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Energy and water budgets of asphalt concrete pavement under simulated rain events

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ABSTRACT

Urban areas are subject to high human pressure and forthcoming enhanced hydrologic and climatic risks due to both city development and climate change. An asphalt concrete parking lot was instrumented in Nantes, France, to quantify the energy and hydrological responses of the surface to simulated rainfalls. The surface fluxes (precipitation, evaporation, radiation exchanges, sensible heat convection and conduction, runoff) were measured in situ and used to close the water budget with residual closure errors lower than 10%, depending on the surface evaporation retrieval method. The latent heat flux estimated from scintillometry measurements provided a better water budget closure than the direct eddy-correlation measurements. Runoff was the primary component of the water budget and represented around 80% of the total precipitation, compared to 17% for surface evaporation. The scintillometry method provided water evaporation time series at a 1-min time scale during the experiment. These series were used to characterize the rapid changes in the hydrological and energetic budgets of the asphalt surface after a precipitation event. During the drying phase the surface evaporation was significantly active, yielding 80% of the turbulent fluxes with a Bowen ratio of 0.25.

1. Introduction

Urban areas concentrate a large portion of human activities that have an increasing impact on the environment due to population growth (Steffen et al., 2015). In particular, rising urbanization significantly modified the hydrological cycle and energy budget of the Earth surface, due to the urban canopy morphology and changes in land use and land cover modes. Due to the complexity and high variety of the urban fabrics, the assessment of environmental impacts, as well as the evaluation of urban planning scenarios and sustainable development in response to climate variability and change increasingly rely on numerical simulations. A large proportion of the urban areas consists of streets, sidewalks, parking lots, and roads, usually made from asphalt concrete pavement. It is therefore

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critical to assess the water and energy budget of asphalt concrete surfaces.

Runoff on urban surfaces is the principal component of the water budget from urban areas. It is usually represented using empirical relationship based on physical initial losses and a constant runoff coefficient. But several studies showed that such parameterization cannot account for all the involved processes (Berthier et al., 1999; Berthier et al., 2004) and that losses through evaporation during frequent rainfall events on these surfaces can reach several millimetres (Gash et al., 2008; Ragab et al., 2003b) particularly on streets (Hollis and Ovenden, 1988; Ragab et al., 2003a; Ramier et al., 2011). Urban surfaces collect atmospheric particulate pollution and the removal by rainwater of this pollution, further conveyed to the catchment outlet by runoff water, is directly influenced by the hydrological cycle and the succession of the wetting–drying periods (Amato et al., 2010). Stream thermal pollution (Herb et al., 2008) is due to the release to runoff water during rainfall events of solar energy absorbed by urban surfaces over warm periods of time and it contributes to increasing the water temperature downstream from urban areas (Kim and Sansalone, 2008; Van Buren et al., 2000). Vice versa this process could also be a solution to a negative impact of urbanization since pavement watering is viewed as a technique to reduce the urban heat island (Kinouchi et al., 1997). A recent experiment has been conducted in Paris in real conditions to improve this technique and to assess its efficiency (Hendel et al., 2016). For these issues the coupled simulation of urban water and energy budgets over long time series would benefit from appropriate experiments, allowing a more detailed parameterisation of both evaporation and runoff losses on urban surfaces (Dupont et al., 2006; Lemonsu et al., 2007; Rodriguez et al., 2008).

Also, interactions between urban canopies and the lower atmosphere have impacts on both the dynamics of the atmospheric boundary layer, through the modification of the partition of latent and sensible heat (Dupont et al., 2006), and the water cycle, enhancing clouds and modifying rain production (Changnon, 1981; Rozoff et al., 2003).

In meteorological models, urban areas were traditionally represented as dry surfaces (i.e., impervious with no or limited infiltration and storage) with high Bowen ratios (Thielen et al., 2000) where rain water is rapidly absorbed by the drainage system (e.g., the gutters). In contrast, Oke (1979) already stressed the variability of urban Bowen ratio, from 1.5 in dry periods to 0.3 after rain events. More recently Ramamurthy and Bou-Zeid (2014) and Santamouris (2014) reported observations of low Bowen ratios for wet urban surfaces and green roofs. In the early development of urban surface energy budget (hereafter denoted SEB) models, rain water and latent heat were not considered or computed separately from the energy budget. Recent models include the influence of evaporation either by combining the water and energy budgets of pervious and impervious surfaces within a tiling approach or by juxtaposing models for the urban (impervious) surfaces and natural (porous and vegetated) areas (see reviews by Grimmond et al. (2010) and Grimmond et al. (2011)). These models are generally derived from physically-based Soil-Vegetation-Atmosphere (SVAT) schemes initially developed for natural areas. However, these models use sets of parameterisations that cannot be easily calibrated due to the difficulties of driving accurate measurements in urban sites and the lack of reliable ground observational networks. SVAT parameterizations are generally derived from isolated measurements at the local scale or on analogies with observations over non-urban sites. Furthermore, based on SVAT formalism, the transfer of energy and water follows a one-dimensional approach that may not be valid in heterogeneous urban environment. Improving our knowledge in this field is of prime importance to foresee and mitigate the climatological change impacts on the urban climate.

The "Role of covered surfaces in urban hydro-system processes" project (ROSURE experiment in 2001–2002 and HydroVille experiment in 2003–2004) was dedicated to the characterization of the water and energy transfer processes within urban canopies, by combining in situ and numerical experiments (Berthier et al., 2004; Dupont et al., 2006; Rodriguez et al., 2008), with emphasis on semi-impervious surfaces, such as roads, streets and parking lots with asphalt concrete pavement.

In this article, we present results from a ground-based experiment conducted in Nantes in June 2004 to describe the water and energy budgets of a homogenous urban area, i.e. a parking lot during and after artificial rain events. This field experiment is unique at this scale (> 1 m^2 and < 1 ha) and in controlled conditions, compared to previous campaigns led on heterogeneous areas: between others, Bubble in Basel (Rotach et al., 2005) or CLU-Escompte in Marseille (Mestayer et al., 2005; Lagouarde et al., 2006) were experiments dealing on energy budget only. The three main objectives of the study were:

- To identify and propose an optimized method to obtain closed energy and water budgets of a semi-impervious parcel at a realistic scale;
- To develop a quality-assessed data set allowing to test and validate urban SEB schemes and hydrological models – this data set is now available upon request to the corresponding author;
- To improve our understanding of the evaporation process and of the energy partition during fair weather showers events.

The methodological issues and the rationale of our study are presented in Section 2. The experimental design and the meteorological data appear in Section 3. Surface flux measurements and uncertainty estimates of energy and water budgets are presented in Sections 4 and 5, respectively. The rapid hydrological and energetic behaviour of the asphalt surface during simulated fair-weather showers is analysed in Section 6. Our results are further discussed in Section 7 and we present a few conclusions in Section 8.

2. Methodological issues and study rationale

The experiment performed in 2004 was devoted to the closure of the water and energy budgets of an asphalt parcel, by measuring or deriving the different fluxes at the surface. The theoretical instantaneous budgets of the water layer covering the measurement area are: