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Comparative microclimate and dewfall measurements at an urban green roof versus bitumen roof

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ABSTRACT

Urban green roofs are discussed as a local climate adaptation measure to limit surface warming and increase evaporative cooling by vegetation in urban environments. A five month measurement campaign was conducted to observe surface and air temperatures as well as dewfall dynamics and amounts on an urban green and co-located bitumen roof. Measurements were performed in the period from August to December 2012.

Surface temperatures indicated differences of up to 17.4 K, which lead to measurable air temperature differences (ΔT_A) at a height of 0.5 m above roof level. During August afternoons (3 pm) the green roof air temperature (T_A) drops below T_A of the bitumen roof by up to 0.7 K on average. By using a linear regression based approach differences in sensible turbulent heat flux densities (Q_H) between green and bitumen roof of 200 W m^{-2} on a hot day with 30 °C and wind velocities of 2 m s^{-1} were estimated.

During the measurement campaign a total of 60 and 52 dew events were observed on the bitumen roof and the green roof, respectively. At both urban sites the number of dewfall events was distinctly smaller compared to the rural site (94 events). Roof dewfall turned out to be a negligible source in the green roof water balance compared to precipitation amounts. Inhibited dewfall on roofs could be one important factor for the phenomenon of urban moisture excess since roofs represent a high fraction of urban surfaces.

1. Introduction

In view of increasing global temperatures different climate adaptation measures are discussed [1]. Cities are particularly vulnerable for the consequences of climate change, e.g. increased heat stress [2–4]. This is mainly due to large fractions of impervious surfaces, limited amounts of vegetated surface cover types and additional emission of anthropogenic heat [5]. Consequently, cities tend to experience higher near surface air temperatures than their rural surroundings which is referred to as the urban heat island effect (UHI, [5–7]). This goes along with a large number of urban inhabitants that are exposed to the modifications of the urban climate. With rising temperatures, heat waves are thought to become more frequent. Li and Bou-Zeid (2013) [8] demonstrate, that heat waves are more pronounced in urban centers than in rural areas and synergistically interact with the urban heat island.

Global metropolises are growing along with their corresponding UHIs [9,10]. This trend underlines the significance of developing adaptation strategies to cope with negative impacts of climate change in urban environments. As an important urban planning strategy, higher green area densities are discussed [11,12].

In dense urban areas (with low sky view factors) where heat island intensities generally reach maximum values the implementation of parks and wooded areas is unlikely [13,14]. As an alternative approach, greening of buildings can be considered as a strategy to focus on. How green roofs - as one part of this strategy - may serve this approach, is currently debated with regard to UHI mitigation potential [15–21], air quality e.g. Ref. [22], runoff quality and quantity e.g. Ref. [23] as well as energy consumption of buildings [24]. Modelling studies have attempted to quantify possible near surface air temperature reductions of green roofs [15–18,20]. Computed temperature reductions range between 0.2 K for Hong Kong, China [17] and 3 K for Chicago, USA [16]. The given range indicates that there is still some uncertainty about the heat island mitigation potential of green roofs. Surprisingly, a

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limited number of studies on air temperatures reductions is published, which are based on empirical data and the majority of these studies refer to tropical climates of south-east Asia, e.g. Refs. [25–30]. Examples from temperate climates are documented in Teemusk and Mander (2010) [31] who analyse below substrate temperatures in comparison with surface temperatures of conventional roof types. Speak et al. (2013) [32] report on temperature effects of an intensive green roof compared to a co-located concrete roof. Under drought conditions unirrigated green roofs can lose their positive microclimatic effects, because of low evapotranspiration rates and higher surface temperatures [33,34]. More than 90% of green roofs in Germany are unirrigated (pers. Communication ZinCO GmbH, Germany). Therefore only precipitation and dewfall provide water resources for these roofs.

Urban dewfall has been rarely studied so far [35–39]. However, dewfall is discussed as one important prerequisite for the phenomenon of urban moisture excess, i.e. nocturnal periods characterised by higher urban atmospheric humidity conditions in comparison to the rural surroundings [40]. Richards (2005) [38] measured similar amounts of dew on an urban tar roof (mean = 0.12 mm night^{-1}) compared to a rural grass site (mean = 0.10 mm night^{-1}). Richards (2002) [36] emphasizes that dew is a non-negligible source in the urban water cycle. To the author's knowledge, there are no publications yet existent, which compare dew data of conventional and green roofs as well as rural areas to examine the potential role of dewfall as a water source for green roofs.

In the present study comparative dew measurements on an urban extensive green roof and an adjacent bitumen roof as well as a rural grass site are presented. Observed differences of the frequency and duration of dew events as well as the quantification of dew amounts with the applied measurement method will be discussed. Additionally, surface and air temperature as well as sensible heat flux differences between the green and bitumen roof are discussed, with regard to the benefit of green roofs as a local climate adaptation measure in cities.

2. Material and methods

2.1. Study area and site description

The green roof is located on top of the town hall in Braunschweig, Germany. Braunschweig is situated in the North German Plain with an average annual temperature of 8.8 °C and average yearly precipitation sums of 618 mm (1961–1990; Data provided by German Weather Service). Precipitation during summer months (197 mm, Jun.–Aug.) is slightly higher than during winter months (135 mm, Dec.–Feb.). The city has about 250,000 residents and a population density of 1275 people km^{-2}. The city centre is characterised by a building fraction of about 30% and mean building heights of about 20 m. It can be classified as local climate zone 4 (open midrise) according to Stewart and Oke (2012) [7]. In summer (August) the maximum UHI intensity measured by an urban-rural climate station pair can reach 7 K at night [41]. The town hall was built in 1971 and is 37 m high (Fig. 1). The unirrigated green roof is sited on the 8th floor of the building, whereas the reference roof is sited on the 9th floor (Fig. 1). The size of the green roof is about 600 m^2 and the bitumen roof 160 m^2. The vegetation was dominated by *Sedum hybridum* and complemented with mosses. The vegetation density was near 100%, i.e. nearly no spots with bare substrate were present during the measurement period. The substrate is about 10 cm thick. The vegetation type and substrate thickness correspond to an extensive green roof type. No maintenance procedures were undertaken during the study period.

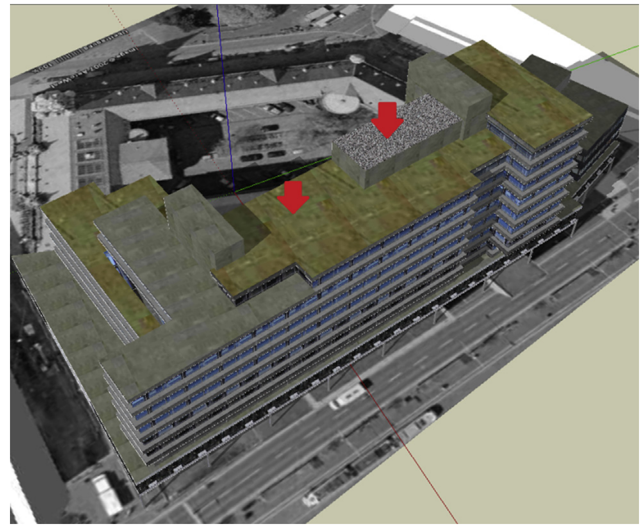

Fig. 1. 3D-model of the town hall of Braunschweig (Google Earth, modified). The locations of the monitoring stations are marked with red arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For dew measurements rural reference data was kindly provided by the German Weather Service located in Braunschweig, Völkenrode. The area corresponds to local climate zone D (low plants, [7]) and is neighboured by a small forest in the south. The horizontal distance between the urban and rural monitoring stations is about 6.3 km. Wind data at roof top height (26 m a.g.l.) were taken from the weather station of the Institute of Geoecology, TU Braunschweig (1.5 km distance to green roof).

2.2. Instrumentation

Measurements started on 01/08/2012 and ended on 31/12/2012. Surface temperatures (T_S) on green roof and bitumen roof were measured with infrared remote temperature sensors (IR100, Campbell Scientific Ltd., USA). The surface temperatures correspond to the temperature of the upper side of the green roof canopy. The measurement spot was almost completely covered with *S. hybridum*, resulting in surface temperatures which can be interpreted as the *Sedum* leaf temperatures. Air temperatures (T_A) and relative humidity (rH) were measured with HOBO U23 Pro v2 at 0.5 m above roof level (Onset Computer Corp., USA). Data acquisition was set to 5 min. For the purpose of comparison near surface air temperatures (3 m) were measured with the same HOBO U23 Pro v2 devices in a nearby street canyon (Münzstraße, Braunschweig).

Different methods to measure dew are reported in literature. These include blotting, drosometer measurements, lysimetry and remote sensing [38]. In the present study dew was measured with leaf wetness sensors (LWS, Decagon Devices Inc., USA). The sensors were placed 2 cm above the vegetation canopy layer and bituminous membrane, respectively. The sensor measures the dielectric constant up to a distance of about 1 cm from the upper sensor surface. Since the dielectric constant of water is different to the dielectric constant of air, surface wetness can be detected. One benefit of this method is that the measurement is not affected by processes of guttation and distillation. A drawback of this method is that dew which accumulates on the studied surface is not measured directly but by the leaf wetness sensor. That implies that differences in dewfall are triggered by the influence of different surfaces on ambient microclimate (above the surface). Dewfall