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Vulnerability to heat waves: Impact of urban expansion scenarios on urban heat island and heat stress in Paris (France)

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ABSTRACT

The evolution of heat-wave risk in cities is related to regional climate change in interaction with urban heat island. Land planning and urban transport policies, due to their long-lasting impact on city's size and shape, can also have an influence. However, these combined effects are complex and strongly depend on the indicators used to quantify heat-wave risk. With Paris area as a case study and using an interdisciplinary modelling chain, including a socio-economic model of land-use transport interaction and a physically-based model of urban climate, air temperature in the city during heat waves is simulated for five urban expansion scenarios. The urban heat island is always higher at night and affects preferentially the city centre. Its intensity and spatial extension are moderately impacted by densification process and choice in urban form. But the variation of heat-wave risk with the densification dynamics is not limited to the effect on urban heat island, and also depends on exposure to heat of population. Spatial distribution of population in the city differs according to urban expansion scenarios. The results show that the compact city, by concentrating the inhabitants in areas the most impacted by heat island effect, amplifies the overall vulnerability of population.

1. Introduction

The global warming induced by greenhouse gases emissions is already observed and is going to intensify during the 21st century according to climate projections at the global scale (Meehl and Tebaldi, 2004; Schär et al., 2004; IPCC, 2013). One of the expected consequences is the raise of occurrences of heat waves, that has been highlighted at global and regional scale by numerous studies (Huth et al., 2000; Beniston et al., 2007; Chauvin and Denvil, 2007; Vautard et al., 2007). This issue has for instance been investigated for France by the IMFREX project (Déqué, 2007; Planton et al., 2008), as well as for the Paris region by Lemonsu et al. (2013, 2014). Especially, Lemonsu et al. (2014) indicate that heat waves will become more frequent at the end of the century (at least one event per year), but also they will last longer and will be more intense than today.

These extreme meteorological events are a source of growing concern for cities and urban populations, because high temperatures reached during heat waves are often exacerbated due to urban heat island (UHI) effect (Basara et al., 2010; Tan et al., 2010; Gabriel and Endlicher, 2011; Li and Bou-Zeid, 2013). As a result, there are rising concerns of public and

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institutional stakeholders about the vulnerability of urban areas facing these events (see for instance, Stone and Rodgers, 2001; Solecki et al., 2005; Hamin and Gurran, 2009; Lambert-Habib et al., 2013).

The specificities of urban climate and the resulting UHI are strongly determined by both morphological characteristics and material properties of the urban landscape. Some local-scale action levers are already considered by architects and urban planners for a better thermal regulation of microclimate; for example the use of light-colour materials favoring the reflective properties (Santamouris et al., 2011; Kolokotsa et al., 2013) or the implementation of urban vegetation either ground-based (Potchter et al., 2006; Shashua-Bar et al., 2009) or on building envelope (Harazono et al., 1991; Wong et al., 2003).

In addition, at any given place in the city, the UHI can be impacted by the characteristics of the city as a whole, e.g. its size and shape or the composition and arrangement of the neighbourhoods within it. The choices of urban planning at the scale of a city or of a community of conurbations may consequently play a key role in adaptation strategies (Bass et al., 2003; Rosenzweig et al., 2009; Masson et al., 2013a). The effects of actions led at city-scale, however, may be tricky to understand and evaluate due to the interaction of multi-scale physical processes (i.e. a local action can influence a place far from it due to atmospheric processes) but also of socio-economical mechanisms (i.e. a local action can induce a change in inhabitants behaviours or choices, such as for instance a relocation in the city).

We propose here to study this question, and to examine to what extent city-wide actions can have an impact on urban heat island effect and heat wave vulnerability. We focus on a representative issue: whether compact or spread-out city developments can have a positive or negative impact on UHI and heat wave risk. The comparison between advantages and costs of compact and spread-out city developments has nourished a long-standing academic debate (see for example Newman and Kenworthy, 1989; Ewing, 1997; Gordon and Richardson, 1997; Ewing et al., 2003; Eid et al., 2008; Brueckner and Largey, 2008). This has been recently revived by climate issues and greenhouse gases emissions reduction concerns. A dense urban form indeed reduces urban expansion. It may help reducing urban travel distances and increasing public transport and non-motorized transport modal share, as well as reducing building energy use (see for instance OECD, 2012; Viguié and Hallegatte, 2012). However, city shape influence on UHI and, consequently, on heat wave vulnerability has been proposed as an important element of the debate. Higher densities may exacerbate UHI, in turn generating the need for more cooling and increasing energy use (McEvoy et al., 2006; Hamin and Gurran, 2009; Mees and Driessen, 2011). This is part of the "density conundrum" (Hamin and Gurran, 2009).

There is no clear consensus so far on how the city densification may influence UHI. Thus, the present study tries to shed new light on how different urban planning policies, leading to more or less compact city shapes, can impact the intensity and form of UHI. This impact is a priori not trivial to infer. The spread-out and compact city forms have different footprints, which may affect the spatial extent of UHI at city scale. In addition, the urban typologies favored by the different urbanization trends modify locally the types of land covers and the morphological characteristics. As an example, the spread-out city favours low-density urban typologies and the presence of vegetation, and limits the proportion of impervious covers, so that the UHI effect can be potentially mitigated. We study this question using Paris urban area as a case study, and compare the impact on UHI and heat wave vulnerability of different prospective city development scenarios.

This work is a result of a French research project (VURCA) that aimed at assessing the vulnerability and possible adaptation strategies of Paris metropolitan area to future heat waves. This issue has been investigated by accounting for the interactions of urban climate, local impacts of climate change, and the evolution of the city itself, thanks to an interdisciplinary approach involving researchers in climate, urban meteorology, economy, and buildings sciences and techniques.

The next section describes the numerical modelling methodology, more particularly the tools used for the production of urban expansion scenarios and the modelling of urban climate. Model evaluation is then presented in Section 3. Section 4 is dedicated to the presentation of indicators used to quantify and compare UHI effects. Finally, Sections 5 and 6 investigate how urban sprawl strategies impact the UHI and urban population. Section 7 concludes.

2. Modelling city evolution and urban climate

2.1. Overall methodology

The climate of Paris region – as it could be in 2100 under heat wave conditions – is studied by combining the local-scale effects of climate change on such extreme meteorological events and the impacts of urban sprawl. This analysis is carried out using a bottom-up approach. We use three steps simulations (see Fig. 1) in which both urban expansion scenarios and regional meteorological forcing conditions are used to feed a physically-based urban climate model.

We review in this section each of these three steps: maps of city evolution and sprawl scenarios are first created using a socio-economic land-use transport interaction model, NEDUM-2D, and technical assumptions about future buildings characteristics (Section 2.2, Step 1 in Fig. 1). Meteorological forcing is then built for an ensemble of heat-wave conditions varying in intensity and duration and defined starting from the analysis of regional climate projections (Section 2.3, Step 2 in Fig. 1). Finally, these two inputs are used by physically-based Town Energy Balance (TEB) urban canopy model in order to simulate the urban climate of Paris, especially the urban heat island (UHI), as well as the thermal comfort conditions for indoor and outdoor environments (Section 2.4, Step 3 in Fig. 1).