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Research Paper

Modeling transpiration and leaf temperature of urban trees – A case study evaluating the microclimate model ENVI-met against measurement data

Helge Simon[a,*], Jenny Lindén[b], David Hoffmann[c], Peter Braun[d], Michael Bruse[a], Jan Esper[a]

[a] Department of Geography, Johannes Gutenberg University Mainz, 55099 Mainz, Germany
[b] Swedish Environmental Research Institute, Air Pollution & Abatement Strategies, 114 27 Stockholm, Sweden
[c] School of Earth, Atmosphere and Environment, Monash University, Victoria 3800, Australia
[d] Department of Pomology, Geisenheim University, Von-Lade-Str. 1, 65366 Geisenheim, Germany

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ABSTRACT

Increasing vegetation cover in cities is a key approach to mitigating urban heat excess. However, both the effect of vegetation on microclimate and the plants' vitality need to be assessed to support and quantify the effects of such strategies. One way to assess the interactions between vegetation and the urban environment is through microclimate models that can simulate the effects of vegetation onto the urban microclimate as well as effects of urban environments onto vegetation. To provide reliable estimates microclimate models need to be parameterized based on empirically obtained data. In this paper we compare modeled transpiration rates and leaf temperatures of a leading microclimate model, ENVI-met V4, with in-situ measured stem sap flow and leaf temperatures of two different trees in an urban courtyard. The vegetation model of ENVI-met is evaluated considering four synoptic situations including varying cloud covers ranging from fully cloudy to clear sky. The comparison of simulation results with empirical data reveals a high agreement. The model is capable of capturing the magnitude as well as short-term variations in transpiration caused by microclimatic changes. However, substantial deviations were found in situations with low photosynthetic active radiation. Modeled and observed diurnal tree transpiration and leaf temperature showed good agreement. These findings indicate that ENVI-met is capable of simulating transpiration rates and leaf temperatures of trees in complex urban environments.

1. Introduction

Vegetation plays a vital role in urban environments: Aside from the aesthetic benefits, trees and other vegetation help mitigate the effects of the urban heat island by increasing the latent heat flux through evapotranspiration and decreasing the sensible heat flux through shading, resulting in lower air temperatures (Anyanwu & Kanu, 2006; Yu & Hien, 2006). Studies of the ambient air temperature in cities have shown a mosaic of cooler and warmer places, with cooler places being closely connected to increased vegetation cover (Alavipanah, Wegmann, Qureshi, Weng, & Koellner, 2015; Fan, Myint, & Zheng, 2015; Harlan, Brazel, Prashad, Stefanov, & Larsen, 2006; Lindén, 2011; Middel et al., 2012; Norton et al., 2015). Harlan et al. (2006) demonstrate that increased urban vegetation strongly correlates with improved thermal comfort conditions, particularly during heat waves. Increasing the vegetation cover in cities is thus one of the key approaches to lowering both air and radiative temperatures and to improving thermal comfort through shading and transpiration (e.g. Bowler, Buyung-Ali, Knight, & Pullin, 2011; Norton et al., 2015).

Quantifying the vegetation-induced air temperature cooling effect in urban areas requires reliable information about the transpiration rate of urban vegetation, which can be obtained through a number of methods. For example, measurements of leaf gas exchange provide a direct measure of transpiration. They are, however, difficult to obtain in heterogeneous environments such as urban areas (Goulden & Field, 1994). Even in natural, more homogeneous environments, such data are typically restricted to short time periods and to only a few leaves that are assumed to represent the whole canopy (e.g. Bowden & Bauerle, 2008; Konarska et al., 2016). Another way to estimate transpiration is through the measurement of sap flowing up the stem, which is directly related to the amount of transpired water (e.g. Forster, 2014; Granier, 1987; Green, Clothier, & Jardine, 2003; Rahman, Moser, Rötzer, & Pauleit, 2017a). Sap flow can be measured and quantified in-situ continuously and over longer periods but instrumentation is often expensive. In addition, the scarcity of suitable locations in urban areas where the risk of vandalism is acceptable often limits measurements to

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* Corresponding author at: Geographisches Institut, Johannes Gutenberg-Universität Mainz, Johann-Joachim-Becher-Weg 21, 55099 Mainz, Germany.
E-mail address: h.simon@geo.uni-mainz.de (H. Simon).

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a few trees. Alternative possibilities, such as remote sensing techniques, bucket modes and microclimate models to estimate the transpiration of urban vegetation, are therefore greatly needed (Gill, Rahman, Handley, & Ennos, 2013).

Apart from transpiration, leaf temperatures and tree vitality are also crucial when trying to assess the microclimatic effects of urban vegetation since only healthy, unstressed plants can fully provide their beneficial effects on the microclimate. In conditions where water supply is limited and air temperature is increased, the plants endure severe drought and heat stress (Moser, Rötzer, Pauleit, & Pretzsch, 2016). Under these conditions the plants regulate their stomata in order to prevent excessive water loss, which in turn decreases the latent heat flux, increases leaf temperature and reduces the cooling effect onto the urban microclimate (May, Livesley, & Shears, 2013; Savi, Bertuzzi, Branca, Tretiach, & Nardini, 2015). Such an increase in leaf temperature can, in turn, cause irreversible damage to plant growth and development (Feller & Vaseva, 2014; Haldimann & Feller, 2004). One way to assess leaf temperatures and tree vitality as well as transpiration is via simulation methods using microclimate models.

A frequently used urban microclimate model is ENVI-met (Bruse, 1999), which considers physical fundamentals based on the principles of fluid mechanics, thermodynamics and atmospheric physics to calculate three-dimensional wind fields, turbulence, air temperature and humidity, radiative fluxes and pollutant dispersion (Bruse, 1999; Morakinyo, Dahanayake, Ng, & Chow 2017; Nikolova et al., 2011; Pastore, Corrao, & Heiselberg, 2017). The advantage of ENVI-met lies in its holistic approach to simulate the complex interactions of building structures, atmosphere, soil and vegetation processes in one model. The vegetation model in ENVI-met allows modeling of the plant-atmosphere interactions through a stomata behavior model at the leaf level (Bruse, 2004). The calculation of stomatal behavior using Jacobs' $A - g_s$ model (Jacobs, 1994) together with the introduction of object-based assessments of plant parameters allows the simulation of the effects of plants on the microclimate as well as the simulation of effects of microclimates on the vitality of plants.

In this paper, the vegetation model of ENVI-met is evaluated based on a comparison of modeled transpiration rates and leaf temperatures with monitored sap flow and leaf temperature measurements of two Platanus × acerifolia under four synoptic summertime conditions. Continuous measurements of meteorological parameters, leaf temperatures and sap flow measurements have been conducted on the two trees located in a confined courtyard in an urban environment in Mainz, Germany. Four different periods were extracted from the measurement data to test the modeled results against the measurements in different conditions. Since the stomata model is mainly driven by differences in the photosynthetic active radiation (PAR) as well as in the air temperature, and to test the model under different conditions, periods featuring different cloud cover and air temperature were chosen (Bruse, 2004). The periods consisted of two to three consecutive days.

2. Methods

2.1. Study site

The study has been performed in the city of Mainz, Germany (50.0°N, 8.3°E, elevation 100 m a.s.l., see Fig. 1). Mainz is an inland city with approximately 200,000 inhabitants, located in a landscape of gently rolling hills along the Rhine river. The climate is temperate with an annual average temperature of 10.4 °C and precipitation of 620 mm (Koeppen Cfb) (DWD, 2017). The summers are warm and humid (June to August: mean air temperature 19.2 °C and mean precipitation 175 mm, from 1981 to 2010, www.dwd.de). The urban architecture is of compact midrise structures (Stewart & Oke, 2012) with smaller parks, grassy areas, and streets with scattered trees.

The examined location is the courtyard of the Landesmuseum Mainz, located in the sparsely vegetated urban center, approximately 350 m away from and 7 m above the Rhine River. The courtyard is 43 × 48 m and completely enclosed by buildings 10–16 m tall (Fig. 2). The ground is covered with lightly colored gravel and the vegetation consists of five mature Platanus × acerifolia reaching heights of 10–18 m, and a 10 × 10 m drip irrigated herb garden. The diameter at breast height (DBH) of the two observed trees was measured using a diameter measurement tape at a height of 1.4 m. The large tree measures a DBH of around 0.8 m, a total height of 18 m, a crown radius of 6 m and a crown height of 14 m. The small tree's DBH measures around 0.4 m, its total height is around 10 m while its crown radius and height are 3 m and 7 m respectively. Records of the Landesmuseum showed that the large tree was planted around 1950, while the small tree was planted around 1970. The trees are not irrigated. Soil conditions at the study site are likely variable and disturbed since the buildings were destroyed in the Second World War and new structures were built on top of the rubble. However, the deeper, natural soil mostly consists out of sandy loam. With the short distance to the Rhine river (see above), it is not unlikely that the trees, especially the large tree, have access to soil water fed by the Rhine river.

2.2. Monitored parameters

2.2.1. Meteorological parameters

Air temperature (T_A) and relative air humidity (RH) were monitored using HOBO U23-001 Pro v2 data loggers placed in RS1 solar radiation shields (Onset, Bourne, MA, USA), at a height of 3 m in the courtyard as well as directly outside the courtyard in a southwest-northeast oriented street. Prior to installation, a comparison among the sensors located in a well ventilated rooftop for a period of 22 days (with T_A ranging from -4°C to 18 °C and RH from 30% to 100%) showed agreement with an average difference in $T_A \pm 0.08$ K ($<$ 2% exceeding $\pm$ 0.2 K), and in RH $<$ 0.2% ($<$ 2% exceeding 1%). These measurements were used to derive specific humidity. Precipitation, wind and global radiation (shortwave direct and diffuse) were obtained from a meteorological station 3 km southwest of the study area. This location is more open than the urban locations and thus only used to define the general daily meteorological conditions.

2.2.2. Tree sap flow

Sap flow velocity was monitored on the two courtyard trees at 30-min intervals using the compensation heat pulse method, sensor type HP4TC (Tranzflo NZ Ltd, New Zealand) connected to Campbell data loggers (CR 1000). With the compensation heat pulse method two temperature probes are placed above and below a heater probe into the sap wood of a tree stem (see Fig. 3). In periodic intervals the heater probe sends a heat pulse into the tree stem. The time delay until both temperature sensors show an equally large temperature rise is then used to trace the sap flow velocity (Green et al., 2003). The sensors were installed in four directions around the stem with a 90° angle between them and, to prevent vandalism, at a height of approximately 2 m above ground, but well below the first branches. Sap flow velocity was measured at four depths reaching a maximum of 6 cm into the sapwood in each direction. Total flux was calculated according to Swanson and Whitfield (1981) and Green et al. (2003). The sap flow velocity data were compared against modeled transpiration rates of entire trees.

2.2.3. Leaf surface temperature

Leaf surface temperatures were measured using a self-built low cost infrared thermometer based on an Arduino microcontroller. An infrared sensor MLX90614ESF-DCI manufactured by Melexis was used to measure thermal radiation within a five degree field of view and to estimate the leaf surface temperature with an emissivity factor of 0.97 (Idso, Jackson, Ehrler, & Mitchell, 1969). The sensor was factory calibrated, offering an accuracy of ± 0.5 °C within a range of 0 °C–60 °C (Melexis, 2015). Measurements of leaf surface temperature were obtained several times a second, and the mean values of these measurements were