Interaction between urban surface boundary and mesoscale weather

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1. Introduction

Urbanization is one of the extreme cases of the change in land-use and land-cover. In a local environment, the urbanization usually influences the boundary layer processes in several ways such as urban heat island (UHI) effect, local circulation, localized convection and consequently, the occurrence of rainfall. The UHI effect is very well known in urban environment. However, our understanding on the urbanization and its impact on the occurrence of rainfall is limited. In view of the scientific interests and implications, the present study is undertaken in order to enhance the understanding of the urban effects on the atmospheric boundary layer (ABL) and the associated interaction with the local weather. Further, urban areas influence ABL structure and its height due to the modification of the near surface atmosphere because of modified surface roughness and thermodynamics. The ABL characteristics can also be modified by the land-sea breeze system and occurrence of rainfall.

The Tropical Rainfall Measuring Mission (TRMM) observations reveal that there is an average increase of about 28% in monthly rainfall rates within 30-60 km downwind direction of cities, with a modest increase of 5.6% over the metropolis (Shepherd et al., 2002). Numerical modelling efforts including that of Guo et al. (2006) showed that the total accumulated precipitation over the urbanized region and its distribution is intensified and concentrated in the down wind direction as well. According to this study, the decrease in moisture availability at the surface modifies the cloud updraft and downdraft. Further, due to the increase in roughness length over land, the upper level convection weakens and the lower level convection strengthens. Another modelling study by Lin et al. (2008) also indicates that the UHI effect can perturb thermodynamic processes to affect the thunderstorms and precipitation is more pronounced in the downwind direction with the increase in urban size. Similarly, the studies carried out by Shem and Shepherd (2009) reveal that the urban modification causes distinct differences in the temporal and spatial evolution of explicitly resolved precipitation during summer time convective conditions and rainfall amounts increase by 10% to 13% within a strip 20-50 km east of the city in the downwind direction. Thus, the past scientific development relating the urban effects indicate that the urban environment has a major impact on the localized precipitation variability and the boundary

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layer characteristics (e. g. Miao et al., 2011). On the other hand, the understanding of the precipitation variability and triggering in rainfall due to urban modifications over a tropical city like Singapore is still unclear. None of the earlier studies emphasized upon the symmetry or asymmetry of land-use distribution when the amount of land available for an urban development is limited like that of Singapore. Therefore, the present study considers the highly resolved terrain (here after micro-terrain) over Singapore having a maximum height of 166m (Li et al., 2013) and the occurrence and non-occurrence of rainfall is analysed especially due to urbanization pattern.

2. Case studies, Numerical model and experimental design

Based upon the observed values of convective available potential energy (CAPE) and 850hPa wind speed, the cases with low advection (≤ median value of all the considered cases ~ 5.44 ms^{-1}) and high CAPE (≥ median value of all the considered cases ~961.08 J kg^{-1}) are chosen for simulation purpose. Out of 28 such cases during 2008-09 inter-monsoon periods, two are considered as a representative of with (wet case) or without (dry case) rainfall for extensive discussion in this paper. These cases are: (i) 12 UTC May 04 – 00 UTC May 06 (dry case) and (ii) 12 UTC April 01 – 00 UTC April 03 (wet case), 2008.

The present study adopts advanced research WRF modeling system (version 3.2.1) in a high resolution framework in order to simulate the two cases. Telescopic one-way nesting technique is used, in order to configure the model domains in 1:3 horizontal grid ratios with five nests having resolutions 24.3, 8.1, 2.7, 0.9 and 0.3 kilometres. Each domain contains 38 vertical eta (η) levels (out of these at least 12 levels are within the boundary layer) with terrain following co-ordinates (Table 1). For all nested domains including their parents, the model top boundary condition is specified by considering a pressure of 50 hPa and the bottom boundary condition is of physical type.

Table 1: Model configuration and physics considered during the simulations

Integration time step	81 seconds
Number of grid points	76 × 76 (domain 1), 79 × 91 (domain 2), 112 × 112 (domain 3 and 4), 211 × 130 (domain 5)
Number of vertical model eta levels	38
Microphysics	Goddard scheme
Radiation scheme (long wave)	RRTM scheme
Radiation scheme (short wave)	Dudhia’s short wave radiation
Surface layer physics	Monin-Obukhov based similarity
Land-surface physics	Unified Noah land-surface model
Urban Parameterization	Single layer Urban Canopy Model (for d05 only)
Boundary layer physics	Mellor-Yamada-Janjic scheme
Cumulus convection	Kain-Fritsch (KF) scheme (for d01 and d02 only)
Dynamic option	Eulerian mass
Time integration	3rd order Runge-Kutta
Mode of simulation	Non-hydrostatic

The model is initialized through a standard procedure using six hourly NCEP (National Center for Environmental Prediction) / NCAR (National Center for Atmospheric Research) global FNL data (http://dss.ucar.edu/datasets/ds083.2/data/) of $1^o x 1^o$ resolution in all simulations. In the initialization process of WRF model, the USGS (United States Geological Survey) geographical land-use and topography data is used along with the 3 seconds (resolution) Shuttle Radar Topography Mission (http://www2.jpl.nasa.gov/srtm/) or SRTM data, MODIS 30 seconds land-use data and the high-resolution (3 seconds) land-use data set obtained from the Centre for Remote Imaging Sensing and Processing (CRISP), National University of Singapore. The land-surface variables and topography height are further modified in domain 4 (d04) and 5 (d05) to maintain the modeling consistency largely with that of the present-day. The high resolution 3 seconds CRISP modified land-use data sets contain three urban land-use categories such as low-intensity residence, high-intensity residence and industrial or commercial areas. Four experiments are primarily designed in order to study the impact of symmetry and asymmetry of land-use distribution in the context of limited availability of land for urban growth in Singapore. The modified land-surface representations are used to carry out the control (here after CTRL) experiment. The other three experiments are: (i) SURB, (ii) NURB and (iii) HURB. In the SURB experiment, southern parts of Singapore are converted to industrial or commercial land-use type and northern parts of the main-land Singapore are converted to tropical ever-green broad-leaf forest (Figure 1a). In contrast to the SURB experiment, the land-use distribution in the southern and northern parts is altered to tropical ever-green broad-leaf forest and industrial or commercial categories respectively in the NURB experiment (Figure 1b).

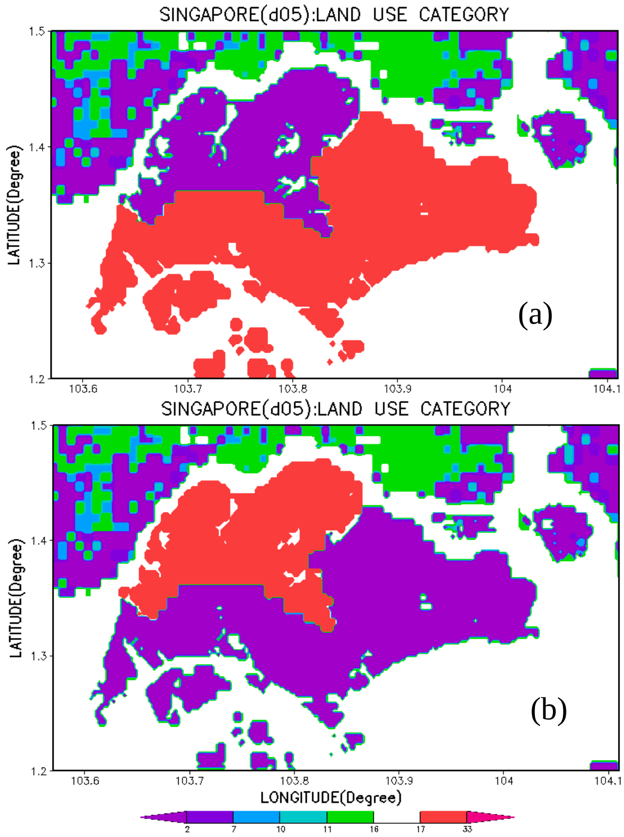

Figure 1: Land-use categories (index) over Singapore and its neighbourhood from domain 5 for: (a) SURB and (b) NURB experiments. Here, 2 – ever green broad-leaf forest, 7 – shrub lands, 10 – grass lands, 11 – permanent wet lands, 16 – sparsely vegetated land, 17 – water and 33 – industrial or commercial areas.

Further, HURB experiment is designed by considering the homogeneous distribution of industrial or commercial land-use (nearly 50% urbanization) and ever-green broad-leaf forest category all over the main-land Singapore and over the islands present in its south (Figure 2). The land-use distribution over the three islands in north-east side of main-land Singapore is kept unchanged for all experiments.

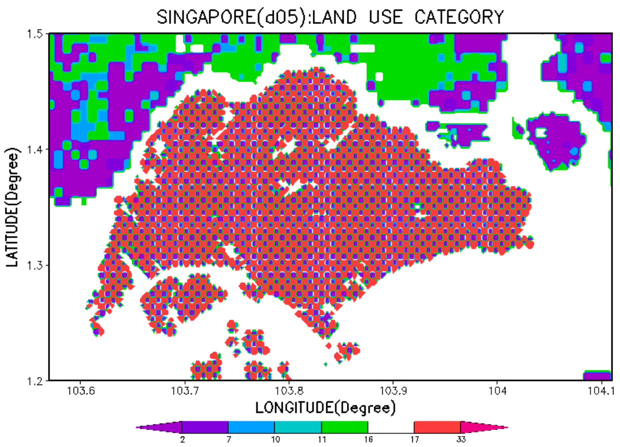

Figure 2: Land-use over Singapore and its neighbourhood from domain 5 for HURB experiment. The land-use categories are the same as given in figure 1.

For simulating the considered cases using WRF model, a set of physics options is chosen (Table 1) taking into account the earlier studies available in literature. In order to taken into account the urban effects, single layer (Kusaka and Kimura, 2004) urban canopy model (UCM) is coupled with the Noah land-surface model (Chen and Dudhia, 2001) or Noah LSM, for providing more accurate forecasts over urban areas of Singapore. The single layer UCM (or SLUCM) estimates surface temperature and fluxes over urban land-use. Since anthropogenic heat (AH) is an important input for the simulation of urban effects (e. g. Li et al., 2013), it is provided to the SLUCM in WRF model through a diurnal profile and a peak value for each of the three urban categories (Quah and Roth, 2012). The peak values of AH for low-intensity and high-intensity residential land-use type are considered as 13Wm^{-2} and 18Wm^{-2} respectively for all simulations. However, the peak value of AH for industrial or commercial land-use category is taken as 113Wm^{-2} in CTRL experiment. The corresponding AH values in SURB, NURB and HURB experiments are 39, 97.5 and 58 Wm^{-2} respectively. The purpose of considering such values is to get the similar area averaged hourly accumulated sensible heat flux from these experiments as that of CTRL experiment in d05. These values are obtained through a rigorous process.

In all experiments, the initial 12 hours of simulation are left out by taking into account the spin-up period. Therefore, the model results from last 24 hours starting from 00 UTC (i. e. from 08AM) next day are considered for discussion in this study. It may be noted that the local time is 8 hours ahead of the universal coordinated time. The simulated results from various experiments performed in this study would be discussed in the following sections in terms of local time (LT).

3. Result and discussion

The model simulated results from the CTRL experiment are compared with those from SURB experiment for the ambient characteristics and are found to be comparable to each other (figures not shown). In view of the similarity of SURB with CTRL, the results from SURB are used as reference in the discussion. Further, the presence of maximum urbanized area in the southern parts of Singapore, offers enough logical view of simplifying the urbanization pattern like that of SURB. The results from dry case would be analysed in view of the evolution of land-sea breeze system whereas the wet case would be highlighted for the occurrence or non-occurrence of localized convective rainfall.

3.1 Impact of asymmetric urbanization

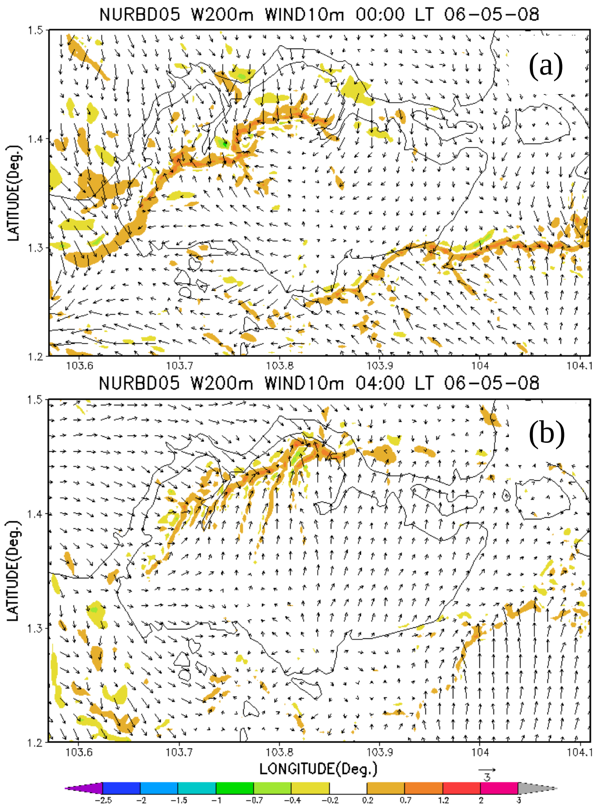

Figure 3: Land-breeze system in dry case during night from NURB experiment on May 06 at: (a) 12:00 am, and (b) 04:00 am. The shaded contours of 200 m (from sea level) vertical wind speed ‘w’ (m s^{-1}) are supper-posed by 10m wind (m s^{-1}) field.

The dry case considered in the present study, shows a systematic evolution of land-breeze during night. Such behaviour of land-breeze system is not witnessed in NURB (Figure 3) in contrast to SURB (Figure 4a and 4b) experiment. In the NURB experiment, part of the land-breeze front is trapped in the urban area and other part travels further towards southeast coast. The trapped part of the land-breeze front in NURB, does not remain stagnant and shows back and forth movement, which is not prevalent in SURB experiment. The trapping of a part of the land-breeze front in the NURB experiment occurred because of the isolation of the urban area (with higher AH) from relatively warmer open sea.

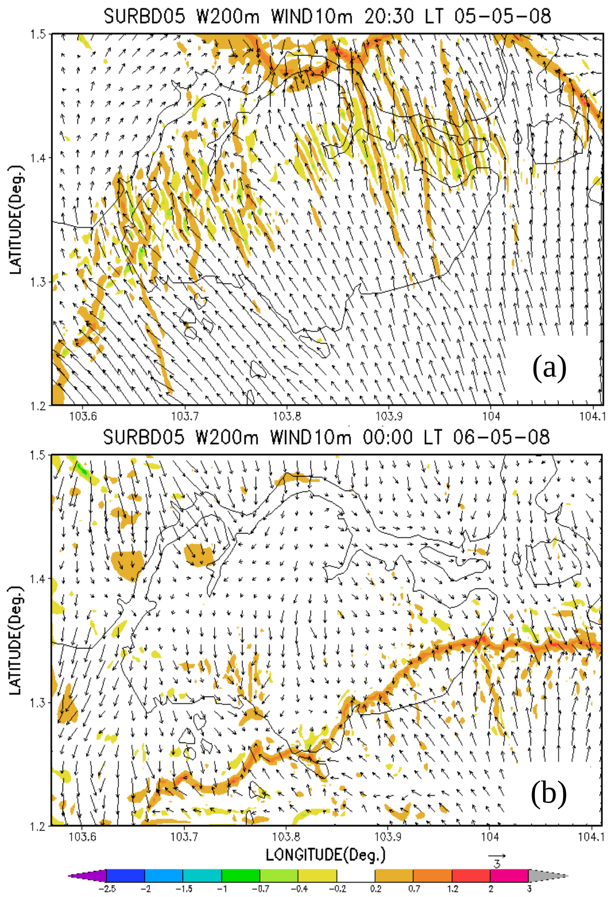

Figure 4: Land breeze system in dry case from inner-most domain at: (a) 08:30 pm on May 05 in SURB, and (b) 12:00 am on May 06 in SURB experiment. The shaded contours of 200 m (from sea level) vertical wind speed ‘w’ (ms^{-1}) are supper-posed by 10m wind (ms^{-1}) field.

It may be noted that the higher heat capacity of water and its slower cooling rate as compared to land causes a lower temperature gradient with the neighbouring urban areas in SURB whereas the presence of forested region in the southern parts of Singapore makes the northern urbanized areas isolated from the warm open sea in NURB experiment. Keeping the urbanized pattern intact, when the supplied AH to urbanized area is reduced, the trapping of land-breeze front is still found to be persistent, along with the back and forth movement (figures not shown for brevity). Therefore, the asymmetric urbanization plays a dominant role in the evolution of land-breeze in general and the trapping effect and back and forth movement in particular.

The land-breeze from peninsular Malaysia side also upsurges the sensible heat in the northern parts of urban areas besides cooling down the near surface air by advection, while it traverses through the urban areas in dry case. This feature is found to be prominent in both NURB and SURB experiments (figures not shown for brevity).

The rainfall episodes usually are of localized in nature. The sea surface is warm enough to encourage the transportation of moisture through the advection of moist air by sea breeze (that comes into effect due to the land-sea temperature contrast and urbanized land-use). The low level convergence of the sea breeze, encouraged by the presence of extra buoyancy in air gives rise to convectively unstable condition over land and consequently, patchy rainfall occurs over northwest parts of Singapore (e. g. Figure 5). This rainfall episode shown as patch A in the northwest part of Singapore starts at 12:10 pm LT in SURB and intensifies during next 20 minutes and appears to split into two parts. One part weakens and gradually decays whereas the other part gradually moves towards farther south and lasts till 1:50 pm LT in the SURB experiment. This rainfall episode corresponding to patch A, is absent in NURB experiment because of unavailability of the extra buoyancy and convective instability while the sea-breeze passes through the southwest parts of Singapore.

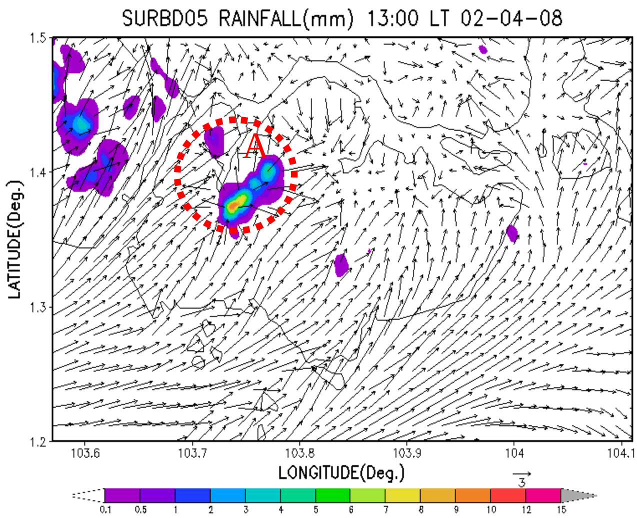

Figure 5: Interaction of sea-breeze (10 m wind; unit ms^{-1}) with the localized opposing flow causing low-level convergence and convective rainfall (mm) in wet case (shaded rainfall patch A) from SURB at 1:00 pm LT.

The southeast rainfall episode indicated as patch B (e. g. Figure 6) starts around 10:00 am LT and persists till noon in SURB experiment. In this episode, the convective instability over the urban areas also gives rise to low-level sea-breeze convergence and thus, leads to convective rainfall.

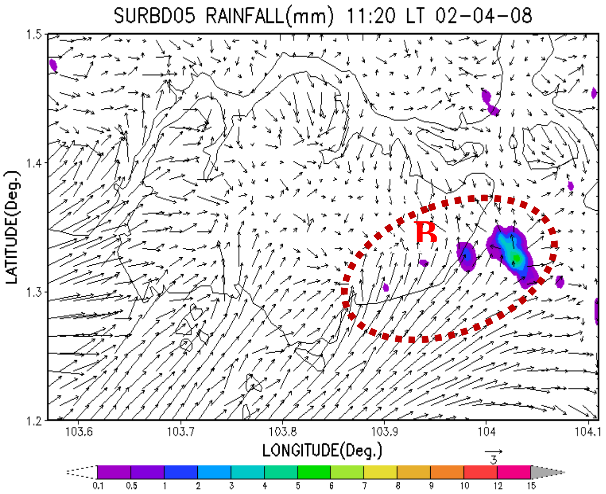

Figure 6: Spatial distribution of rainfall (mm) in wet case from inner-most domain on April 02 at 11:20 am LT ((shaded contours) in SURB experiment superposed by 10m wind (ms^{-1}) vectors.

However, the episode gradually concentrates into two localized patches along the southeast coast; intensify up to 1.5 mm s^{-1} in the NURB experiment and gradually disappears around 1:10 pm. The persistence of the rainfall in the southeast parts of Singapore for more than an hour in NURB experiment and relatively stronger intensity could be attributed to drawing of more moisture by sea-breeze due to isolated northern urbanized region in case of NURB. Consideration of low AH values for urban areas (keeping the urban pattern intact) in different experiments are found to change the intensity and location of rainfall. Therefore, the pattern of urbanization apparently plays a key role in the occurrence and non-occurrence of rainfall during wet case besides the location of the urbanized area.

When it is raining, the rainwater at the surface acts as a thermal buffer since it absorbs heat from the environment, reducing temperature rise or fall. Therefore, the rainfall is able to reduce the skin temperature at the ground slightly over the non-urban area. However, the urban contribution of sensible heat has mitigating effect that gives a negative feedback to the 2m air temperature. On the other hand, the main cause of reduction of skin temperature is cold pool advection (figures not shown).

3.2 Impact of symmetric urbanization

In in the dry case, the simulated land-breeze during night, in HURB experiment evolves in the similar manner as that of SURB. It is because of the homogeneous nature of urbanization pattern throughout main land Singapore in the HURB experiment and the urban areas are not isolated from the warm open sea. Considering same diurnal profile of AH as that of HURB and the same land-use pattern of SURB and NURB (termed as SURBH and NURBH experiments respectively) if the simulations are carried out, the land-breeze evolution in SURBH is found to be similar to that of HURB, whereas NURBH showed trapping effect like that of NURB.

The homogeneous pattern of urbanization over Singapore shows the occurrence of both episodes corresponding to patch A and B. Presence of both northwest and southeast patches in HURB experiment suggests that the homogeneous urbanization bears the characteristics of both SURB and NURB. In HURB, the sea-breeze passing through the southern urbanized area gains extra buoyancy giving rise to convective instability like that of SURB and consequently gives rise to the localized rainfall in the northwest parts. Since the southern parts in HURB contains both urban and non-urban area mixed together, the resulting low buoyancy gives rise to lower convective instability as compared to that of SURB. Similarly, HURB also contains both urban and non-urban areas mixed together in the northern parts and therefore, a relatively weaker sea-breeze in the southeast coastal region draws less moisture compared to that of NURB. Consequently, the lower convective instability results in less intensity rainfall in the southeast coast during HURB experiment as indicated by patch B (Figure 19a). It bears similarity with SURB as far as less intensified southeast rainfall is concerned.

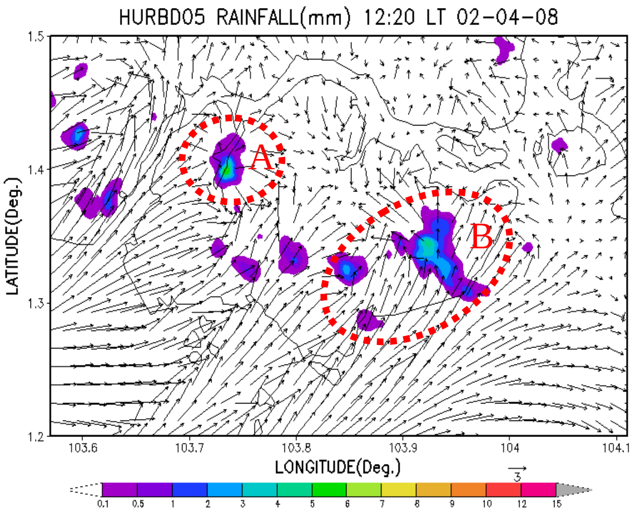

Figure 7: The rainfall (mm) episodes corresponding to northwest patch A and southeast patch B (shaded contours) at 12:20 pm LT on April 02 in HURB experiment and corresponding 10m wind (ms^{-1}) vectors.

In order to find out the significance of urbanization pattern in the occurrence of rainfall, NURBH and SURBH experiments are also carried out in the wet case. The occurrence of northwest episode corresponding to 'patch A' in SURBH shows similarity with SURB and HURB. Similarly, the occurrence of southeast episode corresponding to patch B in NURBH shows similarity with NURB and HURB. However, the intensity, duration and spreading area of rainfall may vary in addition to the slight shift in location. Thus, the homogeneous urbanized pattern in HURB has both the characteristics of NURB and SURB to play a role in the occurrence of both rainfall episodes corresponding to patch A and B and AH has relatively lesser role to play in such episodic occurrences.

4. Concluding remarks

Urbanization in coastal tropical cities in particular is an important aspect of study because of the complex interaction of mesoscale weather including land-sea breeze system and occurrence of rainfall with the underlying land-surface. In view of this, the current study is undertaken over Singapore, where the availability of land is limited for urban growth. In such a situation the symmetric and asymmetric distribution of urbanization gains its importance.

In dry case, the asymmetric urbanization in northern parts of Singapore results in land-use trapping because of the isolation of the urban area from the warm open ocean.

The localized convective rainfall in northwest and southeast parts of Singapore cools the near-surface air by absorbing the heat from the environment and acts like a thermal buffer. The resulting cold pool advection during the occurrence of rainfall reduces the rise or fall of temperature at the surface. Therefore, the localized convective rainfall influences the skin temperature, sensible heat flux and 2 m air temperature. Though the mechanisms are similar irrespective of the experiments designed in this study, it is found that the occurrence and non-occurrence of localized rainfall episodes are dependent upon symmetry and asymmetry of urbanization. Further, the various experiments, show that sometimes the homogeneity nature of land-use distribution tends to average out the effects or complementary in nature like that of wet case. The homogeneous distribution considered in this study contains causal elements of both types of asymmetric distributions, and consequently, shows the characteristics of both otherwise it does not. Therefore, the effects of symmetry and asymmetry urbanization depend upon mechanisms as well.

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