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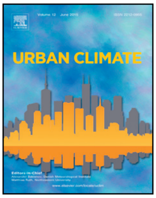

Coupling of physical phenomena in urban microclimate: A model integrating air flow, wind-driven rain, radiation and transport in building materials

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ABSTRACT

Building materials play an important role in the absorption, transport and storage of heat and moisture in the built environment. A fully-integrated urban microclimate model is proposed, which solves for wind flow and for the transport of heat and moisture in the air and building materials. The model includes long-wave and short-wave radiative exchange between surfaces and the distribution of wind-driven rain intensity. Transport in air and building materials are coupled in such a way that the steady Reynolds-averaged Navier-Stokes (RANS) is solved iteratively with the unsteady heat and moisture transfer in building materials. The proposed approach provides the information required for analyzing different contributions of convective cooling, sensible heat transfer due to rain, evaporation, in addition to the thermal storage throughout the day. This approach is demonstrated with a case study investigating the impact of rain deposition on an isolated three-dimensional street canyon lined with porous building materials. The study shows different rate of evaporation and duration of evaporative cooling for a change in wind speed during a rain event. The distribution of wind-driven rain particularly influences the spatial and temporal distribution of surface and air temperatures. A significant influence of neighboring surfaces is found on the surface temperatures.

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1. Introduction

Urban heat island (UHI), which describes the increase in temperature of the urbanized areas compared to the rural one, is observed to intensify due to on-going urbanization and climate change. UHI has adverse effects on thermal comfort and health and leads to increases in energy use for space cooling and in greenhouse gas emissions (Moonen et al., 2012). The main causes of UHI can be summarized as: 1) decreased long-wave radiation loss to the sky due to increase in blockage, 2) increased sensible heat storage due to use of materials with high thermal admittance, e.g. concrete, asphalt, brick, 3) increased absorption of short-wave radiation due to increased reflections and use of low-albedo materials, 4) decreased evapotranspiration due to the reduced presence of soil, water bodies and vegetation, 5) increased anthropogenic heat production due to buildings and traffic, 6) decreased convective heat transport due to reduction in wind speed and 7) increased absorption of long-wave radiation due to air pollution, as proposed by Oke (1982).

A considerable amount of research is currently performed with the aim to decrease the causes that lead to UHI and to assess various mitigation measures. Several recent studies include extensive literature overviews on microclimate (Moonen et al., 2012; Toparlar et al., 2015) and on UHI (Arnfield, 2003; Mirzaei and Haghighat, 2010; Mirzaei, 2015) which mainly categorize the investigation methods in two general groups: observational and numerical methods. Observational methods such as field measurements and thermal remote sensing provide significant information on actual conditions in urban areas. Their main drawbacks are that they are time-consuming and document only the meteorological conditions taking place during the measurements. While it is technically possible to model different environmental conditions in wind-tunnel measurements, such investigations can be very demanding to carry out. Nevertheless, observational methods are widely used to validate and provide boundary conditions for numerical models. More frequently, UHI studies resort to numerical methods. The first type of numerical models consists of urban canopy models (UCM), which solve energy balance equations for a control volume representing typical urban geometries, e.g. two adjacent buildings. UCMs do not model local urban airflow, which is necessary for an accurate prediction of sensible and latent heat fluxes. Instead, such models mostly relate the convective transfer coefficients to a reference wind speed based on empirical correlations (Masson, 2000; Kusaka et al., 2001; de Morais et al., 2016) or drag coefficients (Martilli et al., 2002; Lemonsu et al., 2012). Furthermore, spatial variation of parameters is usually simplified by assuming uniform values over large surfaces, disregarding local effects that are significant at street-canyon scale. An example of local effects is the local temperature difference between air and building surfaces, which is responsible for buoyancy to occur and may thus significantly affect the flow regime (Allegrini et al., 2013) as well as the local air temperature. Air temperature is also influenced by a complex set of parameters such as prevailing wind speed and direction, building and urban environment geometry, building materials and orientation with respect to the sun. To take into account such local effects, the second group of numerical models is based on computational fluid dynamics (CFD), which can resolve buildings and provide detailed information on the local spatial distribution of temperature and wind speed. CFD methods are used commonly in various applications related to urban physics, such as wind comfort, thermal comfort, pollutant dispersion, wind-driven rain (WDR) and ventilation (Blocken, 2014). However, efforts in including all physics are yet to come. Current efforts are mentioned next.

The advantages of CFD are its ability to provide accurate spatial and temporal information and the given possibility to perform parametric studies based on different scenarios. On the other hand, CFD simulations are complex and demanding to perform, which often leads to considerable simplifications in the physics involved in microclimate studies. For example, several numerical studies, which focus on the effect of various urban geometries on the microclimate, use fixed surface temperatures or fixed surface heat fluxes as boundary conditions (Kim and Baik, 2001; Xie et al., 2006). The spatial gradients of these values on the building surfaces, which exist even in the simplest cases, are not considered, nor are their variation during the day and the influence of the thermal storage. However, taking into account heat transport in building materials when modeling urban environments yields the heat stored during day-time due to solar heat flux and the heat released during night-time. These phenomena are the main causes of the UHI. Coupling heat transport in the air with the heat transport in building materials, compared to the cases where a fixed temperature or a fixed heat flux is imposed at building surfaces, gives more realistic boundary conditions for wind flow where buoyancy is significant. Recently, several studies have coupled CFD simulations with heat conduction within the building facades and the ground, using simplified models such as one-directional heat transport (Tominaga et al., 2015; Toparlar et al., 2015) or surface energy-balance models (Li et al., 2005; Kaoru et al., 2011; Ma et al.,

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