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Impact of urban growth-driven landuse change on microclimate and extreme precipitation — A sensitivity study

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ABSTRACT

More than half of the humanity lives in cities and many cities are growing in size at a phenomenal rate. Urbanisation-driven landuse change influences the local hydrometeorological processes, changes the urban micro-climate and sometimes affects the precipitation significantly. Understanding the feedback of urbanisation driven micro-climatic changes on the rainfall process is a timely challenge. In this study we attempt to investigate the impact of urban growth driven landuse change on the changes in the extreme rainfall in and around cities, by means of sensitivity studies. We conduct three sets of controlled numerical experiments using a mesoscale atmospheric model coupled with a land surface model to investigate the hypothesis that the increasing urbanisation causes a significant increase of extreme rainfall values. First we conduct an ensemble of purely idealised simulations where we show that there is a significant increase of high intensity rainfall with the increase of urban landuse. Then four selected extreme rainfall events of different tropical cities were simulated with first current level of urbanisation and then (ideally) expanded urban areas. Three out of the four cases show a significant increase of local extreme rainfall when the urban area is increased. Finally, we conducted a focused study on the city of Mumbai, India: A landscape dynamics model Dinamica-EGO was used to develop a future urban growth scenario based on past trends. The predicted future landuse changes, with current landuse as control, were used as an input to the atmospheric model. The model was integrated for four historical cases which showed that, had these events occurred with the future landuse, the extreme rainfall outcome would have been significantly more severe. An analysis of extreme rainfall showed that hourly 10-year and 50-year rainfall would increase in frequency to 3-year and 22-year respectively.

1. Introduction

Today, more than half of the world's population lives in cities. Due to the increasing concentration of businesses and infrastructure, the urbanisation process continues at a phenomenal rate. The urban water cycle and the local climatic environment are invariably affected by the urban growth (Foley et al., 2005). The causal relationship between urbanisation and increased stormwater flows due to the hydrological changes on the surface is well understood and quantified. It is common knowledge that the urbanisation increases runoff due to the retardation of infiltration and evapotranspiration processes, and decreases the resistance to flow. The question whether the rainfall itself is changed due to the micro-climatic changes above cities as a consequence of urban landuse change, was being asked since the 1960s. Today, there is an increasing body of evidence that the changes in the radiation and heat balance affected by changes in surface albedo and vegetation cover on the urban micro-climate

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can have significant impacts on the precipitation patterns over urban centres and their surroundings (Watkins and Kolokotroni, 2013). These hydro-meteorological effects are caused by a) microphysical changes resulting from urban pollution, b) increased surface roughness due to urban structures and c) heat anomalies resulting from changes in albedo and latent heat flux — 'urban heat island (UHI)' (Sagan et al., 1979). While the urban heat island effect on radiation, temperature and wind has been documented relatively early (Taha et al. (1988), Landsberg (1981) and references therein) modelling investigations on the impact on rainfall appeared late in the literature. Some of the difficulties in the latter endeavour is summarised by Lowry (1998). There have been many empirical investigations indicating the possibility of the urban growth and the resulting UHI modulating precipitation (e.g. Shepherd, 2006; Jauregui, 1996; Subbiah et al., 1990; Lin et al., 2008, 2009; Takahashi, 2003). Of particular interest is the Metropolitan Meteorological Experiment (METROMEX), a major observational study conducted in the US in the 1970s (Changnon, 1979). METROMEX findings showed that precipitation down-wind of large cities can increase 5%–25% from background values (Shepherd, 2005). Charabi and Bakhit (2011) used meteorological data measured over a period of one year over the city of Muscat, Oman, to study the urban heat island over the city. They found that the hottest locations occur at the compactly built 'old Muscat' neighbourhoods in narrow valleys. During the rare winter rainfall spells the intensity of UHI decreased. Meir et al. (2013) examined two 2011 heat events in New York City to evaluate the predictive ability of 1 km resolution US Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) model and 12 km resolution North American Mesoscale (NAM) implementation of WRF model using a land and coastline based observation networks. The high resolution model was able to capture the key features of the heat events, where urban rural temperature differences were as high as 4–5 °C.

Numerical modelling experiments are extremely relevant in understanding and quantifying the possible effect of UHI on rainfall, as this is probably the only way to conduct controlled studies at city and regional scales to investigate the sensitivity of various influencing parameters. Shepherd (2005) noted that there had been relatively few studies in this field. Since then there have been a number of reports on such experiments. Shem and Shepherd (2009) conducted controlled experiments on three landuse scenarios for Atlanta, USA, with different levels of urbanisation and concluded that there is a significant impact of UHI on cumulative rainfall quantities resulting in increases of 10% to 13% for increased urbanisation. Lin et al. (2008) reported results of numerical experiments comparing impacts of UHI on rainfall by comparing the atmospheric response to synthetically increasing urban area in the case of Taiwan. They concluded that the UHI interaction with summer-time sea-breeze and mountain uplifting contributes significantly to increase rainfall in the mountainous areas on the leeward side of the city. On the other hand, analysing the 7th July 2004 thunderstorm over Baltimore, USA by means of controlled modelling studies, Ntelekos et al. (2008) concluded that UHI did not contribute to the heavy rainfall during the event.

Most of the studies in the recent literature on the UHI and precipitation had a strong focus on mesoscale meteorology, and often stopped short of making impact assessment at the urban scale. It is indeed challenging to translate the predictions of the impacts of UHI driven changes in the meteorological events to forms that can be readily used by civil engineers to plan urban water infrastructure. Such an attempt would invariably result in large uncertainties and could leave many gaps in reasoning that future research has to fill in. However, the possible strong causal link of urbanisation on urban extreme rainfall can no longer be ignored, particularly in the context of rapid urban growth and numerous external pressures like global climate change. There is a growing interest on the role of land cover and landuse change on climate change (Solomon et al., 2005), partially due to the awareness raised by events like the Nerima heavy rainfall (Kawabata et al., 2007) and general indications of significant increase of extreme rainfall in rapidly urbanising locations like the Indian subcontinent that are suspected to be triggered by UHI (Kishtawal et al., 2010). However, in order to understand the impacts on the issue of urban drainage and flooding, it is important to understand the influence of UHI on short-term, extreme rainfall — the driving force on urban storm water system. The fact that most populous cities, which happen to be in the Third World, have already over-stressed that storm drainage systems further increase the relevance of it.

In this paper, we present the results of a series of numerical experiments conducted using a state of the art, 3D mesoscale atmospheric model — WRF-ARW (Skamarock et al., 2005) — in order to attempt to understand the impact of urbanisation-driven landuse change on the extreme rainfall events in and around cities. Our hypothesis is that changes in urban landuse cause significant changes in extreme rainfall in urban centres and surrounding areas. We propose that these changes will have significant implications on the planning and implementation of urban drainage projects, mitigation of urban floods and ensuring the human security in cities in general. It should be noted that we limit the scope of this sensitivity study to the possible changes in the urban heat budget, due to changes in the thermal properties (radiative, latent heat) of urban landscape. We ignore the possible changes in boundary layer roughness (due to tall buildings) and microphysical changes due to urban pollution.

First we present the results of idealised experiments that indicate the sensitivity of increase of urban land use to rainfall and the related mechanisms. For the second set of experiments, we have selected a number of extreme rainfall events from around the world that caused significant urban flooding. We conducted 'what-if' type of analyses on these events. We introduced a simplified artificial urbanisation with the scenario that the city grows to twice its original diameter and investigate what level of influence this 'urban-growth' would have on the magnitude of rainfall. Finally, for the City of Mumbai, we conduct detailed urban growth modelling, that would give many more realistic extrapolations of landuse change during the next two decades based on historical trends and various influencing spatial parameters. We used standard statistical techniques used in rainfall frequency analysis to interpret the results in the context of urban storm drainage design and urban flooding, so as to demonstrate the practical implications of the findings.