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Surface energy exchange in a dense urban built-up area based on two-year eddy covariance measurements in Sakai, Japan

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A B S T R A C T

Two-year measurements of the surface energy balance were conducted using the eddy covariance method of a dense urban built-up area in Sakai, Osaka, Japan to identify the diurnal, seasonal, and annual variations in the surface energy exchange. The latent heat flux significantly increased with increasing air temperature above a threshold mean daily air temperature (17 °C) during the summer months. High air temperatures can induce increased cooling loads in the buildings and high anthropogenic water vapor emissions. At the diurnal timescale, the storage heat flux obtained from the residual term of energy balance equation was the most important factor of the urban energy exchange; the maximum fractions of the net radiation were 69% during the day and 173% at night. In contrast, turbulent heat fluxes and anthropogenic heat flux were important at the seasonal and annual timescales. Bootstrapping quantified the potential magnitudes of the uncertainties in the coefficients in the objective hysteresis model, which were 30–50% of the average storage heat fluxes at the diurnal timescale, 40–80% at the daily timescale, and 80–260% at the annual timescale.

1. Introduction

Dense urban built-up areas, which are centers of the world's population, modify the surface energy balance and climate conditions that are associated with their unique morphology and human activities. In particular, the urban heat island has received much attention as an important environmental problem (Landsberg, 1981). Because changes in the surface energy balance induce the urban heat island effect, it is important to

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clarify the surface-atmosphere exchanges over urban areas (Zhao et al., 2014). Direct measurements of the surface energy exchange in cities with large populations are a valuable tool for improving our understanding of the mechanisms of urban environmental problems (Grimmond, 2006).

Eddy covariance measurements have determined the surface energy exchanges in several cities. Most observations have been conducted in suburban and residential areas in mid-high latitude cities (Bergeron and Strachan, 2012; Grimmond and Oke, 1995; Ward et al., 2013) or tropical-subtropical cities (Chow et al., 2014; Ferreira et al., 2013; Park et al., 2016) and have demonstrated that the sensible heat flux and storage heat flux are dominant in the urban surface energy balance. In contrast, the number of flux measurements in densely built-up city centers is limited partly due to the logistical difficulty of performing measurements (Christen and Vogt, 2004; Grimmond et al., 2004; Kotthaus and Grimmond, 2014; Miao et al., 2012). Large cities in Japan are unique in terms of their densely built-up areas, significant human activities and their climate, which include hot and humid summers. Continuous observations were conducted in a residential area of Kugahara, Tokyo (Moriwaki and Kanda, 2004), but there is a lack of observations in densely built-up commercial centers in Japan.

The storage heat flux is an important component of the surface energy balance in most urban cities (Grimmond and Oke, 1999). However, spatially representative measurements of this term are often difficult to obtain at the city scale due to the high heterogeneity within a city (Offerle et al., 2005). Many earlier urban studies have assumed the residual term of the surface energy balance equation as the storage heat flux (Grimmond et al., 2004; Kotthaus and Grimmond, 2014; Moriwaki and Kanda, 2004). This method could contain considerable uncertainties because of a known energy imbalance problem of eddy covariance measurements (Wilson et al., 2002). Other studies have used a parameterization scheme (Grimmond et al., 1991) or numerical modeling (Massman et al., 2002) to estimate the storage heat fluxes in urban areas. Unfortunately, standard methods for estimating storage heat fluxes and quantifying their uncertainties have not yet been established (Roberts et al., 2006).

Anthropogenic heat emissions can be important components of urban energy exchanges (Bergeron and Strachan, 2012). Inventory-based approaches have been developed for specific cities. Sailor and Lu (2004) estimated anthropogenic heat emissions in six large US cities and demonstrated that the magnitudes of the anthropogenic heat fluxes were 5–10 times greater in the urban core than the mean of the entire city. Ichinose et al. (1999) estimated large anthropogenic heat emissions of approximately 400 W m^{-2} in the center of Tokyo. Moriwaki et al. (2008) estimated large anthropogenic water vapor emissions of approximately 400 W m^{-2} during the summer in heavily built-up areas of Tokyo. Kayaba et al. (2010) proposed a multi-regression model using a detailed anthropogenic heat dataset in Tokyo and applied it to three urban areas in Japan. Considering the high spatial heterogeneities of the anthropogenic emissions, their contributions to the surface energy budgets must be considered in dense urban built-up areas.

In this study, we determined the diurnal, seasonal, and annual variations of the surface energy exchanges over a dense urban built-up area in Sakai, Osaka, Japan based on two years (January 2014–December 2015) of measurements using the eddy covariance method. Sakai is the second largest city in Osaka prefecture, is highly urbanized. Thus, the obtained data characterize the micrometeorology near urban surfaces that are affected by urban morphology and human activities. We report 1) the important contributions to the surface energy budgets at different timescales, including the diurnal, seasonal, and annual timescales, 2) large water vapor emissions in the dense urban areas, and 3) the magnitudes of uncertainties of the storage heat flux based on the Objective Hysteresis Model (Grimmond et al., 1991).

2. Methods

2.1. Urban surface energy balance

The urban surface energy balance can be expressed as

$$Q^{*} + Q_{F} = Q_{H} + Q_{E} + Q_{S} \tag{1}$$

where Q^* is the net radiation, Q_F is the anthropogenic heat flux, Q_H is the sensible heat flux, Q_E is the latent heat flux, and Q_S is the storage heat flux. The net radiation is calculated from the upward and downward shortwave radiations and longwave radiations.