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Impact of urban parameterization and integration of WUDAPT on the severe convection

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Abstract

Amplified rates of urban convective systems pose a severe peril to the life and property of the inhabitants over urban regions, requiring a reliable urban weather forecasting system. However, the city scale's accurate rainfall forecast has constantly been a challenge, as they are significantly affected by land use/ land cover changes (LULCC). Therefore, an attempt has been made to improve the forecast of the severe convective event by employing the comprehensive urban LULC map using Local Climate Zone (LCZ) classification from the World Urban Database and Access Portal Tools (WUDAPT) over the tropical city of Bhubaneswar in the eastern coast of India. These LCZs denote specific land cover classes based on urban morphology characteristics. It can be used in the Advanced Research version of the Weather Research and Forecasting (ARW) model, which also encapsulates the Building Effect Parameterization (BEP) scheme. The BEP scheme considers the buildings' 3D structure and allows complex land-atmosphere interaction for an urban area. The temple city Bhubaneswar, the capital of eastern state Odisha, possesses significant rapid urbanization during the recent decade. The LCZs are generated at 500 m grids using supervised classification and are ingested into the ARW model. Two different LULC dataset, i.e., Moderate Resolution Imaging Spectroradiometer (MODIS) and WUDAPT derived LCZs and initial, and boundary conditions from NCEP GFS 6-h interval are used for two pre-monsoon severe convective events of the year 2016. The results from WUDAPT based LCZ have shown an improvement in spatial variability and reduction in overall BIAS over MODIS LULC experiments. The WUDAPT based LCZ map enhances high-resolution forecast from ARW by incorporating the details of building height, terrain roughness, and urban fraction.

Keywords: Urban, WUDAPT, Severe convection, WRF, LCZ

1 Introduction

Due to the variation in global climate associated with anthropological activities, the vicissitudes in rainfall characteristics and hydrological cycle were reported for most of the places across the globe, particularly growing in rainfall extremes (Berg et al., 2013; Groisman et al., 2005; Milly et al., 2008; Trenberth, 2011). By 2030, 80% of the world population (~ 5 billion) will be residing in

towns (Agilan & Umamahesh, 2015). As per the Department of Economic and Social Affairs (DESA) of the USA report (DESA, 2010), more than half of the world's population lives in urban areas. In the chorus, hydro-meteorological related damages are becoming problematic for both developing and non-developing countries. Excessive rain rates have a significant contribution to urban flooding, and the main challenge in the urbanized area is to provide a good forecast in advance with reasonable accuracy.

Urbanization causes modifications in the land use over the urban area. Tall structures in metropolises generate layers of the urban canopy and alter the energy budgets and surface roughness. Therefore, thermo-dynamic

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characteristics change over the surface layer. These vicissitudes will considerably impact the surface heat balance (Arnfield, 2003; Memon et al., 2009; Zhang et al., 2010), water vapor and momentum exchange between the atmosphere and the surface layer (Miao et al., 2009a, 2009b; Zhang et al., 2008.), and change micro to mesoscale weather that affects the urban precipitation (Miao et al., 2009a; Pathirana et al., 2014; Wan et al., 2013).

After the availability of the community weather prediction models such as the Advanced Research Weather Research and Forecasting (ARW-WRF) model, the urban canopy schemes have been coupled with the numerical weather prediction models used to examine the thermodynamical characteristics of the urban weather problems. Chen et al., (2004 and 2011) examined the urban climate change and model prediction ability. Liu et al., 2006 used the heat capacity and energy conductivity to reproduce the heat storage in urban surfaces and considered it the first urban scheme to represent the thermal and dynamic effects of the urban areas. The roughness variables are taken to characterize the momentum sink and turbulence generation (Salamanca et al., 2011). These methods' limitations are that they cannot contain the heterogeneities existing due to an inconsistency of urban morphology between different land zones (Salamanca et al., 2011). Kusaka et al., (2001) and Kusaka and Kimura (2004) developed the more complicated urban canopy model, the single-layer urban canopy model (UCM).

UCM uses urban geometry by considering infinitely-long street canyons and contemplates the 3D urban surface such as walls, roofs, and roads. These improvements are essential, as reflections, shadowing, and trapping of heat is considered. Besides, temperature profiles within the street canyon (calculated from the thermal conduction equation), skin temperature at the roof, wall, and road (calculated from the surface energy budget) are also comprised. Furthermore, using the Monin-Obukhov similarity theory and Jurges formula, the sensible heat fluxes from the ground are computed. Another critical feature is anthropogenic heat (AH) and its diurnal profiles, which are included and added to the sensible heat flux from the street canyon (Chen et al., 2011). Niyogi et al., (2020) demonstrated that the transference of AH greatly influences the urban rainfall patterns.

The multilayer canopy layer model (BEP) is the other urban canopy layer model developed by Martilli et al., (2002). BEP consents a thru interaction between the building and the planetary boundary layer (PBL). BEP also uses the 3D urban surface, and the building's vertical distribution source and momentum sink all over the entire canopy layer. The effects of potential temperature, turbulent kinetic energy (TKE), and vertical and horizontal surface on momentum are included. Like

the Single-layer UCM, the effect, caused by the building walls and roads, of reflection, shadowing, and radiation trapping is also involved in the BEP scheme (Salamanca & Martilli 2010).

In recent, to study the urban weather/ climate issues, the World Urban Database Access Portal Tool (WUDAPT) has been widely used for making a global database of urban regions. The WUDAPT includes information on urban regimes that have been collected reliably and imprisonment variation through the urban landscape (Ching et al., 2014; Mills et al., 2015). The database is organized into levels, which designate the level of feature obtainable for a city. The lowest level data uses the Local Climate Zone (LCZ) classification to categorize a city and its neighborhood area into 17 types, ten of which are urban (Stewart & Oke, 2012). Each urban category has linked variables that define the features of urban morphology and physical characteristics in terms of value ranges. The critical components of the LCZ typology are the building height, the distance among the buildings, adjacent surface cover, and thermal properties of the building materials. Brousse et al., (2016) used a WUDAPT LCZ dataset in the WRF model over Madrid City, Spain, and demonstrated an encouraging effect on temperature simulations for various LCZs. A recent study by Patel et al., 2020 demonstrated the impact of integrating the WUDAPT LCZ dataset in the prediction of heavy rainfall event simulation over Indian megacity Mumbai. The results have shown the positive effect on simulating realistic rainfall patterns over the urban region. However, there are very few literary works in the Indian region on WUDAPT based studies (Niyogi et al., 2017).

Further, the east coast of India contains a cluster of cities starting from Tamil Nadu to West Bengal which plays a crucial role in the country's economy and is very much vulnerable to various extreme weather events ranging from tornadoes to tropical cyclones. Especially, the sudden convection over the urban agglomeration results in flash floods and loss of lives. Hence, this study provides the assessments of the impact of various urban parameterization schemes and considers the WUDAPT LCZs on the simulation of pre-monsoon rainfall over Bhubaneswar city of eastern India.

2 Experimental setup

The study domain covers the twin cities of eastern India, Bhubaneswar, and Cuttack. A total of four experiments have been carried out, namely CNTL (without urban physics), UCM (with single-layer urban canopy model), BEP (with multilayer building energy parameterization scheme), and WUDAPT (with the incorporation of WUDAPT LCZs along with BEP). The LCZs are developed for Bhubaneswar city using the WUDAPT

methodology described by Bechtel et al., 2015 to comprise local experts' inputs and visit the various landmark locations across the city. A brief of the experimental setup is given in Table 1. It is to be noted that for CNTL, UCM, and BEP experiments use IRS-P6 AWiFS derived gridded LULC data over the Indian region available in open access from Bhuvan portal of National Remote Sensing Centre, Indian Space Research Organisation (Gharai et al., 2018).

The WRF-ARW version 3.9.1.1 (Skamarock et al., 2008) is used to simulate pre-monsoon heavy rainfall events over Bhubaneswar city. The WRF model has been widely used to predict heavy rainfall events over the Indian region in real-time and assessment of process studies as well (Nadimpalli et al., 2016; 2019; Osuri et al., 2013, 2017; Chawla et al., 2018). A three domain setup covers 15°N–26.5°N and 79.8°E–93°E with 4.5 km horizontal resolution with the domain centered at 20.5°N and 86.5°E used. Two nested domains at 1.5 km and 500 m are designed accordingly to make the innermost domain (Domain-3) focus on the Bhubaneswar and Cuttack cities. The grid structure follows the Arakawa C-grid. The model is set up with 51 terrain-following hydrostatic

vertical pressure (σ) coordinates. The σ coordinates are placed close together in the lower atmosphere (12 levels below 850 hPa and 22 levels below 500 hPa) and are relatively coarser in the upper atmosphere. The Boullac scheme is used for planetary boundary layer physics with Monin-Obukhov (Janjic Eta) scheme as surface physics. Noah scheme with four layers is used for the land surface model. RRTM and Dudhia schemes are used for longwave and shortwave radiation physics. WSM 6 microphysical parameterization is used with explicit convection. The initial atmospheric conditions are obtained from the real-time global analysis (GFS) available at 0.25 horizontal and 3 hourly temporal resolutions from National Centre for Environmental Prediction (NCEP).

For this study, five severe thunderstorm cases were identified. These events occurred on 06 March 2016 (Case-I), 29 April 2016 (Case-II), 11 May 2016 (Case-III), 30 May 2017 (Case-IV), and 14 May 2018 (Case-V) over the Bhubaneswar city during pre-monsoon time. Representative results have been presented for two cases, i.e., 30 May 2017 (Case-IV) and 14 May 2018 (Case-V). All the cases are initialized at 12 UTC of the previous day, and the forecast is saved in one-hour intervals for 36

Table 1 Experimental setup used for the current study

Spatial resolution	
Horizontal grid	4.5 km: 1.5 km: 0.5 km:
Vertical levels	51 terrain-following sigma (σ) coordinates
Time steps	4.5 km: 18 s; 1.5 km: 6 s; 0.5 km: 2 s
Physics options	
Planetary Boundary Layer	Bougeault (Bougeault and Lacarrere, 1989)
Shortwave radiation	Dudhia (Dudhia, 1989)
Longwave radiation	Rapid Radiative Transfer Model (Mlawer et al., 1997)
Land Surface Model	Noah Land Surface Model (Tewari et al., 2004)
Urban Physics	UCM (Chen et al., 2011) BEP (Salamanca and Martilli, 2010)
Cumulus parameterization	Kain-Fritsch (KF) (Kain, 2004) for 4.5 km domain No CP for 1.5 and 0.5 km
Microphysics	WRF Single Moment 6-Class (WSM6) (Hong and Lim, 2006)
Land use	ISRO (For CNTL, UCM and BEP experiments) WUDAPT (For WUDAPT experiment)

Table 2 Details of the different urban canopy schemes in sensitivity simulation

	CNTL	UCM	BEP
Canopy layer description	No canopy layer	Single-layer	Multilayer
Anthropogenic heat	No	Fixed temporal profiles	No
Fraction of vegetation	No	Yes	Yes
PBL scheme coupling	Bougeault	Bougeault	Bougeault

hours. A brief description is provided in Table 2. All the experiments utilize the same physical options except for the canopy schemes. In the WUDAPT experiment, the BEP scheme with WUDAPT based LULC is used. The urban specific parameters used in UCM and BEP experiments are listed in Tables 3 and 4 with their values obtained from Stewart and Oke (2012).

Further, based on the contingency table (<https://cawcr.gov.au/projects/verification/>) that represents the frequency of "yes" (the event occurred) or "no" (event not occurred) forecast occurrence analysis carried out for the various meteorological values at each grid point of

observed and model outputs over the Bhubaneswar city (Shown in Fig. 2b). The impact of urban physics and WUDAPT is assessed with Hiedke Skill Score (HSS) and BIAS of various meteorological variables simulated by the model, which are computed against IMD station observations (listed in Fig. 2b). The HSS of the 24-h simulation of air temperature, dew point temperature (DPT), relative humidity (RH), and wind speed at various pressure levels is computed at ten vertical levels against upper-air observations at Bhubaneswar city (available from www.weather.uwyo.edu) to assess the model performance. The HSS and BIAS for the 24-h forecast were calculated against 0000UTC and 1200 UTC upper-air observations for both experiments and illustrated in Fig. 4. Due to the non-availability of upper-air observations during 1200 UTC of Case-III, the same has been eliminated from the analysis. The formulation for the HSS and BIAS has been given below.

The four combinations of forecasts (yes or no) and observations (yes or no), called the joint distribution, are (<https://cawcr.gov.au/projects/verification/>):

- hit (H)*—event forecast to occur, and did occur
- miss (M)*—event forecast not to occur, but did occur
- false alarm (F)*—event forecast to occur, but did not occur
- correct rejections (Z)*—event forecast not to occur, and did not occur

Table 3 Urban parameters for UCM and BEP schemes and their usage in the different canopy schemes

Parameter	Unit	Value	UCM ^a	BEP ^a
Building height	m	20	Yes	No
Building width	m	15	Yes	No
Width of the road	m	10	Yes	No
Urban fraction	fraction	0.95	Yes	Yes
Roof albedo	fraction	0.2	Yes	Yes
Wall albedo	fraction	0.2	Yes	Yes
Pavement albedo	fraction	0.2	Yes	Yes
Roof roughness length	m	0.15	Yes	Yes
Wall roughness length	m	0.05	Yes	No
Pavement roughness length	m	0.05	Yes	Yes

^a Yes and No represent for whether parameters used in the scheme or not

Table 4 Some of the UCP values associated with LCZ types from Stewart and Oke (2012). Columns represent the percentage of impervious (λ_i), built (λ_b), and vegetated (λ_v) land cover and mean height of building elements (z), sky view factor (λ_s), albedo (α), and anthropogenic heat flux (QF)

LCZ	λ_i	λ_b	λ_v	Z(m)	λ_s	α	QF(W m ⁻²)
1. Compact high rise	40–60	40–60	< 10	> 25	0.2–0.4	0.10–0.20	50–300
2. Compact midrise	40–70	30–50	< 20	10–25	0.3–0.6	0.10–0.20	< 75
3. Compact low rise	40–70	20–50	< 30	3–10	0.2–0.6	0.10–0.20	< 75
4. Open high rise	20–40	30–40	30–40	> 25	0.5–0.7	0.12–0.25	< 50
5. Open midrise	20–40	30–50	20–40	10–25	0.5–0.8	0.12–0.25	< 25
6. Open low rise	20–40	20–50	30–60	3–10	0.6–0.9	0.12–0.25	< 25
7. Lightweight low rise	60–90	< 20	< 30	2–4	0.2–0.5	0.15–0.35	< 35
8. Large low rise	30–50	40–50	< 20	3–10	> 0.7	0.15–0.25	< 50
9. Sparsely Built	10–20	< 20	60–80	3–10	> 0.8	0.12–0.25	< 10
10. Heavy industry	20–30	20–40	40–50	5–15	0.6–0.9	0.12–0.20	> 300
A. Densse trees	< 10	< 10	> 90	5–30	> 0.4	0.10–0.20	0
B. Scattered trees	< 10	< 10	> 90	3–15	0.5–0.8	0.15–0.25	0
C. Bush, scrub	< 10	< 10	> 90	< 2	0.7–0.9	0.15–0.30	0
D. Low plants	< 10	< 10	> 90	< 1	0.2–0.4	0.15–0.25	0
E. Bare rock or paved	< 10	> 90	< 10	< 0.25	> 0.9	0.5–0.30	0
F. Bare soil or sand	< 10	< 10	> 90	< 0.25	> 0.9	0.20–0.35	0
G. Water	< 10	< 10	> 90	-	> 0.9	0.02–0.10	0

and the total number $(N) = (hits + misses + false\ alarm + correct\ rejections)$

HSS is in the skill score format.

$$HSS = \frac{[(H + Z) - (expected\ correct)]}{[N - expected\ correct]}$$

The range of the HSS is $-\infty$ to 1. Negative values indicate that the chance forecast is better, 0 means no skill, and a perfect forecast obtains an HSS of 1. It measures the fractional improvement in the forecast over the observation.

BIAS is given by:

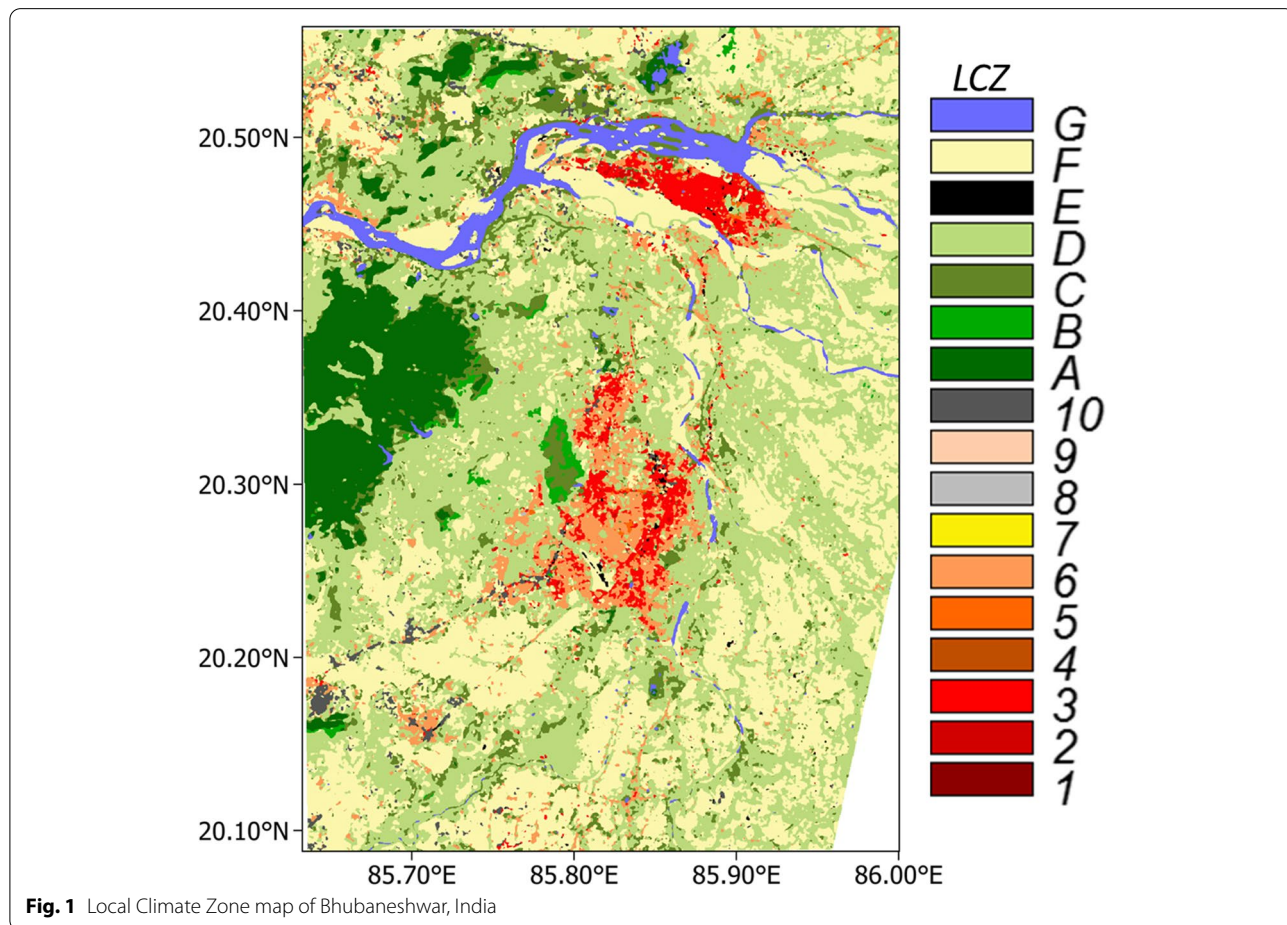
$$BIAS = \frac{[H + F]}{[H + M]}$$

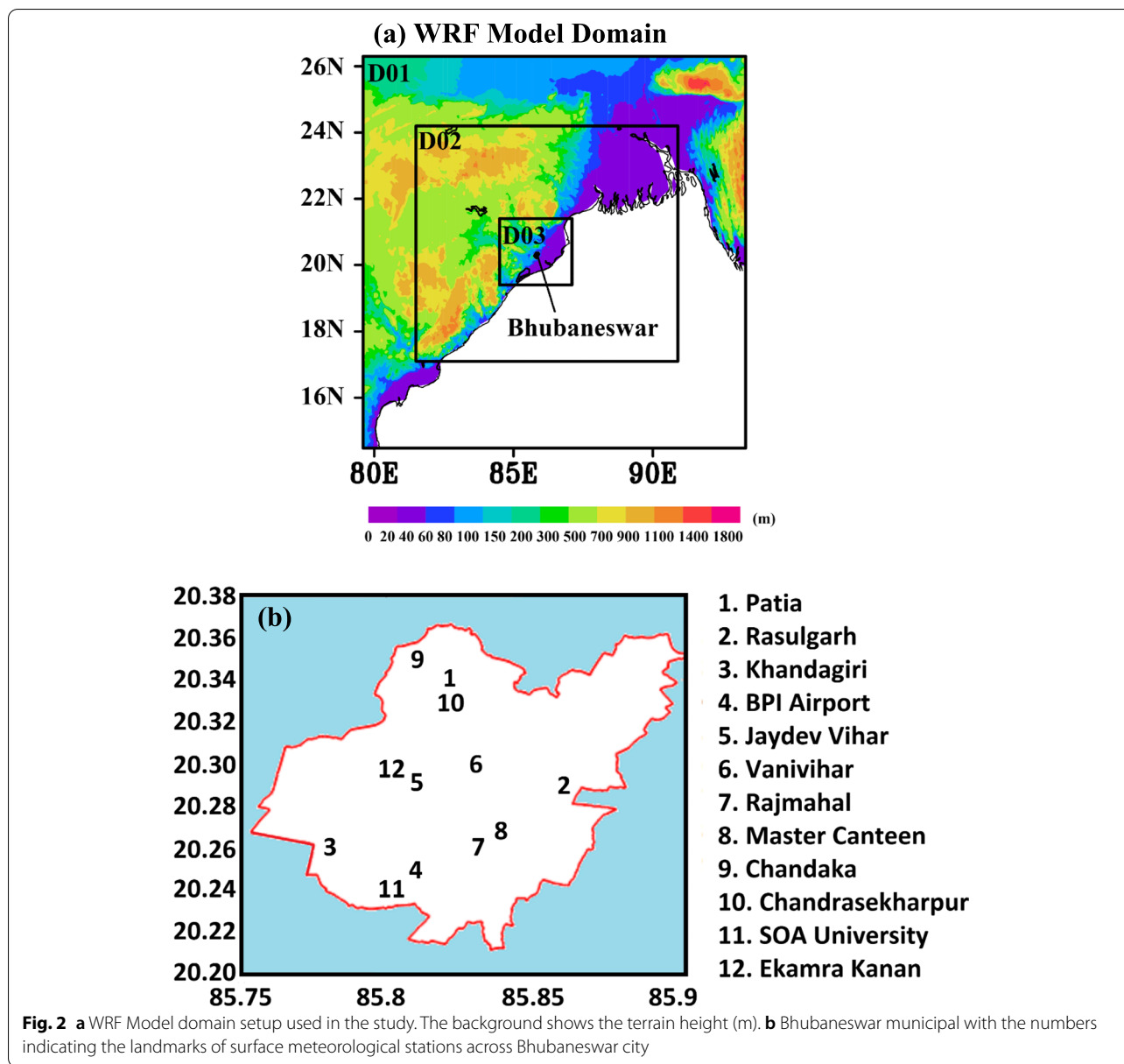
The desirable value for bias is 1, indicating an unbiased forecast where the event is forecast exactly as often as it is observed. When the bias is greater (lesser) than 1, the event is over (under) forecast.

3 LCZ data preparation

The WUDAPT has become a handy tool for creating a global database of urban areas (cities) to study urban climate studies. The WUDAPT mainly combines the information gathered across various urban landscapes measured/calibrated consistently (Ching et al., 2014; Patel et al., 2020). The urban database is organized into levels representing the level of facet existing for a metropolitan region. The WUDAPT uses the Local Climate Zone (LCZ) approach to categorize a city and its peripheral area into 17 types, where ten are urban (Stewart and Oke, 2012). A detailed methodology for preparing WUDAPT datasets can be obtained from Ching et al., 2018.

The LCZ of Bhubaneswar is prepared using the methodology provided by Bechtel et al., 2015. A cloud free Landsat 8 imagery for 15 April 2017 is downloaded and then clipped over the region. The training dataset is created for the supervised classification. The random forest is used as the classification method and the results were visually inspected, and the process is repeated again until an accurate LCZ is obtained.





The LCZ map used is shown in Fig. 1. The urban LCZ classes over Bhubaneswar are LCZ 2 (Compact mid-rise) (1%), LCZ 3 (Compact low-rise) (28%), LCZ 5 (Open mid-rise) (2%), LCZ 6 (Open low-rise) (58%), LCZ 9 (Large low rise) (1%), and LCZ 10 (Heavy Industry) (10%).

4 Study region

Bhubaneswar (centered at 85.84° E and 20.27° N and lies 45m above sea level) is the capital city of Odisha, India, well known for its name as Temple city of India. The city is located in Khordha district, surrounded by Cuttack district on its north, Nayagarh district on the west, Puri

district on its south, and Jagatsinghpur district on the east. Bhubaneswar is one of the fastest-growing urban areas in the country, which is more vulnerable to all kinds of extreme weather events such as tropical cyclones, severe thunderstorms, heavy rainfalls, and heatwaves. Climatologically, the average annual temperature is about 27.4° C, and annual rainfall is about 1505 mm. The maximum temperature is observed during pre-monsoon season (MAM), and maximum precipitation is observed during the July-August month of the year over the city (<https://en.climate-data.org/asia/india/odisha/bhubaneswar-5756/>). The domain extensions are overlaid on geopotential height (m) over the study region and are

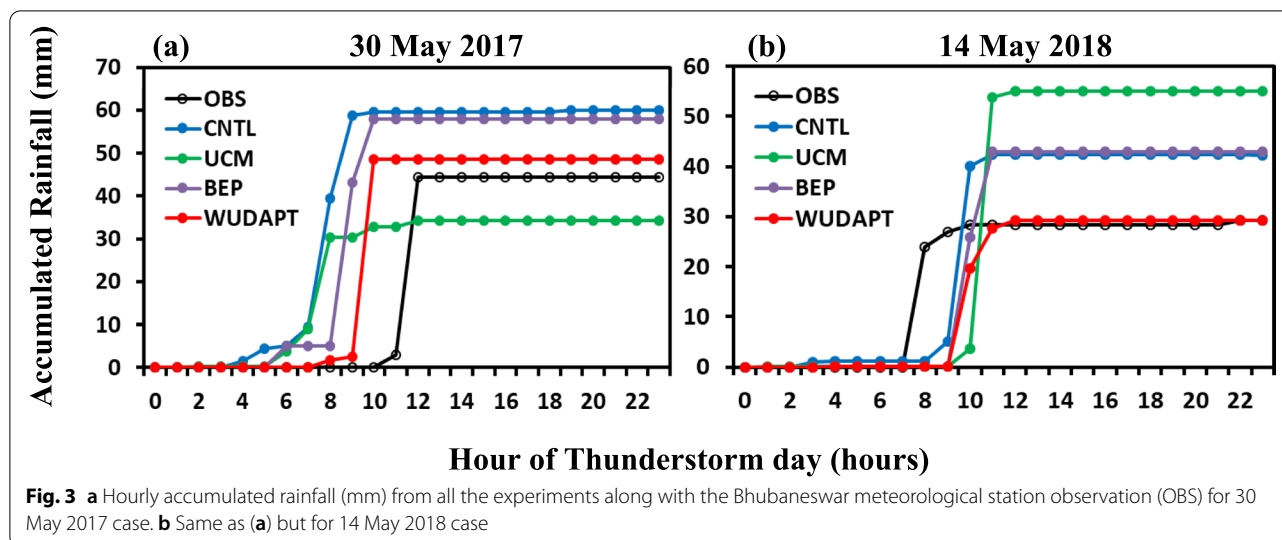


Fig. 3 a Hourly accumulated rainfall (mm) from all the experiments along with the Bhubaneswar meteorological station observation (OBS) for 30 May 2017 case. b Same as (a) but for 14 May 2018 case

presented in Fig. 2a and the list of stations used for validation is presented in Fig. 2b along with station names.

5 Results and discussions

The effect of various urban parameterizations and when WUDAPT LULC data is used to simulate severe convection over the eastern megacity Bhubaneswar is examined. The simulated meteorological parameters and thermodynamic indices during the thunderstorm events are compared against available observations. The rainfall obtained from the model simulations is compared with IMD station observations (<https://cdsp.imdpune.gov.in/>) and the Global Precipitation Measurement (GPM) precipitation data (Huffman et al., 2014).

5.1 Impact on various surface parameters

Figure 3 provides the time evolution of accumulated rainfall at Bhubaneswar city for two representative cases, i.e., case-IV and case-V. The hourly accumulated rainfall (Fig. 3a) for over 24 h starting at 0000 UTC on 30 May 2017 shows that the thunderstorm initiation is early by six-hour in CNTL and UCM experiments. The BEP and WUDAPT experiments simulated the early thunderstorm by 4 and 3 hours, respectively. However, all the experiments have shown the same trend. The rainfall amount (45.9 mm) predicted by the WUDAPT experiment is better than those of CNTL (59.6 mm), UCM (34.2), and BEP (57.9) when compared to that of the observed (44.4 mm). Similarly, for Case-II (Fig. 3b), the model-simulated rainfall with the observed indicates that all experiments simulated the thunderstorm occurrence 2–3 h later than the actual event. However, in the CNTL experiment, the temporal error in thunderstorm

initiation is reduced by 0.5 h more than in others. The maximum observed rainfall is 28.4 mm during the thunderstorm activity, and the approximately same amount of precipitation has been captured by WUDAPT (29.3 mm) simulation. All other simulations captured higher rainfall amounts than WUDAPT.

From Fig. 4(a, b), the categorical performance analysis revealed that the WUDAPT simulations exhibit high skill scores for all the thresholds of the variables compared to the rest. Notable diminutions are detected in the skill scores from smaller to higher thresholds in the CNTL and UCM runs, while the BEP and WUDAPT show high skill scores even for higher thresholds. Compared to skill scores of mass fields, the wind skill scores are inferior in all experiments, representing the wind prediction problem over the Bhubaneswar region. The BEP and WUDAPT show less improvement in zonal wind skill scores, although it is relatively better for the meridional wind component (not shown). This pumps the moisture loading in the atmospheric boundary layer and strengthens BEP and WUDAPT experiments' unstable environment. The WUDAPT experiment shows higher HSS (from 0.6 to 0.8) and less BIAS (less than 3.5) for mass fields (air temperature, DPT, and RH).

5.2 Rainfall prediction

Figure 5(a–e) shows the temporal-longitudinal evolution of hourly rain rate (mm hr^{-1}) averaged over Bhubaneswar city from Global Precipitation Measurement (GPM), CNTL, UCM, BEP, and WUDAPT, respectively. Reviewing the GPM fields, the rainfall started after 11 UTC around 85.75° – 85.95° E and became maximum (28 – 34 mm hr^{-1}) at 12 UTC. The CNTL simulated rain rate is more than 40 mm hr^{-1} . It is early in

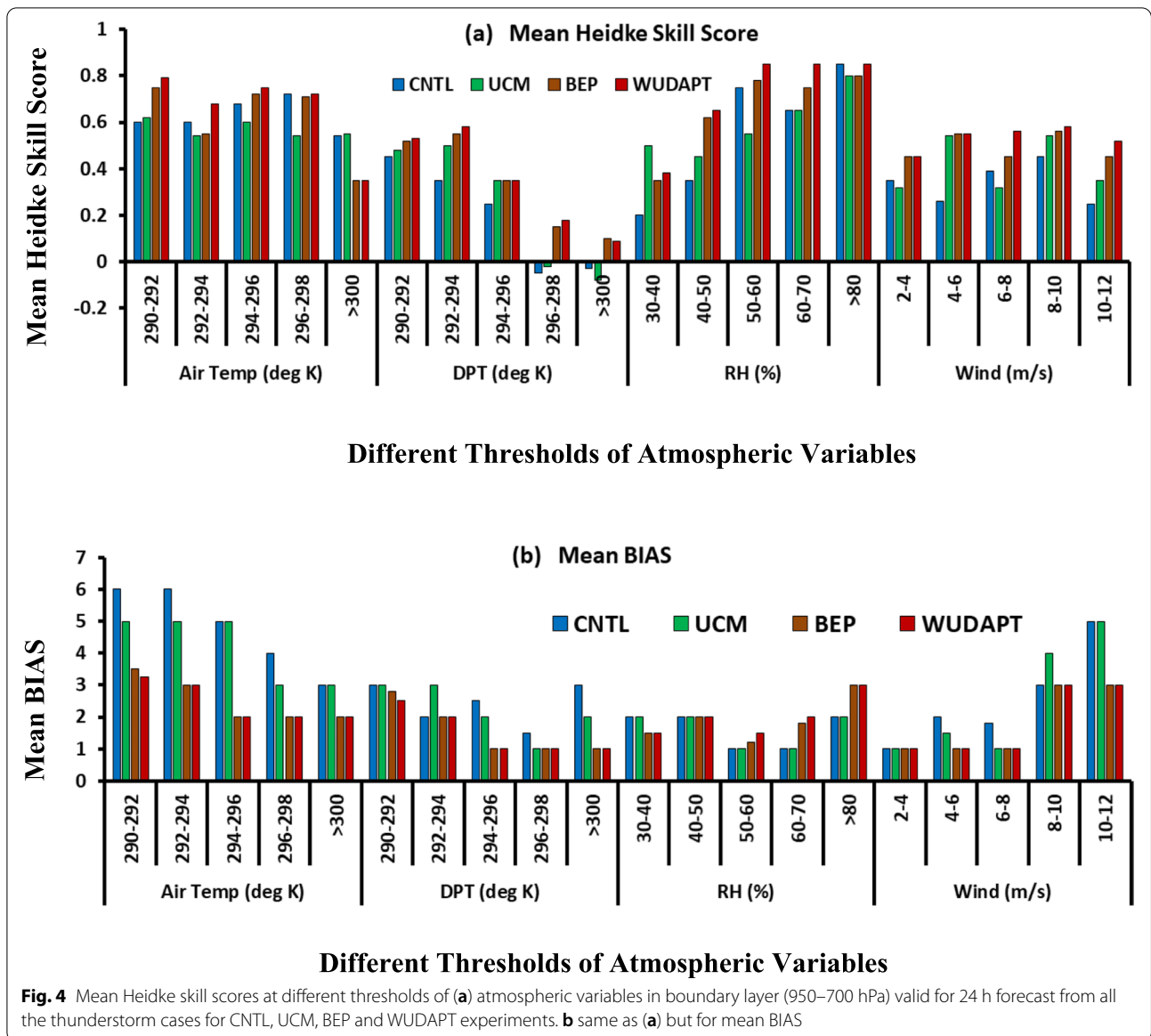
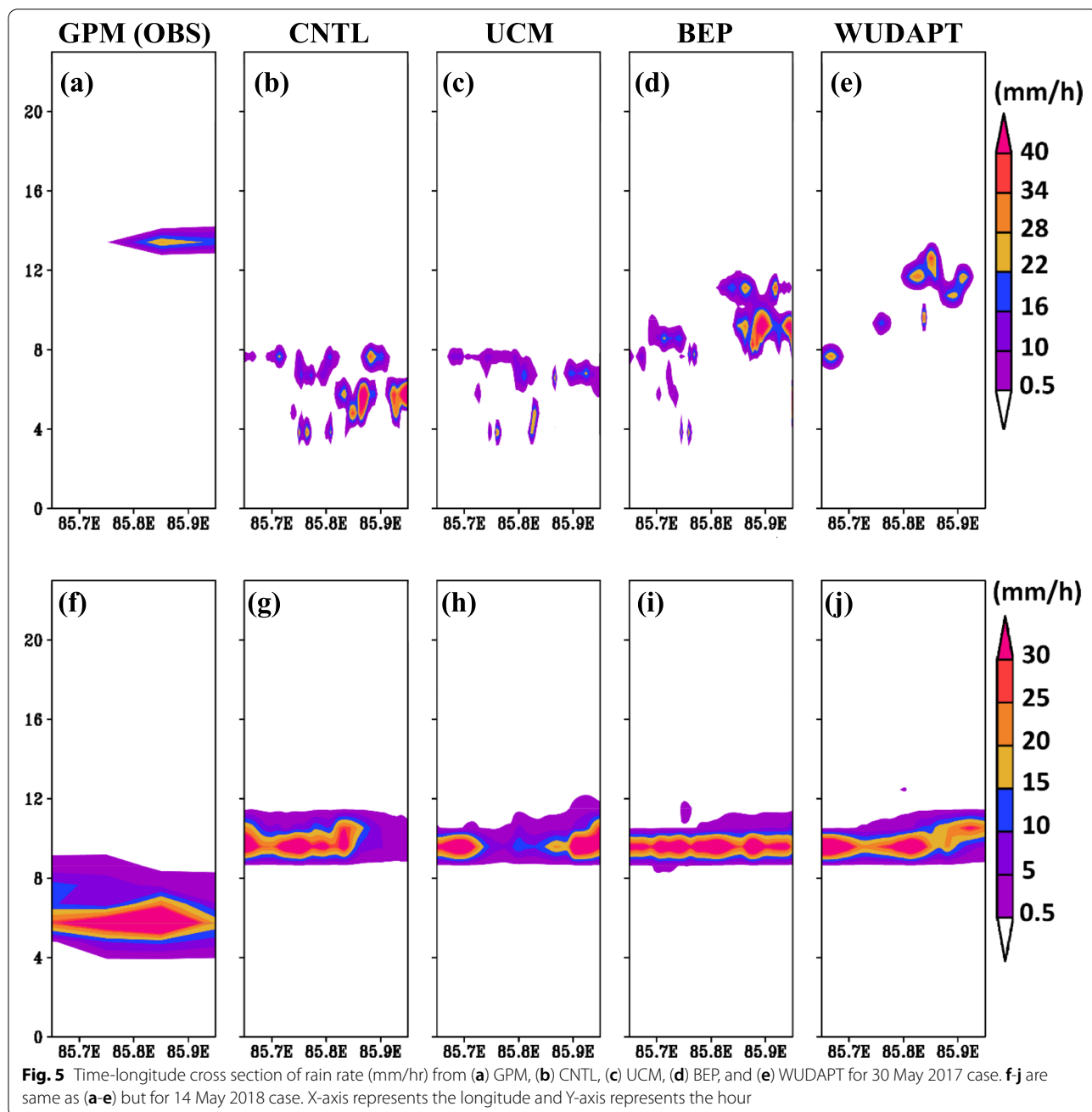


Fig. 4 Mean Heidke skill scores at different thresholds of (a) atmospheric variables in boundary layer (950–700 hPa) valid for 24 h forecast from all the thunderstorm cases for CNTL, UCM, BEP and WUDAPT experiments. **b** same as (a) but for mean BIAS

the occurrence (Fig. 5b) compared to the observations (Fig. 5a). The peak rainfall around 89°E is not simulated in the CNTL run. In the UCM experiment, the rainfall magnitude is 10–16 mm hr⁻¹ only, with early occurrence (Fig. 5c). The BEP and WUDAPT experiments could reduce the error in the time of occurrence (Fig. 5d and e). Further, both the simulated rainfall’s spatial pattern and timing are improved and are closer to observation in the WUDAPT run. On analyzing the results from case-IV (Fig. 5f-j), it can be seen that all the experiments have shown the delay in producing rainfall across the city. From the GPM analysis, the peak rainfall (> 30 mm hr⁻¹) is observed at 5–6 UTC 14 May 2018 (Fig. 5f). There is a four-hour delay in

producing the thunderstorm from all the experiments. In the UCM experiment, two peak cells are simulated on both sides of the city, which were not observed. The BEP and WUDAPT experiments could be able to produce a similar spatial pattern as observed. Further, the HSS and BIAS are computed by considering all the experiments and presented in Fig. 6. The results indicate that the WUDAPT experiment exhibited higher skill (> 0.2) for all the thresholds (>0.2), except >18 mm rainfall (Fig. 6). The UCM followed after the WUDAPT with a considerable skill score. Up to the categorical threshold, 10 mm, the CNTL and UCM experiments exhibited a notable skill score and reduced gradually. The BIAS is almost similar for all the runs up to the 8 mm

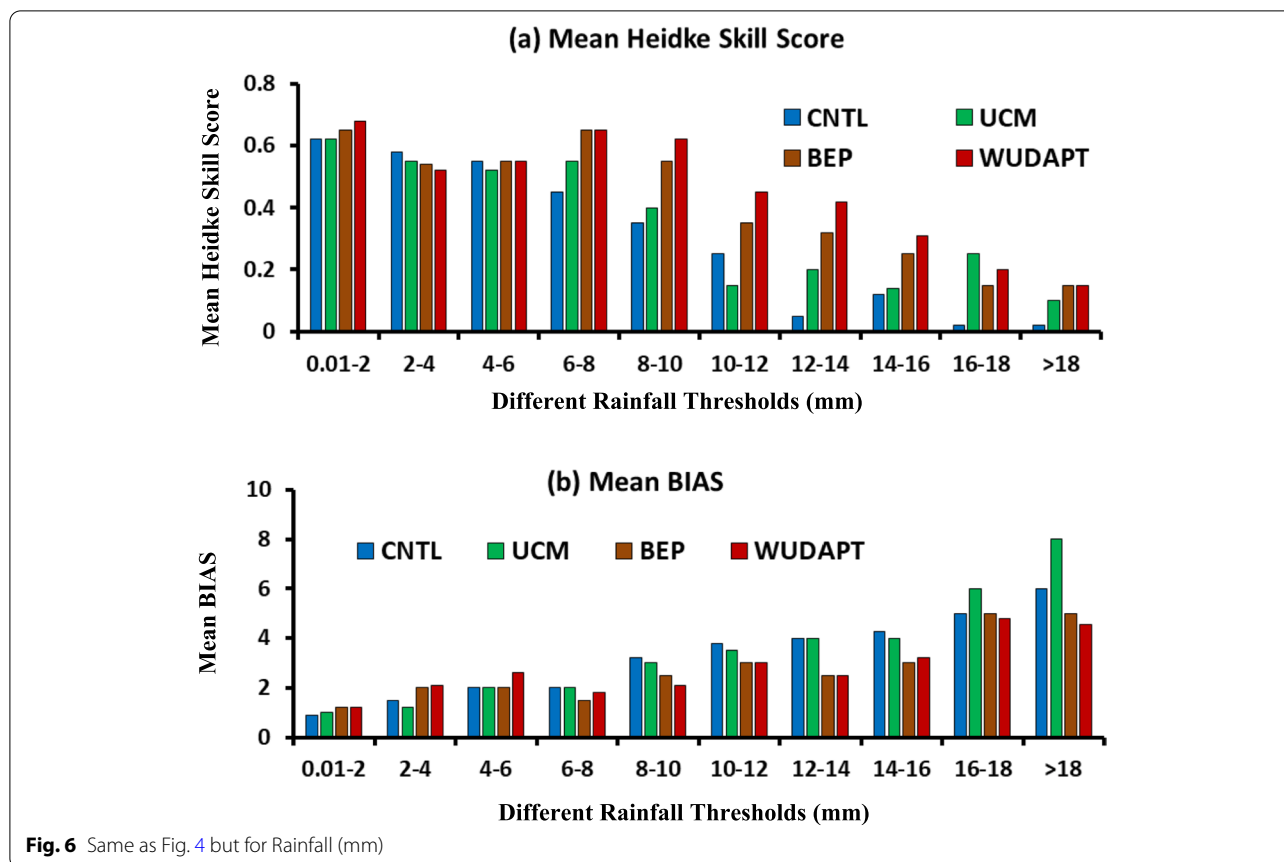


rainfall threshold. After that, the CNTL and UCM BIAS is slightly increased and may be due to the overestimation of rainfall compared with GPM rainfall.

Further, the mean diabatic heating (K/s) averaged over the study region around Bhubaneswar city for all the simulated hours is shown in Fig. 7, along with GPM and model-simulated rain rate. The histograms (lines) represent the diabatic heating (rain rate). Osuri et al., 2017 and 2020 have discussed the role of diabatic heating that influences the local rainfall during a severe convection

event. They have reported that the higher diabatic heating associated with higher moisture availability in the atmosphere leads to increased precipitation. There is higher diabatic heating in the WUDAPT experiment at 11 UTC 30 May 2017 (Fig. 7a), which likely contributed to the rainfall. In other experiments, the higher diabatic heating is seen early than the observed, which are in sync with the associated rainfall patterns.

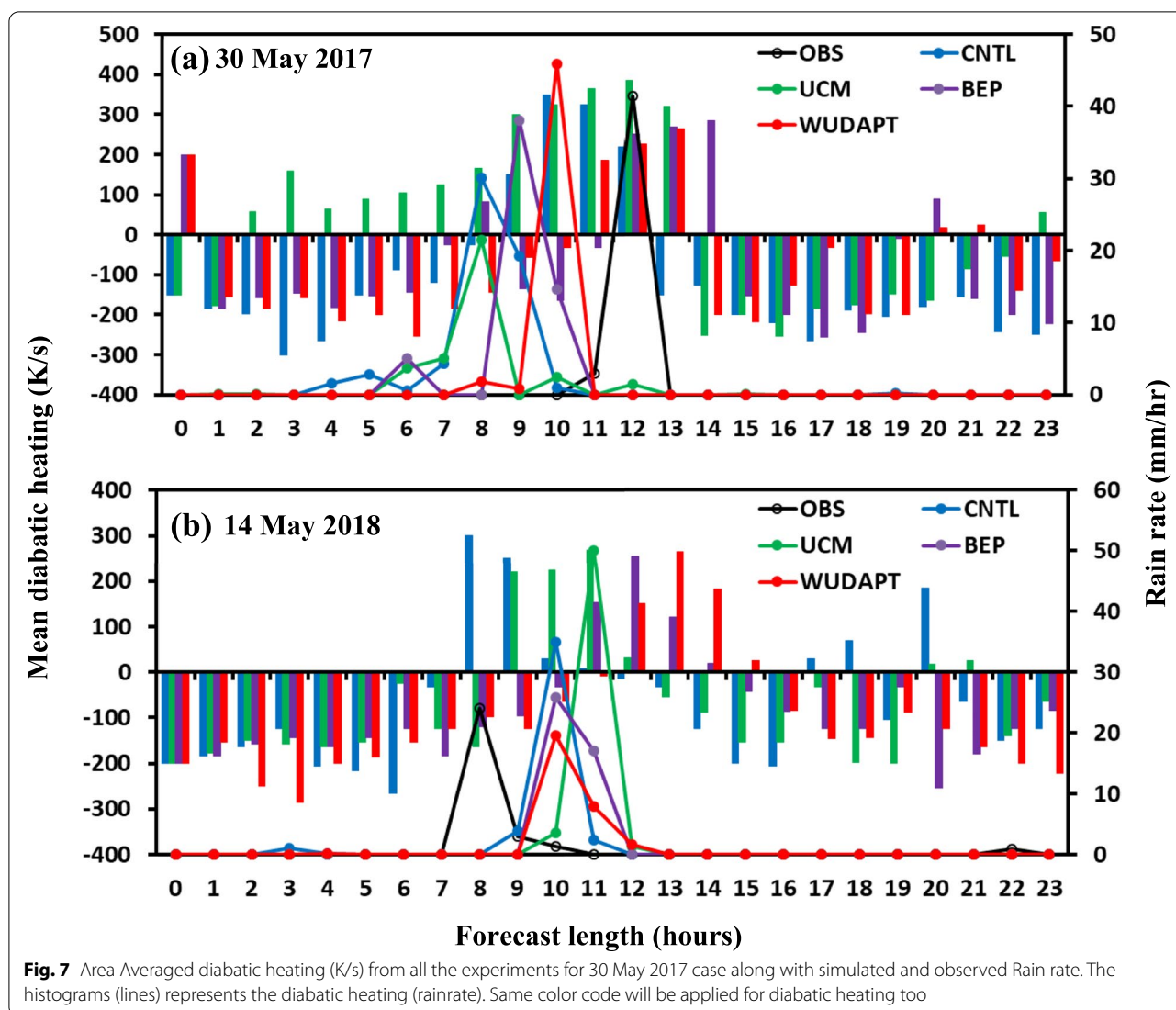
Convection in the atmosphere depends upon thermodynamic instability indices. Conditional instability



is criteria for enough moisture to lift the parcel with a higher value of Convective Available Potential Energy (CAPE). Tyagi et al., (2011) reported a higher value of CAPE indicates how strong the updraft for a convection storm is. There are many thermodynamic indices to estimate stability indices for the occurrence of the TS area. Lifted index (LI), K index (KI), Total Totals Index (TTI), and CAPE indices are considered for 5 cases. LI measures the stability drive from the difference between environment temperature and parcel temperature at 500 mb, which is lesser than the volatile environment. KI index derives from the temperature in 850 mb and 500 mb and moisture content in 850 mb and 700 mb, and the range from 30 to more than 40 increasing value indicates high moisture in the parcel. TTI derives from the temperature in 850 mb, and 500 mb and moisture content in 850 mb, and the range 44 to more than 55 increasing order shows the severity of the storm. More details on computing these indices can be found in Tyagi et al., (2011). Table 5 presents the mean and 95 % confidence interval for indices. The upper air sounding data available from the University of Wyoming (www.weather.uwyo.edu) is used to compute the index observed indices. From the numerics

in the table, the BEP and WUDAPT experiments could exhibit the observed indices with less BIAS.

The values in the parenthesis showed in the mean column are 99% confidence interval (CI). The mean CAPE from the observations is 3291 J/kg with a 99% CI of 292 J/Kg. A mean CAPE value of 3261 (3245) with 99% CI of 349 (210) is produced by BEP (WUDAPT) experiments, which are near to the observation. However, the spread is shallow in the WUDAPT experiment. Similarly, the KI also have been exhibited. Any model simulation does not exhibit the observed mean of KI (37), but the WUDAPT experiment could produce the least KI of 40 with 99% CI of 3. The mean LI and TTI values are the same for all the experiments. However, the analysis of individual cases has shown the credibility of BEP and WUDAPT experiments. These results highlight the importance of land use patterns and resolve urban scale processes through multilayer urban parameterization in rainfall prediction. Patel et al., 2020 and Niyogi et al., 2020 also argued the importance of these processes that could affect India’s severe weather over megacities. They have shown how the accurate simulation of gradients in the urban surface fluxes can create local scale boundaries



that can significantly impact the rainfall intensity and distribution.

6 Conclusions

This study’s primary purpose is to understand the role of urban physical parameterization schemes and enhanced urban land use incorporation in simulating the severe convection over eastern megacity Bhubaneswar. A summary of the results obtained from the study is presented here.

The model simulated time evolution of various parameters such as air temperature, dew point temperature, relative humidity, and wind speed are compared against the observations from IMD. The WUDAPT experiments

could able to produce the higher HSS and lesser BIAS followed by BEP.

The model performance exhibited improvements in the severe convection with BEP and WUDAPT compared to the CNTL and UCM for each of the five cases. The changes in the spatial patterns due to the inclusion of WUDAPT data notably contributed to the timely prediction of rainfall occurrence over the Bhubaneswar city. The BEP and WUDAPT also simulate the higher HSS and lower BIAS. Further, the diabatic heating is well represented in agreement with the observed rainfall in WUDAPT and BEP experiments. However, the error in the time of occurrence of diabatic heating is less in the WUDAPT experiment, unlike the CNTL run. The urban dynamics and micro to mesoscale processes associated

Table 5 Mean and 99% confidence interval (CI) of stability indices for various experiments along with the observation

Case		1	2	3	4	5	Mean \pm 99% CI
CAPE	OBS	3526	3602	3274	3144	2909	3291 \pm 292
	CNTL	2536	3570	2662	3467	3613	3170 \pm 542
	UCM	2896	3560	2853	3465	3779	3311 \pm 428
	BEP	2951	3290	2904	3469	3698	3262 \pm 349
	WUDAPT	3008	3453	3101	3205	3456	3245 \pm 210
KI	OBS	42	35	40	39	30	37 \pm 5
	CNTL	43	42	44	40	37	41 \pm 3
	UCM	42	41	45	41	38	41 \pm 3
	BEP	41	40	44	41	37	41 \pm 3
	WUDAPT	41	39	44	40	36	40 \pm 3
LI	OBS	-8	-8	-5	-6	-5	-6 \pm 2
	CNTL	-8	-4	-4	-5	-4	-5 \pm 2
	UCM	-8	-4	-4	-5	-4	-5 \pm 2
	BEP	-8	-4	-3	-5	-4	-5 \pm 2
	WUDAPT	-8	-5	-4	-5	-4	-5 \pm 2
TTI	OBS	56	50	56	56	46	53 \pm 5
	CNTL	57	51	53	49	50	52 \pm 3
	UCM	56	52	55	51	51	53 \pm 2
	BEP	56	52	55	50	51	53 \pm 3
	WUDAPT	56	51	55	52	50	53 \pm 3

with urban fluxes in the urban boundary layer could be the reason for these changes in the rainfall distribution and quantity. Further, the LCZ based urban classification aided in providing the enhanced urban features to the model, such as building height, building distribution, open surfaces, and other thermal parameters that could affect urban weather. Hence, the WUDAPT LCZ parameters introduced heterogeneity in the city's urban morphological features, which are subsidized to the changes in the surface and atmospheric boundary layer characteristics over the city.

As an overarching conclusion, this study reports the positive encouragement for developing high-resolution realistic urban land use and morphology data for numerical weather prediction (NWP) models for enhancing the urban physical parameterization that could affect urban extremes. These findings are very much beneficial for urban architects and policymakers to appraise the effect of short term severe convection on the urban environment, health, and plan by keeping the view for a specific LCZ (instead of considering a single urban agglomeration). However, there are still some inconsistencies in the simulation of surface parameters, associated rainfall, and distribution. The discrepancies can be declined by introducing high-resolution, realistic land data products, and regional forcing fields to drive the model in future studies (Osuri et al., 2017, 2020).

Abbreviations

LULCC: Land Use/ Land Cover Changes; LCZ: Local Climate Zone; WUDAPT: World Urban Database and Access Portal Tools; WRF-ARW: Advanced Research version of the Weather Research and Forecasting; BEP: Building Effect Parameterization; MODIS: Moderate Resolution Imaging Spectroradiometer; DESA: Department of Economic and Social Affairs; UCM: Single-layer Urban Canopy Model; AH: Anthropogenic Heat; PBL: Planetary Boundary Layer; TKE: Turbulent Kinetic Energy; 3D: Three Dimensional; HSS: Hiedke Skill Score; IMD: India Meteorological Department; DPT: Dew Point Temperature; RH: Relative Humidity; GPM: Global Precipitation Measurement; CAPE: Convective Available Potential Energy; LI: Lifted index; KI: K index; TTI: Total Totals Index; CI: Confidence Interval.

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Code availability

WRF model and verification package are openly accessible.

Authors' contributions

All the authors (R.N., P.P. D.N. U.C.M., and S.D.A.) were involved in the problem conceptualization and establishment of the workflow. R.N. and P.P. wrote the manuscript, conducted the analysis, and produced the figures. D.N. guided the analysis, interpretation, and articulation of results. The author(s) read and approved the final manuscript.

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Availability of data and materials

Data and material will be available on request.

Declarations**Competing interests**

There is no conflict of interest.

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References

- Agilan, V., & Umamahesh, N. V. (2015). Detection and attribution of non-stationarity in intensity and frequency of daily and 4-h extreme rainfall of Hyderabad, India. *Journal of Hydrology*, *530*, 677–697.
- Arnfield, A. J. (2003). Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *23*(1), 1–26.
- Bechtel, B., Alexander, P. J., Böhner, J., Ching, J., Conrad, O., Feddema, J., & Stewart, I. (2015). Mapping local climate zones for a worldwide database of the form and function of cities. *ISPRS International Journal of Geo-Information*, *4*(1), 199–219.
- Berg, P., Moseley, C., & Haerter, J. O. (2013). Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*, *6*(3), 181–185.
- Bougeault, P., & Lacarrere, P. (1989). Parameterization of orography-induced turbulence in a mesobeta-scale model. *Monthly weather review*, *117*(8), 1872–1890.
- Brousse, O., Martilli, A., Foley, M., Mills, G., & Bechtel, B. (2016). WUDAPT, an efficient land use producing data tool for mesoscale models? Integration of urban LCZ in WRF over Madrid. *Urban Climate*, *17*, 116–134.
- Chawla, I., Osuri, K. K., Mujumdar, P. P., & Niyogi, D. (2018). Assessment of the Weather Research and Forecasting (WRF) model for simulation of extreme rainfall events in the upper Ganga Basin. *Hydrology and Earth System Sciences*, *22*(2), 1095–1117.
- Chen, F., Kusaka, H., Tewari, M., Bao, J. W., & Hirakuchi, H. (2004). Utilizing the coupled WRF/LSM/Urban modeling system with detailed urban classification to simulate the urban heat island phenomena over the Greater Houston area. In Fifth Symposium on the Urban Environment. *American Meteorological Society Vancouver, BC, Canada*, *25*, 9–11.
- Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C. S. B., Grossman-Clarke, S., & Zhang, C. (2011). The integrated WRF/urban modelling system: Development, evaluation, and applications to urban environmental problems. *International Journal of Climatology*, *31*(2), 273–288.
- Ching, J., Mills, G., Bechtel, B., See, L., Feddema, J., Wang, X., & Theeuwes, N. (2018). WUDAPT: An urban weather, climate, and environmental modeling infrastructure for the anthropocene. *Bulletin of the American Meteorological Society*, *99*(9), 1907–1924.
- Ching, J., See, L., Mills, G., Alexander, P., Bechtel, B., Feddema, J., & Hanna, A. (2014). WUDAPT: Facilitating advanced urban canopy modeling for weather, climate and air quality applications. In: *94th American Meteorological Society Annual Meeting, 2–6 February 2014*, Georgia, USA
- Desa, U. N. (2010). World urbanization prospects, the 2009 revision. Population Division, department of economic and social affairs, United Nations Secretariat.
- Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of Atmospheric Sciences*, *46*(20), 3077–3107.
- Gharai, B., Rao, P. V. N., & Dutt, C. B. S. (2018). Mesoscale model compatible IRS-P6 AWiFS-derived land use/land cover of Indian region. *Current Science*, *115*(12), 2301–2306.
- Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C., & Razuvaev, V. N. (2005). Trends in intense precipitation in the climate record. *Journal of Climate*, *18*(9), 1326–1350.
- Hong, S. Y., & Lim, J. O. J. (2006). The WRF single-moment 6-class microphysics scheme (WSM6). *A sia-Pacific Journal of Atmospheric Sciences*, *42*(2), 129–151.
- Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., & Xie, P. (2014). Integrated multi-satellite retrievals for GPM (IMERG), version 4.4. NASA's Precipitation Processing Center. *J. ISMAC*, *1*(02).
- Kain, J. S. (2004). The Kain-Fritsch convective parameterization: an update. *Journal of applied meteorology*, *43*(1), 170–181.
- Kusaka, H., & Kimura, F. (2004). Coupling a single-layer urban canopy model with a simple atmospheric model: Impact on urban heat island simulation for an idealized case. *Journal of the Meteorological Society of Japan Ser. II*, *82*(1), 67–80.
- Kusaka, H., Kondo, H., Kikegawa, Y., & Kimura, F. (2001). A simple single-layer urban canopy model for atmospheric models: Comparison with multi-layer and slab models. *Boundary-Layer Meteorology*, *101*(3), 329–358.
- Liu, Y., Chen, F., Warner, T., & Basara, J. (2006). Verification of a mesoscale data-assimilation and forecasting system for the Oklahoma City area during the Joint Urban 2003 field project. *Journal of Applied Meteorology and Climatology*, *45*(7), 912–929.
- Martilli, A., Clappier, A., & Rotach, M. W. (2002). An urban surface exchange parameterisation for mesoscale models. *Boundary-Layer Meteorology*, *104*(2), 261–304.
- Memon, R. A., Leung, D. Y., & Liu, C. H. (2009). An investigation of urban heat island intensity (UHII) as an indicator of urban heating. *Atmospheric Research*, *94*(3), 491–500.
- Miao, S., Chen, F., LeMone, M. A., Tewari, M., Li, Q., & Wang, Y. (2009a). An observational and modeling study of characteristics of urban heat island and boundary layer structures in Beijing. *Journal of Applied Meteorology and Climatology*, *48*(3), 484–501.
- Miao, S., Chen, F., Li, Q., & Fan, S. (2009b, June). Impacts of urbanization on a summer heavy rainfall in Beijing. In The seventh International Conference on Urban Climate: Proceeding (Vol. 29).
- Mills, G., Ching, J., See, L., Bechtel, B., & Foley, M. (2015, July). An introduction to the WUDAPT project. In Proceedings of the 9th International Conference on Urban Climate, Toulouse, France (pp. 20–24).
- Milly, P. C., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: whither water management? *Science*, *319*(5863), 573–574.
- Mlawer, E. J., & Clough, S. A. (1997). On the extension of rapid radiative transfer model to the shortwave region. In Proceedings of the 6th Atmospheric Radiation Measurement (ARM) Science Team Meeting, US Department of Energy, CONF-9603149.
- Nadimpalli, R., Osuri, K. K., Pattanayak, S., Mohanty, U. C., Nageswararao, M. M., & Kiran Prasad, S. (2016). Real-time prediction of movement, intensity and storm surge of very severe cyclonic storm Hudhud over Bay of Bengal using high-resolution dynamical model. *Natural Hazards*, *81*(3), 1771–1795.
- Nadimpalli, R., Osuri, K. K., Mohanty, U. C., Das, A. K., Kumar, A., Sil, S., & Niyogi, D. (2019). Forecasting tropical cyclones in the Bay of Bengal using quasi-operational WRF and HWRF modeling systems: an assessment study. *Meteorology and Atmospheric Physics*, *132*(1), 1–17.
- Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., & Shepherd, M. (2017). Urbanization impacts on the summer heavy rainfall climatology over the eastern United States. *Earth Interactions*, *21*(5), 1–17.
- Niyogi, D., Osuri, K. K., Busireddy, N. K. R., & Nadimpalli, R. (2020). Timing of rainfall occurrence altered by urban sprawl. *Urban Climate*, *33*, 100643.
- Osuri, K. K., Mohanty, U. C., Routray, A., Mohapatra, M., & Niyogi, D. (2013). Real-time track prediction of tropical cyclones over the North Indian Ocean using the ARW model. *Journal of Applied Meteorology and Climatology*, *52*(11), 2476–2492.
- Osuri, K. K., Nadimpalli, R., Mohanty, U. C., Chen, F., Rajeevan, M., & Niyogi, D. (2017). Improved prediction of severe thunderstorms over the Indian

- Monsoon region using high-resolution soil moisture and temperature initialization. *Scientific Reports*, 7(1), 1–12.
- Osuri, K. K., Nadimpalli, R., Ankur, K., Nayak, H. P., Mohanty, U. C., Das, A. K., & Niyogi, D. (2020). Improved simulation of monsoon depressions and heavy rains from direct and indirect initialization of soil moisture over India. *Journal of Geophysical Research: Atmospheres*, 125(14), e2020JD032400.
- Patel, P., Karmakar, S., Ghosh, S., & Niyogi, D. (2020). Improved simulation of very heavy rainfall events by incorporating WUDAPT urban land use/land cover in WRF. *Urban Climate*, 32, 100616.
- Pathirana, A., Denekew, H. B., Veerbeek, W., Zevenbergen, C., & Banda, A. T. (2014). Impact of urban growth-driven landuse change on microclimate and extreme precipitation—A sensitivity study. *Atmospheric Research*, 138, 59–72.
- Salamanca, F., & Martilli, A. (2010). A new building energy model coupled with an urban canopy parameterization for urban climate simulations—Part II. Validation with one dimension off-line simulations. *Theoretical and Applied Climatology*, 99(3), 345–356.
- Salamanca, F., Martilli, A., Tewari, M., & Chen, F. (2011). A study of the urban boundary layer using different urban parameterizations and high-resolution urban canopy parameters with WRF. *Journal of Applied Meteorology and Climatology*, 50(5), 1107–1128.
- Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., & Powers, J. G. (2008). A description of the advanced research WRF version 3, NCAR Tech. Note NCAR/TN-475+ STR. Boulder. *National Center for Atmospheric Research*, pp. 125.
- Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. *Bulletin of the American Meteorological Society*, 93(12), 1879–1900.
- Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M. A., Mitchell, K., & Cuenca, R. H. (2004, January). Implementation and verification of the unified NOAA land surface model in the WRF model. In 20th conference on weather analysis and forecasting/16th conference on numerical weather prediction (Vol. 1115, No. 6, pp. 2165–2170).
- Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climatic Research*, 47(1–2), 123–138.
- Tyagi, B., Naresh Krishna, V., & Satyanarayana, A. N. V. (2011). Study of thermodynamic indices in forecasting pre-monsoon thunderstorms over Kolkata during STORM pilot phase 2006–2008. *Natural Hazards*, 56(3), 681–698.
- Wan, H., Zhong, Z., Yang, X., & Li, X. (2013). Impact of city belt in Yangtze River Delta in China on a precipitation process in summer: a case study. *Atmospheric Research*, 125, 63–75.
- Zhang, H., Sato, N., Izumi, T., Hanaki, K., & Aramaki, T. (2008). Modified RAMS-Urban canopy model for heat island simulation in Chongqing, China. *Journal of Applied Meteorology and Climatology*, 47(2), 509–524.
- Zhang, N., Gao, Z., Wang, X., & Chen, Y. (2010). Modeling the impact of urbanization on the local and regional climate in Yangtze River Delta, China. *Theoretical and Applied Climatology*, 102(3), 331–342.

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