Strong intensification of hourly rainfall extremes by urbanization

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Key Points:

- Observed hourly rainfall extremes have intensified more in urban Kuala Lumpur than the surrounding rural areas over the last three decades
- Convection-modelling experiments provide further support that this intensification comes from urbanization, providing physical mechanisms
- Urbanization increases the potential future risk of urban flash flooding in tropical regions

Abstract

Although observations and modelling studies show that heavy rainfall is increasing in many regions, how changes will manifest themselves on sub-daily timescales remains highly uncertain. Here, for the first time, we combine observational analysis and high-resolution modelling results to examine changes to extreme rainfall intensities in urbanized Kuala Lumpur, Malaysia. We find that hourly intensities of extreme rainfall have increased by ~35% over the last three decades, nearly three times more than in surrounding rural areas, with daily intensities showing much weaker increases. Our modelling results confirm that the urban heat island effect creates a more unstable atmosphere, increased vertical uplift and moisture convergence. This, combined with weak surface winds in the Tropics, causes intensification of rainfall extremes over the city, with reduced rainfall in the surrounding region.

Plain Language Summary

Major floods and rainfall-related impacts are often caused by short-duration heavy rainfall events. Although there is evidence of cities modifying rainfall in many urban areas, uncertainties still exist around their role in intense rainfall episodes. We investigate the impact of the growth of Kuala Lumpur (Malaysia) on intense rainfall using observations and modelling experiments. We find that over the last three decades hourly rainfall events have become more intense over the city than surrounding rural areas. Our modelling experiments support this finding and help us understand mechanisms behind the intensification. The relative warmth of the city with respect to its surroundings contributes to the increase. The city creates a low-level anomaly of warm and dry air that then rises. To compensate for this, the moist surrounding air is brought into the urban area and lifted upwards. This feeds the air above the city with moisture and sustains a local circulation initiated by the relative warmth of the urban area. We find that the city's influence on extreme rainfall is located over the urban area itself, as opposed to other studies that have detected a footprint downwind. This is likely due to the typical calm background wind conditions in the tropics.

1 Introduction

Urban areas are hot spots that drive environmental change at multiple scales [*Grimm et al., 2008*], including the potential for hazardous events like flash floods from intense short-duration storms. A better understanding of how these will change with global warming is crucial for societal adaptation [*Westra et al., 2014*]. Theoretically, extreme rainfall is expected to intensify at a rate of ~7% per °C with warming, according to Clausius-Clapeyron (CC) scaling [*Trenberth et al., 2003*]. However, observed scaling on local near-surface temperature for hourly rainfall extremes [*Guerreiro et al., 2018; Lenderink et al., 2011*] ranges from negative in some tropical locations, to more than 2xCC depending on local environmental characteristics.

Since huge potential for damage results from heavy rainfall in cities, increasing research has focused on urbanization effects on extreme rainfall. Evidence has mainly been found in tropical locations for a strengthening of precipitation systems and significant effects on extreme rainfall events in urban areas [*Lin et al., 2011; Shastri et al., 2015*]. Analysis of the mechanisms affecting urban precipitation has identified the Urban Heat Island (UHI) effect as the major contributor [*Liang & Ding, 2017; Niyogi et al., 2017; Pathirana et al., 2014; Singh et al., 2016; Yang et al., 2017; Liu & Niyogi, 2019*]. The UHI causes urban areas to be significantly warmer than surrounding rural areas with the extra heat potentially triggering convection earlier and leading to a stronger rising motion in convective clouds [*Han & Baik, 2008*]. The higher roughness and anthropogenic aerosols found over cities could also provide potential mechanisms [*Han & Baik, 2008*], with urban roughness shown to be a contributing factor to the stalling and severe rains over Houston from Hurricane Harvey [*Zhang et al., 2018*]. This slowdown, coupled with extra heating from the UHI, increased the vertical uplift and thus moisture convergence upstream of the city [*Zhang et al., 2018*]. This mechanism has also been proposed to explain increased convection initiation upstream of cities in the US Midwest, with convective cells then enhancing precipitation extremes downstream of the city [*Han et al., 2014*].

We hypothesize here that extreme rainfall over urban areas may therefore be more intense and more frequent than for surrounding rural areas. To confirm this hypothesis, we examine hourly rainfall observations for a typical large city in the Tropics which has undergone rapid urbanisation in recent decades, Kuala Lumpur in Malaysia, and compare the number of gauges showing trends in short-duration intense rainfall over 1981-2011 in the urban area with those from surrounding rural areas.

In addition, we use a set of numerical experiments run with a regional convection-permitting atmospheric model [*Argüeso et al., 2016*] with changes to land-use to represent the presence or absence of the city. This allows us to further quantify the effects of urbanization on extreme rainfall and to identify potential mechanisms for the observed changes. Convection-permitting models are run at very high horizontal resolution (usually < 4 km) and have benefits in representing convection [*Prein et al., 2015*], which plays a central role in this study; they better represent the diurnal cycle, intermittency [*Argüeso et al., 2016*], and short-duration extreme rainfall intensities [*Lenderink et al., 2011*].

2 Data and Methods

2.1 Observational analysis

An hourly precipitation dataset for Malaysia has recently been compiled by the INTENSE project [*Lewis et al., 2019*] and was used in this study. Fifteen stations around Kuala Lumpur which have > 80% data completeness for the period 1981-2011 were used. Hourly rainfall data was declustered by using only the maximum hourly intensity for each day to ensure event independence. Daily intensity was calculated by summing hourly intensities over each calendar day. Rain gauges that have more than 20% 'urban' land cover type within a circle of radius 5km were identified as 'urban' stations, while the remainder were classified as 'rural'.

The Q95 index for each year and each station were calculated by: (1) Calculating the 95th percentile of hourly/daily event intensities. We use all-hour/day records to calculate percentiles for trend analysis rather than wet-hour/day considering that an increase in wet-day percentiles does not necessarily reflect an increase in event intensity [*Schar et al., 2016*]. (2) Selecting events with intensity higher than the percentile from step (1). (3) Calculating the mean of those intensities as Q95.

Mann–Kendall nonparametric tests [*Fatichi et al., 2009*] (significance level = 0.05) were applied to assess the significance of trends in Q95 for each station. Field significance tests were conducted by using 1000 bootstrap resamples (with replacement) [*Guerreiro et al., 2014*] for each station (supplementary information Figure S1).

2.2 Model experiments

The model experiments were performed with the Weather Research and Forecasting (WRF) model v3.6 [*Skamarock et al., 2008*]. The spatial configuration consists of a 2-km domain centred on Kuala Lumpur and is nested into 10-km and 50-km domains covering the Western Maritime Continent and the entire Maritime Continent, respectively. Two five-year (2008-2012) simulations were run: one with the default land-use (CTL) from MODIS, which includes urban areas, and a second one where the urban areas are replaced with the dominant surrounding vegetation category (NoUrb). The initial and boundary conditions were obtained from ERA-Interim Reanalysis [*Dee et al., 2011*]. Sub-grid scale processes were parameterized for turbulence in the Planetary Boundary Layer (YSU Scheme), microphysical processes (WRF single-moment 6-class scheme), longwave and shortwave radiation (RRTM and Dudhia schemes) and the surface layer (Eta similarity scheme). The Betts-Miller-Janjic (BMJ) cumulus scheme was used in the coarser domains and was switched off in the 2-km domain, since convection was assumed to be explicitly resolved. The land surface fluxes were simulated with the Noah land surface models and the urban canopy was represented using the Single-Layer Urban Canopy Model [*Kusaka et al., 2001*]. Further details of the model setup and its evaluation are provided in reference [*Argüeso et al., 2016*] and model data is accessible at the Australian NCI National Research Data Collection [*Argüeso and Evans, 2019*].

2.3 Model simulations analysis

To investigate how the presence of the city influences extreme rainfall in Kuala Lumpur, we analyze the outputs of model experiments [*Argüeso et al., 2016*] using a convection-permitting regional atmospheric model. The Weather Research and Forecasting model [*Skamarock et al., 2008*] is used to simulate current regional climate with urban areas (CTL) and without urban areas (NoUrb) from 2008 to 2012. In both experiments, the ERA-Interim reanalysis [*Dee et al., 2011*] is downscaled by a multiple-nesting approach to 2-km grid spacing covering the Kuala Lumpur area.

The comparisons between CTL and NoUrb experiments at hourly scales were conducted by comparing the mean of extreme event intensities at each grid cell, which were computed by the following steps. (1) Select the maximum hourly rainfall for each day at each grid point. (This step was for declustered data. The results without declustering are presented in Figure S5.) (2) Calculate the hourly 95th percentile at each grid point for CTL and NoUrb separately using data from step (1). (3) Select the hourly events from daily maxima above the corresponding 95th percentile at each grid point for CTL and NoUrb. (4) Calculate the mean of all the events from step (3) at each grid point for CTL and NoUrb. (5) Calculate the difference at each grid point between CTL and NoUrb (CTL minus NoUrb). (6) Calculate the significance of the difference using a Mann-Whitney U test on the data from step (3). (7) Repeat steps (2) to (6) for daily total precipitation amounts.

The vertical transects over Kuala Lumpur (3.1°N) were created by computing the differences between CTL and NoUrb for temperature, humidity, cloud mixing ratio (water + ice) and winds averaged over each extreme event and the preceding 6 hours at each grid point.

3 Results and Discussion

We start by analysing the newly-compiled hourly observational rainfall dataset for Malaysia. Kuala Lumpur was selected as the study area due to the dominance of short-duration, convective rainfall and the urban area being large enough to have a significant UHI [*Aflaki et al., 2017*]. We selected fifteen hourly rainfall gauges in and around Kuala Lumpur with at least 80% of hourly data available for 1981-2011. We used the urban area map from 1989 [*Boori et al., 2015*] to classify these into six 'urban' and nine 'rural' gauges for trend testing (details are given in Supplementary Information (SI), Table S1). We use the mean intensity of the 5% most intense events each year as an index (Q95) for short-duration extreme rainfall. Other high indexes (Q90 and Q99) were also examined to verify the robustness of our results (Table S2).

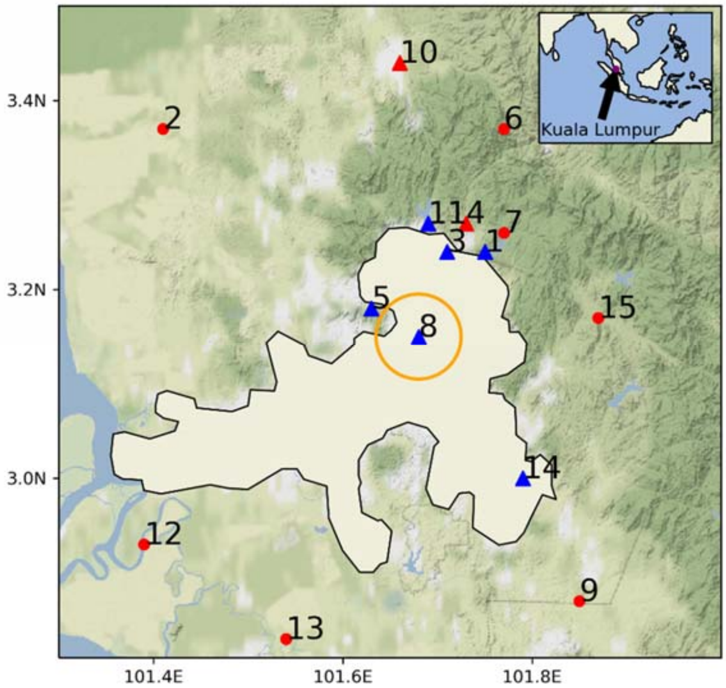

Figure 1. Hourly intensities of extreme rainfall in urban Kuala Lumpur show significant increasing trends, while rural areas are non-significant. Spatial distribution of stations showing significant/non-significant trends. Urban areas of Kuala Lumpur in 1989 are denoted by the white outlined area. Urban gauges throughout the whole study period 1981-2011 are shown in blue, rural gauges in red, with station ID as number labels (Table S1). Up triangles denote significant increasing trends; dots denote no significant trend. The orange circle shows a 5-km radius circle around one station, used in the urban definition (see Methods, Section 2.1). The purple point in the inset of Southeast Asia denotes the location of Kuala Lumpur.

Figure 1 shows the long-term trend of Q95 hourly rainfall intensities at each station, detected using the Mann-Kendall test [*Fatichi et al., 2009*]. All six urban gauges show significant increasing trends from 1981-2011, while only two out of nine rural gauges show significant increasing trends, agreeing with previous studies on historical trends [*Syafrina et al., 2015*] where an increase in frequencies of flash floods in this area was also noted. The choice of index does not change the results significantly (Table S2), thus confirming the robustness of the observed trends. Trends in daily Q95 rainfall intensities follow a similar, but weaker, pattern.

Only two urban and one rural gauge show a significant increasing trend for daily Q95, and no more than 3(1) urban (rural) gauge(s) show(s) a significant increase for any daily index (Table S3). We use a field significance test to further confirm that, for hourly intensities, the observed number of gauges showing increasing trends is very unlikely caused by chance (Figure S1).

Rainfall is highly variable both in time and space, and using 30 year periods to assess changes can lead to spurious results due to the misinterpretation of natural variability. Using 3 different definitions of extreme (top 1%, 5% and 10% using both the quantiles themselves as well as the mean of values above the quantiles), the Mann-Kendal test to assess the significance of trends and field significance to account for spurious significant trends makes the results as robust as possible. Nevertheless, in this paper we are not looking at trends by themselves; we are comparing the different behaviour of the rural and the urban gauges for both hourly and daily rainfall for the 30 years of observed data that are available; and we compare the detected trends to the expected physical behaviour using climate model simulations.

To improve the signal-to-noise ratio, we calculate 10-year rolling averages of Q95 hourly and daily rainfall intensities for each gauge for the whole study period and compare the mean of the 10-year rolling average for urban against rural gauges (Figure 2). We find that the 10-year rolling average Q95 hourly rainfall intensity has increased by ~35% in magnitude during the last three decades at urban gauges; almost three times more than for rural gauges (Figure 2). A simple linear regression gives a similar result. The increase is not as strong for the 10-year rolling averages of Q95 daily rainfall intensities, but there is still a clear rural-urban contrast (see Figure S2). Using extreme value analysis also gave similar results of an increase in urban intensities for the later period (see Supplementary Information, Figures S3 and S4)

In Figure 2, a clear difference between the series emerges in the late 1990s, coincident with the period when the urban area in Kuala Lumpur starts to expand [*Boori et al., 2015*] (Figure S5). Moreover, urbanization causes not only an expansion of the urban area [*Aflaki et al., 2017*] but also an increase in density, which results in a stronger UHI. This result may indicate a direct link between a stronger UHI and more intense extreme rainfall. It is worth noting that some initially rural gauges show an increasing trend in Q95 hourly rainfall since 2005. In particular, gauges 9, 10, and 12 show a > 20% increase in the rolling average of Q95 since 2005 (Figure 2). It is likely that this is caused by urbanization as these initially rural gauges become part of the urban area (compare changes in percentage urban area in Table S1 and the evolution of city expansion in Figure S5). Besides those directly affected by urbanization, other rural gauges (except 6 and 7) also show increases in Q95 hourly rainfall intensity since the mid- to late-2000s. These changes may be caused by a combination of natural variability and large-scale warming effects, but could also include impacts of the propagation of urban effects downwind [*Shepherd, 2005*] that reach further as Kuala Lumpur expands. The dominant factor that explains the changes at rural stations for this later period remains to be identified.

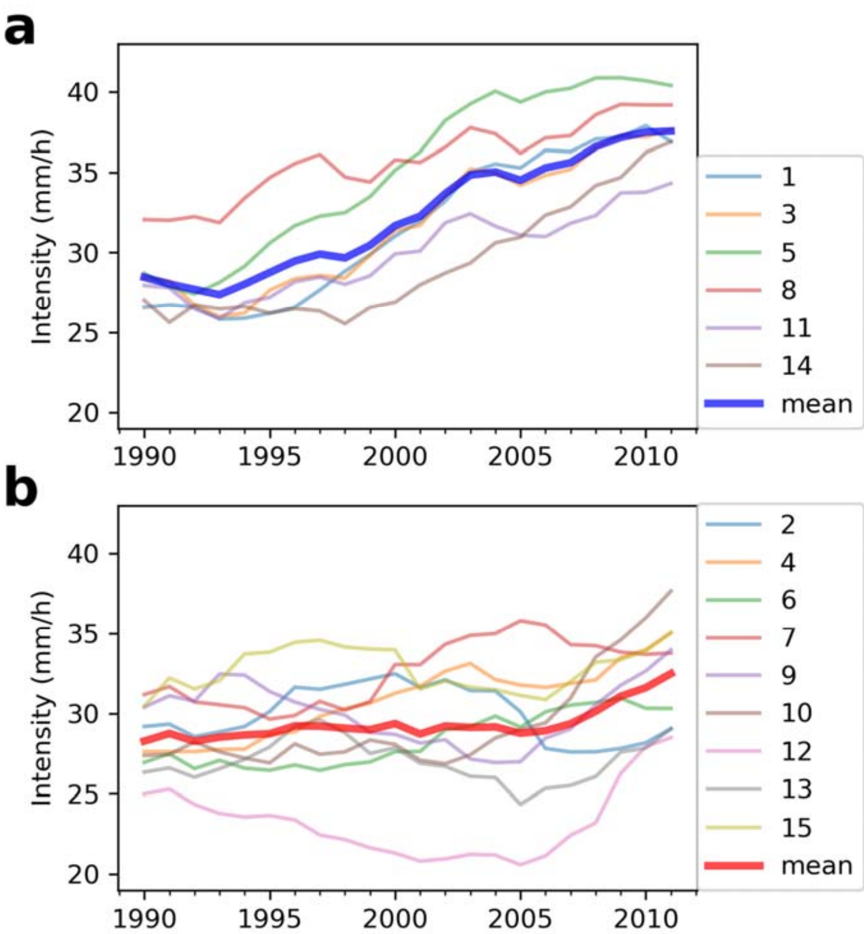

Figure 2. Urban gauges show a more rapid increase in hourly rainfall extremes than rural ones during the last three decades. Ten-year rolling averages of the Q95 of hourly rainfall for (a) each urban station and (b) rural station, and the mean of the gauges. By Q95 we refer to the mean hourly intensity of the declustered events above the 0.95 quantile. See Figure 1 in the main text and Table S1 for locations and other station information. The station IDs are shown in the legend.

Some aspects of simulated rainfall from the model experiments have already been reported on [*Argüeso et al., 2016*]; therefore, here we restrict our discussion to the model's ability to simulate observed extreme hourly intensities. We first compare the timing and intensities of hourly rainfall above the 0.95 quantile for the common period from 2008-2011 for the CTL simulation and observations. The model successfully captures the observed timing of extreme hourly intensities. More than 82% (58%) of Q95 hourly intensities in urban (rural) areas are concentrated in the late afternoon (16-20h), with 58% of simulated hourly extremes over urban areas occurring in this time range (Figure S6b).

We compare the CTL and the NoUrb run model experiments for 2008-2012 in Figure 3a-c, finding the presence of the city produces, on average, an ~11% increase in Q95 hourly rainfall intensities over the urban area of Kuala-Lumpur, while on average there is almost no change (~1% decrease) over the entire domain. The results are similar for daily intensities (Figure 3d-f) and larger if the data is not declustered (see Data and Methods and Figure S7). This suggests the presence of the city not only increases extreme rainfall intensities over the city itself but may also re-distribute the spatial pattern of extreme rainfall, reducing intensities outside the urban area. We find the largest differences (~24%) towards the interior of the urban area (Figure 3). We also find both positive and negative changes outside the urban area, likely due to the non-linear nature of the atmosphere and the chaotic effect of introducing the urban land-use perturbation. Previous modelling experiments have suggested that the urban area generates a warmer and drier environment near to the surface, creating a more unstable atmosphere and enhancing moisture convergence in the lower tropospheric levels, resulting in increased mean precipitation [*Argüeso et al., 2016*]. Here, we confirm that these mechanisms are also likely responsible for enhanced precipitation intensities during strong convective processes that lead to significantly larger extreme rainfall events over the city (Figure S8).

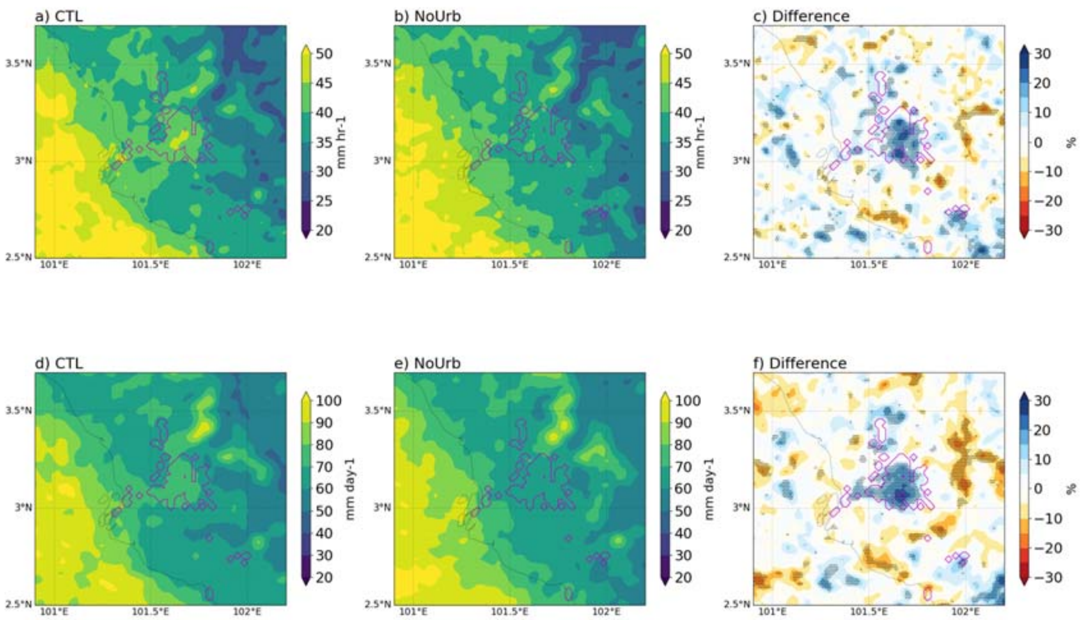

Figure 3. The presence of the city increases heavy rainfall intensities. Mean hourly intensity of events above the 95th percentile for CTL (a), NoUrb (b) and the percentage difference between CTL and NoUrb runs (c). Mean daily intensity of events above the 95th percentile for CTL (d), NoUrb (e) and the difference of CTL minus NoUrb runs (f). Urban areas designated in CTL runs are shown with purple contours (c, f) whilst stippling indicates statistically significant differences using a two-sided Mann-Whitney U test at the 99% confidence level.

Our model results suggest that extreme hourly rainfall intensities are enhanced by the UHI through the following mechanism. (1) In the late afternoon, air above the urban surface, which is well heated during the day, has enough buoyancy to start rising; (2) To replace this rising air, low level air from the surrounding area converges and is heated by the city which produces enough heat to sustain this circulation; (3) The rising tropical moist air condenses and releases latent heat, which makes it hotter and more buoyant, increasing the rising motion and equivalently the low-level convergence (shown in Figure S8). This mechanism is very similar to that proposed to explain super-CC scaling of hourly rainfall intensities in the Netherlands (see their Figure 7) [*Loriaux et al., 2013*] and links to convective initiation processes over warm-dry spots in the Sahel. To illustrate the mechanism, we created vertical profiles of temperature, humidity, cloud mixing ratio (water + ice) and winds averaged over each extreme event crossing Kuala Lumpur (3.1°N, see Figure 4). The surface temperature perturbation extends only a few hundred meters above the city (Figure 4) but is responsible for triggering the atmospheric instability that bring changes to higher levels. A drying effect near the surface extends only a few hundred meters but a positive humidity anomaly appears above (1-3km, Figure 4b), together with an increase in cloud mixing ratio (Figure 4c). According to change in the wind along the cross-section (Figure 4d) and the near-surface moisture convergence increase (Figure S8d), air brought from the surrounding areas rises as it approaches the center of the city and condenses above the city. This makes more water available for precipitation and generates an environment that favors more intense rainfall. Since the climatological mean horizontal wind speed above Kuala Lumpur is very low (Figure S9) we hypothesize that the background climate of Kuala Lumpur further facilitates the UHI effect on hourly rainfall extremes over the city, with the influence of urbanization perhaps more difficult to detect, or occurring downstream of the city [*Han et al., 2014*], in other locations. This confirms results from a meta-analysis of 85 studies on the effect of urbanization on rainfall which shows that rainfall intensification occurring over the urban area is as significant as that downstream of the city [*Liu & Niyogi, 2019*]. Our observational analysis provides a more detailed case study than previously available with complementary modelling experiments to support this effect.

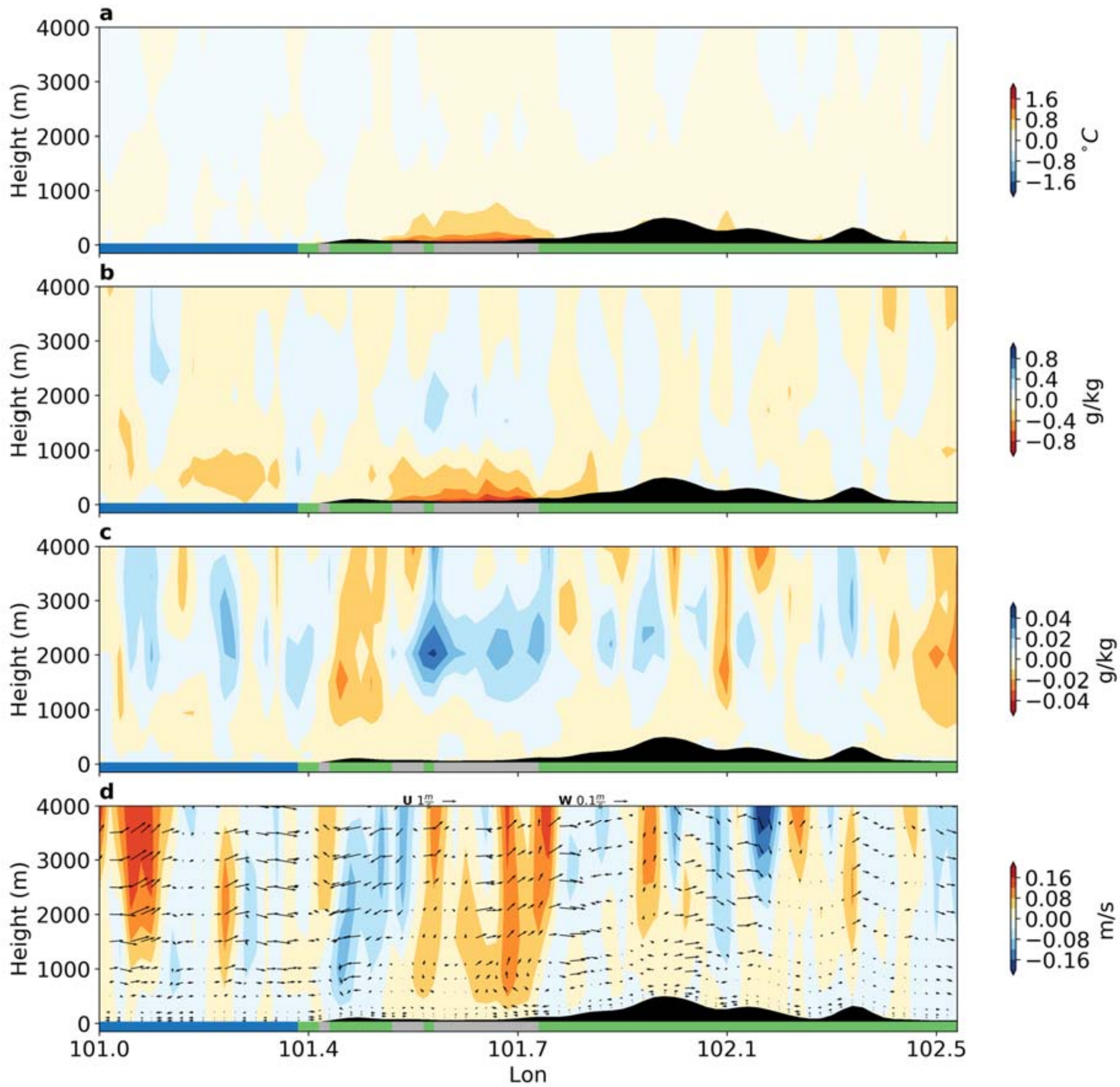

Figure 4. The impact of urban areas on the vertical structure of the atmosphere. Vertical transect along 3.1°N of differences in temperature (a), humidity (b) and cloud water and ice (c) and vertical wind speed (d) between CTL and NoUrb simulations (CTL minus NoUrb) for all hourly rainfall events above the 95^{th} percentile and the preceding 6 hours. Vectors (d) are differences in winds along the cross-section between the two experiments. U and W labels indicate the scale of horizontal and vertical wind vectors. The black area represents topography and the bottom bar shows the ocean (blue), rural (green) and urban (gray) areas in the CTL run.

4 Conclusions

In conclusion, we present clear evidence from observational records that short-duration extreme rainfall has intensified more rapidly from 1981 to 2011 in urban areas of Kuala Lumpur than in its surrounding rural areas. By examining ERA-Interim driven convection-permitting model experiments at 2-km spatial resolution, we confirm that the intensification in urban areas is caused by the presence of the city. In contrast to enhanced intensities downwind of the urban area in the American Midwest [*Han et al., 2014*], our observational and model results indicate that the intensification of extreme rainfall from urbanization in Kuala Lumpur occurs over the city itself, with precipitation redistribution perhaps causing lower intensities outside the city as also found by [*Kusaka et al., 2014*]. This is perhaps due to the low climatological wind speeds and has major implications from an adaptation perspective. Although our results refer to one urban agglomeration only, the mechanisms causing increases to rainfall are not exclusive to Kuala Lumpur [*Liu & Niyogi, 2019*]. Therefore, similar urban intensification may be expected in other cities with similar background climate characteristics and UHI intensity. This highlights the potential for increased future risk of urban flash flooding in tropical regions with global warming. Both longer historical records and greenhouse-gas forced convection-permitting model simulations are needed to better understand the interaction of global warming with the impacts of the UHI on changes to extreme rainfall intensities over cities. Also, the model experiments describe the city as a single high-density urban landscape, thus additional research including the urban heterogeneity would be desirable to further refine our estimates of the urban effects on intense rainfall. Finally, the role of aerosols from urban activity was not represented in the simulations although it may contribute to modify precipitation extremes through suppression and enhancing mechanisms [*Shepherd, 2005*]. Despite these caveats, our study demonstrates the need for consideration of the effects of urbanization in climate adaptation planning.

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