Sensitivity of precipitation statistics to urban growth in a subtropical coastal megacity cluster

Christopher Claus Holst¹,⁎, Johnny C.L. Chan¹,², Chi-Yung Tam³

¹. School of Energy and Environment, City University of Hong Kong, Hong Kong, China
². Guy Carpenter Asia-Pacific Climate Impact Centre, City University of Hong Kong, Hong Kong, China
³. Earth System Science Programme, The Chinese University of Hong Kong, Hong Kong, China

ARTICLE INFO

Article history:
Received 16 December 2016
Accepted 11 January 2017
Available online 27 January 2017

Keywords:
Urban precipitation
Micro climate sensitivity
Urbanization

ABSTRACT

This short paper presents an investigation on how human activities may or may not affect precipitation based on numerical simulations of precipitation in a benchmark case with modified lower boundary conditions, representing different stages of urban development in the model. The results indicate that certain degrees of urbanization affect the likelihood of heavy precipitation significantly, while less urbanized or smaller cities are much less prone to these effects. Such a result can be explained based on our previous work where the sensitivity of precipitation statistics to surface anthropogenic heat sources lies in the generation of buoyancy and turbulence in the planetary boundary layer and dissipation through triggering of convection. Thus only mega cities of sufficient size, and hence human-activity-related anthropogenic heat emission, can expect to experience such effects. In other words, as cities grow, their effects upon precipitation appear to grow as well.

© 2017 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.

Introduction

In this short paper, we present the results of a numerical experiment to investigate how the size of an urban area can affect the local precipitation statistics. The question was motivated by observations made in Hong Kong, situated in the Pearl River Delta at the South China Sea. Mok et al. (2006) reported that urban and rural heavy precipitation trends diverge: heavy rainfall in urban Hong Kong seems to increase at a larger rate than heavy precipitation on offshore islands away from the city. This raises an important question as to whether the difference is locally forced or a side effect of larger scale changes of flow patterns in the atmosphere. From the Metropolitan Meteorological Experiment METROMEX (e.g., Ackerman et al., 1978; Huff and Changnon, 1972; Changnon, 1979), intensification of rainfall downstream of St. Louis has been observed. Recently, similar observations were reported and studied in Beijing (Yu and Liu, 2015; Yu et al., 2013). Other authors reported that the affected areas also expand over cities (e.g., Atkinson, 1971; Bornstein and LeRoy, 1990; Bornstein and Lin, 2000; Shepherd et al., 2002; Dixon and Mote, 2003; Mote et al., 2007; Meng et al., 2007; Krishtawal et al., 2010; Niyogi et al., 2011; Yu et al., 2013). Trenberth et al. (2003) gave an overview about the changes to precipitation statistics that are to be expected when evaluating footprints of climate change as a long-term forcing trend. Most studies related to local forcing emphasized the effects on the temperature and the secondary circulation (e.g., Vukovich et al., 1976; Vukovich and King, 1980). Different interaction mechanisms of urban rainfall have been discussed in the

⁎ Corresponding author.
E-mail address: christopher.holst@cityu.edu.hk (C.C. Holst).

http://dx.doi.org/10.1016/j.jes.2017.01.004
1001-0742/© 2017 The Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. Published by Elsevier B.V.
past, mostly focusing on the mechanical and microphysical effects (e.g., Pielke et al., 2007). Recently, we proposed a thermodynamic contribution as well based on the results of a numerical experiment in which the simulated rainfall statistics in the urban Pearl River Delta responded sensitively to anthropogenic heat flux (AH) at the urban surface, locally causing significant increases of heavy precipitation (Holst et al., 2016). Following up on this work, we now design a relatively simple experiment to test whether the previously described effect could occur in smaller towns as well, if forced by the same magnitude of AH. The setup of the numerical model and the method of modifying the land surface information about urban extend is described in Section 1. An important description of the sampling area and its implications is pointed out in Section 2 and the results are shown in Section 3 together with an interpretation. Finally, the portability and significance of the findings are discussed in Section 4.

1. Model system setup and experiment design

Wu et al. (2015) proposed an indexing method to evaluate the impact of rainstorms in Hong Kong and rank the storms. Their work suggests a number of interesting cases to study, out of which we chose the record-breaking case on 7 June 2008. The case is of substantial interest in several ways because it shows a rather typical synoptic pattern that recurrently has been the cause of rainstorms in the region in the past. Such a pattern consists of a monsoon trough, located slightly north of and parallel to the coastline. In this particular case, the trough formed south of the coastline and over the period of several rainy days the large scale-flow advected the trough towards the north (refer to Fig. 1 for the early development stage). This system draws moisture from the sea and if in the right position, such system has the potential to cause torrential rainfall wherever the moist air is forced to rise in the convergent belt. Rain gauge and anemometer observations show southerly winds causing high instantaneous rainfall rates in Hong Kong (not shown) and radar reflectivity imagery shows a rain belt swiping over the region (Fig. 2a). This storm has been chosen as a benchmark case to investigate as to how the spatial extent of an urban area affects the flow and precipitation behaviour.

We utilize the Weather Research and Forecast Model (WRF, Skamarock et al., 2008) to simulate this case under the influence of several different lower boundary conditions. The two-way nested daughter domains and their urban areas are shown in Fig. 3a, where the outermost domain resolves on 25×25 km² grid cells and the nests obey nesting ratios of 1:5. The initial and lateral boundary conditions were obtained from the National Center for Environmental Prediction Final Reanalysis data set (FNL; National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (updated daily since 2000)), see http://dx.doi.org/10.5065/D6M043C6. The model physics and

Fig. 1 – Surface weather chart depicting the mean sea-level pressure (contours) and station weather conditions on 5 June 2008, at 0800 Hong Kong time from the Hong Kong Observatory data archive (http://envf.ust.hk/dataview/hko_wc/current/).
The essential and important modifications have been made in the realm of the lower boundary conditions, prior to pre-processing. The models pre-processing system evaluates the spatial structure of the domains lower boundary by analysing a stationary surface variable that stores the fraction of different land use categories as defined in the model parameters. This fractional variable should add up to one, if summed over all land use categories, e.g., for any set parameterization are set up in a similar way as described in Holst et al. (2016).

The essential and important modifications have been made in the realm of the lower boundary conditions, prior to pre-processing. The models pre-processing system evaluates the spatial structure of the domains lower boundary by analysing a stationary surface variable that stores the fraction of different land use categories as defined in the model parameters. This fractional variable should add up to one, if summed over all land use categories, e.g., for any set parameterization are set up in a similar way as described in Holst et al. (2016).

The essential and important modifications have been made in the realm of the lower boundary conditions, prior to pre-processing. The models pre-processing system evaluates the spatial structure of the domains lower boundary by analysing a stationary surface variable that stores the fraction of different land use categories as defined in the model parameters. This fractional variable should add up to one, if summed over all land use categories, e.g., for any set parameterization are set up in a similar way as described in Holst et al. (2016).
of horizontal grid indices \(ix\) and \(iy\) the equation \(\sum_{k=1}^{N} LANDUSEF(ix, iy, k) = 1\) holds true, if \(N\) is the total number of land use categories. Given this condition to the variable, modifications can be made without interfering in the pre-processors capability to interpret the lower boundary condition. One can, for example, turn all urban areas into ice, grassland, tundra, thirds of each or any other combination of land surface types as defined by the related parameter tables for studying the effects of doing such modifications upon the local micro climate.

To compare different states of urban development, two sources of data are considered, both of which are freely available with the WRF package. The first is a dataset from the U.S. Geological Survey (USGS), which originates from approximately 1984 and the more recent dataset from approximately 2004, which is derived from satellite measurements. Both data sets are mapped onto the same domain and the recent surface static data are adjusted to include the older urban data with smaller city size. All blank grid cells are replaced with evergreen broad leaf forest, as this is an indigenous form of forest in the region’s low-lying areas. The differences in urban land use are shown in Fig. 3b. The urban area in the region grew from 171 km\(^2\) to 9200 km\(^2\), where the total domain spans over 55,000 km\(^2\). Since the urban area increased by a factor of 50, we expected to find very different sensitivity to local precipitation statistics.

In order to resolve smaller and high intensity rain clusters more accurately, we extract hourly precipitation rates every 5 min by subtracting accumulated precipitation at any point in time with the value that occurred 5 min earlier and multiply that difference by 12. This yields reasonably sharp snapshots of precipitation rate fields over the domain. Vertical cross sections of the temperature and moisture fields (see Fig. 4) show that the model produces boundary layer clouds and precipitation near forest slopes and stratiform as well as convective precipitation as expected. This indicates that the horizontal resolution is sufficiently high to resolve surface-driven micro circulations and allow for the deep convective motion that we aim to investigate in our study of heavy precipitation.

As inferred from our past experiment (Holst et al., 2016), precipitation rates are highly sensitive to surface sensible heat flux, hence this effect needs to be taken into account as well when comparing different boundary conditions. By comparing Fig. 2b, c and d with a, we find that different values of AH produce somewhat similar precipitation patterns. However, the intensities vary greatly and the variations are not systematic in different parts of the domain. Hence we analyse statistics for the simulation period to identify any systematic difference. Averaging three ensemble members initialized at different times is found to yield sufficient sample size and robustness, as there was no significant difference between three and five ensemble members in the statistics.

2. Sampling area

Representativeness of sampling areas is an interesting issue when investigating urban expansion, especially when investigating urban growth of a factor 50 as mentioned earlier when describing Fig. 3b. We chose to investigate the statistics in urban and non-urban grid points and furthermore separated our
analysis into different urban extents. The concept is similar to conducting observations and measuring at the same location at different times, independent of environmental behaviour. If comparing model precipitation statistics for different degrees of urban extent in the sampling area of 1984 (171 urban grid points) we take the perspective of someone who might have been observing weather locally at some station throughout that time. If however we do a similar comparison for the sampling area of 2004 (9200 urban grid points) we can find, how the region that is urban nowadays was affected in the past by the presence of a smaller city, e.g., how the urbanization manifested in the statistical behaviour.

The distinction between the two perspectives yields hints towards the understanding of footprints caused by human activities in precipitation statistics. Remote effects as mentioned and cited in the introduction are difficult to investigate unless large numbers of cases are taken into account, so in this paper we focus on the analysis of local sensitivity to local forcing.

3. Results

In the first part of this discussion we present the results as evaluated from a perspective of a small sampling area extent. For the sake of simplicity, we will discuss based on the case in which the maximum amplitude of AH is assumed to be 500 Wm$^{-2}$ and compare it to the zero AH case. The same arguments may be applied to the discussions of 250 Wm$^{-2}$.

In Fig. 5a we visualize the probability density functions (PDF) of simulated precipitation rates throughout the simulations in different parts of the domain for model grid points marked as urban (left side) and non-urban (right side) respectively. The right inset shows the spatial extent of different forcing areas using the same colours as the bars. We compare six bars referring to three different AH forcing magnitudes (shades) and two different areas (colours, see right inset or Fig. 5b). The left inset shows the ratio of the non-zero AH experiments over the zero AH experiments for direct assessment of the systems sensitivity in the cases of different lower boundary conditions.

The most obvious difference appears when comparing 500 AH 2004 urban to the others, showing a high sensitivity if large amounts of heat are released over large areas. When looking carefully, we also find a decrease of 0 AH 2004 relative to 0 AH 1984 over urban and an increase over non-urban. One can interpret that some precipitation is moved out of the city by initiating vertical velocities that produce precipitation downstream of the city. This effect corresponds to Oke’s description of urban mixed layers that are displaced as plumes by background flows (Oke, 1988) and reflects the findings in METROMEX (Huff and Changnon, 1972) and in Beijing recently (Yu and Liu, 2015). When comparing 0 AH 1984 urban and 0 AH 2004 urban bars we find that the presence of a city itself without heat sources slightly lowers the precipitation in the city, but increases the precipitation in non-urban grid points. This is related to the convergence line effects as well as changes in local evaporation and heat storage. The central urban area appears to be shielded from the precipitation by the increased roughness while the edges of the city are more exposed. It is noteworthy that despite the absence of anthropogenic heat fluxes in the area, the increased absorption of solar irradiation and additional heat storage still change the thermal behaviour of the flow. Once human heat release is turned on however, the precipitation in the central urban area increases dramatically. This effect is related to generation of buoyancy and convection due to increased mixing of warmer air near the surface. The effect does not occur if the model is forced only in the small area of urban extent (compare 500 AH 1984 urban and 500 AH 2004 urban).

When investigating Fig. 5b in a comparable way, we find that the larger sampling area is even less sensitive to the presence of a small city, even when forced with significant human induced heat release (compare 0 AH 1984 and 500 AH 1984). However, this area is also less sensitive to large amounts of heat release on the large area itself (compare 500 AH 2004 urban in Fig. 5a and b) while the non-urban area appears to be slightly more sensitive (500 AH 2004 non-urban Fig. 5a and b). Since most of the urban area of 2004 in Fig. 5b is evaluated as non-urban when evaluated by 1984 urban area standard, much of the urban precipitation in Fig. 5b is non-urban in Fig. 5a.

The differences described above point to the key conclusion, that cities below certain size and degree of human activity density (e.g., AH) may change the flow, but not significant enough to trigger local convection. Once cities exceed a certain size, the local forcing effects become dominant and produce locally specific flow features, for example locally bound convective precipitating clouds.

4. Concluding remarks

In our previously published work (Holst et al., 2016) we established that enhanced fluctuations of turbulence and the relative importance of local buoyancy flux are largely involved in the triggering of local convective flow patterns. This leads to heavier precipitation over large urban areas. In this piece of work, however, we find that this enhancing effect on precipitation is not present if the flow is exposed to a relatively small urban area, despite significant surface heat forcing through human activities as parameterized.

This leads to the conjecture that there is certain critical characteristic of a mega city, below which no human induced effects on precipitation statistics are to be expected locally. This characteristic measure is related to the spatial extent and energy release at the urban surface locally and to synoptic flow pattern and moisture availability on larger scales. The latter have to be taken into account because even a small city or heat source may trigger local convection in a calm flow and the occurrence and magnitude of precipitation are affected by the moisture availability in the lower troposphere in such case.

Consequently the results obtained locally for the Pearl River Delta Region are not portable to the mid latitudes or other regions without careful consideration of the differences in moisture availability and flow behaviour, as well as differences in human activities which determine the magnitude of anthropogenic heat release at the surface. Developed mega cities in tropical and subtropical coastal regions may experience these effects in more drastic ways, as more heat is
generated by extensive use of air conditioning systems, especially during hot humid summer days.

More availability of data resources and more consolidation effort would be needed to produce accurate representations of urban land surfaces in this region, as temporal and spatial heterogeneity of human activities are not well represented in the model we used. A description of some complications involved in modelling AH can be deduced from Allen et al. (2011) who have been modelling AH for many major cities. Yang et al. (2014) reviewed the interaction between global warming and human behaviour changes from the perspective of China as a nation with significant urban growth and huge population. Our experiments are aiming at fundamental and specific questions. However they do not provide a universal solution to improved local precipitation forecast in the region.

The implications to climate sensitivity scenario downscaling simulations are also putting the uncertainty of statistical results of such studies into a concerning perspective with growth of mega cities being difficult to simulate but expected to occur according to United Nations (2012).

Acknowledgement

We thank Prof. Julian Hunt, Keith Ngan and Eric Ng for the fruitful discussions. Chi-Yung Francis Tam acknowledges the

Fig. 5 – Probability density functions for different 5 min interval hourly precipitation rate bands as shown on the horizontal axis. The black bars refer to small city’s forcing effects while the red bars refer to the large city’s effects. The magnitude of the surface heat flux scales from 0 (pale colours) to the maximum amplitude of 500 Wm$^{-2}$ (full colours). The left and right panels of the figure show urban and non-urban behaviour respectively. The sampling was carried out as shown in the right insets for the (a) small (black) and (b) large city extend (red area). The left insets show the different sensitivity of the precipitation to human activities as induced by anthropogenic heat flux.
support of the Hong Kong Research Grant Councils Early Career Scheme (No. 104712). Christopher C. Holst acknowledges the support of the City University Institutional Post Graduate Studentship.

REFERENCES


Mok, H.Y., Leung, Y.K., Lee, T.C., Wu, M.C., 2006. Regional rainfall characteristics of Hong Kong over the past 50 years. Conference on Changing Geography in a Diversified World, Hong Kong Baptist University, Hong Kong, China, 1–3 June 2006, Hong Kong Observatory Reprint 646.


