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Sensitivity study of the energy balance to urban characteristics

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ABSTRACT

A detailed urban heat exchange simulation software, the Town Energy Balance (TEB), has been used to analyse the impact of urban parameters on energy balance during a summer and a winter day under Paris, France, climatic conditions. Computer runs were conducted to explore the influence of each of the urban parameters selected. The results showed that impacts of these parameters differ between summer and winter. In summer, radiative parameters like roof and wall albedo have the strongest influence on urban energy balance. Whereas in winter, thermal parameters like wall and roof thermal insulation have the strongest influence on urban energy balance. This analysis corroborates the great influence of roofs albedo on urban energy balance and its role in urban heat island (UHI) mitigation. This also points out the fact that summer UHI mitigation strategies influence urban heat balance during winter season.

1. Introduction

In comparison to rural areas, built-up areas are subject to a modification of surface energy balance (SEB) due to additional sources of energy (Crutzen, 2004; Fan & Sailor, 2005; Ichinose, Shimodozono, & Hanaki, 1999; Oke, 1978), urban geometry (Aida & Gotoh, 1982; Giridharan, Lau, Ganesan, & Givoni, 2007; Oke, 1988; Yamashita, Sekine, Shoda, Yamashita, & Hara, 1986) and materials (Rosenfeld, Akbari, Bretz, et al., 1995; Taha, Akbari, Rosenfeld, & Huang, 1988). Urban heat island (UHI), a well-known feature of urban climate, is one of its consequences.

Recent simulation models that test the sensitivity of the UHI and of the energy balance to mitigation strategies (light colour surfaces, vegetalization, or reduction of anthropogenic heat) are focused on summer days. Although UHI intensity is more important during summer and especially during summer nights (Cantat, 2004), summer UHI mitigation strategies may have some influence in winter too and we propose to explore this question.

In order to study the contribution of different urban factors to the development of the UHI, we have studied the sensitivity of energetic balance with respect to thermal or geometric characteristics of the urban surface. Simulations were done with various sets of parameters under winter and summer climatic conditions.

The outline of this paper is as follows: first a methods and model description section, then, urban area characteristics and parameters, and finally results and conclusion.

2. Methods and model description

2.1. Urban climatology: a research topic

Urbanization replaces natural surfaces by artificial surfaces and introduces anthropogenic heat generation in the urban tissue. These actions modify the micro- and meso-scale climate (Oke, 1978; Landsberg, 1979). Such modifications alter the radiative, thermal, moisture and aerodynamics properties of the urban environment. As a consequence, in most cities around the world, outdoor temperatures in urban areas are higher than the temperatures of the surrounding rural country (Dettwiller, 1978; Dhakal & Hanaki, 2002; Escourrou, 1986; Rosenfeld et al., 1995; Taha, 1997a). This is known as urban heat island (UHI). UHI intensity $\Delta T_{U\text{-}R}$, is defined as the air temperature difference between the city and the surrounding rural area.

Temperature is not the only climatic parameter influenced by densely built areas. Urban areas affect wind conditions: the wind speed at street level can be decreased by urban elements (Nakamura & Oke, 1988) and the intensity of the wind's turbulence is increased (Rotach, 1995). Observations and modelling have also shown that precipitation spatial distribution and amounts over the urban area are influenced by the convergence zone induced by the UHI (Atkinson, 1971; Bornstein & Lin, 2000; Rozoff, Cotton, & Adegoke, 2003; Shepherd, Pierce, & Negri, 2002).

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Nevertheless, UHI intensity is the most frequently studied parameter. Meteorologists first noticed it more than a century ago (Cotte, 1774; Howard, 1833) during the first measurement observation campaigns. Lot of progresses was made during the second half of the 20th century with 3D space observations, remote-sensing methods, numerical simulations, coupling between UHI and building density, roughness parameter, sky view factor, population, energy and water balance studies, etc. (Yoshino, 1990/1991). Progressively climatologists have highlighted the influence of both urban geometry (Aida & Gotoh, 1982; Giridharan et al., 2007; Oke, 1988; Yamashita et al., 1986) and materials (Rosenfeld et al., 1995; Taha et al., 1988). To study UHI, a common urban structural form has been defined: the urban canyon. Urban canyons are symmetrical canyons characterized by their length, buildings height (H), street width (W) and orientation. Oke (1981) reported a correlation between $\Delta T_{U\text{-}R}$ and H/W ratio during calm clear-sky conditions. This urban structural form is also used to describe high-density urban zones such as Paris, France.

UHI was first a topic for climatologists. It now concerns many other disciplines such as design, geography, architecture or town planning. Interdisciplinary works on UHI make sense and are necessary to include some climatic concerns in urban planning and architecture (Bitan, 1988; Eliasson, 2000; Katzschner, 1988; Oke, 1984; Oke, 2006). Urban climate impacts the energy demand of buildings (Santamouris, Adnot, Alvarez, et al., 2004), air pollution (Sarrat, Lemonsu, Masson, & Guedalia, 2006), human thermal comfort (Steemers, 2006), health (Buechley, Van Bruggen, & Truppi, 1972) and fauna and flora (Sukopp, 2004). A better knowledge of UHI impacts and UHI formation could then be beneficial to architects and planners so as to take into account environmental problems and quality of life. The gap between high level theoretical research on urban climate, UHI and the practice of urban planning and architecture tends to be reduced through numerous studies about urban climate consideration in urban planning and architecture (Dhakal & Hanaki, 2002; Givoni, 1998; Katzschner, 1988; Scherer et al., 1999) or about cooling cities (Alcoforado, 2006; Alcoforado, Lopes, Andrade, Vasconcelos, & Viera, 2006; Rosenfeld et al., 1995; Rosenzweig, Solecki, Parshall, et al., 2006; Sailor & Dietsch, 2005; Santamouris et al., 2004).

These reflections either on the relationship between urban climate, architecture and urban planning or on the reduction of the climatic impact of cities, raise the question of 'ideal' cities (from a climatic perspective). Each study provides solutions to achieve the best climatic conditions (Bitan, 1992; Golany, 1996; Landsberg, 1973; Mills, 2003; Yannas, 2001).

Computer science has also allowed access to increasingly powerful numerical models. Building-scale, local-scale and meso-scale models have been developed to simulate urban climatic effects. With a more or less realistic representation of the city, some of these models parameterize urban effects on energetic and water balances or on thermodynamic and momentum fields. In this study, we use the parameterization of Masson (2000): Town Energy Balance (TEB).

Meso-scale models were first developed to improve town representation and influence in regional atmospheric models. The urban canopy surface energy balance (SEB) is the basis of these models which can be classified into three categories (Masson, 2006): empirical models statically fit to observations like NARPS-LUMPS (Grimmond & Oke, 2002), modified vegetation schemes adapted to include an urban canopy like SM2-U (Soil Model for Sub-Mesoscale Urban) (Mestayer, Dupont, Calmet, et al., 2004) and new urban canopy schemes with both horizontal and vertical surfaces like TEB or the Martilli's scheme (Martilli, Clappier, & Rotach, 2002). The TEB scheme is one of the most complete parameterization of urban effects. Except the Martilli's scheme, no other urban parameterization explicitly considers the effects of buildings, roads, and other artificial materials on the urban surface energy budget.

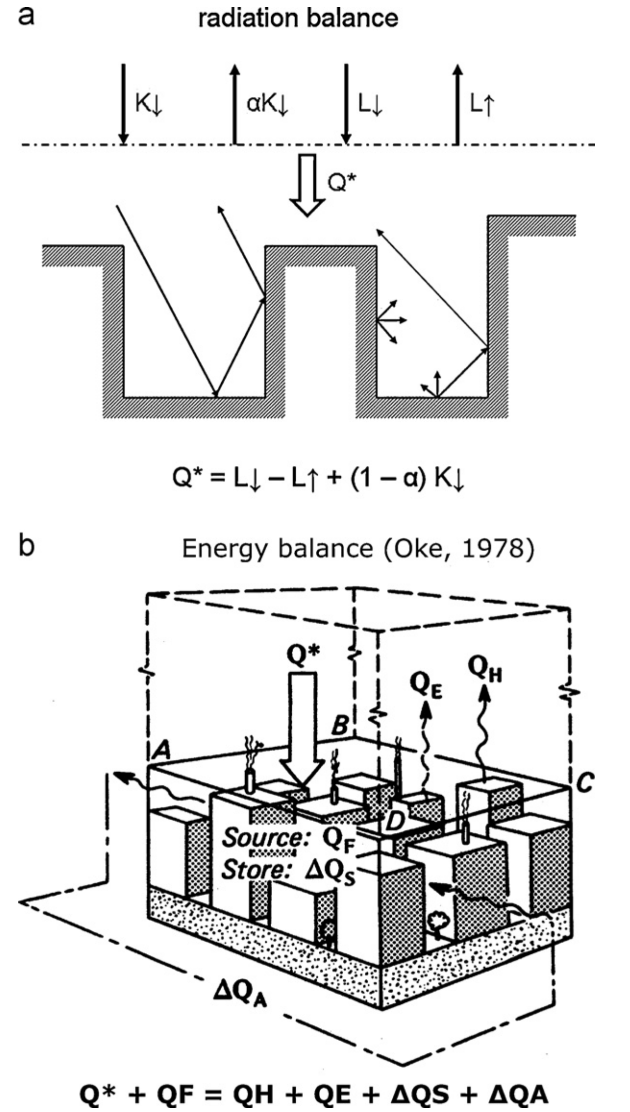

Fig. 1. The (a) surface radiation and (b) energy balance for an urban area. (a) $K\downarrow$: incoming short-wave radiation; $L\downarrow$: incoming long-wave radiation from the atmosphere; $L\uparrow$: outgoing long-wave radiation exiting from a surface; $\alpha K\downarrow$: reflected short-wave radiation (α is surface albedo). (b) Q^*: net all-wave radiation at the top; Q_F: anthropogenic heat flux; Q_H and Q_E: respectively turbulent heat fluxes for sensible and latent heat; ΔQ_S: sensible heat storage by the elements; ΔQ_A: net local advection (the heat advection through the sides of the control volume).

Numerical models are used to represent the realistic climatic influence of a town (Atkinson, 2003; Groleau, Fragnaud, & Rosant, 2003; Ichinose et al., 1999; Krpo, Clappier, & Muller, 2006; Lemonsu, 2003; Masson, Grimmond, & Oke, 2002) but also to study the impacts of strategies for UHI mitigation (Hamdi & Schayes, 2008; Rosenzweig et al., 2006; Yu & Hien, 2006).

2.2. Generation of urban heat island: the surface energy balance

2.2.1. The surface energy balance

The heat generated within and stored by the city can be presented with the surface energy balance (SEB), which takes all the exchanges of energy into account (Fig. 1a), including radiative heat fluxes (Fig. 1b). The SEB is applied to a control volume extending from the ground to the top of the urban canopy layer. Each SEB's