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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

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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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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 ± 0.08 K (< 2% exceeding ± 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

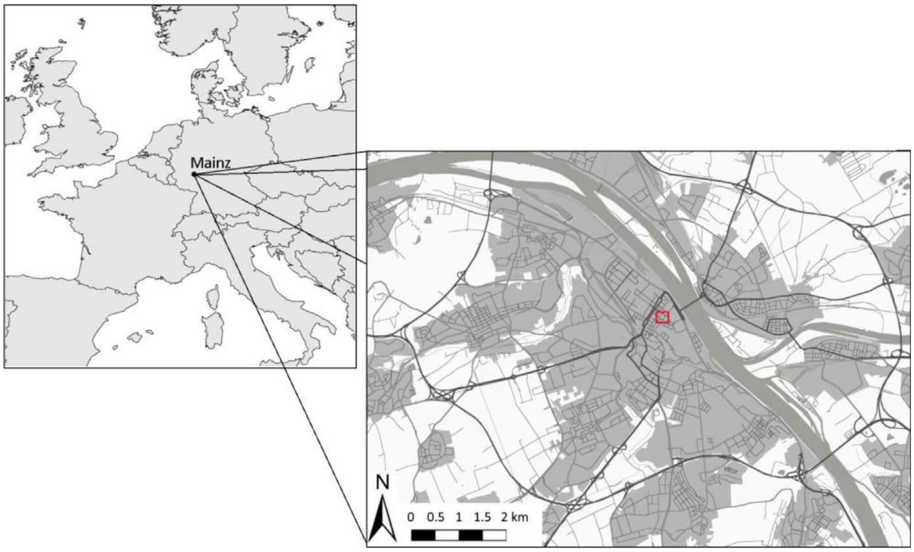

Fig. 1. Location of Mainz and the examined site (red square). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

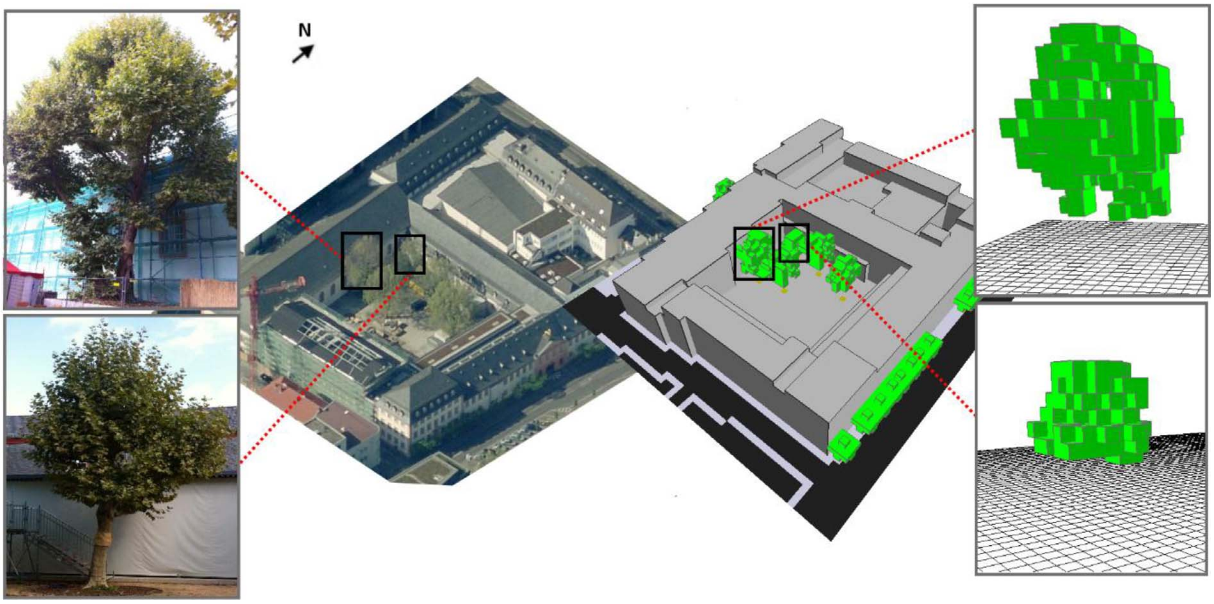

Fig. 2. Monitoring and simulation site: Aerial photo of the courtyard monitoring site together with photos of the large (top left) and small tree (bottom). Digitized model area and trees are shown on the right.

integrated over five-minute intervals. The instrument was mounted on a branch in five meters height above ground and oriented towards a dense leaf cluster three meters below. Since the measured area of approximately 540 cm^2 was positioned in the large tree (see Fig. 4), it remained shaded most of the day. As these leaves constitute only a small sample, they were not compared with the model data of the entire tree, but only with single model output leaf grid cells situated close to the measurement point.

2.3. ENVI-met vegetation model

ENVI-met is a high resolution, three-dimensional prognostic microclimate model (Bruse & Fleer, 1998). A key component of the model is the detailed modeling of vegetation. With the newly developed plant-as-object model, plants in ENVI-met are no longer treated as loose grid cells of leaf area density (LAD) but can be regarded as aggregated, dynamic objects that react to their immediate environmental conditions. With its high resolution, ENVI-met is able to model the exchange of CO_2 and water vapor at the leaf level using an adaptation of Jacobs' $A - g_s$ stomata model (Bruse, 2004). The $A - g_s$ model is used to estimate stomatal behavior of single leaves taking into account the microclimatic conditions of the whole plant. The main assumption of the model is that plants operate stomatal conductance in a way that maximizes CO_2 gain while the associated water loss is minimized (Jacobs, 1994). As an empirical model, the $A - g_s$ model links stomatal conductance (water loss) with photosynthesis (CO_2 gain). Even though there is little indication of a direct causal relation, empirical studies have found a strong correlation between the stomatal conductance of water (g_s) and photosynthesis (A) (Damour, Simonneau, Cochard, & Urban, 2010; Jacobs, 1994).

Using this relation, the calculation of net photosynthesis rates allows the model to calculate the stomatal behavior of the plant. Among other parameters, ENVI-met's stomatal behavior model takes into account the following factors limiting net photosynthesis and thus stomatal conductance:

Fig. 3. Sap flow measurement: Photo of the two temperature probes placed above and below a heater probe into the sap wood (before insulation).

- Insufficient photosynthetically active radiation (PAR)
- Insufficient atmospheric CO_2
- Insufficient water access/soil moisture

The prognostic output parameters of the model are, among others: transpiration rate, leaf surface temperature, root water access, received photosynthetically active radiation and aerodynamical resistance. With the plant-as-object model, the model results of single plant grid cells of leaf area density are aggregated to form an integrated organism – a tree – that allows conclusions about the physiological and climatic parameters at the plant level instead of a grid cell level.

2.3.1. ENVI-met boundary conditions

Based on the meteorological observational data, four simulations of two to three consecutive days were run using ENVI-met 4 Expert. Since PAR is expected to have the biggest impact on plant transpiration, four periods with different cloud covers were chosen to evaluate model performance in different solar radiation and thus PAR conditions.

Using the meteorological measurements and ENVI-met's full forcing option, half-hourly forcings of wind speed, solar radiation, air temperature and humidity were created as boundary conditions for the model. The four simulation periods feature different meteorological conditions (Table 1, Fig. 5). The differences in the absolute amounts as well as in the ratio of direct and diffuse shortwave radiation are clearly visible.

Table 1
Boundary condition of the four simulation periods.

Condition	Parameter (average)		
	Air temperature	Vapor pressure deficit	Wind speed
Clear sky (02.-03. August 2015)	25.6 °C	2.1 kPa	1.3 m/s
Slightly cloudy (06.-07. August 2015)	29.3 °C	2.3 kPa	0.9 m/s
Mostly cloudy (11.-13. August 2015)	26.7 °C	1.4 kPa	1.4 m/s
Fully cloudy (16.-17. August 2015)	16.8 °C	0.3 kPa	1.8 m/s

To ensure sufficient supply of soil water for the trees, the initial soil moisture was set to 65% of the useable field capacity.

2.3.2. ENVI-met model area

The model area covers 140 × 116 × 40 m and was digitized in a resolution of 1 m so that the different tree geometries could be replicated accurately. This is particularly important in the context of this study, which aims to evaluate the vegetation model of ENVI-met based on transpiration flux and leaf temperature. Previous test runs within this study showed that a close representation of a tree's geometry and leaf area density are of utmost importance for the estimation of the actual transpiration flux for a tree.

Fig. 2 shows the two trees in their real environment as well as their represented geometry in the digitized model area. Since leaf area density was not directly measured, this parameter was approximated based on empirical studies. Hipps, Davies, Dunn, Griffiths, and Atkinson (2014) and Van der Zande, Jonckheere, Stuckens, Verstraeten, and Coppin (2008) found that Platanus × acerifolia feature LADs ranging from 0.5 $m^2\,m^{-3}$ to 0.7 $m^2\,m^{-3}$. The individual leaf grid cells were thus set to an LAD of 0.6 $m^2\,m^{-3}$ for both trees in this study.

3. Results and discussion

The vegetation model of ENVI-met is evaluated in two steps. In a first step the measured sap flow is compared against the modeled transpiration flux of the two trees. In a second step the measured leaf temperatures of shaded leaves are compared against modeled leaf temperatures of leaf grid cells situated close to the measurement point. As measures of overall model fit, R^2 and root-mean-square error

Fig. 4. Leaf surface temperature measurement: Photo of the measurement instrument, encased in a radiation shield, mounted on a branch, five meters above the ground (left). On the right the measured area, a dense leaf cluster, three meters below the instrument is shown.

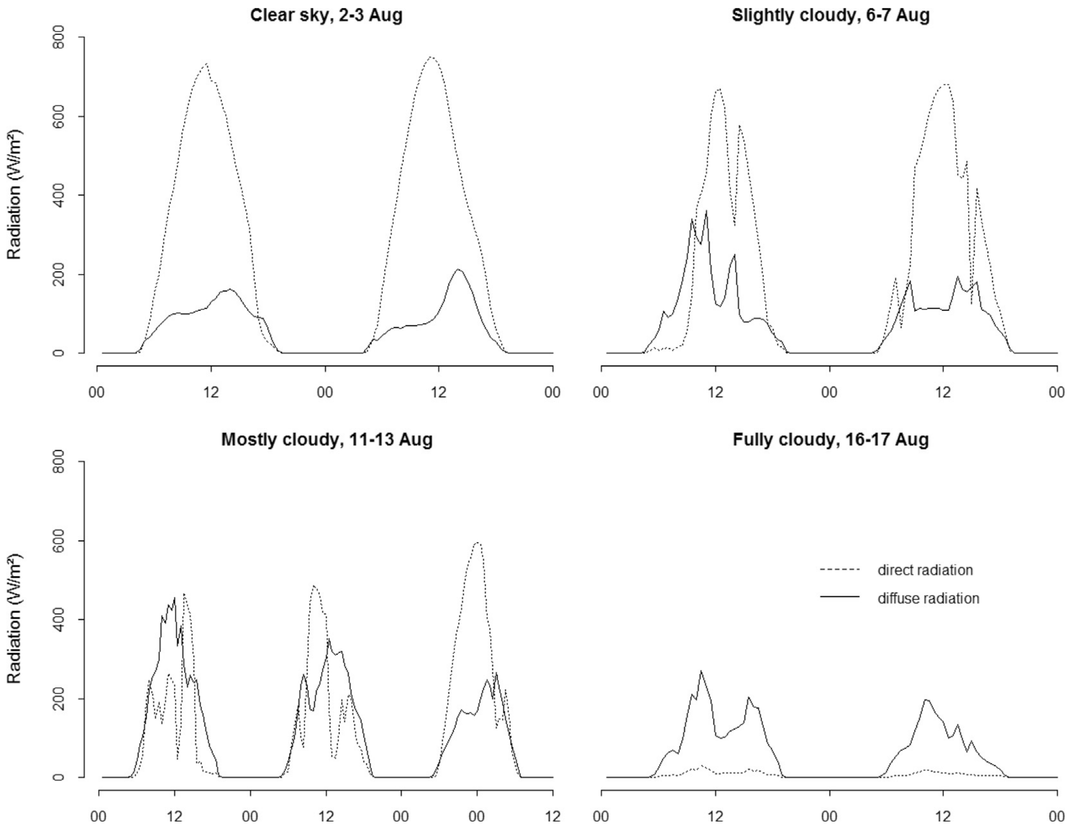

Fig. 5. Diurnal variations of the forced direct (dashed lines) and diffuse (solid lines) radiation of the four simulation periods based on measurements of the meteorological station 3 km SW of the study site.

(RMSE) are being calculated. While R^2 provides information on how much of the variability in the actual values is explained by the model, i.e. on how well the general shapes of the curves match, it does not give any indication about the fit of the absolute values. For example, a model which results in predicted values that are all exactly half of measured values would still return a perfect model fit of $R^2 = 1.0$. To also capture the differences in absolute values between the modeled and measured data, the RMSE is used. Since values of RMSE are dependent on the absolute values and can thus not be readily compared across meteorological conditions and trees, RMSE values are normalized by dividing by the range of measured values (NRMSE). This allows a direct comparison between the different conditions and a comparative assessment of overall model fit. In addition to these measures of overall model fit, the diurnal variations of modeled and measured data are examined in detail to test whether the model is able to also capture short-term variations in transpiration and leaf temperatures.

3.1. Transpiration rates

To evaluate the vegetation model of ENVI-met, first the transpiration rate data as obtained through sap flow measurements on the two trees was compared against the modeled transpiration (Table 2, Fig. 6). High agreement for both the shape of the curves (R2 between 0.73 and 0.91) as well as the absolute values (NRMSE between 0.12 and 0.20) was found between the modeled and measured (sap-flow derived) transpiration rate data for the three examined periods where PAR plays an important role: clear sky, slightly cloudy and mostly cloudy (Table 2). The model fit was lower during the fully cloudy period (R2 between 0.46 and 0.59; NRMSE between 0.22 and 0.39) where PAR was very low and other parameters such as wind speed and vapor pressure deficit might become dominating factors impacting transpiration. As wind speed (and radiation) were measured approximately 3 km southwest of the trees' actual location, the values driving the transpiration model likely differ from the actual conditions at the trees' location. While radiation can – apart from temporary distortions due to passing clouds (see below) – be assumed to be similar between the sites, the wind conditions might differ considerably even though the wind speed was adjusted using the logarithmic wind profile together with the roughness length of the measurement location for the boundary inflow. With the low PAR in the fully cloudy period, the inevitable error caused by the discrepancy between actual and measured (off-site) wind speeds might become a substantial bias affecting the transpiration comparison. Furthermore, the measurement of sap flow shows larger uncertainties in conditions of low sap flow (low PAR or at night), making a validation of

Table 2
Model fit between the simulated and estimated (sap flow derived) transpiration rates in different cloud conditions.

Condition	R^2		RMSE [l/30 min]		NRMSE	
	Small Tree	Large Tree	Small Tree	Large Tree	Small Tree	Large Tree
Clear sky	0.73	0.79	1.58	2.67	0.20	0.19
Slightly cloudy	0.75	0.88	1.64	2.53	0.19	0.17
Mostly cloudy	0.91	0.86	0.86	2.51	0.12	0.18
Fully cloudy	0.59	0.46	0.38	1.62	0.22	0.39

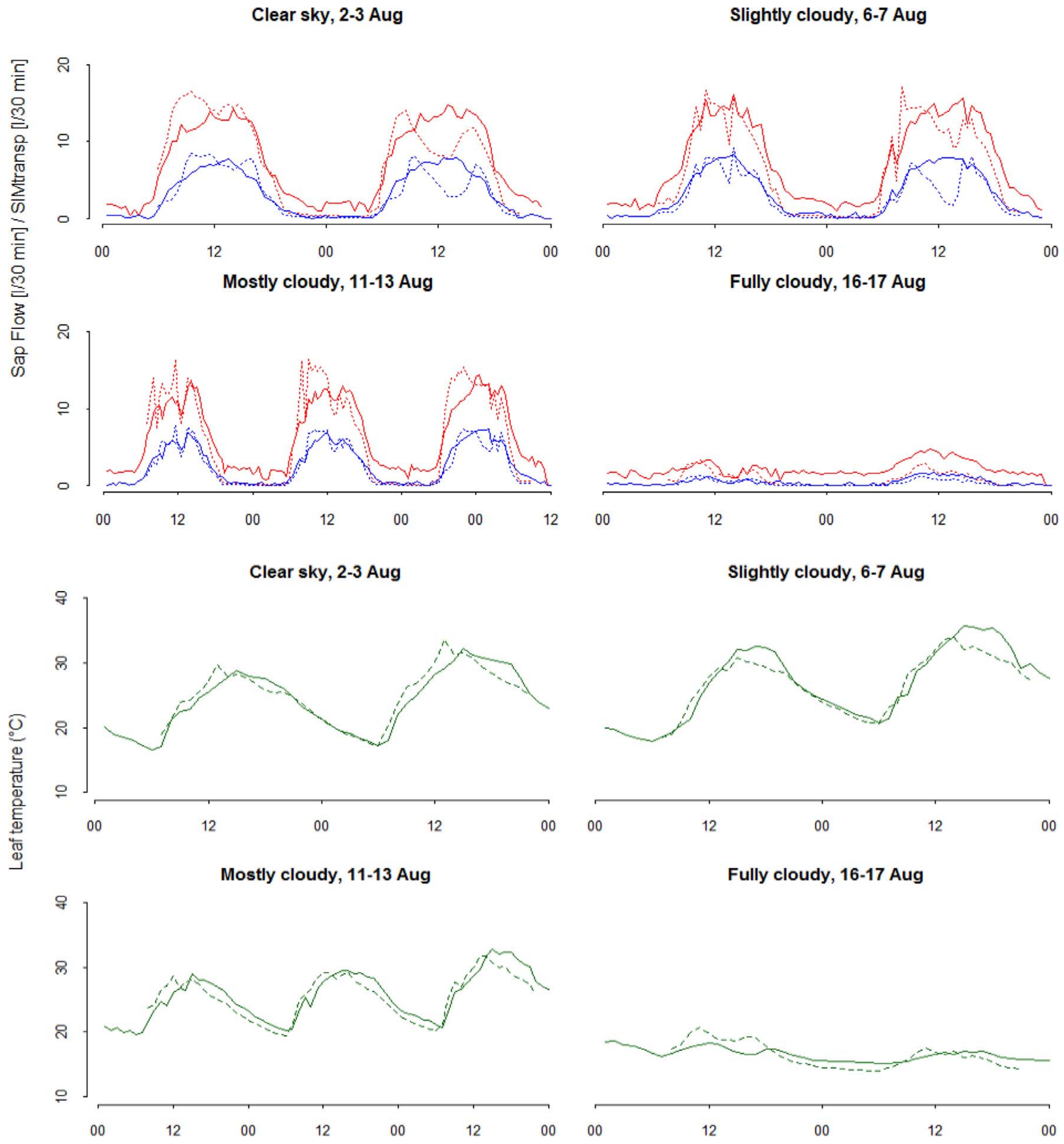

Fig. 6. Comparison of the measured (solid lines) sap flow and leaf temperatures with the modeled (dashed lines) transpiration rates and leaf temperatures of the small (blue) and large tree (red). The bottom panel shows measured temperatures of shaded leaves (green solid lines) compared with modeled temperatures (dashed lines) of leaves close to the measurement point. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the model harder in these conditions (Green et al., 2003).

Despite the discrepancies under low PAR conditions, the comparison of diurnal variations between the modeled transpiration rate and measured sap flow of the two trees shows good agreement between the simulations and measurements over all four periods (Fig. 6). The model accurately simulates most of the short-term variations of tree transpiration in cloudy, slightly cloudy, mostly cloudy and fully cloudy situations.

The differences between the small and large tree are well captured in the model. In both the empirical and simulation data, the maximum transpiration rate for the larger tree is almost twice as high as the rate of the smaller tree. With the exception of the heat-stress related midday depression on the first and second day of the clear sky and slightly cloudy situations (see Fig. 6), the modeled and measured transpiration rates match better for the small tree, compared to the large tree. The disparity of the larger tree is probably caused by its more complex canopy geometry. While the geometry of the small tree, with its dense and compact crown, can be represented easily in ENVI-met, the geometry of the larger tree, with its very heterogeneous crown, is very difficult to digitize correctly. Additionally, the trunk of the larger tree splits right at the base of the trunk (see Fig. 2). While the second trunk (to the left in Fig. 2) is disregarded in the sap flow measurements as well as the transpiration modeling, it does cast a shadow onto the first tree and further complicates the already complex structure of the larger tree.

A quite distinct discrepancy between modeled and empirical data is the reduced transpiration in the simulations after midday on the first and second day of the clear and slightly cloudy situations. A midday depression in transpiration in response to stress is a common water saving adaptation, which has been reported in both tropical and temperate trees (Brodribb & Holbrook, 2004; Gindaba, Rozanov, & Negash, 2004; Kamakura et al., 2012; Kosugi, Takanashi, Matsuo, & Nik, 2009). This water saving strategy is reflected in ENVI-met's vegetation model: In the $A - g_s$ model, trees try to optimize their carbon gain in relation to

Table 3
Model fit between simulated and monitored shaded leaf temperatures.

Condition	R^2	RMSE [K]	NRMSE
Clear sky	0.87	1.55	0.10
Slightly cloudy	0.90	1.85	0.11
Mostly cloudy	0.81	1.59	0.12
Fully cloudy	0.71	1.25	0.38

water loss. In the clear sky and slightly cloudy situations, the model assumes this relation to be less beneficial and induces higher stomatal resistance to save water after midday (Bruse, 2004). The observational data, however, do not show reduced values in the sap flow, pointing to an underestimation of available soil water and an overestimation of the heat stress in the model.

During the first slightly cloudy day, a similar discrepancy between modeled and measured data is visible. However, this is not caused by an overestimation of heat stress in the model but rather by a difference in radiative conditions between the trees' location and the met station site 3 km southwest of the tree location. Fig. 5 shows a drop in the direct shortwave radiation around 13:00, caused by a passing cloud temporarily blocking the sun at the met station site, thus reducing the modeled transpiration. At the same time, the measured tree sap flow shows no reaction indicating that the cloud did not pass over the monitoring site.

The stronger reduction in modeled transpiration at sunset and the negligible transpiration throughout the night are based on the ceased availability of PAR after sunset. The measurements show a slower decline and continued sap flow throughout the night, particularly in the larger tree as the measurement needs some equilibrium time just after sunset. Sap flow has been found to generally continue at night, amounting to on average around 12%–20% compared to daytime (e.g. Forster, 2014; Lindén, Simon, Fonti, Esper, & Bruse, 2015; Rahman, Moser, Rötzer, & Pauleit, 2017b; Zeppel, Lewis, Phillips, & Tissue, 2014). Although nocturnal sap flow is partly used for embolism refilling and recharge of capacitance, studies have shown that 50–95% of this nocturnal flow is lost through transpiration from the canopy (Alvarado-Barrientos et al., 2015; Moore, Cleverly, & Owens, 2008; Zeppel, Tissue, Taylor, Macinnis-Ng, & Eamus, 2010). While these processes seem to be captured by the model in general, the nocturnal transpiration may still be underestimated in the simulations. Although limited in comparison to daytime levels, the cooling induced by nocturnal transpiration has been found to be more important for urban climates as it can have significant effects on the local climate due to the low atmospheric mixing at this time (Konarska et al., 2016). Quantifying the stored versus transpired fractions of measured nocturnal sap flow and exploring the possibility to adjust modeled evening and night transpiration was not addressed at this stage. However, due to the potential impact on the nocturnal urban climate, this issue needs to be examined in future research.

3.2. *Shaded leaf temperatures*

In addition to the transpiration rate, the leaf temperatures measured on a single branch were compared with modeled leaf temperatures of the corresponding single grid cell. Very high overall agreement for both the shape of the curves (R^2 between 0.81 and 0.90) as well as the absolute values (NRMSE between 0.10 and 0.12) was again found between the modeled and measured data for the clear sky, slightly cloudy and mostly cloudy periods, which are characterized by a dominant role of PAR (Table 3). The reduced model fit of $R^2 = 0.71$ and NRSME = 0.38 for the fully cloudy situation can again be explained by the more dominant role of other microclimatic parameters in situations where PAR is low. Since wind speed and wind direction were not measured at the exact location of the trees, the effects of advective cooling might not be captured correctly by the model resulting in a higher deviation of modeled leaf temperatures for the fully cloudy situation.

The comparison of diurnal variations in simulated and measured leaf temperatures (Fig. 6, bottom panel) demonstrates that the model is capable of predicting the short-term variations in leaf temperatures accurately as well. Only in the evening hours, the model seems to underestimate the measured leaf temperatures slightly, reaching a maximum difference of 3 K.

4. Conclusion

In this paper, the vegetation and plant-as-object models of the microclimate model ENVI-met were compared against monitored and simulated transpiration fluxes and leaf temperatures of two urban trees. The monitored transpiration rates were derived from sap flux measurements. To test the modeled transpiration under different conditions, four different synoptic situations including clear sky, slightly cloudy, mostly cloudy and fully cloudy periods extending over two to three days each were chosen. Different cloud covers were considered as the availability of photosynthetically active radiation is key to plant transpiration. To replicate the different situations, the model was run in a full-forcing mode allowing the definition of diurnal variations as boundary conditions for the measured meteorological parameters: air temperature and humidity, wind speed and direction and radiation (shortwave direct, diffuse and longwave). To accurately simulate the transpiration rate of the trees, the model area and particularly the replication of tree geometry in the model proved to be important.

The comparison of the simulation results with the measurement data showed high agreement – R^2 values between 0.73 and 0.91 for the clear sky, slightly cloudy and mostly cloudy period and between 0.46 and 0.59 for the fully cloudy period. ENVI-met's vegetation model was capable of not only capturing the magnitude but also the short-term variations in the transpiration that were caused by minor environmental changes such as local cloud cover. On the warmer days, however, the model predicted a midday depression in stomatal conductance leading to reduced transpiration. Even though the microclimatic conditions were quite hot and dry, the measured data showed no such depression. In addition, the modeled data did not closely fit the measured data in the fully cloudy simulation. This discrepancy is partly explained by uncertainties of the measurement method with transpiration rates derived from very low sap flow rates as well as by discrepancies between the actual and measured (off-site) wind speeds acting as boundary conditions for the model. An underestimation of modeled transpiration was also found in the evening and during night, but as the connection between nocturnal sap flow and transpiration was not determined at this stage, this discrepancy could not be addressed yet. Due to the potentially strong influence of nocturnal transpiration cooling on the nocturnal urban climate (Lindén, 2011; Lindén et al., 2015), this issue requires further research. The comparison of simulated and monitored shaded leaf temperatures confirmed the high agreement between the model and measurements. Both the diurnal variations as well as the absolute values matched very well.

The study showed that the microclimate model ENVI-met, running in the full-forcing mode, was able to accurately simulate the transpiration rate and the changes of leaf temperatures of the two trees in a complex urban environment. It confirmed that ENVI-met is a viable tool to assess the effects of trees on the urban microclimate (transpirational cooling effects) as well as to simulate tree vitality parameters in specific microclimate conditions.

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