of PET for Noah, Noah-MP, RUC, and CLM4 schemes were found to be 45.2ºC, 45.4ºC, 44.1ºC and 48.5 ºC, respectively where the observed value was 43.1 ºC. For both the cases, YSU-MM5 and Noah land surface model have shown the closest value to the observed one. In Table-5, comparing all PBL-SL combinations, the minimum RMSE is obtained in YSU-MM5 scheme which may be associated with the strong exchange of heat flux near the surface. For LSMs, the minimum RMSE is obtained in Noah which may be related to the strong heat exchange between the soil moisture content.

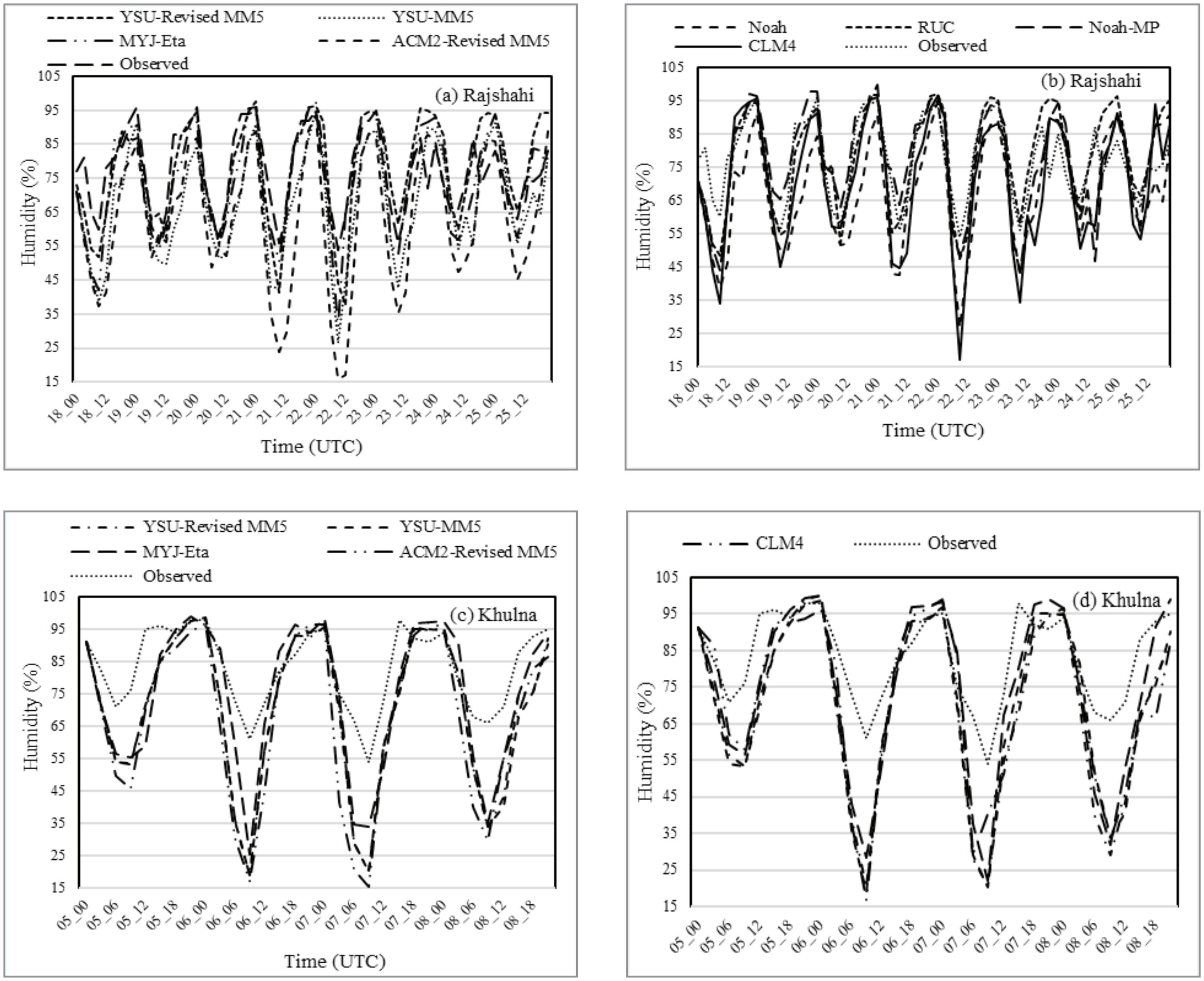

Fig. 4(a-d). Comparison of Model simulated and observed relative humidity (rh2) using PBL-SL and LSMs schemes of Event-1 and Event-2

Comparing all PBL-SL schemes, minimum RMSE is found in case of YSU-MM5 scheme. The minimum RMSE is obtained for RUC LSM in case of LSMs schemes (Table-5).

Table 5. RMSE of RH2 and PET.

Schemes	RMSE Event-1		RMSE Event-2	
	PET(°C)	RH2 (%)	PET(°C)	RH2 (%)
YSU-Revised MM5	3.676	7.02	3.336	18.54
ACM2-Revised MM5	4.022	2.43	3.501	22.10
MYJ-Eta	4.015	18.77	3.541	15.49
YSU-MM5	2.785	14.06	2.803	18.91
RUC	3.836	8.872	3.491	16.12
Noah-MP	3.867	9.37	3.988	19.85
CLM4	3.084	12.02	3.333	18.01

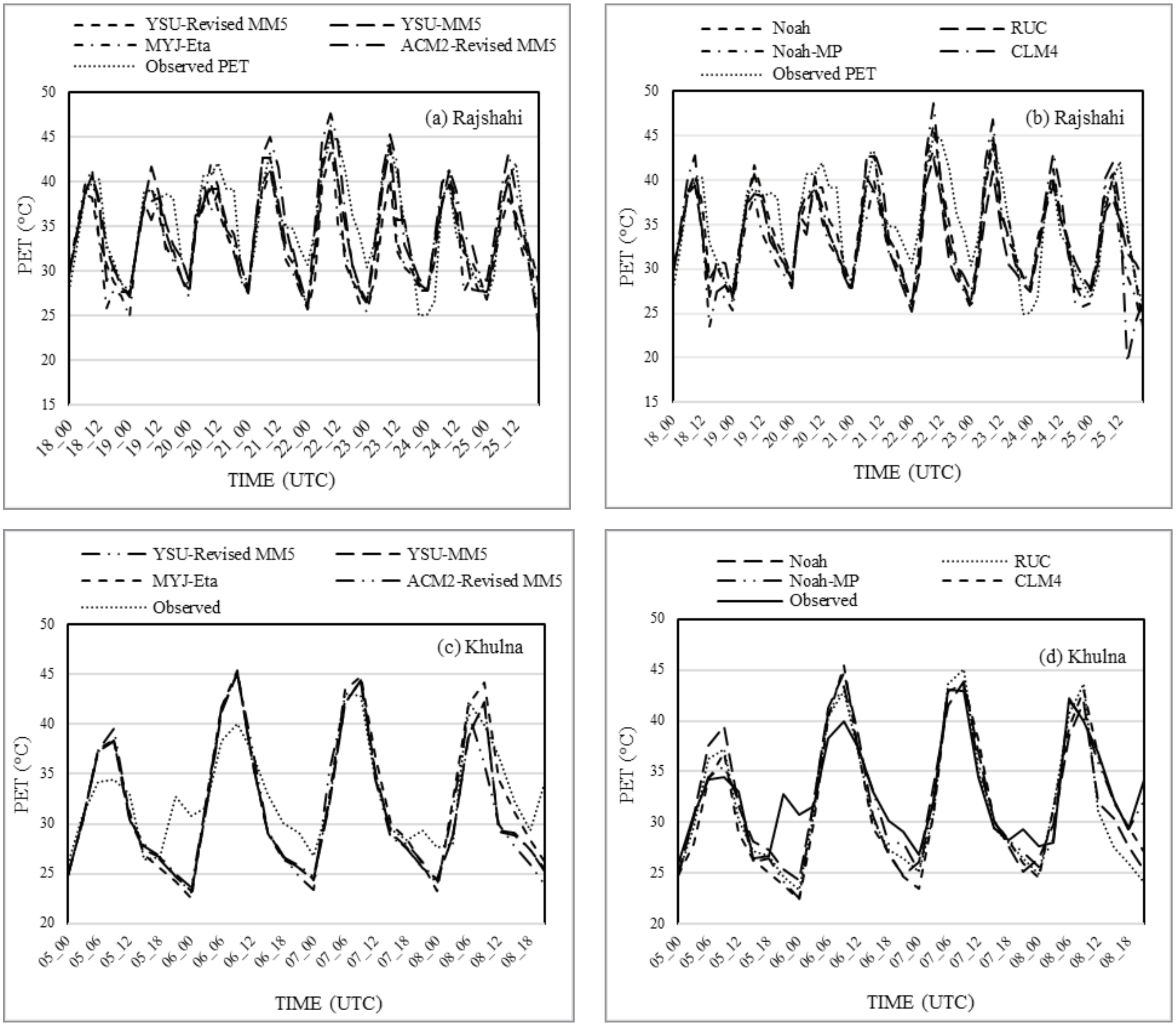

Fig. 5(a-d). Comparison of Model simulated and observed PET using PBL-SL and LSMs schemes of Event-1 and Event-2.

Comparison of air temperature and PET

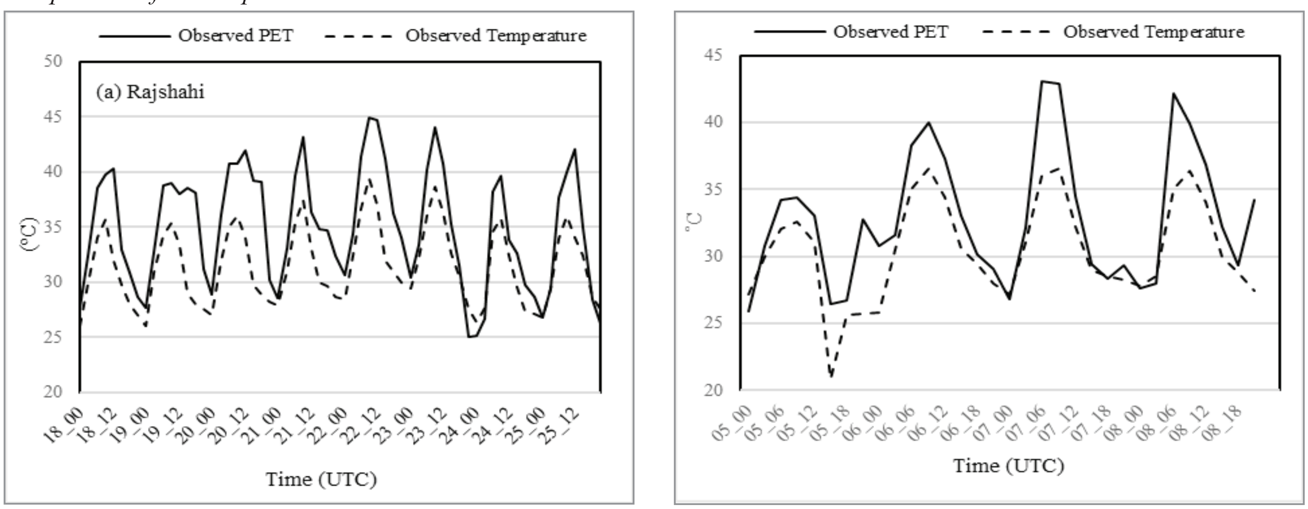

Fig. 6 (a,b). Comparison of air temperature and PET

It is evident from Fig. 6(a,b) that the PET is different and mostly greater than the actual air temperature. These deviations can be associated with the impact of heat flux on a human body, relative humidity, wind speed, and cloud cover. The maximum air temperature was $39.4°C$ on 0900 UTC of 22 May, 2015 in Rajshahi, whereas the temperature felt by the human body (i.e. PET) was $44.7°C$ on that time. For Khulna the deviation was approximately $7°C$ on 0600 UTC of 7 April, 2015. Hence, the study suggests that the temperature which is felt in human body, the Physiological Equivalent Temperature (PET), is the temperature which needed to be forecasted to minimize the casualties associated with the HWs in Bangladesh.

IV. Conclusions

In this study, the impact of planetary boundary layer, surface layer and land surface model parameterizations have been investigated using WRF-ARW model. Four widely used land surface schemes (i.e Noah, Noah-MP, RUC and CLM4), and four combinations of PBL-SL (YSU-Revised MM5, YSU-MM5, MYJ-Eta and ACM2-Revised MM5) schemes were examined during two heat wave episodes (12 HW days) that arose in 2015. WRF model performed better to reproduce observed T2, RH2 and PET values in the YSU-MM5 option, compared to other PBL-SL combinations. Noah scheme gave better results for T2 and PET in comparison with other LSMs. The study of Giannarosa et al. (2019)[20] showed that ACM2-Revised MM5 PBL-SL schemes and RUC land surface model simulated slightly better results. The soil structure and different land positions of different regions may cause this disparity between Giannarosa and our study. The combination of YSU-MM5 and Noah schemes may be more suitable to simulate HW events in our region, though more studies are needed to suggest the appropriate physics combinations for our region in order to predict the HWs.

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