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Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change

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A B S T R A C T

Recent climate projections predict an amplification of global warming and more frequent extreme events such as heat waves. Therefore, the adaptation of cities to counterbalance these adverse changes is urgent. Among available adaptation strategies, urban greening is a measure that is frequently encouraged to improve thermal comfort or energy demand, but whose impacts are not well known at the scale of cities. In this study we evaluate the effects of various urban greening scenarios based on urban climate simulations across the Paris area. The modelling relies on the Town Energy Balance model. The scenarios tested consist of an increase in ground-based vegetation or an implementation of green roofs on compatible buildings, or the two combined. Results show that increasing the ground cover has a stronger cooling impact than implementing green roofs on street temperatures, and even more so when the greening rate and the proportion of trees are important. Green roofs are however the most effective way to reduce energy consumption, not only in summer but also on an annual basis. The effects the various greening measures may have over different seasons is finally addressed in order to draw up a comprehensive inventory of the climatic impacts of such strategies.

1. Introduction

Current climate projections forecast an amplification of the global warming (Meehl and Tebaldi, 2004; Stocker et al., 2013) and an increase in extreme events (Giorgi, 2006). Those global trends that translate at regional and local scales, are likely to have significant impacts in cities, that are home to the majority of the population, namely a change in the intensity of the urban heat island (highly dependent on the soil water resources, such as highlighted by the work of Lemonsu et al., 2013), increased health risks (as attested by the 15,000 excess deaths due to extreme heat observed in August 2003, Hémon and Jougla, 2004), not to mention the increase in the use of air conditioning to meet the comfort needs of the inhabitants (180% between 2003 and 2020 according to Adnot, 2003a,b) . These perspectives make cities territories where not only mitigation issues will be the strongest, but also potentially territories more vulnerable to climate change than natural environments.

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There are different forms of adaptation strategies to reduce this urban vulnerability, involving actions on requalification of surfaces, urban forms, inner and outer building envelopes, or on individual behaviors. Urban greening strategies, more specifically, have multiple interests. Thanks to vegetation cooling potential, they are both adaptation measures to climate change and mitigation measures for urban heat island and air-conditioning demand. Beyond climatic considerations, urban greening also delivers additional benefits to the urban ecosystem, such as a better management of stormwater (Ashley et al., 2011; Stovin, 2010; Stovin et al., 2008), a reduction of air pollution (Currie and Bass, 2008; Hill, 1971; Nowak et al., 2006; Pugh et al., 2012) or an increase in urban biodiversity (Getter and Rowe, 2006; Madre et al., 2014; Mullaney et al., 2015) for example.

This is by modifying its radiative, thermal, hydrological and aerodynamic properties that vegetation affects the urban environment. These modifications result from three physical processes: direct evaporation of the water held in the soil and intercepted by the foliage of plants (daytime and nighttime), the transpiration of all types of plants (generally daytime, but can also occur at nighttime for some plant species or under certain climates), and finally the interception of solar radiation for tree species (daytime). But there is a wide range of greening solutions that have different effects depending on the scale at which they are implemented (building, street, neighbourhood, city), on the plant species selected, on the local climatic conditions, but also on the aspects studied (thermal comfort, energetics, dynamics, hydrology, etc.). This is shown by the vast literature on the subject, whether from experimental or numerical studies.

Greening the building envelopes can reduce surface temperatures compared to artificial surfaces, which limits the amount of heat that can penetrate into buildings (Eumorfopoulou and Kontoleon, 2009; Kontoleon and Eumorfopoulou, 2010; Onmura et al., 2001; Sternberg et al., 2011; Takebayashi and Moriyama, 2007; Wong et al., 2010). In doing so, they diminish the seasonal temperature variations inside buildings (Castleton et al., 2010), generating energy savings, but without totally achieving the efficiency of conventional insulation according to Eumorfopoulou and Aravantinos (1998) and Eumorfopoulou and Kontoleon (2009). Urban greening takes also other forms through street trees, urban parks or forests. On the basis of a meta-analysis of the literature on these types of strategies, Bowler et al. (2010) show that urban parks generate an average day cooling in the range of 0.94 °C, with variations which are explained in particular by the size of the park (Barradas, 1991; Chang et al., 2007) and its composition (tree/lawn ratio, Potchter et al., 2006) but also the surrounding climate. They also highlight that the temperatures under the trees are systematically cooler than the surroundings during the day, with variations depending on tree shading capacity Shashua-Bar and Hoffman (2000). At nighttime, however, tree canopy could retain heat (Liangmei et al., 2008; Souch and Souch, 1993; Taha et al., 1991). Besides, a study by Souch and Souch (1993) suggests that the thermal performance of trees can vary depending on the type of surface on which they are planted (grass or concrete, for example). The evapotranspiration potential conditioned to water status of plants and soils, and irrigation practices, is also a crucial point which has received very little attention to date, except by Shashua-Bar et al. (2009) who propose an efficiency coefficient which links cooling effect and evaporation.

For operational purposes within the frameworks of urban policies, the analysis and evaluation of such strategies need to be examined at a large scale. So far, only a few numerical studies investigate the cooling potential of large-scale strategies of urban planning, such as the implementation of green and blue corridors for Paris urban area (Groupe Descartes, 2009), or of green roofs over Toronto (Bass et al., 2003) and New York City (Rosenzweig et al., 2009).

Our study aims to complement the scientific literature, but also better meet the expectations of urban planners and decision makers, through a physically-based and detailed modelling of urban climate, using Paris urban area as a study case. The originality of the work lies (1) in the development of realistic urban greening scenarios, implemented locally but assessed at city scale; (2) in the comparison of different vegetation installations in urban environment, on roofs (with or without irrigation) and on the ground (lawns, mixed vegetation); (3) in the multi-criteria evaluation of scenarios which covers the issues of heat exposure and thermal comfort, energy consumption, and water demand; and (4) in the time scales that are investigated (for a specific heat wave, as well as at seasonal and annual scales).

The next section (Section 2) presents the basis for the construction of the different scenarios that we simulated, the numerical configuration used as well as its evaluation before greening. Then various impacts are assessed, both in extreme summer conditions (heat wave, Section 3) and for the rest of the year (Section 4) to evaluate whether these greening measures devised to meet heat wave issues have adverse effects on the rest of the year or not. The impacts studied are thermal comfort and energy consumption for use of air-conditioning (AC) and heating, which are good indicators of the vulnerability of cities to heat waves, but are also about the management of urban water (volumes required for watering the vegetation and generated by surface runoff throughout the year). The last section (Section 5) draws the conclusions of this work and suggests ways to develop this approach.

2. Methodology for evaluating greening scenarios at city-scale

The initial aim of this study is to evaluate, based on modelling, greening scenarios which may represent strategies to improve future summer conditions in cities. As the European heat wave of 2003 is identified by the scientific community to be representative in mean temperatures of summers of the second half of the 21st century (Déqué, personal communication), the meteorological conditions associated to this heat wave are taken as a study case to evaluate greening scenarios. This methodology, focusing on Paris city, relies on simulating the urban climate of Paris with the Town Energy Balance (TEB) urban canopy model (Hamdi and Masson, 2008; Masson, 2000). The first step consists in designing for Paris city greening scenarios that are at the same time realistic and promising and that can also be taken into account by our model. In a second step, the urban climate of Paris is simulated at the spatial resolution of 1 km with TEB in offline mode (with meteorological forcings) for each