Impacts of Urbanization, Aerodynamic roughness and Land Surface Processes on the Extreme Heavy Rainfall over Chennai, India

J. R.Rajeswari^{1,2}, C.V. Srinivas^{1,2#}, V.Yesubabu³, D.Hari Prasad⁴ and B. Venkatraman^{1,2}

1. Health, Safety and Environment Group, Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamilnadu-603102, India.
2. Homi Bhabha National Institute, Anushakti Nagar, Mumbai, 400094, India
3. National Atmospheric Research Laboratory, Gadanki, Tirupati, India
4. Physical Sciences and Engineering Division, King Abdullah University of Science and Technology, Kingdom of Saudi Arabia

#Corresponding Author: C.V.Srinivas, Health, Safety & Environment Group, Indira Gandhi Centre for Atomic Research, Kalpakkam – 603102, India

Email: cvsri@igcar.gov.in; venkatasrinivasc@yahoo.com; [Tel:91+44+27480500\(Ext:23574\)](tel:914427480500)

26 **Key Points:**

- 27 • We study the impact of urban land surface processes on the heavy rainfall event using WRF.
- 28 • Increased urbanization and moderately increased roughness ($Z_o=1.08$ m) enhanced the
- 29 rainfall and corrected the location of maximum rainfall.
- 30 • Urban surface drag played crucial role in heavy rainfall by accentuating the low-level
- 31 convergence and convection

32

33

34

35

36

37

38

39

40

41

42

43

44

Abstract

In this study, the impacts of urban land surface processes on the extreme heavy rainfall event on 01 December 2015 over Chennai, located in north coastal Tamil Nadu, India are analyzed using convection permitting WRF simulations. A series of numerical experiments are conducted using different land cover data (USGS-1992, NRSC-2004, NRSC-2015), aerodynamic roughness, and land surface models (LSM) to assess their sensitivity on the predicted rainfall. Results suggest that experiments with NRSC-2015 with increased urban extent improved the rainfall prediction in terms of rainfall intensity and its distribution. Though temperatures, sensible heat, and Planetary Boundary Layer height (PBLH) increased due to urbanization in both dry and wet phases, the humidity and Convective Available Potential Energy (CAPE) reduced during the dry phase suggesting thermal convection played a secondary role in rainfall. Considerable increase of surface drag, momentum transport, wind shear and Turbulent Kinetic Energy are found in simulations with updated land use and roughness, which determined the location of the cyclonic circulation, convergence and maximum precipitation. LSM sensitivity experiments indicated that while the five-layer model substantially increased the sensible heat, temperature and PBLH, it reduced the moisture convergence and CAPE relative to Noah and Noah-MP thus resulting in low rainfall. The simulation with Noah-MP enhanced the low-level shear and convergence over other LSMs thus produced a wide spread rainfall along the coast. Our results demonstrated that the momentum transport due to urban drag played a vital role by strengthening the low-level convergence and moist convection, which caused heavy precipitation over Chennai.

[Key words: Urbanization, heavy rainfall, roughness, surface drag, shear, WRF]

1. Introduction

An increasing frequency of heavy rainfall events has been reported over various urban areas across the globe in recent times (e.g., Wang et al., 2018; Kistawal et al., 2011; Luong et al., 2020). Among several factors, land-surface and boundary layer processes seem to strongly influence the development of convective storms, local weather systems and extreme rainfall events (Pielke et al., 2011; Shem and Shepherd, 2009). Urbanization induced land use/ land cover (LULC) change has been attributed as one of the causative factors for localized heavy rainfall events over cosmopolitan cities (Chang et al., 2009; Kalnay and Cai, 2003; Lei et al., 2008; Paul et al., 2018) by modifying the transport of heat and convective energy through the changes in surface physical characteristics and energy budget.

The positive feedback of urbanization on precipitation is explained through anthropogenic heat release to lower atmosphere, enhanced heat flux and resulting changes in thermodynamic structure of atmospheric boundary layer (Bornstein and Lin, 2000; Miao et al., 2011; Shem and Shepherd, 2009). Urbanization increases the surface temperatures as well as the roughness due to altering thermal heat capacities and resistance offered by urban canopy which potentially modulates the flow features over the urban boundary (Oke, 1982). Moreover, the LULC is an important land surface parameter in determining the exchange of heat and momentum between the land and air through heat capacity, aerodynamic roughness, surface emissivity, surface hydrology, evaporation and the thermo-dynamical structure of the atmospheric boundary layer (Oke, 1982; Maslin, 2004). Also, urbanization studies (Mölders and Olson, 2004; Wang et al., 2012a) suggest that the enhanced aerodynamic roughness increases the planetary boundary layer height (PBLH) through amplifying surface sensible heat flux and helps in the vertical mixing of the heat and water vapor. Several studies (Craig and Bornstein, 2002; Shepherd, 2005; Niyogi et al., 2006) have indicated that small scale convective cells while approaching an urban area get organized and strengthened due to

enhanced surface drag and convergence near the urban-rural boundary and produce heavy precipitation in the downwind side of an urban area. The modification of approaching convective storms (Niyogi et al., 2011) by urban canopy also produce aerosol-induced microphysical changes, through the urban-aerosols which potentially acts as cloud condensation nuclei, thereby generate thermal instability (Kishtawal et al., 2010; Molders and Olson, 2004; Shepherd et al., 2010; Sarangi et al., 2018).

Few studies on the role of urbanization on convective precipitation events reported (Guo et al., 2006; Zhang et al., 2009; Zhang et al., 2015; Wang et al., 2018) a reduction in rainfall due to inhibition of surface evaporation, reduction in surface latent heat flux and consequent decrease in convective available potential energy (CAPE). On the other hand, other modeling studies show that urbanization leads to enhancement in warm season precipitation over the downwind parts of major cities (Lin et al., 2008; Shepherd et al., 2002, Shepherd, 2005; Shem and Shepherd, 2009; Zhang et al., 2009; Kishtawal et al., 2010; Miao et al., 2011; Yan et al., 2016; Han et al., 2014; Yang et al., 2014; Wang et al., 2012b; Wang et al., 2015; Cao et al., 2020). Furthermore, the change of precipitation by urbanization depends on the degree of urbanization (Miao et al., 2011) and an extensive urbanization enhanced localized rainfall as the thermal transport plays a higher role than the momentum transport. Majority of these studies are mainly focused on summer (warm season) convective storms over large cities with moisture supply from the sea or surrounding water bodies. However, the impact of urbanization on the heavy rainfall events which occur in association with strong synoptic forcing has not been studied in detail.

A few studies analyzed the consequences of urban expansion and induced land use changes on extreme rainfall scenarios over Tropical Indian cities (Kishtawal et al., 2010; Misra, 2011; Paul et al., 2018; Mohan and Kandya, 2015; Boyaj et al., 2020). Kumar et al. (2008) showed that the highly localized heavy rainfall event (August 2005) over Mumbai was produced as a result of the

interaction of synoptic-scale low-pressure system with the typical mesoscale land-surface features of this region. Moreover, the mesoscale land-surface feed-back modulated the location and intensity of the heavy rainfall through changes in the winds and moisture convergences. Lei et al. (2008) using Regional Atmospheric Modelling System (RAMS) for Mumbai rainfall showed that increased urbanization creates heterogeneity in surface temperatures, which significantly influenced the vertical wind and precipitation. Thus, the preceding review indicates that the urbanization can have a positive or negative impact on convection and precipitation depending on the season, geographical setting, synoptic meteorological scenario and sources of moisture etc.

Chennai (13.07° N, 80.28°E) the coastal capital city of Tamil Nadu, India has undergone rapid urbanization in the last three decades. Recent studies (Aithal and Ramachandra, 2016; Mathan and Krishnaveni, 2020) reported that the urban area is increased by 60% and forest and agricultural area is reduced by 40 % causing large urban heat island (Devadas and Rose, 2009; Anushiya et al., 2014). The average building heights of Chennai city also rapidly increased, vary in the range of 40 to 168 m and recent observational study (Bagavath Singh et al., 2015) highlighted the significant variations in aerodynamic roughness (0.5 to 2.05 m) under different synoptic flows. The Chennai city region experienced extremely heavy rainfall and extensive flooding during 1-2 December 2015 (Oldenborgh et al., 2016) under a low-pressure system over southwest Bay of Bengal (BOB) and adjoining Tamil Nadu on 27 November 2015 during the northeast monsoon (IMD, 2015; Mishra, 2016). The trough line passed along coastal Tamil Nadu extending from 9° N (1010 hPa) to 14°N (1014 hPa) and was associated with a cyclonic circulation extending up to 3.1 km from the sea level. Previous studies suggested that the moisture transport from BOB and its convergence under the persistent synoptic low-pressure trough caused the heavy rainfall (Chakraborty, 2016; Narasimhan et al., 2016; Srinivas et al., 2018). Also the recent studies (Boyaj et al., 2020) on urban impacts on

Chennai heavy rainfall emphasized the role of enhanced thermal transport and ignored the role of urban induced roughness and the associated physical processes in the simulations.

This study investigates (i) interaction of the synoptic scale circulation with the local topography, (ii) the role of the underlying urban induced land surface processes, and (iii) the physical mechanism leading to the convection and localization of heavy rainfall. Towards this objective a series of sensitivity experiments are conducted using a high resolution WRF mesoscale model with different LULC data sets, roughness factors, and land surface physics. Through a systematic representation of changes in land surface features, we seek to elucidate the near-surface and boundary layer response to different representations of urban forcing on the meteorological setting of the heavy rainfall. The study is organized in to 4 sections. In section 2, we provide details of the modeling system, data sets, and sensitivity experiments. Section 3 provides the results of our study. Finally, section 4 discusses the major conclusions.

2. Details of Model, Data and Experimental design

2.1 Model configuration

The WRF-ARW mesoscale atmospheric model version 4.2 (Skamarock et al., 2008) configured with four interactive nested domains of resolutions 27, 9, 3, and 1 km and 51 vertical levels (Table 1) is used for the study. The outer domain covers Indian subcontinent and adjoining Indian Ocean. The fourth domain (1 km) with 328 x 343 grid cells covers the north Tamil Nadu. Several short-range prediction (integrating for 48 hours) experiments are conducted by initializing the model at 0000 UTC 30 November 2015. The model physics includes RRTMG scheme for shortwave and longwave radiation transfer (Clough et al., 2005), Mellor-Yamada Nakanishi and Niino level 2.5 closure scheme for planetary boundary layer processes (Nakanishi and Niino, 2004), MM5 scheme for surface layer, Noah scheme for land surface processes (Tewari et al., 2004) and Thompson scheme

(Thompson et al., 2008) for cloud microphysical processes. The Kain Fritsch cumulus convection scheme (Kain, 2004) is used for the model coarse domains 1 (27-km) and 2 (9-km) and only microphysics is used in the convection permitting inner domains 3 (3-km) and 4 (1-km).

2.2 Data sets

The National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) $0.5^\circ \times 0.5^\circ$ (~50 km) analysis is used for model initial condition and the boundary conditions are updated from three hourly GFS forecasts. The United States Geological survey (USGS) terrain and Food and Agriculture Organization (FAO) soil categories data at arc10 min, 5 min, and 30 s resolutions are used to define the static surface fields in the model. The LULC is defined from different sources USGS, and Indian Space Research Organization- National Remote Sensing Centre (ISRO-NRSC) at arc 30s resolution in different simulations. The USGS 24-category LULC data is generated from 1 km Advanced Very High-Resolution Radiometer (AVHRR) satellite images obtained in 1992-1993 (Sertel et al., 2010). The National Remote Sensing Centre (NRSC) LULC data over Indian region is generated using Indian Resource sat (IRS-P6) multispectral Advanced Wide Field Sensor (AWiFS) imagery following the USGS classification (Biswadip, 2014). Green vegetation fraction (GVF) for all the simulations is defined from the new MODIS based normalized difference vegetation index (NDVI) monthly climatological data available at $0.144^\circ \times 0.144^\circ$ resolution.

The LULC data sets of 2004 and 2015 (Fig.1) indicate significant variation in the land-cover compared to its base level in 1992 over the study area (Table 4). The irrigated crop/ pastures covered a major portion of the domain and urban lands, forests, grasslands, and crop mosaics to a smaller extent in 1992. A striking feature is that the urban area over Chennai and surroundings (box region 12.65°N - 13.2°N 79.8°E - 80.3°E) is expanded by 15% in 2004 and further increased by 23% in 2015 compared to its extent in 1992 (Table 4). We have also noticed a substantial decrease of

irrigated croplands (40-60%), mixed vegetation and dense forests (50-75%), moderate increase of deciduous forests (10-15%), shrub lands (6-9%) and water bodies (4-7%) in 2004-2015 compared to 1992 (Table 4). These LULC changes correspondingly affect the albedo, moisture availability, thermal inertia and roughness factor (Maslin, 2004) in the simulations. The LULC of NRSC exhibits high spatial heterogeneity than the USGS with many varieties of land use and sharp increase in the dry / irrigated croplands and urbanized areas.

The simulated rainfall is compared with the rainfall data from 18 IMD rain-gauge stations, and simulated spatial rainfall is compared with the interpolated rainfall data using 285 station observations from Tamil Nadu Agriculture University (TNAU), daily gridded precipitation products of IMD Doppler Weather Radar (DWR) and $0.1^{\circ} \times 0.1^{\circ}$ Global Precipitation Mapper (GPM) IMERGE rainfall data (Huffman et al., 2014). The surface meteorological parameters are also compared at 8 IMD and ISRO Automated Weather Stations (Table 3). Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) data with temporal coverage 3 hours and spatial resolution $0.25^{\circ} \times 0.25^{\circ}$ is also used for rainfall comparison (TRMM, 2011).

2.3 Experimental design

A series of sensitivity experiments are conducted to study the impact of the land-cover, roughness factor, and land surface physics on the simulation of heavy rainfall. In the first part, we analyzed the sensitivity of rainfall to different degrees of urbanization. For this, we conducted three simulations by using the Noah Land surface model, and varying the LULC data from three different sources :i) USGS-1992 (low urban cover),ii) NRSC-2004 (moderate urban cover), and iii) NRSC-2015 (extensive urban cover) and the experiments are denoted by USGS, NRSC1, and NRSC2, respectively. Observational studies suggest that urban areas with tall buildings can have aerodynamic roughness length (Z_0) in the range of 0.5 - 2 m (Fang et al., 1992; Li et al., 2009; Jancewicz and

Szymanowski 2017). Bagavath Singh et al., (2015) observed the Z_o values varies between 1.08 and 2.0 m under different background winds (Summer, SW monsoon, NE monsoon) over Chennai due to the tall buildings which vary between elevations of 40 and 160 m above ground level (a.g.l). Considering these factors in the second part, to adequately represent the Z_o (Grimmond and Oke, 1999) and to illustrate the their impact over Chennai, we conducted sensitivity experiment using NRSC-2015 land cover and updating the Z_o in WRF based on observational estimates (Bagavath Singh et al., 2015). Two experiments NRSC2Z1 and NRSC2Z2 are conducted by increasing Z_o for urban class from default value (0.5) to 1.08 m and 2.0 m respectively.

Finally, to study the role of Land-surface processes on the convection and precipitation through transport of heat and moisture from surface to atmosphere, we have performed three more experiments by using three different land surface models namely, i) five-layer soil thermal diffusion model (hereafter FL) ii) Noah LSM (hereafter NL) and iii) Noah Multiphysics (hereafter NMP). All these simulations used NRSC-2015 land cover and $Z_o=1.08$ m to assess the impact of ground hydrology and urban vegetation canopy effects on simulated heavy rainfall over Chennai. These simulations are termed as NRSC2Z1-FL, NRSC2Z1 (with NL) and NRSC2Z1-NMP. Table 1 provides the details of model domain, physics options used in this study, and Table 2 provides the details of the sensitivity experiments.

3. Results and discussion

We first discuss the role of the changes in urbanization on the atmospheric conditions associated with Chennai heavy rainfall event by analyzing the high resolution 1-km model outputs of surface drag, wind flow, and surface energy budgets. We also present the role of the considered parameters on the low-pressure, thermo-dynamical and dynamical processes, and further discuss the impact of different roughness parameter and land surface models on the considered parameters.

3.1 Sensitivity to LULC data

The 24 h cumulative rainfall for the period 0300 UTC of 01- 0300 UTC of 02 December 2015 from DWR, GPM gridded rainfall and interpolated rain-gauge data is presented in Figure 2. The observed rainfall (Figs. 2 a-c) varied as 200 mm at north Chennai (13.35°, 79.7° N), 300 mm at central Chennai (12.90°, 79.7° N), 400-475 mm over southwest Chennai (12.9° N, 79.7° E), 390 mm in the south at Chengalpattu (12.45° N, 79.7° E) and 170 mm at Kancheepuram (12.60° N, 79.5° E) stations indicating large spatial variability with peak rainfall located in the southwestern part of Chennai (Figs. 2 a-c), which are in line with Srinivas et al., (2018). Simulated 24 h accumulated rainfall on 01 December (Figs. 2d-h) indicates a large spatial variation among experiments using different LULC data. The USGS experiment shows three rainfall peaks i) 280-340 mm near Tambaram (13.0°, 79.65° E N), 220-300 mm over northern part of Chennai close to Pulicat Lake (13.5° N, 80.2° E) and ii) 250-370 mm over the coast of Pondicherry (12.0°-12.25N). However, this experiment underestimated the rainfall over the south-west area of Chennai and overestimated over Pondicherry-Cuddalore coast (12.0°-12.5° N). Also, it shows secondary rainfall peak extended to northern areas upto Nellore (13.6° N) / Pulicat lake. The NRSC1 produced a band of heavy rainfall (280-400 mm) over north Chennai and extending to 50 km southward with a few isolated peaks near Tambaram (Chennai) and Kovalam (12.75° N). The two peaks that appeared in the USGS seem to be merged in NRSC1 to produce significantly high rainfall in the northern parts of Chennai (13.0°-13.4° N) compared to the observed estimates. The peak rainfall (250-400 mm) in NRSC2 is shifted 40-50 km southwest towards Tambaram from Chennai coast. Simulated rainfall pattern agrees well with the DWR, gridded rain-gauge and G PM-IMERG data though the GPM-IMERG shows higher rainfall intensity compared to the DWR and rain-gauge data. The GPM-IMERG shows southward extension of rainfall along the coast upto 12° N and further to southeast BOB. The location of

maximum precipitation and the southward extension of rainfall are better captured in NRSC2 though it slightly under predicted the amount of rainfall in the southern coastal regions. Thus, there is a gradual southward shift and increase of heavy rainfall (Table 5, Figs.2d-f) over the southwest of Chennai and its surroundings (12.65°N - 13.2°N ; 79.8°E - 80.3°E) which are also noticed from the simulations USGS to NRSC2 with increasing urban canopy from 1992 to 2015.

As shown in Figure 3, simulated hourly rainfall at different IMD stations (Chennai, Chembarapakkam, Hindustan University, Madhavaram, Taramani and Tambaram) indicates high spatial variability. Observations indicate that the first rainfall peak around 0600 UTC is not captured well by the model at Tambaram, Chembarapakkam, and Hindustan University. Though, in general, the model slightly underestimated the rainfall in the period 0000 - 0700 UTC and overestimated during 0900-1700 UTC, the predictions are improved in NRSC1 and NRSC2 over USGS which produced large deviations in both the phases. While USGS and NRSC1 show an extended period of minimum rainfall with sudden spike at 1300 UTC, the NRSC2, NRSC2Z1 and NRSC2Z1-NMP with updated LULC (NRSC-2015) produced prolonged intense rainfall of ≥ 10 mm in good agreement with the observations. Simulated rainfall for all the six rain gauge stations has a mean error of -6.72, 2.45, and -2.01 mm for USGS, NRSC1, and NRSC2 respectively indicating NRSC2 shows low mean error and good skill at different stations.

To illustrate the response of dynamical and thermo-dynamical fields in producing the spatial rainfall variability among different sensitivity experiments, we analyze the variations in wind flow, sea level pressure/ geopotential, vorticity distributions at different levels (Figs.4-5) at 1200 UTC 01 December just before the rainfall intensification at different stations. The low-pressure trough actually extended over a larger area from 9°N (1010 hPa) to 14°N (1014 hPa) which was not covered by model domain 4. At low levels (925-hPa), an increase in convergence of winds and decrease in the pressures are noticed at coastal regions of the north Tamil Nadu along the trough

suggesting a cyclonic circulation (Fig. 4). The presence of the cyclonic circulation is seen upto 500 hPa with a southward tilt (Figs.5, S1 and S2). Simulations indicate (Fig. 4) that the low pressure trough is aligned along the coast over the land area north of 12.25° N and shifts further to the southeast over the sea in the southern parts thus producing rainfall over the sea also south of 12.25° N (Figs. 2 a-c). A northward shift of the trough and cyclonic circulation and increased positive vorticity are noticeable (Figs. 4a-c) in NRSC1 (12.75° N) and NRSC2 (12.90° N) relative to USGS (12.2° N).

Retardation of wind speed over the urban area and acceleration over downwind southwestern areas are clearly evident in the experiments with increased urban area (NRSC1 and NRSC2). All the simulations reveal the presence of an organized and stronger cyclonic flow at mid-tropospheric levels (500 hPa) (Fig.5) compared to lower level (925 hPa). However, the position and intensity of mid-tropospheric cyclonic circulation is differently represented, with higher intensity and northward shift in the increased urbanization simulations (NRSC1 and NRSC2) relative to USGS. These spatial features of wind field, pressure trough, and vorticity suggests a slight northward shift of the trough, and associated cyclonic circulation with increased urban canopy ultimately influencing the spatial rainfall pattern.

Previous studies (Chakraborty, 2016; Narasimhan et al., 2016; Srinivas et al., 2018) highlighted that the heavy rainfall over Chennai occurred mainly due to the strong moisture transport from Bay of Bengal and its convergence along the low-level trough in association with mid-tropospheric cyclonic circulation. The differences in mean vertical velocities at 850 hPa and the mean integrated moisture convergence between the layers of 1000 and 500 hPa during the peak heavy rainfall period i.e., 0900-1500 UTC 01 Dec 2015 for the sensitivity experiments with respect to land cover (USGS, NRSC1, NRSC2), roughness factors (NRSC2, NRSC2Z1, NRSC2Z2) and

land surface models (NRSC2Z1, NRSC2Z1FL, NRSC2Z1NMP) are presented in Figure 6. In all the simulations, the areas of stronger convergence are associated with intense vertical motions in and around Chennai. The experiments with increased urbanization (NRSC1, NRSC2) clearly indicate enhanced moisture convergence (500 to 1000 $\text{kg m}^{-1}\text{s}^{-1}$ for NRSC1; 500 to 1500 $\text{kg m}^{-1}\text{s}^{-1}$ for NRSC2) and vertical motion (40 to 80 cm s^{-1} for NRSC1; 40 to 70 cm s^{-1} for NRSC2) relative to the one with low urbanization (USGS). The area of stronger moisture convergence is co-located with the highest rainfall and cyclonic vorticity (Figs. 3 and 4). The urban induced modifications in organization and intensification of moisture convergence are seen in the windward side of the urban region with a stronger vertical transport and these features are more clearly visible in NRSC1 (Fig.6a) and NRSC2 (Fig. 6b) compared to USGS.

3.2 Sensitivity to aerodynamic roughness

Simulated rainfall in the experiments with increased roughness factor (NRSC2Z1 and NRSC2Z2), successively improved (Figs. 2g-h) the southward extension of heavy rainfall along the coast as seen in GPM-IMERG rainfall pattern. Though the rainfall over the BOB is under predicted (Figs. 2d-h) by all experiments, the simulations with increased roughness (Figs. 2g-h) reduced the uncertainties. Moreover, the spatial extent of maximum rainfall is stretched in the N-S direction and contracted in E-W direction (Fig. 2g) with the increase of surface roughness. The band of peak rainfall confined to above 12.5°N with a moderate southward extension is seen in NRSC2Z1 similar to the observed rainfall distribution (Figs. 2a-b). Though the increased roughness enhanced the simulated rainfall over Chennai (from NRSC2 to NRSC2Z2), the NRSC2Z2 slightly overestimated the rainfall extending to a wider land area relative to observed rainfall.

Simulated rainfall at different stations (Fig. 3) shows that NRSC2Z1 with updated roughness ($Z_0=1.08 \text{ m}$) improved the rainfall prediction compared to NRSC2 both in timing and quantity.

However, the experiment NRSC2Z2 with further increase in roughness ($Z_o=2.0$ m) over predicted the rainfall in the late phase 1800-2100 UTC indicating the extension of convection and rainfall spell to the late night in contrast to observations. The NRSC2Z1 provides better agreement with the observation by following the trend. The mean error is reduced to 0.54 mm in NRSC2Z1, however it increased to -1.05 mm in NRSC2Z2.

As shown in figure 4, experiments NRSC2Z1 and NRSC2Z2 with increased roughness simulated further northward movement of low pressure, corresponding shift in cyclonic vorticity and wind field towards the inland regions. With increasing roughness, the simulated cyclonic flow at mid-tropospheric levels (500 hPa) is strengthened, the strength of winds and circulation features progressively reduced in inland regions while the offshore features of wind and vorticities are enhanced. These changes are attributable to changes in surface energy fluxes, momentum transport and convection induced by enhanced surface drag and vertical motion (Table 5).

The experiments NRSC2Z1 and NRSC2Z2 produced further increase in moisture convergence (500 to $1700 \text{ kg m}^{-1}\text{s}^{-1}$ for NRSC2Z1; 500 to $2000 \text{ kg m}^{-1}\text{s}^{-1}$ for NRSC2Z2) and vertical motions (40 to 70 cms^{-1} for NRSC2Z1; 40 to 80 cms^{-1} for NRSC2Z2) over wide areas along the coast, enhancing the cyclonic circulation and rainfall (Figs. 4 and 5) over NRSC2 with low roughness factor (0.8 m) (Figs. 6 c-d). These results clearly suggest that the location of low-pressure trough, cyclonic flow and vorticity field are sensitive to the representation of urban land cover and roughness factor in the model. The simulated rainfall from NRSC2Z1 better represents the precipitation pattern compared to USGS, NRSC1 and NRSC2 simulations.

3.3 Sensitivity to Land Surface Models

Here, we present a sensitivity analysis with three LSMs (FL, NL, and NMP) on simulation of heavy rainfall. The experiment NRSC2Z1-FL failed to simulate the spatial and temporal patterns of

observed rainfall pattern. NRSC2Z1-FL (Fig. 2) shows that the band of maximum rainfall stretches in a northwest direction from Chennai to Pulicat lake (13.35°N; 79.75° N) and the rainfall is grossly underestimated over south Chennai and adjoining southern coastal parts. Rainfall time series (Fig.3) also confirms that NRSC2Z1-FL produces considerable deviation from observations. The results of LSM sensitivity experiments clearly suggest that the rainfall is more organized and is successively enhanced along the coast with NL and NMP as compared to FL model. Among the three simulations the NRSC2Z1-NMP best simulated the rainfall in both timing and amount. Though it slightly overestimated the rainfall during peak phase (0900-1700 UTC), it produced a more realistic temporal pattern over the 24-hour period by reducing the underestimation in the first spell (0300-0600 UTC) and also over prediction in the late phase (1800-2100 UTC).

The sensitivity in simulated rainfall with the LSMs is possibly due to the simulated changes in the pressure and winds (Figs.4 and 5). The shift in the rainfall band towards northwest of Chennai in NRSC2Z1-FL is due to the northward shift of the low-pressure trough (indicated by 1008-1009 hPa). We also notice relative intensification of the low-level trough in NRSC2Z1 and NRSC2Z1-NMP over NRSC2Z1-FL which leads to the changes in wind field, resultant convergence and vertical motion in the simulations (see section 3.4). The NRSC2Z1-MP shows (Fig. 6) stronger moisture convergence and vertical motions ($1900\text{--}2200 \text{ kg m}^{-1}\text{s}^{-1}$; 50-90 cm/s) relative to NRSC2Z1 (Fig. 6f) in and around the urban area. The NRSC2Z1-FL shows weakly organized moisture convergence and vertical motion ($500\text{--}1000 \text{ kg m}^{-1}\text{s}^{-1}$; 40-50 cm/s) compared to NRSC2Z1 within the urban and surroundings. The changes are mainly due to the differential transports of heat, and moisture in the LSMs.

We have computed the correlations and error metrics (mean bias, mean absolute error, and root mean square error) between the station rainfall, GPM-IMERGE rainfall and model rainfall for 00-23 UTC 01 December 2015 over Chennai (box region shown in Fig.1) from all the sensitivity

experiments (Table 6). Our analysis shows that the correlations improved from USGS (0.4) to the NRSC2 updated land cover (0.61) and further to NRSC2Z1 (0.67) and the errors in simulated rainfall decreased with increased roughness factor.. Also the error statistics for the surface meteorological parameters (wind speed, temperature and humidity) is improved in experiments with a higher roughness factor.

3.4 Physical and Dynamical processes

3.4.1 Thermodynamical processes

To examine the underlying physical mechanisms for the precipitation enhancement and its localization with increased urbanization, we analyzed the time average spatial changes in surface air temperature (T), sensible heat flux (SHF), latent heat flux (LHF), surface relative humidity (RH), planetary boundary layer height (PBLH), CAPE and wind speed averaged over Chennai region in the dry period for 0400-1200 UTC 30 November 2015 (Fig. 7) before the heavy rainfall event and during the event for 0900-1500 UTC 01 December 2015 (Fig.8) for the simulations USGS and NRSC2Z1. The comparison between USGS and NRSC2Z1 for the dry or clear sky dry condition (0400-1200 UTC) on 30 November 2015 shows clear enhancements in the mean values of T ($\Delta T \sim 1.0$ K), SHF ($\Delta SHF \sim 50-100$ W m⁻²), reduction in LHF ($\Delta LHF \sim 100-150$ W m⁻²), R ($\Delta RH \sim 10\%$), increase in PBLH ($\Delta PBLH \sim 200-400$ m) and reduction in CAPE ($\Delta CAPE \sim 400-600$ J/kg). This indicates that the enhanced urban area increased the mean air temperature by 1.0 K and heat flux by 100 Wm⁻² through urban boundary layer processes such as trapping of shortwave radiation and enhancing the longwave emission etc. The increased PBL height is due to the increase of heat flux and stronger vertical mixing due to the increased urbanization.

The time series of area average surface parameters over Chennai area (Fig.9) clearly suggest that the simulations with higher degrees of urbanization produce relatively larger (smaller) sensible

heat flux (latent heat flux) in NRSC2 (~45%) and NRSC1 (~25%) relative to USGS. Consequently, the simulated PBL height is enhanced by 50% in NRSC2Z1, 40% in NRSC2 and 25% in NRSC1 over USGS indicating the formation of deeper boundary layers with increased urbanization and their further growth with increased roughness. The higher heat fluxes in NRSC2Z1, NRSC2 and NRSC1 led to higher surface air temperatures and lead to stronger turbulent mixing of heat, moisture and momentum, over urbanized portions relative to USGS. Although the widespread urbanization increased the surface air temperature and sensible heat flux, it greatly reduced the latent heat flux and relative humidity due to decrease of evaporation and evapotranspiration (not shown) over the urban areas. The well mixing of this reduced latent heat flux in a deeper PBL led to a reduction in the CAPE over large parts of the urban area (Fig. 7f) which is corroborating with the studies by Guo et al. (2006), Zhang et al. (2009) and Wang et al. (2018). These lower CAPE levels in extensive urbanization scenario as seen during the dry weather condition, seem to be not conducive for rainfall under weak synoptic forcing. Further, the Convective Inhibition (CIN) values also (Fig. 9g) are high in increased urbanization simulations. These results of higher heat fluxes, temperatures, deep PBL, lower humidity and CAPE for the dry phase on 30 November for the Chennai urban region corroborate with the findings from Rath et al. (2019) and indicate that the local urban effects dominated during the dry phases. An interesting result is that the mean surface winds are reduced by 1 to 2 m/s over Chennai (Fig.7g; Fig.10c) in NRSCZ1 over USGS due to increased urbanization as well as increased roughness.

Although similar trends as that of pre-storm dry condition are found in most of the parameters except CAPE, which is more for the heavy rainfall event 0900-1500 UTC (Fig. 8), the changes are less during the wet phase. In contrast to the pre-storm condition, a considerable increase in the PBL height and CAPE are noticed during the wet phase (Fig. 8). This clearly indicates that the development of deep boundary layer and sharp increase in CAPE during the rainfall event is not

419 purely by the local urban PBL thermo-dynamical processes. The time series of area average
 420 temperature, RH, SHF, LHF, PBLH, CAPE and CIN (Fig. 9) during the wet phase are consistent
 421 with the spatial differences found in Figure 8. However, they show diffused trends during
 422 intermittent rainfall spells possibly by transition of boundary layer stability to neutral and stable
 423 states under cloudy atmospheric condition. One of the important results is that there is a progressive
 424 increase in the frictional surface drag (Fig. 10a) resulting in the sharp changes in momentum
 425 transport (Fig. 10b) leading to the retardation of surface wind speed (Fig. 10c), increase in the
 426 shallow layer (1000-850 hPa) shear (Fig. 10d) and an increase of turbulent kinetic energy (TKE)
 427 (Fig. 10e) in the simulations with increased urbanization and roughness factor. A large variation in
 428 the surface drag, momentum flux and wind speed over the urban area is evident among different
 429 simulations with NRSC2Z2 (land cover in 2015 with $Z_o = 2.0$ m) producing the highest drag and
 430 momentum flux and lowest wind speed followed by NRSC2Z1, NRSC2, NRSC1 and USGS. The
 431 surface drag is increased by 80%, 40%, 20% in NRSC2Z1, NRSC2, and NRSC1 respectively over
 432 USGS indicating higher increments of drag with increased roughness compared to increased urban
 433 extent. The momentum flux has correspondingly increased and wind speed decreased by 70%, 35%
 434 and 25% in NRSC2Z1, NRSC2 and NRSC1 over USGS (Figs.10b-c). It may be noted that the
 435 changes in wind speed by surface drag force also influenced the position and orientation of the
 436 trough, the vorticity and circulation patterns (Figs. 4 and 5) in simulations with different extents of
 437 urbanization. The urban-induced shear has enhanced the shear vorticity, thus increasing the total
 438 relative vorticity in NRSC2Z1, NRSC2, NRSC1 relative to USGS.

439 As seen from Figure 10e the TKE significantly increased during the heavy rainfall event compared
 440 to the dry-phase and is associated with large shear (Fig. 10d) and convection (Fig. 10 f). The
 441 stronger surface drag led to stronger frictional convergence of the moist air in the lower atmosphere
 442 (Fig. 6) to increase vertical velocities (Fig. 10f) and decrease of CIN (Fig. 9g) ultimately leading to

buildup of stronger CAPE (Fig. 9f) in the simulations with extensive urbanization and drag (Craig and Bornstein, 2002; Lin et al., 2008; Shem and Shepherd, 2009). The CAPE and vertical winds produced by NRSC2Z1, NRSC2, NRSC1 are about 40%, 50%; 30%, 40%; and 20%, 25% higher respectively than that by USGS. These increments in CAPE and vertical motion are due to the urban-induced drag effect resulting increase of convergence along the trough.

LSMs compute the fluxes of heat and moisture at the ground surface using the incoming solar radiation flux, and these fluxes act as the lower boundary conditions for PBL schemes. The changes in the calculation of the energy distribution among the FL, NL and NMP resulted in significant difference in the simulated surface fluxes and surface variables (Figs. 9 and 10). The NRSC2Z1-FL produced warmer temperatures and deeper PBL consistent with higher sensible heat and lower latent heat flux (Fig. 9 c) compared to both NRSC2Z1 and NRSC2Z1-NMP. This may be due to lack of explicit computation of vegetation and hydrological effects (Fig. 9b) and neglecting ground heat flux in surface energy balance in FL (Dudhia et al., 1996) unlike NL (Ek et al., 2003) and NMP (Niu et al., 2011) which calculate time-dependent soil moisture using a multi-layer moisture diffusivity equation and also predict the canopy moisture. The FL model also produced a more humid boundary layer during daytime (Fig. 9e) consistent with the increased latent heat flux relative to NL and NMP. The lower sensible and latent heat fluxes in the case of NMP relative to NL (Figs. S3 and S4) are possibly due to simulating higher ground heat flux because of separation of vegetation canopy from soil surface (Niu et al., 2011). But some variations are noticed during the rainfall event where both NL and NMP produced higher humidity over the FL which is possibly due to the precipitation feed-back in these schemes. The moist and unstable boundary layer would enhance the convergence and convection thereby producing higher amount of rainfall over the city and downwind areas for NL and NMP. The NL and NMP LSMs include the vegetation and hydrological processes which are not parameterized in FL. The NRSC2Z1-NMP under cloudy

atmospheric condition (Figs. 15g, 12g) produced a further decrease in the sensible heat flux, temperature and wind speed and increased the humidity (Figs. S3 and S4) relative to NRSC2Z1. In addition, it also produced a higher drag (~53%) and momentum flux (~28%), shallow layer shear and TKE (~75%) relative to NL (NRSC2Z1) (Fig. 10) thus enhancing the frictional convergence and vertical motion leading to further increase in rainfall.

Laux et al. (2016) suggest that single realizations (simulations) with regional climate models (RCM) are not sufficient to infer the model sensitivity with respect to LULC and other surface parameters especially in the case of rainfall. A set of simulations are conducted to check whether the obtained model responses/ signals with LULC, roughness parameter and land surface schemes in this study are merely a result of model internal variability or due to physical response to the forcings. We have conducted four sets of ensemble WRF simulations consisting of 10 ensemble members for each sensitivity experiment in terms of land cover, aerodynamic roughness length and land surface models by perturbing the initial conditions. The ensembles for each sensitivity test are generated by perturbing the background of the control run for the same initial time (00 UTC 30 Nov 2015) by introducing a Gaussian random noise using a random perturbation method available in the WRF Variational Data Assimilation System (WRFDA). The ensembles are generated for experiments with two land cover data (USGS, NRSC2015), roughness parameter (NRSC 2015 land cover with updated roughness $Z_0=1.08$ m) and land-surface model (NRSC 2015 land cover with updated roughness $Z_0=1.08$ m and NMP). Figures S5 to S9 show the time series of spread / range of area average parameters rainfall, T2, SHF, LHF, drag coefficient, momentum flux, TKE, 10 m wind speed, vertical velocity, shallow layer shear, CAPE and PBLH for ensembles of USGS, NRSC2, NRSC2Z1 and NRSC2Z1-NMP experiments. The ensemble members for each sensitivity test show a large spread but follow similar temporal variations as in control simulations (Figures 9 and 10). The ensembles have larger spread for rainfall (Table 7), momentum flux, TKE, w and

CAPE compared to T2, SHF, LHF (Table 7) and drag coefficient. Similar features are noticed in the ensemble mean estimates of different sensitivity experiments for simulated rainfall when compared to TRMM observations. These results suggest that the model responses are due to actual physical forcings rather than the internal variability. Moreover, the close trends of ensemble mean rainfall in the case of NRSC2Z1 with observations clearly indicate the impact of updated land cover and increased roughness ($Z_0=1.08$ m) on the rainfall. These ensemble results provide additional confidence in our findings of urban effects on the simulated rainfall.

We further studied the time-height variation of the changes (NRSC2Z1-USGS) in atmospheric profiles of various variables averaged over Chennai region (Fig. 11). In general, it is found that extensive urbanization increased the lower atmospheric temperature and reduced the water vapor mixing ratio (WVMR) during the dry phase before the rainfall event (0000 UTC-0500 UTC) but reduced the temperature and increased the WVMR during the cloudy condition (06UTC-10UTC; 18UTC-00UTC) and increased the air temperature and also increased the WVMR during the peak precipitation phase (11UTC-16UTC). This anomalous behavior during the wet spells could be due to stronger moisture convergence and its vertical transport in NRSC2Z1. We also found significant changes in equivalent potential temperature (θ_e) and vertical velocity (w) on 01 December suggesting gradual enhancement of θ_e with height by increased roughness from 0600 UTC peaking to very high values between 1200 and 1500 UTC and gradually decreasing after 1800 UTC (Fig. 11d). This indicates development of strong instability associated with strong vertical motions between 1200-1500 UTC during the heavy rainfall. Further, we see that there is an enhancement (reduction) in the rainwater mixing ratios and cloud fractions during the wet spells (dry spells) in NRSC2Z1 relative to USGS (Fig. 11g). The low values of cloud fraction, WVMR and vertical motion during the dry phase 0000-0600 UTC indicates the increased urban land actually reduced the surface evaporation and its conversion to clouds. The increased WVMR and enhanced

cloud formation subsequent to 0600 UTC is associated with increased convergence, instability and vertical motions in the trough region. The NRSC2Z2 produced further increase in the WVMR with slight cooling, vertical motion and cloud fraction over NRSC2Z1 which is due to the increase in convergence, shear turbulence by enhanced drag, and consequent stronger mixing of heat and moisture in the PBL (Figs. 11b,eand h).

In the LSM sensitivity experiments, the NMP produced a decrease in the WVMR along with cooling (-2.0 to -0.4 C) and formation of stable layers in the lower levels but an increase above 850 hPa with slight warming (unstable layers) over NL (Fig. 11c). But it produced increased rain water mixing ratio and cloud fractions upto 3-4 km during the rainfall event which is due to enhanced vertical motion caused by the increase of convergence by increased roughness and its influence on the momentum transport (Figs. 11e,h). The area averaged vertical profiles of hydrometeor mixing ratios shows (Fig. 12) that the NRSC2Z1-NMP produced the highest amounts of various hydrometeors except Qcloud, followed by NRSC2, NRSC2Z1, NRSC2Z1-FL, NRSC1, NRSC2Z2 and USGS indicating impacts of LSMs, roughness factor as well as LULC changes on the cloud processes. Increased urbanization has significantly increased the Qrain and Qcloud concentrations (~50%) but the increased roughness seems to have a negative impact on these two parameters. The roughness has a positive impact on Qsnow which is mainly responsible for producing sustained rainfall. The increased roughness in NRSC2Z2, NRSC2Z1-NMP, NRSCZ1 enhanced the concentrations of Qsnow in the layer 500-200 hPa suggesting deeper convective storm compared to USGS and NRSC2. The impacts are large for NRSC-2015 land cover (NRSC2), roughness factor $Z_0=1.08$ m (NRSC2Z1), and NMP (NRSC2Z1-NMP). The cloud reflectivity profiles indicate (Fig. 12g) that NRSC2Z1-NMP simulated the maximum rainfall followed by NRSC2Z1 and NRSC2Z1-FL. Comparison of simulated maximum reflectivity (dBz) with that of DWR from IMD Chennai clearly suggests that the simulations with increased roughness factor and updated LSM (NRSC-

2015) provide better agreement with the spatial and vertical distribution of the DWR reflectivity (Fig. S10).

3.4.2 Dynamical processes

The convergence associated with the trough and instability is analyzed to assess the extent of simulated changes with the changes in urbanization, roughness and LSMs. Figure 13 shows the vertical section of circulation vectors, potential temperature (black contour - K), WVMR (blue contour - g/kg) and vertical motion (shaded - cm/s) in W-E direction across the coast at 13.0°N for 12 UTC 01 Dec 2015. This indicates development of convergence at the coast below 2 km leading to vertical motion and buildup of instability and moisture along the trough region (longitude 79.816°E - 80.314°E) in all the simulations. The relatively weak surface winds indicate retardation due to the changes in urban aerodynamic roughness. Large differences in convergence and vertical motion are seen among different simulations. Experiments with increased urban area and enhanced roughness (NRSC2, NRSC2Z1, NRSC2Z2, NRSC2Z1-FL and NRSC2Z1-NMP) showed increased convergence, humidity and vertical motion among all simulations.

To examine the changes in thermodynamics and dynamics before and during the rainfall event, we analyze the vertical profiles of the equivalent potential temperature and vertical velocity at 0800 UTC in the dry phase before the heavy rainfall event and 1200 UTC during the event. As shown in figure 14 we find steep lapse rates in theta-e in the lower atmosphere (below 500 hPa), a mixed layer upto 700 hPa and slightly stable atmosphere above 600 hPa before the event. Compared to USGS, the experiments NRSC2Z1-NMP, NRSC2Z1, NRSC2 produce relatively more unstable conditions and theta-e changes (~13 K) from 1000 hPa to 700 hPa. NRSC2Z1 followed by NRSC2, NRSC1 and NRSC2-NMP produced larger theta-e values. We find that the vertical variation of

theta-e during the rainfall event is less (7 K) but extends to higher layers (400 hPa) indicating relatively less instability compared to the dry phase though the same vertical changes are maintained among different simulations. While the vertical motion is nearly the same and very small (0.05 m/s) during the dry phase, it considerably increased during the rainfall event with NRSC2Z2 producing the strongest updrafts followed by NRSC2Z1-NMP, NRSC2Z1-FL, NRSC2Z1, NRSC2, NRSC1 and USGS. These average urban results for different simulations are consistent with the features found from cross-sectional fields (Figs.11 and 13) suggesting that the deep convection was initiated by lower to mid-tropospheric convergence along the trough and urbanization increased this convergence due to increased surface drag. The larger aerodynamic roughness length associated with the extensive urbanization causes an enhancement of frictional convergence of flow to the low pressure through retardation of winds, reduction of Coriolis force and consequently the dominance of pressure gradient force in the boundary layer. The enhanced frictional convergence of moist air in the boundary layer under extensive urbanization supplies more moisture and latent heat to the system by rising air which would enhance the formation of clouds, rain and ultimately leads to diabatic heating which further strengthens the system through a positive feed-back. In the absence of this dynamical convergence, the thermo-dynamical factors such as local evaporation, increased sensible heat fluxes, temperature and deep dry PBL cannot lead to higher CAPE as seen in the dry phase. Thus, the above analysis indicates that the surface drag effect due to extensive urbanization and related aerodynamic roughness is the key factor leading to strong shear, low-level convergence, increased vorticity, convection and higher CAPE leading to higher rainfall as well as its localization in and around the city.

4. Conclusions

The present study examines the role of urbanization and aerodynamic roughness in modulating the heavy precipitation event occurred on 01 December 2015 in the coastal city of Chennai, Tamilnadu,

India by conducting numerical simulations with WRF. A series of experiments are conducted with WRF using different LULC data sets (USGS-1992, NRSC-2004, NRSC-2015) representing different degrees of urbanization in the period 1992-2015, aerodynamic roughness factors, and the land surface models to test the sensitivity of simulated rainfall to these factors.

Our results indicate that the urban area has increased by 17-23% in 2004-2015 and croplands and forests are substantially decreased compared to 1992. The simulations of USGS to NRSC2 indicate a progressive increase of simulated rainfall over the southwest of Chennai and its surrounding areas indicating a strong impact of the land cover change on the rainfall amount over the city region. Sensitivity runs with different LULC data suggest the flow dynamics is altered with increased urbanization in terms of strength of inland flow, northward movement of the trough, location of convergence zone, vertical motion and associated cyclonic flow in the simulations. It has been also found that extensive urbanization increased the lower atmospheric temperature and reduced the WVMR during the dry phase before the event (00 UTC-05 UTC) but also increased the water vapour during the peak wet phase indicating different roles of PBL during dry and wet periods. The increased water vapour, air temperature, CAPE and PBL height during the peak rainfall phase are largely due to mechanical effects (increased drag, shear and TKE) which enhanced the convergence and vertical motion although the slightly increased heat flux also enhanced the instability of the atmosphere.

The simulations with different roughness factors indicated that NRSC2Z1 produced a realistic rainfall pattern in terms of the N-S extension of heavy rainfall band. Simulations also showed that increased roughness has led to increase in surface drag and wind retardation which shifted the zone of convergence and vertical motion towards the coast. The simulation with $Z_o = 2.0$ m further enhanced the convergence and vertical motion leading increase of peak rainfall along the coast but it curtailed the east-west spread.

610 The LSM sensitivity experiments revealed that the NRSC2Z1-NMP (NRSC2Z1-FL) reduced
611 (increased) surface temperature, wind speed and sensible heat flux in comparison to the NRSC2Z1
612 due to the variation in the simulated energy fluxes among the three LSMs. This modulation in
613 temperature, energy fluxes and winds along with the drag effect enhanced the low level shear and
614 effectively increased the TKE. These surface alterations modified the synoptic flow system through
615 significant variation in the low level shear, convergence, moisture transport, TKE, and updrafts. The
616 NRSC2Z1-NMP enhanced the convergence, triggered a wide spread rainfall along the coast relative
617 to the NRSC2Z1-FL and NRSC2Z1. Though NRSC2Z1-NMP simulated low values of surface heat
618 flux, temperature and wind speed, it produced higher surface drag, momentum flux and shear that
619 resulted in the prediction of higher rainfall as compared to NRSC2Z1 and NRSC2Z1-FL. This
620 shows the role of dynamical convergence in the simulated rainfall pattern by NRSC2Z1-NMP.

621 The results of the study conclusively indicates that the surface drag effect due to extensive
622 urbanization and related aerodynamic roughness is the key factor leading to strong shear, low-level
623 convergence, increased vorticity, convection and higher CAPE, ultimately producing higher rainfall
624 as well as its localization in and around the city. Thus, the above results demonstrate that the
625 dynamical convergence led by urbanization induced surface drag and shear in the zone of low
626 pressure trough dominated over the thermodynamic factors (local evaporation, sensible heat,
627 temperatures) and controlled the convection during the heavy rainfall event. These results are
628 slightly different to the recent study by Boyaz et al. (2020) which suggested that the increased
629 thermal transport through enhanced surface temperatures, sensible heat fluxes, and deep and moist
630 boundary layers facilitated higher CAPE resulting in heavier rainfall. Though urbanization indicated
631 enhanced temperatures and heat fluxes, their contributions are found to be considerably small during
632 the wet phase and the dominating mechanism for higher CAPE, deep moist PBL and moisture
633 transport is found to be stronger dynamical convergence led by enhanced surface drag and shear.

The results of the sensitivity experiments in this study clearly demonstrate the necessity of a precise representation of surface characteristics (land use and land cover type and aerodynamic roughness) and land-atmospheric interaction (land surface models) in numerical models for the realistic simulation of the physical forcing mechanism to simulate extreme rainfall phenomena over cities. These results will provide a basis for development of a better forecast system for predicting the heavy rainfall events over metropolitan cities.

Acknowledgements

Authors thank Dr. A.K.Bhaduri, Director of IGCAR, for the encouragement and support. The first author is grateful to HBNI for providing the research fellowship and IGCAR DAE for extending facilities to conduct the study. The updated land use/land cover data over the Indian region are obtained from Bhuvan of ISRO-NRSC (https://bhuvan.nrsc.gov.in/bhuvan_links.php). Authors are thankful to Dr. P.V.N.Rao and Mr. Biswadeep, NRSC-Hyderabad for technical discussions on the NICES landuse/land cover data used in the study. Mrs. Deepu Radhakrishnan is acknowledged for the assistance in GIS aided land cover analysis. Doppler Weather Radar reflectivity images and station rainfall data are obtained from the India Meteorological Department. The GPM IMERG precipitation data is obtained from NASA Global precipitation project (<https://gpm.nasa.gov/data/directory>).

References:

- Aithal, B. H., & Ramachandra, T. V. (2016). Visualization of urban growth pattern in Chennai using geoinformatics and spatial metrics. *Journal of the Indian Society of Remote Sensing*, 44(4), 617-633. doi:[10.1007/s12524-015-0482-0](https://doi.org/10.1007/s12524-015-0482-0)
- Anushiya, J., Andimuthu, R., Prasannavenkatesh, R., & Kumar, D. S. (2016). Spatial variation of temperature and indicative of the urban heat island in Chennai Metropolitan Area, India. *Theoretical and applied climatology*, 123(1-2), 83-95. doi:[10.1007/s00704-014-1331-8](https://doi.org/10.1007/s00704-014-1331-8)
- Bagavathsingh, A., Srinivas, C. V., Maran, P. S., Baskaran, R., & Venkatraman, B. (2016). Wind Direction Dependent Vertical Wind Shear and Surface Roughness Parameterization in Two different Coastal Environments. *International Journal of Geology, Agriculture and Environmental Sciences*, 4(3), 1-9.
- Biswadip, G. (2014). *IRS-P6 AWiFS derived gridded land use/land cover data compatible to mesoscale models (MM5 and WRF) over Indian region. NRSC Technical Document. NRSC-ECSA-ACSG-OCT-2014-TR-651.*
- Bornstein, R., & Lin, Q. (2000). Urban heat islands and summertime convective thunderstorms in Atlanta: Three case studies. *Atmospheric Environment*, 34(3), 507-516. doi:[10.1016/S1352-2310\(99\)00374-X](https://doi.org/10.1016/S1352-2310(99)00374-X)
- Boyaj, A., Dasari, H. P., Hoteit, I., & Ashok, K. (2020). Increasing heavy rainfall events in South India due to changing land use land cover. *Quarterly Journal of the Royal Meteorological Society*. 1-22. <https://doi.org/10.1002/qj.3826>
- Cao, R., Li, F., & Feng, P. (2020). Impact of Urbanization on Precipitation in North Haihe Basin, China. *Atmosphere*, 11(1), 16. doi:[10.3390/atmos11010016](https://doi.org/10.3390/atmos11010016)
- Chakraborty, T., Sarangi, C., & Tripathi, S. N. (2017). Understanding diurnality and inter-seasonality of a sub-tropical urban heat island. *Boundary-Layer Meteorology*, 163(2), 287-309. doi:[10.1007/s10546-016-0223-0](https://doi.org/10.1007/s10546-016-0223-0)
- Chang, H. I., Kumar, A., Niyogi, D., Mohanty, U. C., Chen, F., & Dudhia, J. (2009). The role of land surface processes on the mesoscale simulation of the July 26, 2005 heavy rain event over Mumbai, India. *Global and Planetary Change*, 67(1-2), 87-103. doi:[10.1016/j.gloplacha.2008.12.005](https://doi.org/10.1016/j.gloplacha.2008.12.005)
- Clough, S. A., Shephard, M. W., Mlawer, E. J., Delamere, J. S., Iacono, M. J., Cady-Pereira, K., et al. (2005). Atmospheric radiative transfer modeling: a summary of the AER codes. *Journal of Quantitative Spectroscopy and Radiative Transfer*, 91(2), 233-244. doi:[10.1016/j.jqsrt.2004.05.058](https://doi.org/10.1016/j.jqsrt.2004.05.058)
- Craig, K.J.(2002). MM5 simulations of urban induced convective precipitation over Atlanta, GA" (2002).Master's Theses.2266.

690 Craig, K. J., & Bornstein, R. D. (2002) MM5 simulation of urban induced convective precipitation
691 over Atlanta. Preprints, Fourth Symp. on the Urban Environment, Norfolk, VA, Amer. Meteor. Soc.,
692 5–6.

693 Devadas, M. D., & Rose, A. L. (2009). Urban factors and the intensity of heat island in the city of
694 Chennai. paper presented at *The seventh international conference on urban climate* (Vol. 29).
695 Yokohama, Japan

696 Dudhia, J. (1996). A multilayer soil temperature model for MM5 . Preprints, Sixth PSU/NCAR
697 Mesoscale Model Users' Workshop, Boulder, CO, PSU/NCAR, 49–50.
698 <http://www.mmm.ucar.edu/mm5/mm5v2/whatisnewinv2.html>

699 Ek, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grunmann, P., Koren, V., et al. (2003).
700 Implementation of Noah land surface model advances in the National Centers for Environmental
701 Prediction operational mesoscale Eta model. *Journal of Geophysical Research: Atmospheres*,
702 *108*(D22), 8851. doi:10.1029/2002JD003296.

703 Fang, C., & Sill, B.L. (1992). Aerodynamic Roughness Length: Correlation with Roughness
704 Elements. *Journal of Wind Engineering and Industrial Aerodynamics*. 41-44, 449-460.

705 Grimmond, C. S. B., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from
706 analysis of surface form. *Journal of applied meteorology*, *38*(9), 1262-1292.
707 doi:10.1175/1520-0450(1999)038<1262:APOUAD>2.0.CO;2

708 Guo, X., Fu, D., & Wang, J. (2006). Mesoscale convective precipitation system modified by
709 urbanization in Beijing City. *Atmospheric Research*, *82*(1-2), 112-126.
710 doi:10.1016/j.atmosres.2005.12.007

711 Han, J. Y., Baik, J. J., & Lee, H. (2014). Urban impacts on precipitation. *Asia-Pacific Journal of*
712 *Atmospheric Sciences*, *50*(1), 17-30. doi:10.1007/s13143-014-0016-7

713 Huffman, G., Bolvin, D., Braithwaite, D., Hsu, K., Joyce, R., & Xie, P. (2014). Integrated multi-
714 satellite retrievals for GPM (IMERG), version 4.4. NASA's Precipitation Processing Center.
715 <ftp://arthurhou.pps.eosdis.nasa.gov/gpmdata/>

716 IMD, (2015). Climate Diagnostics Bulletin of India. Dec 2015, Near Real-Time analysis. India,
717 National Climate Centre, Pune, Meteorological Department, Ministry of Earth Sciences,
718 Government of India. 23

719 Jancewicz, K., & Szymanowski, M. (2017). The relevance of surface roughness data qualities in
720 diagnostic modeling of wind velocity in complex terrain: a case study from the S'nieznik Massif
721 (SW Poland). *Pure and Applied Geophysics*. doi:10.1007/s00024-016-1297-9.

722 Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate. *Nature*,
723 *423*(6939), 528-531. doi:10.1038/nature01675.

724 Kishtawal, C. M., Niyogi, D., Tewari, M., Pielke Sr, R. A., & Shepherd, J. M. (2010). Urbanization
725 signature in the observed heavy rainfall climatology over India. *International journal of*
726 *climatology*, *30*(13), 1908-1916. doi:10.1002/joc.2044

727 Kumar, A., Dudhia, J., Rotunno, R., Niyogi, D., & Mohanty, U. C. (2008). Analysis of the 26 July
 728 2005 heavy rain event over Mumbai, India using the Weather Research and Forecasting (WRF)
 729 model. *Quarterly Journal of the Royal Meteorological Society*, 134(636), 1897-1910.
 730 [doi:10.1002/qj.325](https://doi.org/10.1002/qj.325)

731 Laux, P., Nguyen, P. N., Cullmann, J., Van, T. P., & Kunstmann, H. (2017). How many RCM
 732 ensemble members provide confidence in the impact of land-use land cover change?. *International*
 733 *Journal of Climatology*, 37(4), 2080-2100. [doi: 10.1002/joc.4836](https://doi.org/10.1002/joc.4836)
 734

735 Lei, M., Niyogi, D., Kishtawal, C., Pielke, R. A., Beltrán-Przekurat, A., Nobis, T. E., & Vaidya, S.
 736 S. (2008). Effect of explicit urban land surface representation on the simulation of the 26 July 2005
 737 heavy rain event over Mumbai, India. *Atmospheric Chemistry and Physics Discussions*, European
 738 Geosciences Union, 8(3), 8773– 8816. <https://hal.archives-ouvertes.fr/hal-00304159>

739 Li, L., Shaomin, L., Ziwei, X.U., Kun, Y., Xuhui, C., Li, J., & Jiemin, W. (2009). The
 740 Characteristics and Parameterization of Aerodynamic Roughness Length over Heterogeneous
 741 Surfaces. *Advances in Atmospheric Sciences*, 26(1), 180-190.

742 Li, J., Yu, R., & Wang, J. (2008). Diurnal variations of summer precipitation in Beijing. *Chinese*
 743 *Science Bulletin*, 53(12), 1933-1936. [doi:10.1007/s11434-008-0195-7](https://doi.org/10.1007/s11434-008-0195-7)

744 Lin, C. Y., Chen, W. C., Liu, S. C., Liou, Y. A., Liu, G. R., & Lin, T. H. (2008). Numerical study of
 745 the impact of urbanization on the precipitation over Taiwan. *Atmospheric Environment*, 42(13),
 746 2934-2947. doi.org/10.1016/j.atmosenv.2007.12.054

747 Liu, C., Dudhia, J., & Moncrieff, M. W. (2010). Comparison of two land surface schemes in week-
 748 long cloud-system-resolving simulations of warm season precipitation. *Meteorology and*
 749 *Atmospheric Physics*, 107(1-2), 9-15. [doi:10.1007/s00703-010-0064-1](https://doi.org/10.1007/s00703-010-0064-1)

750 Luong, T.M., Dasari, H., Hoteit, I. 2020. Impact of Urbanization on the Simulation of Extreme
 751 Rainfall in the City of Jeddah, Saudi Arabia. *J. Appl. Meteor. Climatol.* 59 (5), [doi:10.1175/JAMC-](https://doi.org/10.1175/JAMC-D-19-0257.1)
 752 [D-19-0257.1](https://doi.org/10.1175/JAMC-D-19-0257.1)

753 Maslin, M. (2008). *Global warming: a very short introduction*. Oxford University Press, Oxford,
 754 New York.

755 Mathan, M., & Krishnaveni, M. (2020). Monitoring spatio-temporal dynamics of urban and peri-
 756 urban land transitions using ensemble of remote sensing spectral indices-A case study of Chennai
 757 Metropolitan Area, India. *Environmental Monitoring and Assessment*, 192(1),
 758 15. [doi:10.1007/s10661-019-7986-y](https://doi.org/10.1007/s10661-019-7986-y)

759 Miao, S., Chen, F., Li, Q., & Fan, S. (2011). Impacts of urban processes and urbanization on
 760 summer precipitation: A case study of heavy rainfall in Beijing on 1 August 2006. *Journal of*
 761 *Applied Meteorology and Climatology*, 50(4), 806-825. [doi:10.1175/2010JAMC2513.1](https://doi.org/10.1175/2010JAMC2513.1)

762 Mishra, A. K. (2016). Monitoring Tamil Nadu flood of 2015 using satellite remote sensing. *Natural*
 763 *Hazards*, 82(2), 1431-1434. [doi:10.1007/s11069-016-2249-5](https://doi.org/10.1007/s11069-016-2249-5)

764 Mohan, M., & Kandya, A. (2015). Impact of urbanization and land-use/land-cover change on
765 diurnal temperature range: A case study of tropical urban airshed of India using remote sensing data.
766 *Science of the Total Environment*, 506, 453-465.[doi:10.1016/j.scitotenv.2014.11.006](https://doi.org/10.1016/j.scitotenv.2014.11.006)

767 Mölders, N., & Olson, M. A. (2004). Impact of urban effects on precipitation in high latitudes.
768 *Journal of Hydrometeorology*, 5(3), 409-429. [doi:10.1175/1525-
769 7541\(2004\)005<0409:IOUEOP>2.0.CO;2](https://doi.org/10.1175/1525-7541(2004)005<0409:IOUEOP>2.0.CO;2)

770 Nakanishi, M., & Niino, H. (2004). An improved Mellor–Yamada level-3 model with condensation
771 physics: Its design and verification. *Boundary-layer meteorology*, 112(1), 1-
772 31.[doi:10.1023/B:BOUN.0000020164.04146.98](https://doi.org/10.1023/B:BOUN.0000020164.04146.98)

773 Narasimhan, B., Bhallamudi, S. M., Mondal, A., Ghosh, S., & Mujumdar, P. (2016). Chennai floods
774 2015: A Rapid Assessment. Interdisciplinary Centre for Water Research Indian Institute of Science,
775 Bangalore, Retrieved from [http://itra.medialabasia.in/img/ Chennai%20Floods-Rapid%
776 20Assessment%, May, 2023, 202016](http://itra.medialabasia.in/img/Chennai%20Floods-Rapid%20Assessment%20May,2023,202016).(accessed on 20 May 2017)

777 Niu, G. Y., Yang, Z. L., Mitchell, K. E., Chen, F., Ek, M. B., Barlage, M., et al. (2011). The
778 community Noah land surface model with multi-parameterization options (Noah-MP): 1. Model
779 description and evaluation with local-scale measurements. *Journal of Geophysical Research:*
780 *Atmospheres*, 116(D12). [doi:10.1029/2010JD015139](https://doi.org/10.1029/2010JD015139)

781 Niyogi, D., Holt, T., Zhong, S., Pyle, P. C., & Basara, J. (2006). Urban and land surface effects on
782 the 30 July 2003 mesoscale convective system event observed in the southern Great Plains. *Journal*
783 *of Geophysical Research: Atmospheres*, 111(D19). [doi:10.1029/2005JD006746](https://doi.org/10.1029/2005JD006746)

784 Niyogi, D., Pyle, P., Lei, M., Arya, S. P., Kishtawal, C. M., Shepherd, M., et al. (2011). Urban
785 modification of thunderstorms: An observational storm climatology and model case study for the
786 Indianapolis urban region. *Journal of Applied Meteorology and Climatology*, 50(5), 1129-
787 1144.[doi:10.1175/2010JAMC1836.1](https://doi.org/10.1175/2010JAMC1836.1)

788 Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal*
789 *Meteorological Society*, 108(455), 1-24.

790 Oldenborgh, G. J., Otto, F. E., Haustein, K., & AchutaRao, K. (2016). The heavy precipitation event
791 of December 2015 in Chennai, India. *Bulletin of the American Meteorological Society*, 97(12), S87-
792 S91.[doi:10.1175/BAMS-D-16-0129.1](https://doi.org/10.1175/BAMS-D-16-0129.1), 2016.

793 Paul, S., Ghosh, S., Mathew, M., Devanand, A., Karmakar, S., & Niyogi, D. (2018). Increased
794 spatial variability and intensification of extreme monsoon rainfall due to urbanization. *Scientific*
795 *reports*, 8(1), 1-10.[doi:10.1038/s41598-018-22322-9](https://doi.org/10.1038/s41598-018-22322-9)

796 Pielke Sr, R. A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., et al. (2011).
797 Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley*
798 *Interdisciplinary Reviews: Climate Change*, 2(6), 828-850. [doi:10.1002/wcc.144](https://doi.org/10.1002/wcc.144)

799 Rath, S. S., & Panda, J. (2019). A Study of Near-Surface Boundary Layer Characteristics During the
800 2015 Chennai Flood in the Context of Urban-Induced Land Use Changes. *Pure and Applied*
801 *Geophysics*, 176(6), 2607-2629.[doi:10.1007/s00024-018-2069-5](https://doi.org/10.1007/s00024-018-2069-5)

802 Sahany, S., Venugopal, V., & Nanjundiah, R. S. (2010). The 26 July 2005 heavy rainfall event over
803 Mumbai: numerical modeling aspects. *Meteorology and atmospheric physics*, 109(3-4), 115-
804 128.[doi:10.1007/s00703-010-0099-3](https://doi.org/10.1007/s00703-010-0099-3)

805 Sarangi, C., Tripathi, S. N., Qian, Y., Kumar, S., & Ruby Leung, L. (2018). Aerosol and urban land
806 use effect on rainfall around cities in Indo-Gangetic Basin from observations and cloud resolving
807 model simulations. *Journal of Geophysical Research: Atmospheres*, 123(7), 3645-3667.
808 [doi:10.1002/2017JD028004](https://doi.org/10.1002/2017JD028004)

809 Sertel, E., Robock, A., & Ormeci, C. (2010). Impacts of land cover data quality on regional climate
810 simulations. *International Journal of Climatology*, 30(13), 1942-1953. [doi:10.1002/joc.2036](https://doi.org/10.1002/joc.2036)

811 Shem, W., & Shepherd, M. (2009). On the impact of urbanization on summertime thunderstorms in
812 Atlanta: Two numerical model case studies. *Atmospheric Research*, 92(2), 172-
813 189.[doi:10.1016/j.atmosres.2008.09.013](https://doi.org/10.1016/j.atmosres.2008.09.013)

814 Shepherd, J. M. (2005). A review of current investigations of urban-induced rainfall and
815 recommendations for the future. *Earth Interactions*, 9(12), 1-27. [doi:10.1175/EI156.1](https://doi.org/10.1175/EI156.1)

816 Shepherd, J. M., Carter, M., Manyin, M., Messen, D., & Burian, S. (2010). The impact of
817 urbanization on current and future coastal precipitation: a case study for Houston. *Environment and*
818 *planning B: Planning and Design*, 37(2), 284-304. [doi:10.1068/b34102t](https://doi.org/10.1068/b34102t)

819 Shepherd, J. M., Pierce, H., & Negri, A. J. (2002). Rainfall modification by major urban areas:
820 Observations from spaceborne rain radar on the TRMM satellite. *Journal of applied meteorology*,
821 41(7), 689-701. [doi:10.1175/1520-0450\(2002\)041<0689:RMBM UA >2.0.CO;2](https://doi.org/10.1175/1520-0450(2002)041<0689:RMBM UA >2.0.CO;2)

822 Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Duda, M. G., et al. (2008).
823 A description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN-
824 475+STR.

825 Srinivas, C. V., Yesubabu, V., Prasad, D. H., Prasad, K. H., Greeshma, M. M., Baskaran, R., &
826 Venkatraman, B. (2018). Simulation of an extreme heavy rainfall event over Chennai, India using
827 WRF: sensitivity to grid resolution and boundary layer physics. *Atmospheric Research*, 210, 66-82.
828 [doi:10.1016/j.atmosres.2018.04.014](https://doi.org/10.1016/j.atmosres.2018.04.014)

829 Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M., et al. (2004). Implementation and
830 verification of the unified NOAA land surface model in the WRF model (Formerly Paper Number
831 17.5). In *Proceedings of the 20th Conference on Weather Analysis and Forecasting/16th Conference*
832 *on Numerical Weather Prediction, Seattle, WA, USA*. (pp. 11-15).

833 Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit forecasts of winter
834 precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow
835 parameterization. *Monthly Weather Review*, 136(12), 5095-5115.[doi:10.1175/2008MWR2387.1](https://doi.org/10.1175/2008MWR2387.1)

836 Tropical Rainfall Measuring Mission (TRMM) (2011), TRMM (TMPA) Rainfall Estimate L3 3
837 hour 0.25 degree x 0.25 degree V7, Greenbelt, MD, Goddard Earth Sciences Data and Information
838 Services Center (GES DISC), Accessed: [15 January 2020], [doi:10.5067/TRMM/TMPA/3H/7](https://doi.org/10.5067/TRMM/TMPA/3H/7)

- Wang, J., Feng, J., & Yan, Z. (2015). Potential sensitivity of warm season precipitation to urbanization extents: Modeling study in Beijing-Tianjin-Hebei urban agglomeration in China. *Journal of Geophysical Research: Atmospheres*, 120(18), 9408-9425. doi:10.1002/2015JD023572
- Wang, J., Feng, J., & Yan, Z. (2018). Impact of extensive urbanization on summertime rainfall in the Beijing region and the role of local precipitation recycling. *Journal of Geophysical Research: Atmospheres*, 123(7), 3323-3340. doi:10.1002/2017JD027725
- Wang, J., Feng, J., Yan, Z., Hu, Y., & Jia, G. (2012a). Nested high-resolution modeling of the impact of urbanization on regional climate in three vast urban agglomerations in China. *Journal of Geophysical Research: Atmospheres*, 117(D21). doi:10.1029/2012JD018226
- Wang, J., Zhang, R., & Wang, Y. (2012b). Areal differences in diurnal variations in summer precipitation over Beijing metropolitan region. *Theoretical and Applied Climatology*, 110(3), 395-408. doi: 10.1007/s00704-012-0636-8
- Yan, Z. W., Wang, J., Xia, J. J., & Feng, J. M. (2016). Review of recent studies of the climatic effects of urbanization in China. *Advances in Climate Change Research*, 7(3), 154-168. doi:10.1016/j.accre.2016.09.003
- Yang, L., Tian, F., Smith, J. A., & Hu, H. (2014). Urban signatures in the spatial clustering of summer heavy rainfall events over the Beijing metropolitan region. *Journal of Geophysical Research: Atmospheres*, 119(3), 1203-1217. doi:10.1002/2013JD020762
- Zhang, C. L., Chen, F., Miao, S. G., Li, Q. C., Xia, X. A., & Xuan, C. Y. (2009). Impacts of urban expansion and future green planting on summer precipitation in the Beijing metropolitan area. *Journal of Geophysical Research: Atmospheres*, 114, D02116 doi:10.1029/2008JD010328
- Zhang, L., & Zhou, T. (2015). Drought over East Asia: a review. *Journal of Climate*, 28(8), 3375-3399. doi:10.1175/JCLI-D-14-00259.1

872

List of Tables

873 Table 1. Domain and physics used in WRF model

874 Table 2. Summary of different simulations

875 Table 3. List of stations used for comparison of rainfall and surface meteorological parameters

876 Table 4. Area (%) of different land-cover classes of the total area in USGS-1992, NRSC-2004 and
877 NRSC-2015. Blank for zero distribution of the corresponding land cover class.

878 Table 5. Time and area-averaged rainfall (mm/day) and surface parameters from observations and
879 different experiments over the Chennai urban region and its surroundings (79.8 E, 12.65N- 80.3E,
880 13.2 N) on 1 December 2015.

881 Table 6. Error statistics for model simulated rainfall and surface meteorological parameters in
882 different sensitivity experiments over the Chennai urban region and its surroundings (79.8 E,
883 12.65N- 80.3E, 13.2 N) on 1 December 2015.

884 Table 7. Mean and standard deviation of air surface temperature (T2) ($^{\circ}\text{C}$), sensible heat flux (SHF)
885 (Wm^{-2}), latent heat flux (LHF) (Wm^{-2}) and rainfall (mm) for the simulations USGS, NRSC2,
886 NRSC2Z1 and NRSC2Z1-NMP.

887

888

List of Figures

889 Figure 1. Land use and Land cover (LULC) in the model inner domain a) USGS 1992 b) NRSC
890 2004 and c) NRSC 2015.

891 Figure 2. Spatial pattern of 24-h rainfall (mm) on 1 December 2015 over Tamilnadu. The first row
892 shows observed rainfall from a) DWR data b) GPM Imerge c) Raingauge data; the second row
893 shows simulated rainfall in sensitivity experiments with different LULC d) USGS e) NRSC1 f)
894 NRSC2; and the third row from sensitivity experiments with different roughness factor g) NRSC2Z1
895 h) NRSC2Z2 and land surface models i) NRSC2Z1-FL and j)NRSC2Z1-NMP.

896 Figure 3. Time series of Rainfall simulated over a) Chennai b) Chembrapakam c) Hindustan
897 university d) Madhavaram e) Taramani f) Tambaram along with IMD AWS observations.

898 Figure 4. Simulated wind field (ms^{-1}), sea level pressure (hPa, in contours) and relative vorticity
899 ($\times 10^{-5} \text{ s}^{-1}$ shaded) at 12UTC of 01 December 2015 at 925 hPa for the simulations a) USGS b)
900 NRSC1 c) NRSC2 d) NRSC2Z1 e) NRSC2Z2 f) NRSC2Z1-FL and g) NRSC2Z1-NMP .

901 Figure 5. Simulated wind field (ms^{-1}), geopotential (m, in contours) and relative vorticity ($\times 10^{-5} \text{ s}^{-1}$
902 shaded) at 12UTC of 01 December 2015 at 500 hPa for the simulations a) USGS b) NRSC1 c)
903 NRSC2 d)NRSC2Z1 e)NRSC2Z2 f) NRSC2Z1-FL and g) NRSC2Z1-NMP.

904 Figure 6. Spatial difference of time averaged moisture convergence (shaded ; Unit $\text{kg m}^{-1}\text{s}^{-1}$) in the
 905 layer 1000-500 hPa along with vertical motion (contours; cms^{-1}) at 850 hPa during 9-15 UTC 01
 906 December 2015 from simulations a) NRSC1-USGS b) NRSC2-USGS c) NRSC2Z1-NRSC2 d)
 907 NRSC2Z2-NRSC2 e) NRSC2Z1-FL-NRSC2Z1 f) NRSC2Z1-NMP-NRSC2Z1.

908 Figure 7. Changes to various PBL variables due to increased urbanization (NRSC2Z1-USGS): (a)
 909 surface air temperature (K), (b) sensible heat flux (Wm^{-2}), (c) latent heat flux (Wm^{-2}) (d) 2m relative
 910 humidity (%), (e) PBL height (m), and (f) convective available potential energy (CAPE; J/ kg), (g)
 911 surface wind speed (m/s) averaged over 04-12 UTC 30 November 2015 prior to the event.

912 Figure 8. Changes to various PBL variables due to increased urbanization (NRSC2Z1-USGS): (a)
 913 surface air temperature (K), (b) sensible heat flux (Wm^{-2}), (c) latent heat flux (Wm^{-2}) (d) 2m relative
 914 humidity (%), (e) PBL height (m), and (f) convective available potential energy (CAPE; J/ kg) and
 915 (g) surface wind speed (m/s) averaged over 09-15 UTC01 December 2015 during the heavy rainfall
 916 event.

917 Figure 9. Time evolution of area averaged (12.917N 80.035E - 13.167N 80.2995E) (a) surface
 918 Relative Humidity (%) (b) surface air temperature ($^{\circ}\text{C}$) (c) sensible heat flux (W/m^2) (d) latent heat
 919 flux (W/m^2) (e) PBL height (m) (f) CAPE (J/kg) and (g) CIN (J/kg).

920 Figure 10. Time evolution of area averaged (12.917N 80.035E -13.167N 80.2995E) (a) drag
 921 coefficient (b) momentum flux (N/m^2) (c) surface wind speed at 10 m (m/s) (d) shallow layer shear
 922 (m/s) (e) TKE ($\text{m}^2 \text{s}^{-2}$) and (f) vertical velocity (m/s) .

923 Figure 11. Time –height profiles of regional average changes in (a,b,c) air temperature (contour
 924 shade; unit: K) and water vapor mixing ratio (contour; g kg^{-1}), (d,e,f) vertical velocity (shaded; cm
 925 s^{-1}) and equivalent potential temperature (contour; K), and (g,h,i) rain water mixing ratio (shaded; g
 926 kg^{-1}) and cloud fraction (contour; %) due to increased Urbanization over Chennai and its
 927 surroundings. The panels (a,d,g) are for NRSC2Z1-USGS, (b,e,h) are for NRSCZ2-NRSCZ1 and
 928 (c,f,i) are for NRSC2Z1-NMP-NRSC2Z1.

929 Figure 12. Vertical profiles of simulated hydrometeors a) Qvapour b) Qrain c) Qcloud d) Qgraup e)
 930 Qice f) Qsnow and g) maximum reflectivity dBz from different experiments at 12 UTC 1 December
 931 2015. The simulated cloud reflectivity values (g) are compared with Chennai DWR reflectivity.

932 Figure 13. Cross section of vertical velocity (shaded; cms^{-1}), potential temperature (black contour 1
 933 K), water vapor mixing ratio (blue contour g kg^{-1}), and circulation vectors (m s^{-1}) along 12.9698 $^{\circ}\text{N}$
 934 between 79.816-80.314 $^{\circ}\text{E}$ at 1200 UTC 1 December 2015 for all the experiments a) USGS b)
 935 NRSC1 c) NRSC2 d) NRSC2Z1 e)NRSC2Z2 f) NRSC2Z1-FL and g) NRSC2Z1-NMP.

936 Figure 14. Vertical profiles of equivalent potential temperature theta-e (degree K) and vertical
 937 velocity (ms^{-1}) averaged over the urban area (12.917N 80.035E - 13.167N 80.2995E) from
 938 different simulations at a)08 UTC and b) 12 UTC 01 December 2015. Top panels are for theta-e and
 939 bottom panels are for w (ms^{-1}).

940 Figure S1. Simulated wind field (ms⁻¹), geopotential (m, in contours) and relative vorticity (x10⁻⁵ s⁻¹ shaded) at 12UTC of 01 December 2015 at 850 hPa for the simulations a) USGS b) NRSC1 c) NRSC2 d)NRSC2Z1 e)NRSC2Z2 f) NRSC2Z1-FL and g)NRSC2Z1-NMP.

943 Figure S2. Simulated wind field (ms⁻¹), geopotential (m, in contours) and relative vorticity (x10⁻⁵ s⁻¹ shaded) at 12UTC of 01 December 2015 at 700 hPa for the simulations a) USGS b) NRSC1 c) NRSC2 d)NRSC2Z1 e)NRSC2Z2 f) NRSC2Z1-FL and f)NRSC2Z1-NMP.

946 Figure S3. Changes to various PBL variables due to increased urbanization (NRSC2Z1-NMP - NRSC2Z1) (a) surface air temperature (K), (b) sensible heat flux (Wm⁻²), (c) latent heat flux (Wm⁻²) (d) 2m relative humidity (%), (e) PBL height (m), and (f) convective available potential energy (CAPE; J/ kg), (g) ground heat flux (Wm⁻²), (h) surface wind speed (m/s) averaged over 04-12 UTC 30 November 2015 prior to the event.

951 Figure S4. Changes to various PBL variables due to increased urbanization (NRSC2Z1-NMP- NRSC2Z1): (a) surface air temperature (K), (b) sensible heat flux (Wm⁻²), (c) latent heat flux (Wm⁻²) (d) 2m relative humidity (%), (e) PBL height (m), and (f) convective available potential energy (CAPE; J/ kg), (g) ground heat flux (Wm⁻²), (h) surface wind speed (m/s) averaged over 09-15 UTC01 December 2015 during the heavy rainfall event.

956 Figure S5. Time series of area average (Chennai city box area) simulated hourly rainfall for the period 01 - 02 December 2015. Grey area shows 10-member ensemble simulations and red line shows ensemble mean for model configuration with a) USGS land cover, b) NRSC2015 land cover, c) NRSC 2015 land cover with updated roughness Zo=1.08 m and d) NRSC 2015 land cover with updated roughness z0=1.08 m and NMP LSM. Blue dots show observed rainfall.

961 Figure S6. Time series of area average (Chennai city box area) simulated hourly 2m temperature (a-d), sensible heat flux (e-h), latent heat flux (i-l) for the period 30 November - 02 December 2015. Grey shade shows 10-member ensemble simulations, pink line shows ensemble mean for model configurations with (a,e,i) USGS land cover, (b,f,j) NRSC 2015 land cover, (c,g,k) NRSC 2015 land cover with updated roughness Zo=1.08 m and (d, h, l) NRSC 2015 land cover with updated roughness Zo=1.08 m and NMP LSM.

967 Figure S7. Time series of area average (Chennai city box area) simulated hourly drag coefficient (a-d), momentum flux (e-h), TKE (i-l) for the period 30 November - 02 December 2015. Grey shade shows 10-member ensemble simulations, pink line shows ensemble mean for model configurations with (a,e,i) USGS land cover, (b,f,j) NRSC2015 land cover, (c,g,k) NRSC 2015 land cover with updated roughness Zo=1.08 m and (d, h, l) NRSC 2015 land cover with updated roughness Zo=1.08 m and NMP LSM.

973 Figure S8. Time series of area average (Chennai city box area) simulated hourly 10-m wind speed (a-d), vertical velocity (e-h), shallow layer shear (i-l) for the period 30 November - 02 December 2015. Grey shade shows 10-member ensemble simulations, pink line shows ensemble mean for model configurations with (a,e,i) USGS land cover, (b,f,j) NRSC 2015 land cover, (c,g,k) NRSC

2015 land cover with updated roughness $Z_0=1.08$ m and (d, h, l) NRSC 2015 land cover with updated roughness $Z_0=1.08$ m and NMP LSM.

Figure S9. Time series of area average (Chennai city box area) simulated hourly CAPE (a-d), PBL height (e-h) for the period 30 November - 02 December 2015. Grey shade shows 10-member ensemble simulations, pink line shows ensemble mean for model configurations with (a,e,i) USGS land cover, (b,f,j) NRSC 2015 land cover, (c,g,k) NRSC 2015 land cover with updated roughness $Z_0=1.08$ m and (d, h, l) NRSC 2015 land cover with updated roughness $Z_0=1.08$ m and NMP LSM.

Figure S10. Simulated radar reflectivity by a) USGS, b)NRSC1, c) NRSC2, d) NRSC2Z1, e) NRSC2Z2 f) NRSC2Z1-FL g) NRSC2Z1-NMP h) DWR observation at 12 UTC 1 December 2015.

TABLES

Table 1. Domain and physics used in WRF model

Model	WRF V4.2			
Dynamics	Primitive equation, non-hydrostatic, fully compressible, terrain following			
Initial and boundary conditions	NCEP GFS 0.5 x 0.5 degree analysis, 3 hourly forecasts			
Vertical levels	51 sigma levels			
Map Projection	Mercator			
Horizontal grid	Arakawa C-grid			
Model top	10 hPa			
Horizontal resolution	27 km	9 km	3 km	1 km
	-0.72-27.83° N 66.13-95.86° E	4.78-19.72°N 71.37-87.54 °E	7.63-15.56 °N 75.45-83.55 °E	10.67-14.13 °N 78.06-81.44 °E
Radiation	RRTMG for shortwave and longwave radiation			
Surface layer	MM5 similarity scheme			
Land surface model	5 Layer, NOAH , NOAH-MP			
PBL turbulence	Mellor-Yamada-Nakanishi MYNN 2.5			
Cumulus convection	Kain-Fritsch			
Microphysics	Thompson			
Land Use/ Land Cover	USGS 1992-1993, NRSC 2004-2005, NRSC 2015-2016; All with 24 land cover classes.			

Table 2. Summary of different simulations

Experiment Name	Land Surface Model	Land Use / Land Cover
USGS	Noah, default Zo for urban	USGS 1992-1993 24 cat arc 30sec
NRSC1	Noah, default Zo for urban	NRSC 2004-2005 24 cat arc 30sec
NRSC2	Noah, default Zo for urban	NRSC 2015-2016 24 cat arc 30sec
NRSC2Z1	Noah, Zo=1.08 m for urban	NRSC 2015-2016 24 cat arc 30sec
NRSC2Z2	Noah, Zo=2.00 m for urban	NRSC 2015-2016 24 cat arc 30sec
NRSC2Z1-FL	5 Layer Soil, Zo=1.08 m for urban	NRSC 2015-2016 24 cat arc 30sec
NRSC2Z1-NMP	Noah-MP, Zo=1.08 m for urban	NRSC 2015-2016 24 cat arc 30sec

1013 Table 3. List of stations used for comparison of rainfall and surface meteorological parameters

Station Name	Longitude (deg E)	Latitude (deg N)	Parameter
Chennai	80.200	13.100	Rainfall, Wind Speed, Temp, RH
Chennai Hindusthan Univ.	80.229	12.799	Rainfall
Madhavaram	80.200	13.200	Rainfall, Wind Speed, Temp, RH
Tambaram	80.117	12.917	Rainfall, Wind Speed, Temp, RH
Taramani	80.243	12.986	Rainfall
Chembrambakkm	80.038	13.032	Rainfall
Cholavaram	80.241	13.230	Rainfall
Red Hills	80.160	13.200	Rainfall
Tiruvallur	80.050	13.133	Rainfall
Poondi	79.700	12.800	Rainfall
Thiruvallangadu	79.782	13.128	Rainfall
Nungambakkam	80.200	13.100	Rainfall
Poonamalle	80.199	13.075	Rainfall
Airport	80.171	12.994	Rainfall
Kancheepuram	79.933	12.633	Rainfall
Chengalpattu	79.965	12.692	Rainfall
Mahabalipuram	80.193	12.626	Rainfall
Chennai DGP Office	80.251	13.052	Rainfall
Ennore port	80.300	13.200	Wind Speed, Temp, RH
Kalavai	79.400	12.800	Wind Speed, Temp, RH
Tamarapakam	80.030	13.230	Wind Speed, Temp, RH
GBNagar Kalavi Vellore	79.430	12.800	Wind Speed, Temp, RH
Kelavakkam	80.100	12.860	Wind Speed, Temp, RH
Magaral Chennai	80.050	13.216	Wind Speed, Temp, RH

1014

1015

1016 Table 4. Area (%) of different land-cover classes of the total area in USGS-1992, NRSC-2004 and
1017 NRSC-2015. Blank for zero distribution of the corresponding land cover class.

LULC No.	Description	Chennai & Neighborhood (79.8 E, 12.65N- 80.3E, 13.2 N)			Total domain		
		USGS 1992 (%)	NRSC 2004(%)	NRSC 2015 (%)	USGS 1992(%)	NRSC 2004(%)	NRSC 2015 (%)
1	Urban and Built-Up Land	3.46	17.63	26.56	0.41	1.26	5.41
2	Dryland Cropland and Pasture	6.32	11.13	8.80	5.63	35.11	9.17
3	Irrigated Cropland and Pasture	84.82	20.67	24.50	79.64	20.01	33.77
4	Cropland/Grassland Mosaic	0.45	31.44	7.21	1.14	14.129	15.59
5	Cropland/Woodland Mosaic	-	-	-	7.81	-	-
6	Grassland	-	-	-	0.002	-	0.002
7	Shrubland	1.04	4.73	1.41	0.61	10.25	1.97
8	Savanna	-	-	-	1.23	-	-
9	Deciduous Broadleaf Forest		2.92	5.92	0.035	11.80	11.76
10	Evergreen Broadleaf Forest				1.98	1.99	1.78

11	Mixed Forest		0.78	1.52		1.93	4.22
12	Water Bodies	3.82	8.00	19.72	1.47	1.82	8.25
13	Barren or Sparsely Vegetated	0.08	2.69	4.35	0.04	1.70	8.06

1018

1019 Table 5. Time and area-averaged rainfall (mm/day) and surface parameters from observations and
1020 different experiments over the Chennai urban region and its surroundings (79.8 E, 12.65N- 80.3E,
1021 13.2 N) on 1 December 2015.

Parameter	Raingauge gridded data	USGS	NRSC1	NRSC2	NRSC2Z1	NSRCS2Z2	NRSC2 Z1-FL	NRSC2 Z1-NMP
Rainfall (mm/day)	232.46	191.68	214.33	250.97	253.43	279.44	268.62	277.91
Drag coefficient	-	0.006	0.01	0.011	0.011	0.012	0.015	0.019
Sensible heat flux (Wm^{-2})	-	4.64	20.72	15.95	26.59	27.80	15.96	15.75
Latent heat flux (Wm^{-2})	-	61.2	46.58	44.18	46.23	47.38	53.64	35.39
Momentum flux (m^2s^{-2})	-	0.25	0.35	0.37	0.379	0.39	0.41	0.49
PBLH (m)	-	802.28	907.59	741.45	863.11	959.67	896	936.43
Shallow layer shear (ms^{-1})	-	8.36	8.26	8.65	8.68	8.69	8.77	8.93
TKE ($m^2 s^{-2}$)	-	0.16	0.25	0.27	0.35	0.85	0.60	0.46
Vertical velocity (ms^{-1})	-	0.1	0.13	0.14	0.15	0.18	0.15	0.16
CAPE (JKg^{-1})	-	1468.03	1495.68	1513.99	1588.72	1459.48	1503.85	1363.08
CIN (JKg^{-1})	-	4.55	3.99	4.05	2.86	4.86	6.08	4.36

1022

1023 Table 6. Error statistics for model simulated rainfall and surface meteorological parameters in
1024 different sensitivity experiments over the Chennai urban region and its surroundings (79.8 E,
1025 12.65N- 80.3E, 13.2 N) on 1 December 2015.

1026

Parameter	Sensitivity Experiment						
	USGS	NRSC1	NRSC2	NRSC2Z1	NRSC2Z2	NRSC2Z1-FL	NRSC2Z1-NMP
(a) GPM IMERGE Rainfall (mm)							
Mean bias	-157.79	-149.74	-96.38	-93.79	-101.46	-141.72	-111.76
RMSE	176.11	176.21	125.14	119.98	149.12	169.27	179.24
MAE	161.83	157.79	105.02	106.04	135.32	153.28	149.67
CC	0.40	0.57	0.61	0.67	0.59	0.53	0.67
(b) Rain-Gauge Station Rainfall (mm)							
Mean bias	-118.13	-75.09	-88.85	-70.76	-23.44	-60.98	-6.23
RMSE	151.24	125.39	114.38	108.52	100.41	115.69	92.21
MAE	125.94	109.61	91.29	90.39	86.39	91.69	78.79
CC	0.36	0.364	0.57	0.53	0.49	0.31	0.55

(c) 10 m Wind Speed (m s^{-1})							
Mean bias	2.83	2.8	2.33	1.93	2.56	2.97	2.68
RMSE	3.37	3.26	2.99	2.72	3.14	3.52	3.18
MAE	2.86	2.78	2.47	2.32	2.68	3.01	2.76
CC	0.57	0.61	0.63	0.67	0.64	0.55	0.66
(d) 2 m Temperature ($^{\circ}\text{C}$)							
Mean bias	2.14	2.07	1.74	1.62	2.1	2.18	1.8
RMSE	2.36	2.27	2.05	1.99	2.33	2.42	2.16
MAE	2.12	2.08	1.76	1.65	2.1	2.16	1.88
CC	0.4	0.48	0.43	0.41	0.52	0.38	0.28
(e) 2m Relative Humidity (%)							
Mean bias	-5.23	-5.74	-6.73	-7.21	-7.11	-5.69	-2.15
RMSE	7.49	7.99	9.06	9.36	9.39	7.70	5.42
MAE	5.75	6.16	7.14	7.43	7.42	5.97	3.33
CC	0.56	0.61	0.57	0.57	0.54	0.60	0.53

1027

1028 Table 7. Mean and standard deviation of air surface temperature (T_2) ($^{\circ}\text{C}$), sensible heat flux (SHF)
1029 (Wm^{-2}), latent heat flux (LHF) (Wm^{-2}) and rainfall (mm) for the simulations USGS, NRSC2,
1030 NRSC2Z1 and NRSC2Z1-NMP.

Parameter	Mean (standard deviation)			
	USGS	NRSC2	NRSC2Z1	NRSC2Z1-NMP
Temperature (T_2)	26.42 (0.41)	26.94(0.26)	26.98(0.35)	26.66 (0.30)
Sensible heat flux	12.32(6.76)	29.99(7.05)	34.74(7.28)	19.05(3.11)
Latent heat flux	67.07(11.15)	44.17 (3.96)	45.14 (4.91)	38.62(3.63)
Rainfall	12.1 (9.8)	15.89(10.21)	16.31(9.47)	22.43(14.22)

1031

1032

Figure1.

USGS 1992 LULC

NRSC 2004 LULC

NRSC 2015 LULC

- Urban and Built-Up Land
- Dryland Cropland and Pasture
- Irrigated Cropland and Pasture
- Mixed Dryland/Irrigated Cropland
- Cropland/Grassland Mosaic
- Cropland/Woodland Mosaic
- Grassland
- Shrubland
- Mixed Shrubland/Grassland
- Savanna
- Deciduous Broadleaf Forest
- Deciduous Needleleaf Forest
- Evergreen Broadleaf Forest
- Evergreen Needleleaf Forest
- Mixed Forest
- Water Bodies
- Herbaceous Wetland
- Wooded Wetland
- Barren or Sparsely Vegetated
- Herbaceous Tundra
- Wooded Tundra
- Mixed Tundra
- Bare Ground Tundra
- Snow or Ice

Figure2.

Figure3.

Figure4.

Figure5.

(a) USGS

(b) NRSC1

(c) NRSC2

(d) NRSC2Z1

(e) NRSC2Z2

(f) NRSC2Z1-FL

(g) NRSC2Z1-NMP

Figure6.

Figure7.

T2 NRSC2Z1-USGS

Sensible heatflux NRSC2Z1-USGS

Latent heatflux NRSC2Z1-USGS

RH2 NRSC2Z1-USGS

PBLH NRSC2Z1-USGS

CAPE NRSC2Z1-USGS

10m wind speed NRSC2Z1-USGS

Figure8.

T2 NRSC2Z1-USGS

Sensible heatflux NRSC2Z1-USGS

Latent heatflux NRSC2Z1-USGS

RH2 NRSC2Z1-USGS

PBLH NRSC2Z1-USGS

CAPE NRSC2Z1-USGS

10m wind speed NRSC2Z1-USGS

Figure9.

Figure10.

Figure11.

Figure12.

Figure13.

Figure14.