Impact of urbanization on the simulation of extreme rainfall in the city of Jeddah, Saudi Arabia

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Abstract

The city of Jeddah, Kingdom of Saudi Arabia is characterized by a hot and arid desert climate. Occasionally, however, extreme precipitation events have led to flooding that caused extensive damage in human life and infrastructure. This study investigates the effect of incorporating an urban canopy model and urban land cover when simulating severe weather events over Jeddah using the Weather Research and Forecasting (WRF) model at a convective-permitting scale (1.5-km resolution). Two experiments were conducted for 10 heavy rainfall events associated with the dominant large-scale patterns favoring convection over Jeddah: (i) an “urban” experiment included the urban canopy model and modern-day land cover, and (ii) a “desert” experiment replaced the city area with its pre-settlement, natural land cover. The results suggest that urbanization plays an important role in modifying rainfall around city area. The “urban” experiment enhances the amount of rainfall by 26% on average over the Jeddah city area comparing to the “desert” experiment in these extreme events. The changes in model-simulated precipitation are primarily tied to a nocturnal heat island effect that modifies the planetary boundary layer and atmospheric instability of the convective events.

1. Background and Motivation

Mesoscale convective systems associated with strong moisture convergence ahead of an upper-level trough that merged with the Red Sea Trough (RST) were suggested to be the dominant patterns behind the formation and intensification of the extreme precipitation events in Jeddah, Saudi Arabia (Dasari et al. 2018; Deng et al. 2015). The complex geographical features of the region, such as the Hijaz Mountains to the East of the city, and a land-sea boundary to the West further enhance low-level moisture convergence and convection activities. Under specific synoptic conditions, the orographic effect occurs on the windward side of the mountain ranges and may trigger strong and rapid rainfall bursts from convective storms (Haggag and El-Badry 2013). The runoffs due to intense rainfall from the desert foothills generate surface flow toward the city and sometimes significant flood damages.

The city of Jeddah has witnessed bursting urbanization and population growth over the past three decades, during which it has almost tripled in size. This resulted in an overall land surface cover change from natural desert-type to areas of urban development (Alqurashi and Kumar 2016). Large metropolitan regions in the middle of deserts, which occupy about a thousand square kilometers in geographic space, modify their surrounding environment in a variety of ways (Bornstein and LeRoy 1990). Changes in land use/land cover alter the surface energy and moisture exchanges with the atmosphere and thus the thermodynamic characteristics of the planetary boundary layer. The increase in surface roughness due to the presence of buildings and urban structures mechanically increases turbulence downwind and generates upward vertical motion (Bornstein and LeRoy 1990; Diem and Brown 2003).

86   The best-recognized modification effect of cities on their surrounding environment
87   is that urbanized surfaces reduce albedo and absorb more incoming solar radiation, which
88   is then converted to sensible heat. In large cities surrounded by highly vegetated natural
89   landscapes, like forests and croplands, the city would then tend to become a “heat island.”
90   Higher surface temperatures and deeper planetary boundary layers (PBL) are typical
91   conditions over a city, as compared to the surrounding rural areas (Rozoff et al. 2003).

92   It has been well documented in cities located in the central and eastern United States
93   that a deeper PBL in association with the urban “heat island” causes low-level convergence
94   favorable for the enhancement of convective precipitation downwind of the city (Bornstein
95   and Lin 2000; Cotton and Pielke 2007; Rozoff et al. 2003). Numerous case studies have
96   been conducted based on modeling sensitivity experiments and observational analyses, as
97   for instance for New York City, New York (Bornstein and LeRoy 1990); Atlanta, Georgia
98   (Bornstein and Lin 2000; Shem and Shepherd 2009); St. Louis, Missouri (Rozoff et al.
99   2003); Chicago, Illinois (Changnon 2001); Houston, Texas (Burian and Shepherd 2005;
100   Orville et al. 2001; Shepherd et al. 2010); and Oklahoma City (Hand and Shepherd 2009).

101   Urbanization was documented to increase the precipitation leeward of the urban
102   area and to decrease it in the area further inland in the coastal city of Tokyo (Kusaka et al.
103   2019; Kusaka et al. 2014). Horizontal divergence and moisture convergence are the
104   triggering mechanisms of thunderstorms in another coastal city of Sydney (Gero and
105   Pitman 2006). The presence of urban areas in other coastal cities in the tropic such as
106   Jakarta and Kuala Lumpur enhances precipitation due to an intensification of the diurnal
107   cycle (Argueso et al. 2016). Comparatively, much less is known about how anthropogenic
108   land-use change affects convective precipitation in a coastal-desert city like Jeddah,

109 especially in terms of numerical atmospheric modeling, where model sensitivity
110 experiments were conducted with respect to changes to land use/land cover classifications.

111   Increases in moisture, instability, and precipitation during the winter months in
112 Jeddah are associated with the Red Sea Trough (RST), a northward extension of the
113 southern Red Sea low-pressure system at lower atmospheric levels (de Vries et al. 2013).
114 The large-scale features are important regional factors that produce extreme precipitation,
115 which for a particular case, may exceed three times the average annual rainfall. During
116 such events, a short quasi-stationary mesoscale convective system (MCS) often produces
117 severe weather with heavy precipitation and flash flooding (de Vries et al. 2016; Deng et
118 al. 2015; Yesubabu et al. 2016). Impact of urbanization on thunderstorm development and
119 evolution in the Jeddah area is yet to be revealed when these extreme events occur during
120 the winter season.

121   Precipitation in the city of Jeddah is generated by thunderstorms on the mesoscale
122 and is intimately linked to the diurnal cycle of heating of terrain and generation of
123 mountain-valley circulations (Diem and Brown 2003). Synoptic-scale features, as for
124 instance transient inverted troughs, facilitate quasi-geostrophic upward vertical motion and
125 provide favorable wind shear profiles for convective organization and propagation
126 (Lahmers et al. 2016). Under these types of conditions, organized convection, in the form
127 of MCSs and squall lines, may propagate into the Jeddah area. Convective propagation is
128 made possible through successive outflow boundaries, or cold pools, from leading
129 convective lines. The outflow boundaries mechanically lift moist and unstable air, which
130 trigger more convection (Corfidi 2003). The resultant MCSs may well sustain into the
131 morning hours.

The question of interest in this study is: Does the aforementioned heat island in Jeddah locally affect the thunderstorms? The influence of urbanization on severe thunderstorms over the region is, as yet, poorly understood. Our main objective is to evaluate how changes in land use/land cover in the Jeddah urban area could impact severe thunderstorm events, and if so to explain the physical mechanisms behind them.

2. Analysis and Methods

a. Experiments strategy

Ten severe weather events were simulated in numerical weather prediction (NWP) mode with a convection-permitting regional atmospheric model. The strategy for simulating and evaluating the results is as follows. We focused on and analyzed in details the event of the 2009 flood (Yesubabu et al. 2016), which is one of the most severe and well-documented weather event that occurred in the Jeddah area. We retrospectively modeled it following a short-term, numerical weather forecast-type mode, based on two simulations accounting for desert and urban land use/land cover: one desert with no urban scheme and one city with urban scheme. This specific event is described in more details in the next subsection. We evaluated both simulations in details as an idealized case study, in the context of the changes in model-simulated precipitation and their physical causes. Another set of nine rainfall events were conducted following the same strategy for a total of ten extreme events to assess the general physical mechanisms of urbanization impact on precipitation. These ten events were selected as they are all active Red Sea trough cases, and associated with similar synoptic/mesoscale features with strong tropical-extratropical interactions.

b. Summary of the severe weather event on 25–26 November 2009

One of the most severe weather events that occurred over the Jeddah region over a period of approximately 24 hours on 25 and 26 November, 2009 was selected as an idealized test case. During the storm event, the Presidency of Meteorology and Environment (PME) surface observatory at King Abdulaziz International (KAI) Airport in Jeddah recorded accumulated rainfall of 140 mm between 0600 UTC and 1200 UTC. The synoptic meteorological conditions of the event have been well described by (de Vries et al. 2016; Yesubabu et al. 2016), and are summarized below.

Prior to the event, a northward extension of the RST and intensification of the Arabian Anticyclone (AA) provided warm moist air to the region, creating favorable conditions for the development of an extreme weather event. Later, the intrusion of a mid-latitude upper-level trough generated cyclonic flow and cold air advection, and the intensification of the subtropical jet due to midlatitude forcing enhanced the upper-level divergence that triggered the event. The rainfall was fueled by enhanced moisture transport from the Red Sea, and upward motions resulted predominantly from tropospheric instability. The configuration of the AA and upper trough allowed moist airflow to converge over the Jeddah region, producing what could be described as a quasi-stationary MCS (Haggag and El-Badry 2013). The event resulted in an estimated damage of about 1 billion USD (de Vries et al. 2013), and the attendant flash flooding caused 161 fatalities.

c. Convection-permitting regional atmospheric simulations

Convection-permitting modeling is essential for the proper representation of precipitation extremes and organized convective structures (Kendon et al. 2017; Prein et al. 2015), particularly over desert areas (Luong et al. 2018; Luong et al. 2017). Model simulations have also been demonstrated to be more successful at simulating heavy rainfall over the

Jeddah area at high resolution and without using a convective parameterization scheme (Deng et al. 2015; Yesubabu et al. 2016). Convection-permitting simulations were therefore performed to achieve the best model performance, as described below.

The Weather Research and Forecast (WRF) model version 3.9 (Skamarock et al. 2008) was used to generate the convection-permitting simulations over the Jeddah region. Lateral boundary forcing was obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset (Dee et al. 2011). The model was used to produce short-term numerical weather forecast-type simulations of 36 hours duration from 1200 UTC of the previous day to 0000 UTC of the next day, with a twelve-hour model spin-up period. The first twelve hours of the simulation is considered as the model spin-up period and therefore was not included when calculating total precipitation or studying the model behavior. We produced a total of ten 36-hour simulations for each experiment. The dates as well as rainfall characteristics of the ten cases are summarized in Table 1. Meteorological outputs are saved every hour.

A three-domain one-way nesting strategy was implemented with a coarse domain of 22.5-km grid spacing (d01), an intermediate domain of 4.5-km grid spacing (d02), and a convection-permitting domain of 1.5-km grid spacing (d03). The model grid structure is shown in Fig. 1 with the city of Jeddah located in the center of the third domain.

The physical parameterizations used in these WRF model simulations are consistent over all three domains. These include the Predicted Particle Property scheme for microphysics (Morrison and Milbrandt 2015), the Mellor-Yamada-Janjic planetary boundary layer scheme (Janjic 1994), the RRTMG shortwave and longwave schemes (Iacono et al. 2008), the unified Noah land surface model (LSM) (Tewari et al. 2004), and

the Eta similarity scheme for the surface layer (Janjic 2002; Janjic 1994; Monin and Obukhov 1954). We also used the one-layer Urban Canopy Model (UCM) (Chen et al. 2011; Kusaka and Kimura 2004; Kusaka et al. 2001) within the Noah land surface model, which was applied over those areas where the land use tiling was defined as URBAN in Fig. 2a. The urban land use tiles were then replaced with the natural desert land cover in the DESERT simulation, as outlined in Fig. 2b. The “barren or sparsely vegetated” landuse was selected for the DESERT experiment because Jeddah is built within a desert with very sparse vegetation. Anthropogenic heating was not included in the UCM.

d. Land surface scenario sensitivity experiments

In the WRF model, the Noah UCM and LSM were applied to a fraction of the model grid cells with built and natural surfaces, respectively. The Noah UCM considers urban geometry in the surface energy balance and momentum flux calculations (Chen et al. 2011). We applied the UCM over all cities defined as urban in the region in the third domain at 1.5-km resolution.

Two land surface scenarios were considered in the two model sensitivity experiments that were conducted for the 10 rainfall events: (i) an urbanized scenario with the current land coverage of the region (referred to as the URBAN simulation), and (ii) a pre-settlement scenario with natural landscape (referred to as the DESERT simulation). The two simulations were analyzed and compared to evaluate salient differences.

The default 21-class MODIS land-use data of WRF version 3.9 has been used to identify urban grid points. The value of the urban fraction is fixed and the urban morphology parameters (e.g. urban fraction, anthropogenic heat, surface albedo, roughness length for momentum over roof, ground or building, roof height) are specified from lookup

table URBPARM.TBL. The urban dataset is of circa 2001. The specific values of the urban parameters are outlined in Table 2. The results of extensive simulations that we have conducted in several previous studies, using the same urban scheme and urban parameters, suggest that the WRF model performs well at simulating the regional-urban rainfall (Dasari et al. 2017; Dasari et al. 2019; Viswanadhapalli et al. 2017; Yesubabu et al. 2016).

3. Effect of urbanization on the rainfall pattern

The simulations of the extreme event that occurred on 25 November 2009 are first analyzed in details to evaluate the land coverage effects on precipitation. The other nine cases of the similar synoptic condition that produce heavy rainfall in Jeddah are then added to have a statistical assessment of the rainfall modification from urbanization. As mentioned above, the land surface cover in the URBAN simulation includes the city signatures of major areas (Jeddah, Mecca, and Taif) in the convection-permitting domain through the use of the Urban Canopy scheme (Fig. 2). Information regarding how precipitation changes and how this can be explained from the standpoint of changes in meteorological conditions at the surface and in the local atmosphere, is provided in the subsequent sub-sections.

a. Urbanization impacts on model-simulated precipitation

Observed and modeled precipitation for the time period 0000 UTC 25 November 2009, to 0000 UTC 26 November 2009, along with the difference in simulated precipitation over the Jeddah area, are shown in Fig. 3. The area of interest (Jeddah City) is circled. Interestingly, the southwest-northeast direction and position of the maxima over Jeddah (Fig. 3c) are well captured by the model in the URBAN experiment, which represents the real-world scenario (Fig 3.a). The model reasonably represents an MCS within its domains. The WRF model simulations tend to overestimate precipitation in the upper and lower third

of the domain in comparison to the radar observations. However, the model result is in very good agreement with the actual observations (on the order of 100 mm day^{-1}) in the center of the domain over Jeddah (Fig. 3). This rainfall pattern indicates a robust performance from the model.

With that in mind, we focused our attention to the effect of urbanization on precipitation, which is the primary objective of this study. Figure 3d shows that precipitation consistently falls over the city in the URBAN simulation compared to the DESERT simulation. The area of the Jeddah City in the DESERT experiment exhibited a wider range of rainfall amount, from about 50 to over 140 mm day^{-1} (Fig. 3b). In contrast, in the URBAN experiment, the lowest range was 70 mm day^{-1} (Fig. 3a). The URBAN simulation also revealed a larger area of maxima (over 140 mm day^{-1}) in the south of the city. Using urban land cover and the UCM in the URBAN simulation increased the average daily precipitation over Jeddah by over 30% ($93.45 \text{ mm day}^{-1}$ compared to $71.83 \text{ mm day}^{-1}$ in the DESERT simulation). Notably, the differences in rainfall patterns from the two experiments were widespread along the coast. Immediately to the north and south of Jeddah City, outside the urban core, decreases in the precipitation area are observed in the URBAN simulation. In contrast, a significant increase of URBAN rainfall was recorded around Jeddah, where the land tiles were changed and where the peak rainfall occurred. Consequently, we were interested in investigating two questions: what is the physical explanation of the differences in the rainfall pattern over Jeddah? And why the urban effect is significantly noticeable?

b. Urban heat island and its association to the progress of thunderstorms

Hourly analysis of the progress of thunderstorms during this extreme weather event may provide more physical insights about the storm evolution and into how sensitive that process was to the presence of the city of Jeddah. The simulated rainstorm moved from the northwest to the southeast, passing over Jeddah at about 0700–0800 UTC (Fig. 4a-f). The early morning storm seemed to propagate faster in the DESERT experiment, resulting in a negative difference area located next to a positive area paralleling the direction of the storm movement (Fig. 4g-i). These differences were mostly revealed after the storm approached the city vicinity (after 0700 UTC) with rainfall intensity over 100 mm hour⁻¹. Jeddah City was exposed to heavier and more prolonged rainfall rates in the URBAN experiment. This implies a blocking or enhancing feature that reduced the propagation speed of the storm in the URBAN experiment. The change in land use was next investigated to assess any direct connection with the differences in precipitation.

Modeled surface heat fluxes (sensible and latent) along with precipitation and boundary layer height diurnal cycles are presented in Fig. 5. During the nighttime and early morning hours before the arrival of the storm (from 0000 UTC to 0600 UTC), the sensible and latent heat flux of the two simulations were minimal and practically not distinguishable. The boundary layer, however, was deeper before any convective activity takes place in the URBAN experiment. The boundary layer height started to increase from 0200 UTC (200–300 m) to 0500 UTC (900–1000 m), with the increase occurring earlier in the URBAN than in the DESERT experiment (double at 0300 UTC). The deeper PBL therefore locally intensified the atmospheric instability over the urban area, in comparison to the surrounding desert (Stull 1988). This is an important indication of the impact of urbanization.

Heat storage relative to desert soils is shown in Fig. 6. Urban surfaces in all the cities of the region consistently exhibited higher surface temperature from 0000 to 0400 UTC, relative to the desert. The existence of a nocturnal urban heat island could be the reason to modify the movement of the thunderstorm cells around Jeddah in the simulations. Higher heat storage in the URBAN simulation provided instability in the environment for a couple of hours before the storm. That condition favored rapid cyclogenesis, as revealed next in Fig. 7.

The influence of urbanization on the intensification of heavy rainfall over Jeddah due to land-use/land cover and the UCM was about 30% of the total averaged daily precipitation. This was mainly due to strong convergence at the lower levels, with deep convection caused by strong vertical motion leading the development of mesoscale upper-air cyclonic circulation. The dynamical mechanism behind the extreme event was investigated using the vorticity tendency equation. The analysis of the vorticity equation allows us to evaluate the contributions of the terms describing the different dynamical and physical processes. The vorticity equation in an isobaric coordinate system can be written as

$$\frac{\partial \zeta}{\partial t} = - \left(u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} \right) (\zeta + f) - \omega \frac{\partial \zeta}{\partial P} - (\zeta + f) \left(\frac{\partial u}{\partial x} + v \frac{\partial v}{\partial y} \right) + \left(\frac{\partial u}{\partial P} \frac{\partial \omega}{\partial y} - \frac{\partial v}{\partial P} \frac{\partial \omega}{\partial x} \right) + \left(\frac{\partial F_y}{\partial x} - \frac{\partial F_x}{\partial y} \right).$$

The horizontal advection of absolute vorticity is represented by the first term on the right-hand side. The second term denotes the vertical advection of relative vorticity. The third term (called the stretching term) indicates the divergence acting on absolute vorticity. The fourth term denotes the tilting of vertically sheared flow. And the last term represents gradients in the force of friction. The different terms of the vorticity tendency equation over Jeddah for both URBAN and DESERT experiments were computed hourly based on

the model simulations. The time-height sections between 0200 UTC and 1300 UTC of 25 November 2009, of the vorticity terms, are presented in Fig. 7. The vorticity tendency is relatively small ($1 \times 10^{-8} \text{ s}^{-2}$) until 0600 UTC of 25 November 2009 in both experiments (Fig. 7a-b). A significant increase (more than $50 \times 10^{-8} \text{ s}^{-2}$) of the vorticity tendency was noticeable until 0800 UTC. In URBAN, the vorticity tendency is concentrated between the surface and 100 hPa (Fig. 7a) and in DESERT it extends to 600 hPa (Fig. 7b). In URBAN, the cyclonic vorticity exhibited a tower shape that persisted for about three hours from 0600 UTC to 0900 UTC, whereas in DESERT, the experimental cyclonic vorticity initially persisted for about one hour (up to 0700 UTC) and extended to around 600 hPa. It then became negative, indicating anti-cyclonic vorticity (until 0800 UTC) before it turns cyclonic again for about one hour (0900 UTC). This suggests that the URBAN experiment experienced a substantial increase of cyclonic vorticity that persisted longer than in the DESERT experiment, which means that the inclusion of the URBAN conditions enhanced the strength and duration of the storm.

The analysis of the different terms of the vorticity tendency equation suggests that the horizontal (Fig. 7c-d) and vertical (Fig. 7e-f) advection, stretching (Fig. g-h) terms are the main factors contributing to the vorticity dynamics. The horizontal advection in URBAN (Fig. 7c) shows that it positively contributed to the increase of vorticity in the lower layers (below 600 hPa) for about four hours by transporting the moisture from regions of the neighboring Red Sea. In DESERT (Fig. 7d), however, the horizontal advection exhibited a shape of a narrow tower extending up to 300 hPa for about 1–2 hours. The vertical advection and stretching terms in URBAN (Fig. 7e, g) exhibits higher magnitudes than those in DESERT from 800 to 400 hPa. This establishes that the lifting of

moisture to the upper levels by strong vertical motions enables deeper convection in URBAN. The higher magnitudes of the stretching term in URBAN also indicates a more significant increase in the low-level convergence than in DESERT. Analysis of the last term in Fig. 7i, j demonstrates that the negative influence of the tilting term on the vorticity tendency in the upper atmosphere, which led to the dissipation of the system, is observed in both experiments. There is, however, a positive contribution to the vorticity in the lower layers in URBAN (Fig. 7i) that is not realized in the DESERT experiment (Fig. 7j).

In summary, the rise of convection activities in the URBAN experiment was due to higher and longer positive vorticity advection, stronger upward motion, greater surface convergence, and increased amount of low-level moisture convergence from the Red Sea region and low vertical wind shear. This suggests that urbanization was an important factor in the storm development and associated rainfall intensify over the city of Jeddah.

We also conducted a moisture analysis to assess how storms are affected in this coastal city. Fig. 8 represents the moisture available in the region via the total column water (TCW) in millimeters for both experiments (a, b) and their differences (c, d) averaged from 0000 UTC to 0800 UTC. The figure was plotted within a zoomed-in perspective to show the gradient of moisture from sea to land. An east-west gradient is observed overall in the domain with drier area inland and moister area near the coast. East of 40.2° E, the TCW is quite dry with only 10 to 20 mm. TWC in the Jeddah area ranged from more than 40 mm to 55 mm for both experiments (Fig. 8 a-b). The differences, however, suggest a significant increase in moisture in the URBAN case, specifically around Jeddah. Changes in land-use primarily increase the TCW by about 2.06 mm, or about 4.25% in URBAN. With natural

land surfaces instead of the city, the DESERT experiment simulated 4.25% less moisture (Fig. 8 c-d).

Vertically integrated horizontal water vapor fluxes (IVF) [$\text{kg m}^{-1} \text{s}^{-1}$] $\left(\frac{1}{g} \int_{p_s}^{p_t} q \mathbf{V} dp \right)$ or moisture fluxes are analyzed in Fig. 9. A flow of moisture is initiated from the Red Sea predominantly from the south-southwest (Fig. 9 a-b) perpendicular to the general direction of the storm, which is from the north-northwest. Additional moisture from the Red Sea to the Jeddah area accumulated hours before the arrival of the storm. This added energy was vital for the MCS development and propagation and provided a cold pool development mechanism for the MCS. An enhancement of the flux is observed in the URBAN experiment (Fig. 9c). The stronger moisture flux simulated by URBAN paved the way for stronger storm development, and hence increasing the precipitation intensity. It is to be noted that land-use affects both the dynamics (Fig. 7) and the thermodynamics (Fig. 8-9) of the MCS. The extreme Jeddah precipitation event occurred because of its unique location near the Red Sea and because of the prevailing synoptic conditions of the day. Urbanization enhanced the development of the storm by providing more favorable thermodynamics and dynamics conditions.

c. General feature of urban precipitation enhancement

To further support the results of urbanization impact on the Jeddah city rainfall, we extended our simulations for a total of ten case studies of extreme precipitation over Jeddah. The considered ten events are selected due to their similar synoptic/mesoscale features following a dominant mode that produce heavy rainfall over the city of Jeddah. These events are associated with strong tropical-extratropical interactions and the presentation of the RST. Thunderstorms are initiated by the upper-level trough intrusion into low latitudes.

A combination of stationary Arabian anticyclone, low-level convergence, and deep moist convection produce extreme rainfall in these cases (ALKhalaf A. and Abdel Basset H. 2013; Dasari et al. 2018; Haggag and El-Badry 2013; Kumar et al. 2016). Simulated rainfall from the two experiments and their differences for all ten heavy rainfall events are displayed in Figure 10. All cases exhibit enhancement of precipitation over the city of Jeddah. Composite mean of the ten cases also outlines the same conclusion (Fig. 11). Both URBAN and DESERT show similar patterns but the peaks of rainfall occur at different locations (Fig. 11 a, b). Mean rainfalls in the Jeddah area (over circled region) are 46.2 mm and 36.8 mm for URBAN and DESERT experiments, respectively.

Rainfall changes from urbanization is about 26% on average over the 10 heavy rainfall events (Table 1). All these convective events occurred at night time in the winter. Storm directions are generally from the Southwest to Northwest. Nocturnal urban heat island is revealed by surface temperature with a mean increase of 0.36K. Sensible and latent heat fluxes differences are minimal before sunset. The boundary layer, however, is deeper in the URBAN experiment with a mean increase of 76.7 m, about 24%. Total column water is 1.3 mm (3%) higher in the URBAN experiment (Table 1). These indicators suggest that URBAN exhibits more favorable thermodynamic and dynamic conditions to strengthen convective activities. The urban surface therefore acts as a redistributor, which enhances rainfall in the city and reduces it around the city.

Because of the lack of an observation network in the Jeddah region, we analyze the spatial distribution of heavy rainfall events and associated trends over Jeddah using different gridded rainfall datasets: the climate prediction centre MORPHing (CMORPH) (Joyce et al. 2004) and the tropical rainfall measuring mission (TRMM) (Huffman et al.

2007). Both datasets available at a resolution of 0.25° indicate a significant increase in heavy rainfall events intensity in recent decades over Jeddah (Fig. 12). Analyses from modeling and observational data are therefore in agreement regarding the increase in intensity of heavy rainfall over Jeddah, due to urbanization as suggested by our modeling study. Observations from the sole station that have long term daily precipitation records in Jeddah from Ministry of Water and Electricity (MOWE) also imply a significant rainfall trend in the urban core (Fig. 13). The precipitation trend is increasing overall with a slope of $+0.51 \text{ [mm year}^{-1}\text{]}$ based on linear regression. This is in agreement with the increasing trends from TRMM and CMORPH (Fig. 12) for the city of Jeddah.

Different from other desert cities, e.g. Phoenix, where North American monsoon precipitation in the summer plays an important role (Georgescu et al. 2008, 2009), the majority of Jeddah heavy precipitation is produced by MCSs in the winter propagating to the city at night to the early morning. The physical process that enhances precipitation in the city area and reduce rainfall outside of the city is a “heat island” effect that leads to a deeper boundary layer, stronger baroclinicity, and a more unstable atmosphere inside the city.

4. Discussion and Conclusions

Numerical simulations and flux tower observation studies have suggested that the daytime cooling of the urban area (oasis-effect) relative to the surrounding desert is due to increased heat storage in the urban fabric, rather than changes in latent heat fluxes (Chow et al. 2014; Georgescu et al. 2011; Grossman-Clarke et al. 2010). The very substantial heat storage fluxes in the urban core are caused by a reduced albedo and increase in the surface area from complex urban structures. During nighttime this stored heat is released and

therefore cities in arid environments, including Jeddah, are characterized by relatively large urban heat island effects and increased planetary boundary layer height.

Ten heavy rainfall events associated with similar synoptic/mesoscale features related to a cold midlatitude upper-level trough, a stationary Arabian anticyclone, low-level convergence, and deep moist convection are analyzed to study the impact of urbanization on the Jeddah city rainfall. Simulations from the URBAN and DESERT experiments for all ten heavy rainfall events suggested an enhancement in precipitation of about 26%, on average, inside the city area in the URBAN experiment. Observations from different gridded rainfall datasets also indicated an increase in the intensity of heavy rainfall events over Jeddah in recent years. One of the extreme weather events from the 10-event set that occurred on 25 November 2009 is analyzed in details to assess how urbanization affects thunderstorms.

An urban canopy model was used within WRF to explicitly account for urban surfaces. Two 30-hour convection-permitting simulations were performed per each event: an URBAN experiment used the UCM, and a DESERT experiment removed the city and replaced it with its natural desert land surface cover. Changes in the simulations related to precipitation pattern, thunderstorm progress, heat fluxes, depth of the boundary layer, cyclogenesis dynamics, and moisture fluxes were analyzed. Our primary conclusion from the model sensitivity experiments is that the city of Jeddah urban area exhibits a nocturnal “heat island” effect that leads to a deeper boundary layer, stronger baroclinicity, and a more unstable atmosphere. These factors have favored convective activities, initiating the development of thunderstorms, and increasing urban rainfall. Relatively to the direction of the upper-level flow, rainfall decreases immediately downwind of the city to the southeast.

The enhancement of rainfall by urbanization is concurrent with an Active Red Sea Trough weather phenomenon that produce heavy rainfall in the winter.

An unsettled question was not addressed in the present study: which specific components of the UCM physics is most critical for explaining the model simulated differences in precipitation? Additional model experiments to investigate the sensitivity of the model to the individual UCM physical components are therefore needed to further assess this urbanization effect in the coastal city of Jeddah.

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621 **Figure 1:** Positions of domains 2 and 3 with 4.5-km and 1.5-km resolution, respectively,
622 inside the 22.5-km coarse resolution domain 1 map with terrain height shaded (m).

Figure 2: Land-use index of (a) Modern (URBAN) and (b) Pre-settlement (DESERT) experiments. Urban land-use tiles (category 13 - red) have been replaced by desert (category 16 - gray) in the bottom panel. The Jeddah city area is circled.

Figure 3: Simulated 24 h accumulated rainfall [mm day⁻¹] on 25 November 2009 from the two experiments (a) Urban and (b) Desert, (c) Observation from radar, and (d) Rainfall differences (URBAN minus DESERT). The Jeddah city area is circled.

Figure 4: Evolution of the storm revealed by hourly precipitation [mm hour^{-1}]. URBAN, DESERT, and their differences (URBAN minus DESERT) are plotted in (a–c) Upper, (d–f) Middle, and (g–i) Bottom panels, respectively. Timeline from left to right: 0600–0700 UTC, 0700–0800 UTC, and 0800–0900 UTC on 25 November 2009. The Jeddah city area is circled.

Figure 5: Hourly evolution of precipitation [mm hour^{-1}], sensible and latent heat fluxes [W m^{-2}], and planetary boundary layer height [m] plots for 25 November 2009. URBAN and DESERT experiments are displayed with blue and orange lines, respectively. Values are averages over Jeddah area.

Figure 6: Hourly differences (URBAN minus DESERT) in skin temperature [K] from 0000 UTC to 0300 UTC on 25 November 2009: (a) 0000 UTC, (b) 0100 UTC, (c) 0200 UTC, and (d) 0300 UTC.

Figure 7: Vorticity tendency equation terms [$\times 10^{-8} \text{ s}^{-2}$] for the URBAN (left panels) and DESERT (right panels) experiments: (a–b) Vorticity tendency, (c–d) Horizontal advection, (e–f) Vertical advection, (g–h) Stretching, and (i–j) Tilting.

Figure 8: Total column water (TCW) [mm] averaged from 0000 UTC to 0800 UTC for the (a) URBAN and (b) DESERT experiment. (c) TWC differences [mm] (URBAN minus DESERT) and (d) Relative differences [%]. The Jeddah area is indicated by black lines. The differences averaged over Jeddah are 2.06 mm or 4.25%.

Figure 9: Vertically integrated horizontal water vapor fluxes (IVF) [$\text{kg m}^{-1} \text{s}^{-1}$] averaged from 0000 UTC to 0800 UTC for the (a) URBAN and (b) DESERT experiment. (c) IVF differences [$\text{kg m}^{-1} \text{s}^{-1}$] (URBAN minus DESERT). The Jeddah area is indicated by the black lines.

1987-12-05

1989-12-11

1992-01-10

1996-11-15

1996-11-18

(a) URBAN

(b) DESERT

(c) $\Delta=(a)-(b)$

Figure 10: Simulated 24 h accumulated rainfall [mm day⁻¹] of 10 extreme events from the two experiments (a) Urban and (b) Desert, and (c) Rainfall differences (URBAN minus DESERT). The Jeddah city area is circled. Event dates are denoted on the left of each rows.

1996-12-29

2002-11-30

2009-11-25

2010-12-30

2011-01-26

(a) URBAN (b) DESERT (c) $\Delta = (a) - (b)$

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Figure 10: continued.

Figure 11: The mean simulated 24 h accumulated rainfall [mm day⁻¹] of 10 extreme events from the two experiments (a) Urban and (b) Desert, and (c) Rainfall differences (URBAN minus DESERT). The Jeddah city area is circled.

Figure 12: Trend of winter precipitation [mm year⁻¹] associated with rainfall days heavier than 30mm day⁻¹ in the past 3 decades over Jeddah from (a) TRMM and (b) CMORPH. The values over 0.02 and under -0.02 are statistically significant (at 90% confident level using Student t-test). The Jeddah city area is circled.

Figure 13: Jeddah station daily precipitation [mm] from 1984 to 2013. The x-axis displays the year. The trend of 3-decade period is +0.51 [mm year⁻¹].

Tables

Table 1. Rainfall [mm], surface temperature [K], sensible heat flux [W m⁻²], latent heat flux [W m⁻²], PBL height [m], and TCW [mm] of 10 extreme events averaged over Jeddah from the two experiments Urban and Desert, and the changes (URBAN minus DESERT). Rainfall changes are display in percentage. The first row of rainfall is from Jeddah station daily records.

Date		1987-12-05	1989-12-11	1992-01-10	1996-11-15	1996-11-18	1996-12-29	2002-11-30	2009-11-25	2010-12-30	2011-01-26	Mean
Rainfall [mm]	Station	21.0	30.0	38.4	24.0	46.5	23.6	29.0	80.0	29.0	124.0	44.6
	URBAN	18.75	24.05	45.19	54.81	34.46	41.32	32.77	93.45	62.60	54.45	46.2
	DESERT	11.57	20.86	37.68	42.16	19.56	35.80	24.73	71.83	57.72	45.72	36.8
	Changes	62%	15%	20%	30%	76%	15%	33%	30%	8%	19%	26%
Surface temperature [K]	URBAN	297.0	295.5	293.4	295.8	297.7	295.0	297.7	297.1	295.7	294.4	295.9
	DESERT	296.9	295.2	292.6	295.2	297.5	294.5	297.4	296.6	295.3	294.4	295.6
	Changes	0.07	0.25	0.77	0.59	0.24	0.59	0.29	0.45	0.39	0.01	0.36
Sensible heat flux [W m ⁻²]	URBAN	-1.7	-1.4	-9.7	-9.5	-19.3	-17.2	-17.4	-11.9	-21.7	-16.2	-12.6
	DESERT	-4.3	-1.5	-11.6	-13.0	-24.1	-19.6	-20.8	-13.8	-24.6	-17.1	-15.0
	Changes	2.6	0.1	1.9	3.4	4.8	2.4	3.4	1.8	2.9	0.9	2.4
Latent heat flux [W m ⁻²]	URBAN	0.2	-0.4	-0.7	0.7	3.3	-0.1	0.3	0.4	0.1	-0.1	0.4
	DESERT	0.4	0.0	-0.4	1.4	4.7	0.4	1.5	0.6	1.0	0.9	1.0
	Changes	-0.2	-0.3	-0.2	-0.7	-1.4	-0.5	-1.2	-0.2	-0.9	-1.0	-0.7
PBL height [m]	URBAN	63.9	92.0	179.3	289.5	896.0	467.1	546.5	429.0	561.9	435.3	396.1
	DESERT	59.4	76.8	94.4	257.0	775.6	351.7	507.2	305.6	464.0	301.8	319.4
	Changes	4.5	15.2	84.9	32.5	120.4	115.4	39.3	123.4	97.9	133.5	76.7
TCW [mm]	URBAN	41.9	42.0	41.5	33.8	27.6	29.7	45.8	49.2	41.2	43.9	39.6
	DESERT	39.8	40.3	40.2	33.2	27.3	29.4	44.9	47.1	40.0	41.7	38.4
	Changes	2.06	1.69	1.26	0.60	0.30	0.32	0.92	2.06	1.21	2.14	1.26

Table 2. The default urban parameters used in the UCM.

Urban Parameters [Unit]	Value
Roof level (building height) [m]	7.5
Standard Deviation of roof height [m]	3.0
Roof (i.e., building) width [m]	9.4
Road width [m]	9.4
Coefficient modifying the Kanda approach to computing surface layer exchange coefficients.	1.29
Thickness of each roof layer [m]	0.05, 0.05, 0.05, 0.05
Thickness of each building wall layer [m]	0.05, 0.05, 0.05, 0.05
Thickness of each ground (road) layer [m]	0.05, 0.25, 0.50, 0.75
Lower boundary condition for roof layer temperature	Zero-Flux
Lower boundary condition for wall layer temperature	Zero-Flux
Lower boundary condition for ground layer temperature	Zero-Flux
Ch of Wall and Road	Empirical Form of Narita et al. (1997)
Surface and Layer Temperatures	4-layer model
Anthropogenic heating	No
Anthropogenic latent heat	No
Oasis effect	Not active
Evaporation scheme for impervious surfaces (for roof, wall, and road)	Hypothesized evaporation during large rainfall events (Original)
Urban irrigation scheme, for vegetation in urban area and green roof	No irrigation
Green roof	No
Fraction of the urban landscape which does not have natural vegetation. [Fraction]	0.9
Heat capacity of roof [J m ⁻³ K ⁻¹]	1.0x10 ⁶
Heat capacity of building wall [J m ⁻³ K ⁻¹]	1.0x10 ⁶
Heat capacity of ground (road) [J m ⁻³ K ⁻¹]	1.4x10 ⁶
Thermal conductivity of roof [J m ⁻¹ s ⁻¹ K ⁻¹]	0.67
Thermal conductivity of building wall [J m ⁻¹ s ⁻¹ K ⁻¹]	0.67
Thermal conductivity of ground (road) [J m ⁻¹ s ⁻¹ K ⁻¹]	0.4004
Surface albedo of roof [fraction]	0.2
Surface albedo of building wall [fraction]	0.2
Surface albedo of ground (road) [fraction]	0.2
Surface emissivity of roof [-]	0.9
Surface emissivity of building wall [-]	0.9
Surface emissivity of ground (road) [-]	0.95
Lower boundary condition for roof temperature [K]	293.0
Lower boundary temperature for building wall temperature [K]	293.0
Lower boundary temperature for ground (road) temperature [K]	293.0