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RESEARCH ARTICLE

Urban-induced modifications to the diurnal cycle of rainfall over a tropical city

Quang-Van Doan[1,2] | **Anurag Dipankar**[1] | **Andrés Simón-Moral**[3] | **Claudio Sanchez**[4] | **Venkatraman Prasanna**[1] | **Matthias Roth**[3] | **Xiang-Yu Huang**[1]

[1]Centre for Climate Research Singapore, Meteorological Service Singapore, Singapore

[2]Center for Computational Sciences, University of Tsukuba, Tsukuba, Japan

[3]Department of Geography, National University of Singapore, Singapore

[4]The Met Office, Exeter, UK

Correspondence
Quang-Van Doan, Center for Computational Sciences, University of Tsukuba, Tsukuba, Japan.
Email: doan.van.gb@u.tsukuba.ac.jp

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[Correction added 13 February 2021, after first online publication: References Simon-Moral et al. 2020 and Bush et al. 2020 have been added in this version]

Abstract

There is still no consensus on the mechanisms that modify precipitation over and around cities, especially for those located in the tropics where convective processes primarily drive rainfall. Here we contribute to the ongoing discussion about the urban-associated precipitation by investigating the urban effect on the diurnal cycle of rainfall over Singapore. We use the urban version of the numerical weather prediction system of the Meteorological Service Singapore (hereafter called uSINGV) at a 300 m horizontal resolution to simulate the rainfall conditions over Singapore and its surroundings during the inter-monsoon period between 2010 and 2014. Two simulations with different land surface conditions are conducted: one with urban areas (i.e. present conditions) and one without urban areas. uSINGV is shown to perform well for rainfall when compared to observations. Comparison between simulations reveals that the urban area is responsible for the formation of a rainfall "hot spot" over Singapore and Johor Bahru, located at the southern tip of the Malay Peninsula, and the urban effect is accountable for 20–30% of total rainfall during late afternoons and evenings, highlighting a strong urban effect on localized rainfall over a tropical city. Enhancement of convection due to the urban heat island effect, increased frictional convergence due to buildings' drag, the seaward shift of the sea-breeze front, and the increased inflow of boundary-layer moisture by the stronger sea breeze are suggested as most probable reasons for the increased rainfall in the urban area.

KEYWORDS

Singapore, tropical climate, urban precipitation, uSINGV model

1 | INTRODUCTION

During the last decades, extensive efforts have been undertaken towards the better understanding of urban effects on convective precipitation in and around cities. One focus has been to quantify the urban-induced modification of precipitation regarding its spatial pattern, temporal variability, and intensity. Consistent findings have begun to emerge. For example, urbanisation is said to be a reason for the increase in the amount and frequency of precipitation over and/or downwind of cities (e.g. Changnon, 1992; Shepherd *et al.*, 2002; Zhang *et al.*, 2009; Kishtawal *et al.*, 2010; Niyogi *et al.*, 2011; 2017; Ashley *et al.*, 2012; Mitra *et al.*, 2012; Haberlie *et al.*, 2015; Lorenz *et al.*, 2019; Singh *et al.*, 2020). The urban effect is known to be most obvious during afternoons of warm seasons (e.g. Burian and Shepherd, 2005; Haberlie *et al.*, 2015) and more apparent for heavy rainfall rather than light rainfall (e.g. Kishtawal *et al.*, 2010; Schlünzen *et al.*, 2010). The evidence of urban rainfall modification is confirmed also in arid/semi-arid cities (e.g. Li *et al.*, 2020a; Luong *et al.*, 2020). Also, some studies argue the reverse effect: urbanisation that reduces local precipitation (e.g. Diem and Mote, 2005; Kaufmann *et al.*, 2007; Zhang *et al.*, 2009).

Physical mechanisms responsible for the change in urban precipitation have been identified. There is general agreement that the increase in precipitation downwind of urban areas is due to the enhancement of low-level wind convergence as a consequence of the urban heat island (UHI) effect (Rozoff *et al.*, 2003; Baik *et al.*, 2007; Miao *et al.*, 2011). Some studies also suggested that convection over urban areas can be initiated by urban thermals (Rozoff *et al.*, 2003; Shem and Shepherd, 2009). Also, urban roughness can be a contributing factor to the stalling of rain (Zhang *et al.*, 2018). For cities located in geographically or topographically complex locations, urban effects interact with other mesoscale circulations such as the land–sea or mountain–valley breezes, which complicate the processes generating precipitation (e.g. Gero and Pitman, 2006; Lin *et al.*, 2011; Kusaka *et al.*, 2014; 2019; Argüeso *et al.*, 2016; Freitag *et al.*, 2018). For example, a stronger sea breeze (as a secondary urban effect) could transport more moisture onshore, thus enhancing the chance of convection and precipitation (e.g. Argüeso *et al.*, 2016).

As the majority of the studies have been derived for midlatitude cities, primarily located in the USA or China, there is a lack of geographical diversity in analyses (Liu and Niyogi, 2019). Few, but an increasing number of, studies have addressed this topic for tropical cities, emphasizing the uniqueness of the urban–convection interaction given the strong convective characteristics of the atmosphere in the tropics. These studies have been carried out in Kolkata and Mumbai, India (Mitra *et al.*, 2012; Shatri *et al.*, 2015), Jakarta, Indonesia and Kuala Lumpur, Malaysia (Argüeso *et al.*, 2016; Ooi *et al.*, 2017; Li *et al.*, 2020b). Argüeso *et al.* (2016) found that urban areas experience significantly increased rainfall over Jakarta and Kuala Lumpur, especially during the inter-monsoon season when convective processes dominate.

Singapore, a city in the Maritime Continent, a region of Southeast Asia, is characterised by a typically tropical climate with abundant rainfall, and high temperature and humidity throughout the year. The rainfall here has a distinct diurnal variation. It occurs more frequently in the afternoon, which in most cases is driven by localised thunderstorms as a result of intense heating of the Earth's surface. Diurnal rainfall variation becomes more explicit during the inter-monsoon months (April–May and October–November) when prevailing winds are relatively weak, hence favouring the development of localised convection (Fong, 2012).

Singapore is an island city separated by a narrow waterway from the southern tip of the Malay Peninsula (Figure 1). Due to this particular location and smaller landmass, the local land–sea breeze circulation in Singapore is relatively weak. At the same time, its proximity to the eastern and western coasts of the Malay Peninsula implies that sea-breeze fronts from these two coastlines can potentially travel to Singapore. The possibility of co-existence of three sea-breeze fronts makes the mean circulation around Singapore more complicated than that of coastal cities usually considered in the existing literature. Hence, the understanding of the urban influence on convective processes from typical coastal cities (e.g. Argüeso *et al.*, 2016; Ooi *et al.*, 2017; Li *et al.*, 2020b) may not *a priori* apply to Singapore.

Similar to the major cities in the region, Singapore has experienced rapid urbanisation during the last several decades, which resulted in a substantial and growing UHI effect (e.g. Chow and Roth, 2006; Roth and Chow, 2012; Li *et al.*, 2013). Unlike for the UHI, there is still no understanding of how urbanisation affects the rainfall in Singapore. For example, Li *et al.* (2016) showed that the urban area does not significantly impact local rainfall over the city. Using a numerical modelling approach for the April–May inter-monsoon period, they suggested that urbanisation adds two opposing effects which balance each other. One effect enhances buoyancy by increasing the UHI, while the other effect decreases rainfall by reducing moisture due to reduced evapotranspiration. It is difficult to say why no urban impact was detected by Li *et al.* (2016), but we believe that it is due to their urban domain being too small to accurately capture the

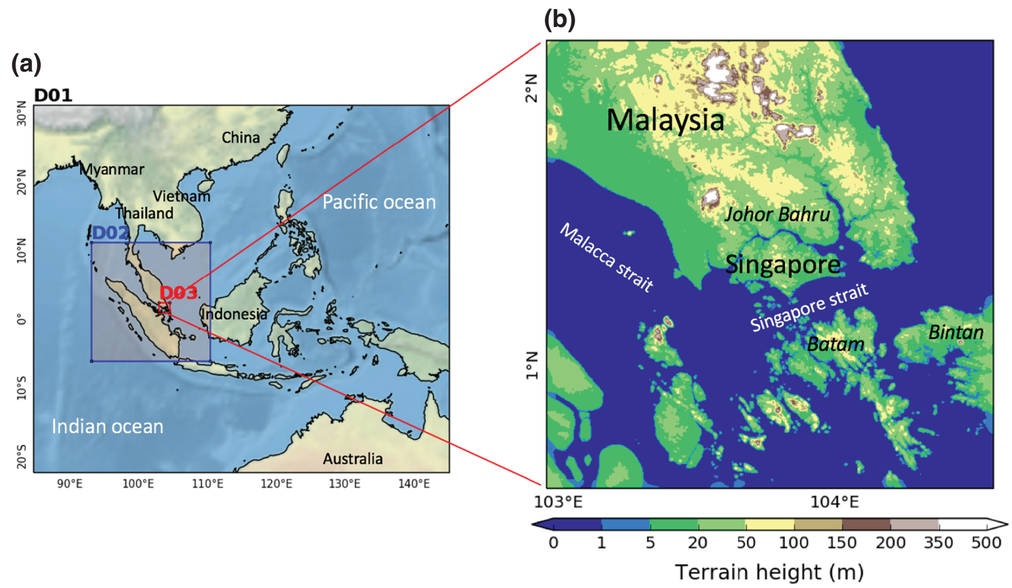

FIGURE 1 (a) Nested domain configuration. Three domains D01, D02 and D03 have a horizontal resolution of 8 km, 2 km and 300 m, respectively. (b) Topography of the innermost domain D03

interaction of local thunderstorms across a larger region that is also affected by the land–sea breeze circulation originating over the eastern and western coast of the southern Malay Peninsula. At the same time, a recent study by Li *et al.* (2018) analysing long-term rainfall observational data finds statistical evidence of a local urban effect on the increase in precipitation extremes. However, Li *et al.* (2018) do not explain the mechanisms that potentially drive this rainfall increase.

The research presented herein is aimed at investigating the role of the urban area on the diurnal cycle of convective rainfall in Singapore. This study focuses on the climatological effect of urban areas, primarily to answer the following two questions: (a) Does the urban area modify the diurnal cycle of local rainfall? (b) What physical mechanisms are responsible for this modification, if any? The reason we focus on the diurnal cycle is because it is the most important mode of rainfall variability in the Maritime Continent, and we consider it a characteristic of the tropical climate.

Section 2 presents the methodology, including model details and the experimental design. Results from the numerical experiments and model validation are presented in Section 3. The findings are discussed in detail in Section 4, and some conclusions are offered in Section 5.

2 | METHODOLOGY

2.1 | uSINGV model

The model used in the present work is based on the regional climate model SINGV (Huang *et al.*, 2019), which is adapted from the UK Met Office's Unified Model (Brown *et al.*, 2012). A nesting approach is used for the simulations, with three domains (Figure 1) of 8 km (D01), 2 km (D02) and 300 m (D03) horizontal resolution, respectively, each using a different set of physical schemes (or science configurations). The model includes 80 vertical levels with the upper atmospheric level at 38.5 km in all the domains.

D01 and D02 use the model configuration described in Dipankar *et al.* (2020) and the references therein. Results used in the present study are from D03 that uses an urban version of SINGV (uSINGV) as described in Simón-Moral et al. (2020). Model details related to uSINGV are summarised below for easy reference.

The Joint UK Land Environment Simulator (JULES: Best *et al.*, 2011) single-layer land surface parametrization is used to calculate the surface energy balance (SEB) fluxes between the land surface and the lowest atmospheric level. JULES is coupled with the Met Office Reading Urban Surface Exchange Scheme (MORUSES) urban canopy parametrization, which calculates the urban SEB fluxes by dividing the urban fraction into two tiles, namely roof and canyon. MORUSES uses detailed urban morphology and is therefore expected to improve the representation of the urban canopy in the model (Porson *et al.*, 2010). The boundary-layer scheme in uSINGV is three-dimensional based on Lilly (1962). The Smith (1990) diagnostic cloud scheme is used with critical relative humidity set to unity on all the vertical levels (Simón-Moral *et al.*, 2020). The rest of the model formulation is the same as SINGV and can be found in Dipankar *et al.* (2020). This modelling configuration has been shown to accurately represent the SEB and temperature above the urban canopy layer in an evaluation over Singapore presented in Simón-Moral *et al.* (2020).

2.2 | Design of numerical experiments

The model is run for five Novembers from 2010 to 2014, forced by ERA-5 reanalysis (Hersbach *et al.*, 2019). November is chosen for the study because of its distinct diurnal rainfall variation with a distinct afternoon peak as shown in Figure S1, Appendix S1. Each simulation is initialised on 29 October, 0800 hr and run until 1 December, 0800 hr (local time LT = UTC + 8 hr). The first 3 days are excluded from the results for model spin-up. Simulations are run continuously with three-hourly sea-surface temperature (SST) update from ERA-5. Soil moisture is initialised from ERA-5 at the beginning of each run. The lateral boundary conditions (LBC) for D01 are updated three-hourly from ERA-5 whereas for D02 and D03 they are updated every hour and half-hourly, respectively. The temporal resolution of the model output is 10 min.

We run two scenarios, a control scenario (URB), which uses present urban surface conditions (urban fraction, morphology and anthropogenic heat release) and a non-urban scenario (NO_URB) in which the urban fraction is replaced by broadleaf trees (which is the dominant land cover type over the surrounding region). Both scenarios use the same LBC from D02. The result from URB is used for model evaluation, and the comparison between URB and NO_URB is to assess the impact of the urban area on the rainfall. High-resolution land-use data obtained from Landsat 8 satellite images are used for estimation of the tile fraction (Figure 2a) and urban morphology over Singapore and Johor-Bahru. A three-dimensional (3D) building database is also employed to estimate urban-morphology parameters, including aspect ratio, building-width to canyon-width ratio, and mean building height (see Simón-Moral et al. (2020) for further details on land use and urban morphology calculations).

The anthropogenic heat flux is included in the model as a 300 m resolution inventory-based 2D database (Figure 2b) (Simón-Moral and Roth, 2020). The anthropogenic flux inventory includes the contributions from commercial, residential and office buildings, light and heavy industry, road traffic and subway. Due to model limitations, only one diurnal profile of the anthropogenic heat flux can be used for the entire domain, which is calculated as the average of the diurnal profiles defined in Quah and Roth (2012) for low-, high-rise residential and commercial areas, respectively. A climatological aerosol concentration is included in both the scenarios to consider its effect on radiation (absorption and scattering) and on the initial distribution of cloud droplet number concentration (Bush et al., 2020). Urban (Singapore) induced aerosols are not considered in the present work to simplify the analyses, but we do intend to pursue their effect in a future study.

2.3 | Observational data

Observational data used for the model validation are from five manned weather stations, located in Changi, Paya Lebar, Seletar, Sembawang and Tengah (S-24, S-06, S-25, S-80, and S-23 in Figure 3). These stations are managed by the Meteorological Service Singapore (MSS). The variables used for validation are air temperature (°C), relative humidity (%), wind speed ($m{\cdot}s^{-1}$), wind direction (degrees from north), and rainfall ($mm{\cdot}hr^{-1}$). Rainfall values are hourly totals (e.g. 1600 LT rainfall is that accumulated between 1501 and 1600 LT), the wind is based on 10 min average (e.g. 1600 LT wind is average of wind between 1551 and 1600 LT), while air temperature and relative humidity are instantaneous values. For the rainfall data, a quality check is conducted by comparing against both tipping

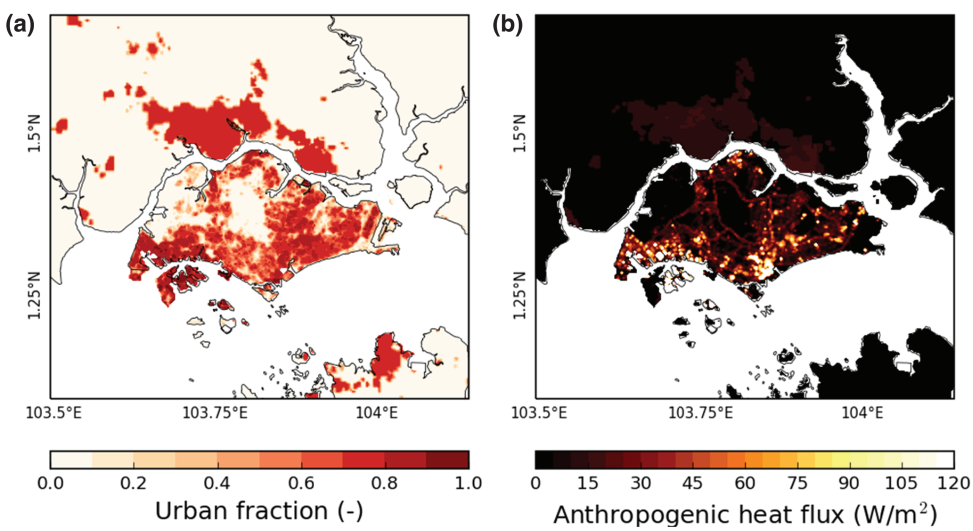

FIGURE 2 (a) Spatial distribution of urban fraction, which is derived from Landsat 8, and (b) daily-mean anthropogenic heat flux ($W{\cdot}m^{-2}$), which is derived from an inventory-based 2D database, over Singapore and Johor Bahru (see Figure 1 for locations)

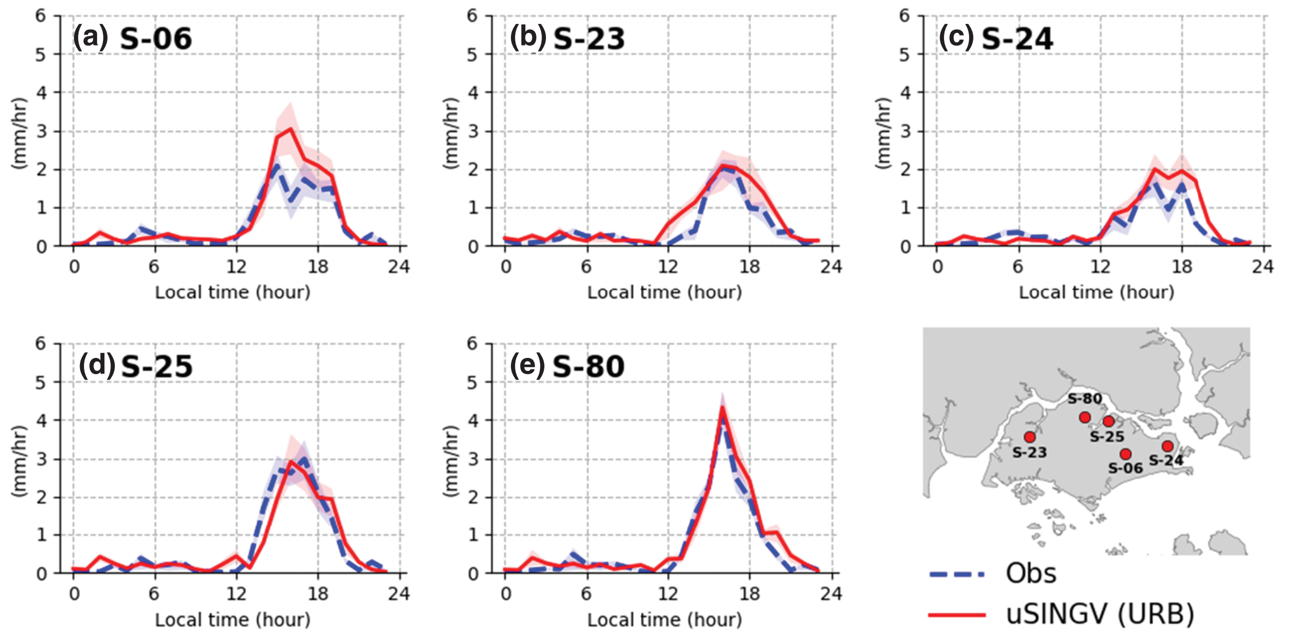

FIGURE 3 (a–e) Diurnal cycle of November rainfall rate averaged over 5 years (2010–2014) from uSINGV (URB) and ground-based observations (Obs) at five sites (S-06, S-23, S-24, S-25 and S-80). The colour-shaded areas indicate the uncertainty ranges, which are derived using a bootstrapping approach and defined as a range between 25 and 75% quantiles of the bootstrap means

buckets and radar images. For other parameters like temperature, relative humidity and wind, recorded values are checked every day by the station supervisors to exclude any unrealistic extreme values and minimise any typing error or wrong reading. The sounding data used for validation include air temperature, specific humidity, wind speed and direction, measured by the Vaisala RS41-SG radiosonde released from Paya Lebar (S-06) twice per day (i.e. 0730 and 1840 local time).

3 | RESULTS

3.1 | Model validation

We evaluate uSINGV's performance on the diurnal cycle of rainfall by comparing the simulated climatological mean rainfall (from simulation URB), over five Novembers, with the corresponding rain-gauge data measured at the weather stations mentioned above. Modelled data used for comparison are extracted from the grid cell closest to the respective weather station. Overall, uSINGV reproduces reasonably well the mean diurnal variation of November rainfall at all weather stations (Figure 3). Rainfall rates are low during the night and morning hours but reach peaks of about 2–4 $mm{\cdot}hr^{-1}$ between 1400 and 1700 LT. This variability is consistently seen in both observed and modelled data at all weather stations. The afternoon peak characteristics are well captured by the model with a slight overestimation at some stations, that is, S-06 and S-24.

The model's ability to capture the rainfall intensity distribution is shown in Figure 4, which compares the histograms of the modelled hourly rainfall (higher than 0.1 $mm{\cdot}hr^{-1}$) and those of the observations. The results show that uSINGV performs well, especially at moderate intensities (from 0.1 to 7.6 $mm{\cdot}hr^{-1}$). This performance is consistent at all weather stations. At the same time, there is an underestimation of heavy rainfall (>7.6 $mm{\cdot}hr^{-1}$) at station S-25 and very heavy rainfall (>20 $mm{\cdot}hr^{-1}$) at stations S-23 and S-80.

Additional evaluation of the model's performance is conducted for the mean diurnal cycle of other surface variables: air temperature (Ta), relative humidity (RH), wind speed (WS) and direction (WD) (Figures S2–S5). The diurnal variation of both Ta and RH is reasonably well captured, and the daytime minimum RH is underestimated. On the other hand, the daytime WS, in particular, is less well predicted with a general underprediction of the maximum generally observed during the early afternoon. Compared to WS, WD is better represented, and the model is able to capture the change in direction from north/northwesterly to the south/southeasterly flow between 1300 and 1500 LT and back to northerly flow around 1700–1800 LT. Despite underestimation of the surface wind speed, the model tends to predict well both the magnitude and direction of the upper wind (Figure 6).

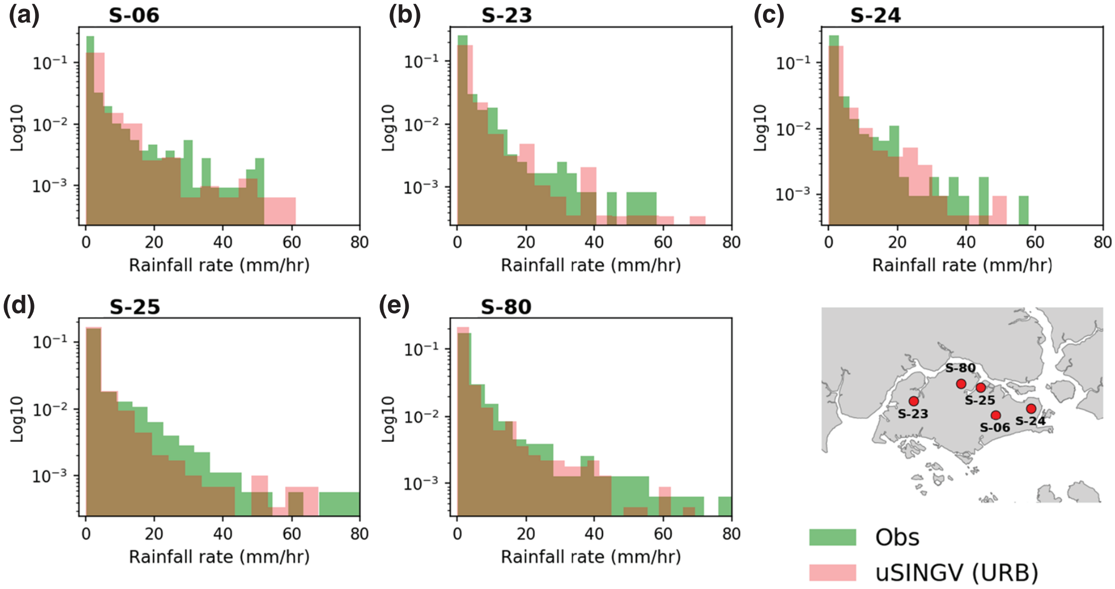

FIGURE 4 (a–e) Histograms of hourly rain-rate (mm·hr^{-1}) from uSINGV (URB) and ground-based observations (Obs) at five sites (S-06, S-23, S-24, S-25 and S-80). In plots, the pink/green colour indicates histograms of uSINGV/Obs; meanwhile, the brown colour indicates the overlaid area between them

3.2 | Urban impact on rainfall

To understand how the urban area changes the rainfall pattern in Singapore, we compare URB and NO_URB. Figure 5 shows the mean diurnal cycles of rainfall, averaged over an area covering part of Singapore and Johor Bahru (referred to as SGJB hereafter). The result shows that URB tends to generate more rainfall than NO_URB in the late afternoon (1500–1900 LT). The largest difference between the two simulations is about 1.0 mm·hr^{-1} and coincides with the time when the rainfall is at its peak (1600 LT). This corresponds to about 25% of the rain rate simulated in URB. On the other hand, no significant difference is seen throughout the night and during the morning hours (Figure 5). This result highlights the role of the urban area in enhancing afternoon convective activity, which is the primary driver of November rainfall in Singapore.

The urban footprint is further seen when comparing the spatial distribution of the simulated rainfall between the two simulations. Figure 6 shows the spatial distribution of rainfall rates at 1600 LT. At this time of maximum rainfall rate, rates are significantly enhanced over SGJB in URB compared to the NO_URB simulation. Spatial differences in rainfall rates between URB and NO_URB are shown in Figure 6c, and those areas where the differences are statistically significant (greater than 95% over SGJB and lower in the rest using the Wilcoxon test in Figure 6d). This result highlights the possible link between the urban area and the formation of the rainfall "hot spot" above it in the late afternoons of November.

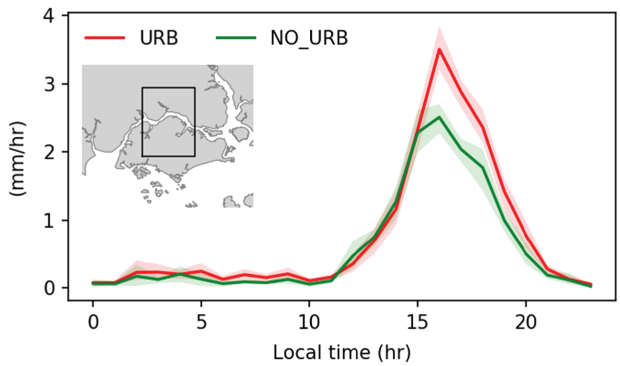

FIGURE 5 Diurnal cycle of simulated rain rate from URB and NO_URB. The values shown here are five-November (2010–2014) averages over the rectangle shown in the inset map which includes parts of Singapore and Johor Bahru in Malaysia (referred to as SGJB in the text). The colour-shaded areas indicate the uncertainty ranges, which are derived using a bootstrapping approach and defined as a range between 25 and 75% quantiles of the bootstrap means

3.3 | Physical processes responsible for urban rainfall modification

In this section, we try to understand why simulation URB produced more rainfall over SGJB than simulation NO_URB. Figure 7 shows vertical profiles of air temperature, specific humidity, vertical wind speed, cloud liquid water, and cloud ice, for URB and NO_URB. The values shown are for a grid cell closest to station S-06. At low heights (<750 m above ground), air temperature (specific

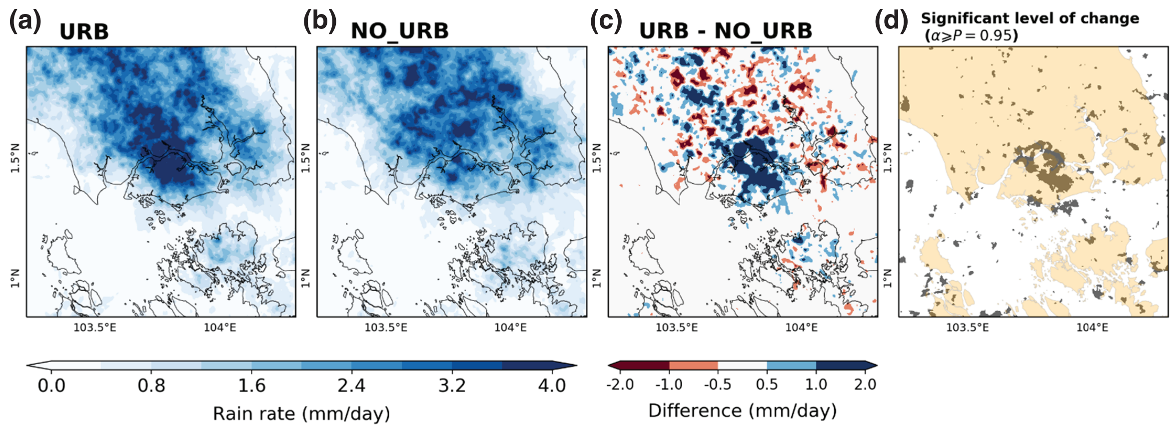

FIGURE 6 Spatial distribution of rain rate (mm·day^{-1}) at 1600 LT (1501–1600) from simulations (a) URB and (b) NO_URB, (c) the difference between them, and (d) the area (grey colour shaded) with a significant level of the difference greater than 0.95 according to the Wilcoxon test. Results for five Novembers from 2010 to 2014

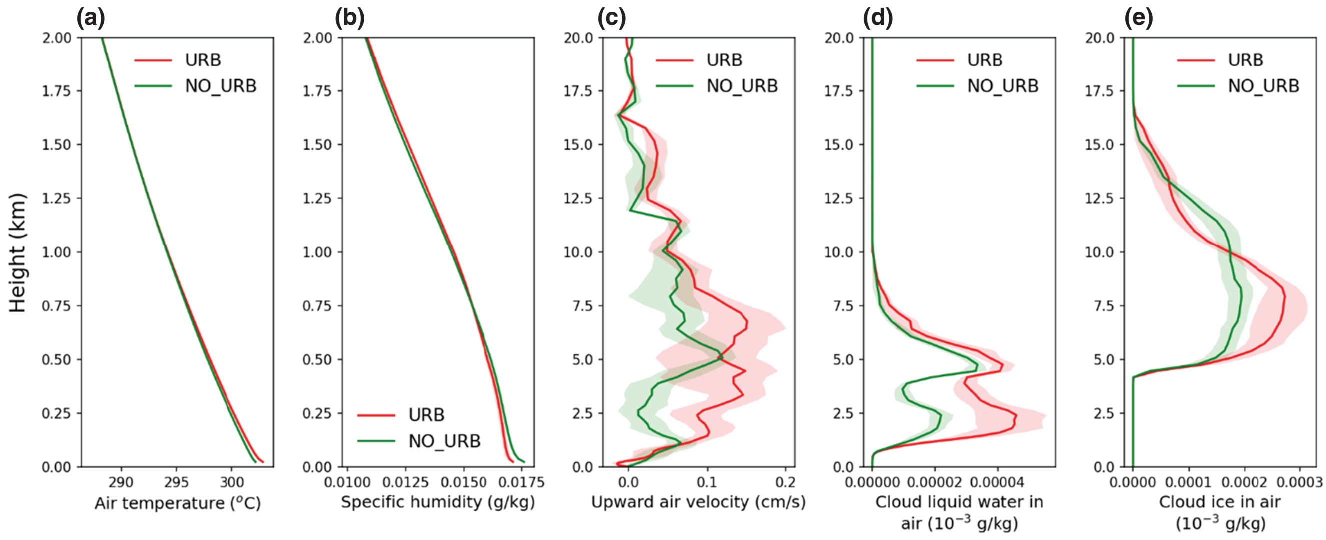

FIGURE 7 Vertical profiles (km) of (a) air temperature (°C), (b) specific humidity (g·kg^{-1}), (c) vertical velocity (cm·s^{-1}), (d) cloud liquid water (10^{-3} g·kg^{-1}), and (e) cloud ice in the air (10^{-3} g·kg^{-1}), at 1600 LT, averaged for November across 5 years. The colour-shaded areas indicate the uncertainty ranges, which are derived using a bootstrapping approach and defined as a range between 25 and 75% quantiles of the bootstrap means. Values are extracted from an urban grid cell closest to site S-06 for simulations URB and NO_URB

humidity) is higher (lower) in URB compared to NO_URB. Vertical wind speed is consistently higher in URB than in NO_URB up to ~17 km above the ground. Cloud liquid water and cloud ice content are also higher in URB compared to NO_URB, up to two times in the case of cloud liquid water at the height of 2.5 km. Similarly, higher cloud ice amount is seen in URB at the height of ~7.5 km.

Similar results to those above are also obtained in other grid cells over SGJB. Together they suggest that the urban area enhances vertical wind speed and increases cloud liquid water and ice content in the mid- and upper atmosphere. Next, we investigate (a) how the urban area enhances vertical wind speed, and (b) why there are more liquid water and cloud ice in the atmosphere despite the reduction of evapotranspiration at the urban surface.

To answer the first question, we analyse the surface heat budget for the two simulations. Sensible heat (QH) and latent heat (QE) fluxes from URB and NO_URB are compared with each other for the grid cell closest to S-06 in Figure 8. Similar results are obtained over other urban grid cells. A significant and consistent increase in QH and decrease in QE can be observed for URB compared to NO_URB. Adding an urban surface to the simulation almost doubles the midday QH peak to over 200 W·m^{-2} while decreasing the QE maximum from about 320 to

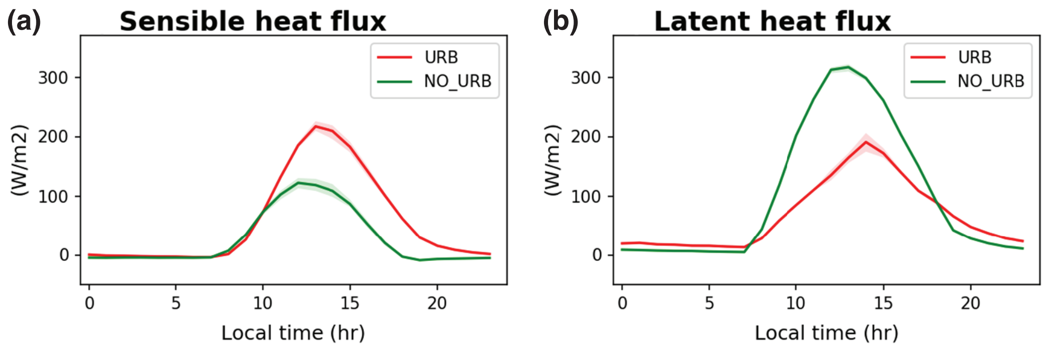

FIGURE 8 Average diurnal cycles of (a) sensible (QH) and (b) latent (QE) heat fluxes ($W \cdot m^{-2}$) simulated by URB and NO_URB for five November months between 2010 and 2014. The narrow colour-shaded areas indicate the uncertainty ranges, which are derived using a bootstrapping approach and defined as a range between 25 and 75% quantiles of the bootstrap means

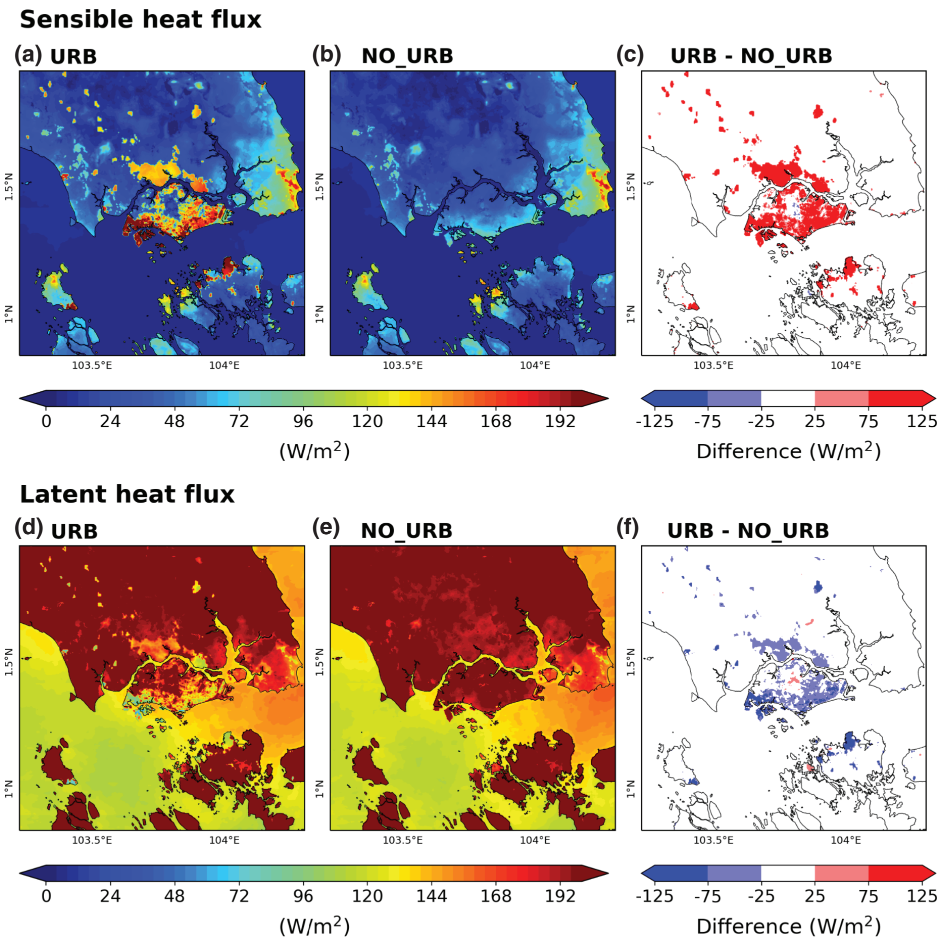

FIGURE 9 (a–c) Spatial distribution of November-mean surface sensible heat fluxes ($W \cdot m^{-2}$) at 1600 LT from simulations URB, NO_URB, and the difference between them; (d–f) the same for latent heat fluxes

180 $W \cdot m^{-2}$. Spatially, the changes in heat fluxes follow the urban surface coverage (Figure 9). As expected, significant changes are only seen in urbanised areas. The enhanced vertical wind speed (shown in Figure 7) is therefore likely due to stronger buoyancy forces caused by the surplus QH from the urban surface. The urban area also increases near-surface drag causing a decrease in wind speed of the order of 1.0 $m \cdot s^{-1}$ in the present case (Figure 10). Enhanced low-level horizontal wind convergence over the urban area could therefore be another potential cause for the enhanced vertical wind speed.

The present study also suggests a change in the location of the sea-breeze front (Figure 11). At 1600 LT, the time when the sea breeze is at its peak, a sea-breeze front, identified as the convergence area of low-level horizontal wind, is moved about 5–10 km towards the southern coast

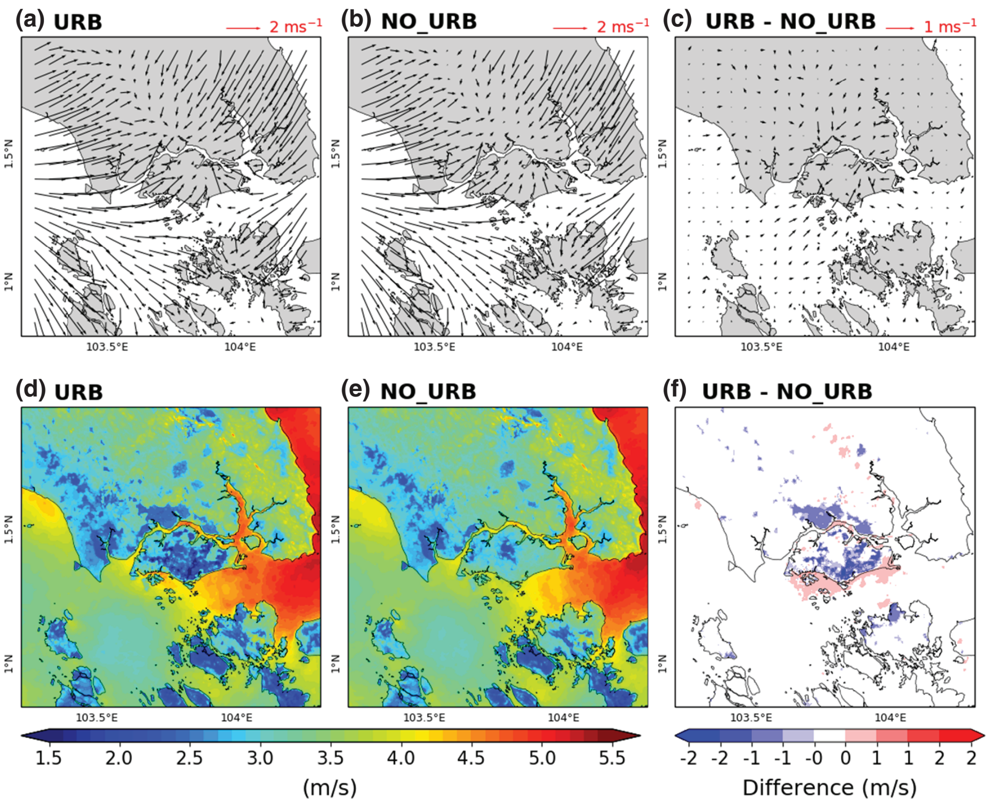

FIGURE 10 Spatial distribution of November-mean 10 m (a–c) wind vector and (d–f) wind speed (m·s^{-1}), at 1600 LT from simulations URB, NO_URB, and the difference between them

of Singapore in simulation URB as compared to NO_URB. This result, due to the larger friction over URB, would increase the chances for sea breeze penetration-related convection, and hence precipitation, to occur over SG.

The increase in vertical wind speed partly explains the increase in cloud liquid water and ice over SGJB. The vertical velocity, which is enhanced above 1.5 km height (i.e. around cloud base height) in the urban simulation would transport more moisture upward, increasing the cloud liquid water and ice condensation. Another reason for the increase in moisture can be attributed to horizontal convergence that is strengthened due to a higher land–sea temperature contrast. This convergence results in moisture being advected from the sea. As seen in Figure 12, the wind speed over the water just south of Singapore in URB is about 1 m·s^{-1} higher than in NO_URB. The wind decelerates more as it penetrates inland in URB compared to NO_URB because of the increased drag induced by buildings. The same can be seen in Figure 10. Therefore, despite the reduction in evaporation over the urban area, extra moisture imported from the nearby sea could provide a moisture source for enhanced convective rainfall.

4 | DISCUSSION

Using a 300 m horizontal resolution convection-permitting model we have shown the urban effect which significantly modifies the local diurnal rainfall cycle over SGJB, and have further attempted to explain associated physical processes responsible for the observed results. Our findings support the conclusion of an observational study carried out by Li *et al.* (2018) who suggested a strong local urban effect on precipitation extremes over Singapore. On the other hand, the present results contradict those of Li *et al.* (2016) who, in another modelling study using the Weather Research and Forecasting model (WRF), did not find any profound urban effect on rainfall. Their result could possibly be a consequence of using an urban domain that was too small to accurately capture the potential interaction with thunderstorms associated with sea-breeze systems coming from the east and west coasts of Malaysia.

In the present study, we note that the urban effect increases buoyancy by increasing the UHI, and reduces evaporation. Moreover, we emphasise the combination of the destabilisation of the urban boundary layer and the strengthening of low-level wind convergence as mechanisms for enhanced convection and upward transport of water vapour. We have also shown the additional impact of the shift in the location of the sea-breeze front due to surface roughness, which will likely increase the chances of convection in the urban area.

This present study shows that the urban effect can contribute 20–30% of the total peak rainfall amount over the urban area and downwind of SGJB in November. This

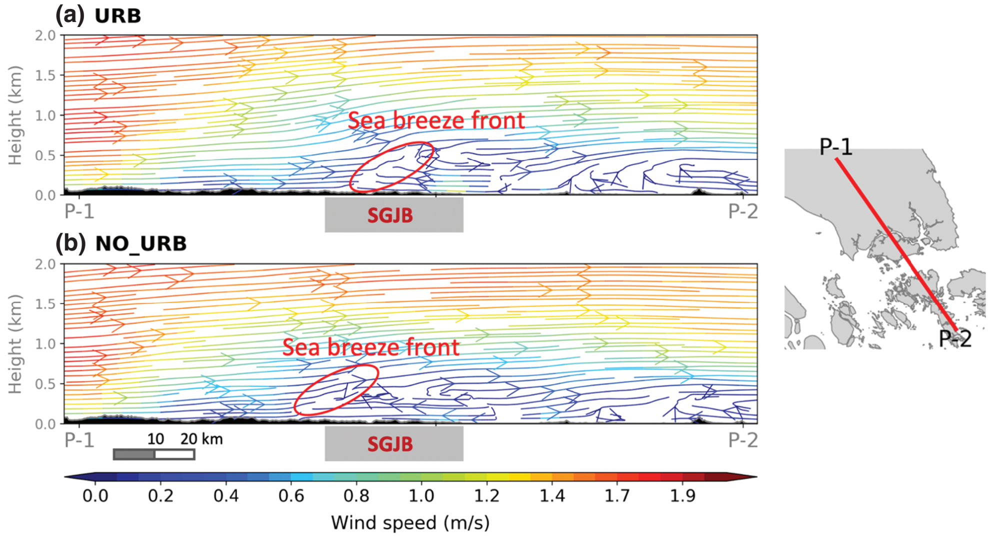

FIGURE 11 Wind streamlines (speed: m·s^{-1}) projected on a vertical cross-section along the line between points P-1 and P-2 from simulations (a) URB and (b) NO_URB, at 1600 LT. SGJB indicates the location of part of the Singapore and Johor Bahru urban area defined in Figure 5

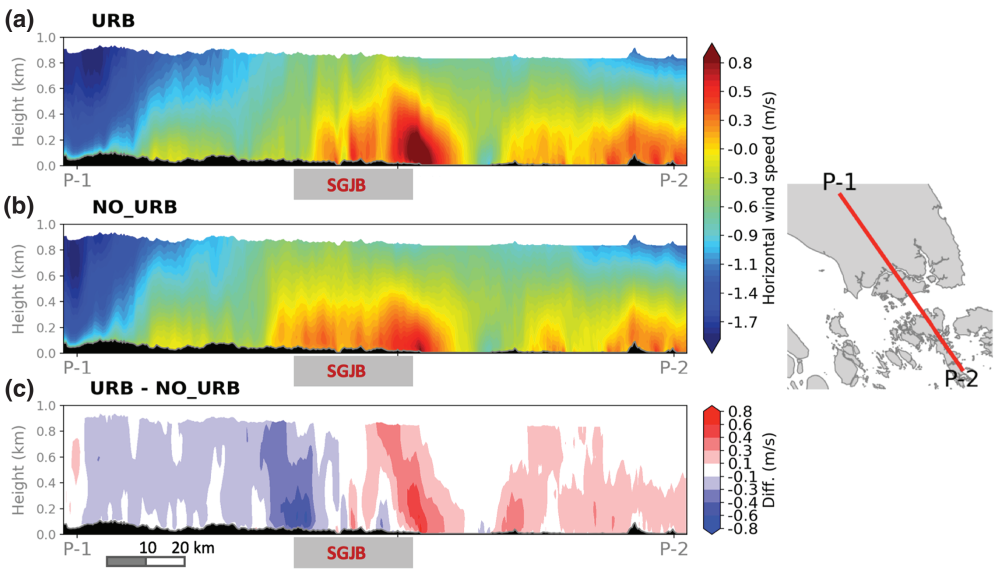

FIGURE 12 Projected horizontal wind speed (m·s^{-1}) on cross-section along P-1 and P-2 from (a) URB, (b) NO_URB, and (c) the difference between them. Positive (negative) values show northward (southward) wind. SGJB indicates the location of part of the Singapore and Johor Bahru urban area defined in Figure 5

contribution is relatively high compared to those in mid-latitude cities, which are estimated at around 10–20% (Liu and Niyogi, 2019). We suggest that the strong urban signal in a tropical city is due to the localised nature of rainfall, which is driven by interactions between meso- and synoptic-scale circulations. Such strong urban impacts on rainfall have also been found in other studies over tropical cities, e.g. Jakarta and Kuala Lumpur (e.g. Argüeso *et al.*, 2016; Li *et al.*, 2020b), or subtropical cities, for example, in Pearl River Delta (south China) (Wang *et al.*, 2015).

There are limitations to our results. First, we did not consider the impact of urban aerosols produced during industrial and transportation activities. Some studies suggested that aerosols can increase the number of cloud condensation nuclei, thus enhance convective precipitation (e.g. van den Heever and Cotton, 2007). However, the number of such studies is still few, and there is still no robust understanding about the role of aerosol types and concentrations in urban precipitation (Liu and Niyogi, 2019). Owing to the importance of Singapore as a major logistics hub, aerosol emissions from extensive transshipment activities could considerably influence convection processes. Additional studies addressing the potentially important role of aerosols on rainfall in Singapore are therefore needed, especially those that consider historical changes in aerosol emissions due to urbanisation and transshipment activities during the last decades.

The present article presents an overview of the urban impact on rainfall over Singapore. It also suggests some mechanisms to explain the observed urban rainfall enhancement. The scope is limited to an urban mean-signal. Thus, questions related to the urban impact from the perspective of individual events and specific rainfall intensities remain. We suggest a further study to address issues such as the urban area's impact on the spatial and temporal change of rainfall for different intensities and the impact on the frequency of occurrence and intensity of thunderstorms.

5 | CONCLUSIONS

This present study investigated the role of the urban area on the diurnal cycle of convective rainfall in Singapore. The 300 m resolution NWP model uSINGV was used to simulate inter-monsoon conditions present during November averaged across 5 years (2010–2014). The urban simulations were validated against observations, and comparisons were carried out against simulations using vegetated surface cover. The major conclusions are as follows:

- uSINGV is able to predict the main characteristics of the inter-monsoon rainfall climate in Singapore. The model captures the observed diurnal variation and magnitude of the peak rainfall during the late afternoon and evening very well.
- Model results show that the urban area is responsible for the formation of a rainfall "hot spot" over the urban areas of Singapore and Johor Bahru during late afternoon and evening. The urban effect contributes 20–30% of the total peak rainfall.
- Reasons for the increase in rainfall are suggested to be (a) enhancement of convection as the increased urban sensible heat flux destabilises the low-level atmosphere, (b) frictional convergence due to the reduction of wind speed over the rough urban area, (c) shift of the sea-breeze front from inland towards the coast, and (d) increase in upper-air moisture as a stronger sea breeze transports more moisture inland and enhanced vertical velocity brings this moisture aloft.

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ORCID

Quang-Van Doan https://orcid.org/0000-0002-2794-5309
Anurag Dipankar https://orcid.org/0000-0002-1410-4324
Andrés Simón-Moral https://orcid.org/0000-0002-2662-9750
Claudio Sanchez https://orcid.org/0000-0002-5069-6849

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