Observed and modeled transpiration cooling from urban trees in Mainz, Germany

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Abstract

In order to assess and mitigate urban heat stress and increase comfort, urban climate models are employed in the development of urban areas. These models ideally reproduce the cooling influence of urban vegetation, both at a temporal scale and in response to weather situation and water availability. In this paper, we present a case study on how the microclimate cooling of urban trees varies at the diurnal scale. We assess transpiration effects in relation to drought stress at two adjacent sites with differing vegetation cover in Mainz, Germany. The temperature differences between the two sites were strongest at night, but appeared reduced during very dry conditions. Nocturnal transpiration was indicated as an important cooling factor in the more vegetated site. The spatial pattern found here was compared with modeled data obtained with the ENVI-met model. This comparison revealed the nocturnal transpiration cooling to be underestimated by the model, likely due to the assumption that transpiration almost ceases at sunset. Further studies are needed to improve our understanding of nocturnal transpiration effects in differing atmospheric situations characterized by changing evaporative demand and water availability.

1. Introduction

Increasing the vegetation cover in cities is one of the key approaches to mitigate urban heat, and trees are perhaps the most important vegetation as they intercept sunlight and cool the air by transpiration (Ennos 2011). The general influence of urban vegetation is relatively well documented (e.g. Bowler et al. 2011; Qiu et al. 2013), but relatively little is known about the magnitude of cooling from transpiration and how this varies on a diurnal scale in response to heat and drought stress. Urban climate models are frequently consulted to assess heat stress mitigation when developing urban areas. One frequently used urban climate model is ENVI-met (Bruse; Fleer 1998), 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. The influence of vegetation transpiration is modelled in ENVI-met using the Jacobs' A – gs model (Jacobs 1994) in order to balance water use with CO_2 assimilation to maximize carbon gain and minimize water loss (Bruse 2004).

Here we present results from a case study linking diurnal tree transpiration to urban cooling by comparing daily patterns in urban air temperature and humidity with transpiration (derived from sap flow) during the summer 2013 in two areas with contrasting tree cover and geometry. The possibility to replicate the measured spatial patterns with the urban climate model ENVI-met was examined.

2. Methods

The study was performed in the city of Mainz in western Germany (50.0°N, 8.3°E, population 200 000). Mainz is located in a landscape of gently rolling hills on the western shore of the Rhine River. Climate is temperate and humid with an annual air temperature of 10.7 °C and precipitation of 620 mm. The summers are warm reaching 19.2°C from June to August, and humid with an average precipitation of 175 mm (from 1981 to 2010, www.dwd.de). The examined summer was warm and dry (20.2 °C and 102 mm) and included a 21-day long period in July with no precipitation.

Two adjacent areas of differing vegetation cover in the city center of Mainz were examined; one completely closed-in courtyard (45 x 50 m) with five large trees (*Platanus x acerifolia)* and no other vegetation, and the wide street (33 m wide) directly outside, with widely spaced, small trees (*Acer platanoides*) along both sides of the road (Figure 1). Buildings 13-18 m high surround the courtyard and the street. In these two locations, air temperature (TA) and relative humidity (RH) were measured every 30 minutes at a height of approximately 3 m with HOBO U23-001 Pro v2 data loggers placed in RS1 solar radiation shields (Onset, Bourne, MA, USA). In order to estimate transpiration, sap flow (SF) was measured on one of the courtyard trees using thermal dissipation probes; Granier, SF-L (Ecomatik, Munich, Germany, e.g.; (Granier 1985). Sap flow were calibrated according to manufacturer's recommendation (Liu; Schweighoefer 2011). Wind speed and radiation data were obtained from a meteorological station run by the institute of Atmospheric Physics at Johannes-Gutenberg University, in a higher and more open location at the outskirts of the city, approximately 5 km form the measurement sites. The area including the sites was digitized with 140 x 140 x 30 grids in a resolution of 2.5 meters, resulting in ENVI-met model area of 350 x 350 x 75 meters (Figure 1).

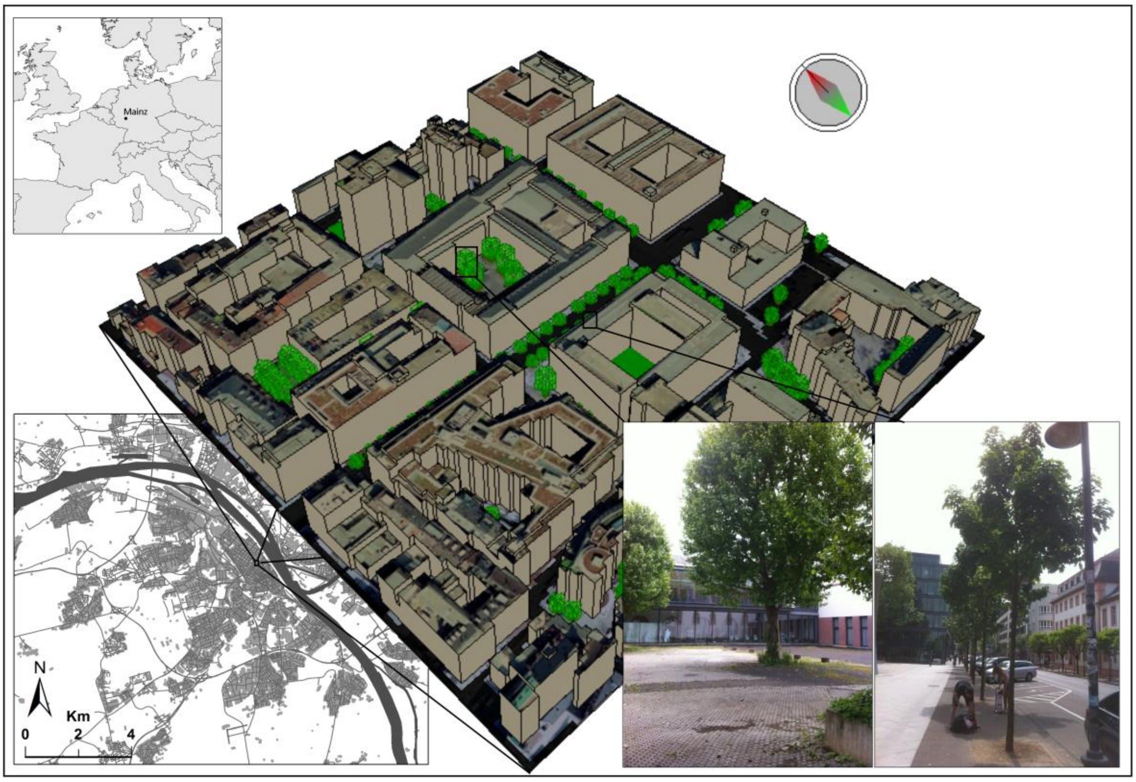

Figure 1. 3D reconstruction of the location performed with the ENVI-met model domain, with photos of the two selected monitoring sites (courtyard and street) in Mainz, Germany.

For site comparisons, HR was transformed in specific humidity (HS). Vapor pressure deficit (VPD), and the number of days since the last precipitation event (dsP) were used to examine the influence of synoptic weather patterns and water availability on transpiration. A total of 60 examined days were grouped into three equally sized groups of low (VPD < 1,1 kPa), medium (1,1 < VPD > 1.6 kPa) and high (VPD >1.6 kPa) atmospheric evaporative demand. Additionally, high VPD days were divided into two classes based on soil water availability estimated from dsP (0-7 and >7 days dsP) for a total of four categories (VPD_L, VPD_M, VPD_{Hwet} and VPD_{Hdry}). Meteorological conditions for these four categories are presented in Table1.

Table 1. Average meteorological conditions for the four different day categories

	VPD_L	VPD_M	VPD_{Hwet}	VPD_{Hdry}
TA, °C	18,4	19,8	23,6	26,3
Wind speed, ms^{-1}	1.8	1.5	1.5	1.8
VPD, kPa	0,64	1,1	1,8	1,8
HR, %	67.4	55.3	48.7	42.7
Solar radiation, % of daily max.	20	47	59	65

Based on data of three consecutive days from the VPD_{Hwet} and VPD_{Hdry} categories, simulations were run with the prognostic, three-dimensional, high resolution microclimate model ENVI-met, using the measurement data to create diurnal cycles of wind speed, radiation, air temperature and humidity as boundary conditions. The ΔTA and ΔHS found between the two examined sites, as well as the estimated transpiration from SF, were compared with output from the model. From the two categories of atmospheric evaporative demand with high evaporative demand (VPD_{Hwet}, VPD_{Hdry},), coherence over three consecutive days was examined. Since SF is not provided as an output variable from ENVI-met, we compared the modelled transpiration of the individual tree with measured SF. As these variables have different units, we focused on the shape of the diurnal curves.

3. Results and Discussion

3.1 Diurnal temperature and humidity differences in relation to evaporative demand

The diurnal temperature profiles show that the courtyard is colder than the street at night and generally slightly warmer in the day (Fig. 2). The courtyard was also generally more humid. The most interesting differences are found between the wet and dry days during periods of high atmospheric evaporative demand ($VPD_{Hwet+dry}$). When more soil water is available, the courtyard heats stronger than the street in the morning, followed by a reduced warming of the courtyard (compared to the street), and from early afternoon and throughout the night it is cooler than the street. The average difference reaches a maximum of 0.8 °C in the early night when also peak humidity is recorded in the courtyard. During VPD_{Hdry}, the courtyard remains warmer throughout the day and is only slightly colder at night, and humidity is very similar between the two sites. The SF increases rapidly after sunrise, stays high throughout the day, and slowly decreases in the late afternoon and night. The average level of SF is half of the daytime maximum at sunset, 25% at midnight, and reaching a minimum before sunrise.

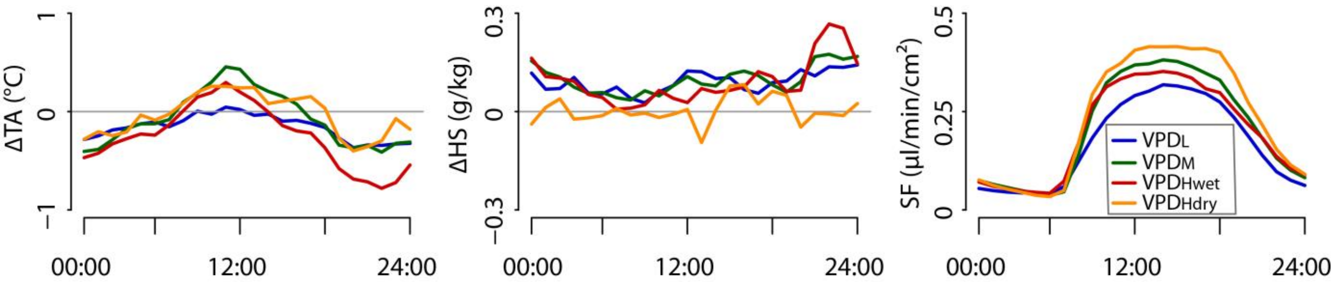

Figure 2. Average hourly differences (Courtyard – Street) in air temperature (left), specific humidity (middle), and sap flow (right), divided into groups based on atmospheric evaporative demand; VPD_L (N=20), VPD_M (N=20), VPD_{Hwet} (N=12), and VPD_{Hdry} (N=8).

ΔHS during VPD_{Hwet}, originated from a stronger increase in courtyard humidity rather than a reduction in street humidity. Since there is no other source for humidity than evapotranspiration in the courtyard, this finding indicates that evapotranspiration is the cooling source in this site. While the 0.3 ms^{-1} higher wind speed during the VPD_{Hdry} category, could slightly reduce spatial differences it is likely too small to be the only cause for the reduction in ΔTA and ΔHS, and a reduction in the transpiration cooling seems likely. However, the highest afternoon SF is found during VPD_{Hdry} days, thus not indicating a reduced transpiration cooling at this time. The influence of drought on transpiration cooling can thus not be confirmed and needs to be studied further for better understanding.

The influence of transpiration on ΔTA and ΔHS was tested by calculating Pearson correlations between SF and ΔTA, as well as ΔHS for each hour of the day (Fig. 3). Significant correlation was found with SF and ΔTA throughout the night, showing that the courtyard is increasingly colder than the street when the SF is higher. During daytime the relationship is reversed, indicating that a warmer courtyard coincides with higher SF, likely due to that stronger heating increases the evaporative demand and thus the sap flow, though this relationship is mainly insignificant. The humidity is mostly positively correlated with SF – courtyard humidity is higher when SF is stronger – although mainly significant at night.

Larger nocturnal differences and a stronger influence of site specific properties are often found and attributed to the generally more stable nocturnal boundary layer preventing mixing of air from different areas, supporting site-specific nocturnal cooling (e.g. Krueger; Emmanuel 2013). During daytime, unstable conditions caused by solar heating enhance vertical mixing and subsequent horizontal winds, which mitigate spatial air temperature differences. Previous studies have also found that vegetated areas show strongest cooling at night (Holmer et al. 2013; Lindén 2011; Spronken-Smith; Oke 1998).

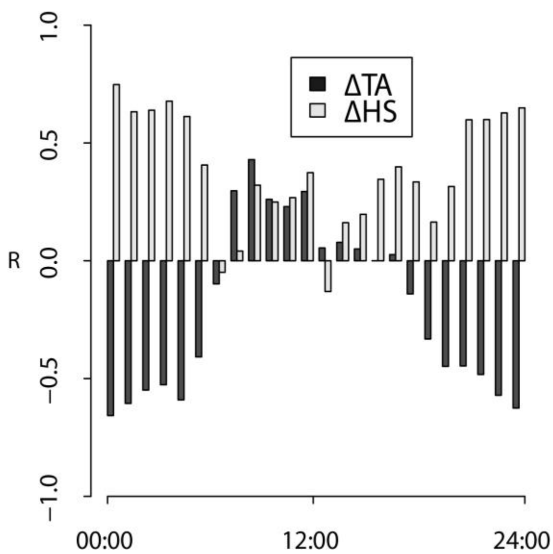

Figure 3. Pearson correlations between hourly values of SF and ΔTA (and ΔHS) for Courtyard-Street. Correlation above 0.32 is significant at p>0.01.

The association between transpiration and ΔTA and ΔHS found here reveal these influences are strongest during night. However, nocturnal transpiration is often assumed insignificant, as the stomata are thought to close in response to the lack of photosynthetically active radiation (Berninger et al. 1996; Cowan; Farquhar 1977) (Hari et al. 1986). This assumption has been questioned, however, and recent reviews concludes that nocturnal SF occurs at a rate of on average 12% of daytime maximum (Forster 2014), and that although part of the nocturnal SF is used for refilling of stem water storage, the nocturnal water loss through transpiration constitutes of 10 – 25 % of total water loss (Resco de Dios et al. 2015; Zeppel et al. 2014). Although it is not possible to determine how much of the measured nocturnal SF is transpired in this study, studies revealed that 50–95 % of the nocturnal SF is lost through transpiration from the canopy (e.g. Alvarado-Barrientos et al. 2015; Moore et al. 2008; Zeppel et al.

2010), and it is therefore reasonable to assume that it constitute a significant proportion of the daytime values in this study as well. While the nocturnal transpiration rate is much lower compared to daytime, dispersion of the air cooled by transpiration would be considerably reduced at nigh time, indicating that the connections between nocturnal SF and ∆TA and ∆HS is physically meaningful and that nocturnal transpiration is an important cooling factor in the urban courtyard in Mainz.

3.3 Agreement between measured and modeled results

Agreement in absolute values between the measured and modelled TA and HS were good (<±1°C, and <±0.5 g/kg), but some distinct differences were found when comparing the ability to reproduce spatiotemporal differences (Fig. 4). While ENVI-met predicts the spatial temperature differences rather well during daytime, the courtyard cooling and humidity levels, relative to the street, are underestimated during night. This is particularly the case during days with high evaporative demand and water availability (VPD_{Hwet}). During the drier category, VPD_{Hdry}, the nocturnal differences are less pronounced. For VPD_{Hdry}, afternoon cooling of the courtyard is instead overestimated. The shape of the observed SF and modelled transpiration profiles also deviates during night, where the model indicates that transpiration is quickly reduced after sunset, reaching less than 1 % of daytime levels. In contrast, SF slowly decreases until sunrise.

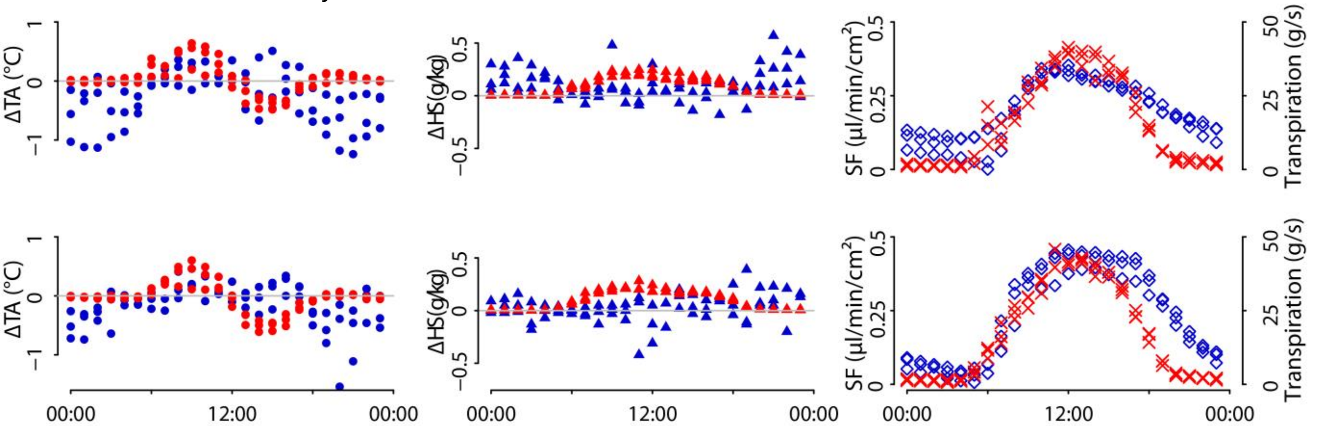

Figure 4. Comparison of measured (blue) and modeled (red) data for diurnal Courtyard - Street ∆TA (left), ∆HS (middle), and measured SF and modelled transpiration (right) for the atmospheric evaporative demand classes VPD_{Hwet} (top, N=3), and VPD_{Hdry} (bottom, N=3).

These results indicate that the amount of nocturnal transpiration from the plants in the Courtyard is underestimated in the model. This is most likely due to the estimation of the stomatal behavior in the Jacobs' A – gs model (Jacobs 1994) that after ceasing of the main driving parameters for the photosynthesis, like the PAR (photoactive radiation) shortly after sunset, the stomatal resistance rises very quickly leading to only a minimal exchange of water vapor during the dark respiration. Due to the low stomatal conductance the transpiration is reduced leading to only minor cooling effects on the air temperature

In order to provide a better understanding of the diurnal transpiration patterns in urban trees, an extended study including more sap flow, diurnal stem radius change, leaf gas exchange, spatial TA, HS, and wind as well as canopy temperature data is planned for summer 2015. The objective is to provide a more robust dataset of diurnal transpiration that could serve as input data for the modelling the urban climate.

4. Conclusion

In this paper, we present a case study on the effects of microclimate cooling of urban trees vary at the diurnal scale, and in relation to drought stress intensity. The differences between two adjacent sites within a city were strongest during night, and correlation with sap flow indicated nocturnal transpiration is an important cooling factor in the more vegetated site. When comparing two periods of different water availability, the cooling appeared reduced, particularly in the afternoon and night, during the drier period.

When comparing measured data with ENVI-met output, the modelled nocturnal transpiration cooling appeared underestimated, likely due to the assumption that transpiration ceases rapidly with sunset. In order to improve model performance of nocturnal influence of vegetation in urban areas, the vegetation input data should allow for higher nocturnal transpiration rates. Further studies are needed to assess the general nocturnal transpiration rates for different species and different atmospheric evaporative demand and water availability.

References

Alvarado-Barrientos, M. S., F. Holwerda, D. Geissert, L. Muñoz-Villers, S. Gotsch, H. Asbjornsen, and T. Dawson, 2015: Nighttime transpiration in a seasonally dry tropical montane cloud forest environment. *Trees*, **29,** 259-274.

Berninger, F., A. Makela, and P. Hari, 1996: Optimal control of gas exchange during drought: Empirical evidence. *Annals of Botany*, **77,** 469-476.

Bowler, D. E., L. Buyung-Ali, T. M. Knight, and A. S. Pullin, 2011: Urban greening to cool towns and cities: A systematic review of the empirical evidence. *Landscape and Urban Planning*, **97,** 147-155.

Bruse, M., 2004: ENVI-met implementation of the Jacobs A−gs Model to calculate the stomata conductance, . *http://envi-met.com/documents/new_a_gs.pdf. 18.04.2015.*

Bruse, M., and H. Fleer, 1998: Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. *Environmental Modelling & Software*, **13,** 373-384.

Cowan, I. R., and G. D. Farquhar, 1977: Stomatal function in relation to leaf metabolism and environment. *Symposia of the Society for Experimental Biology*, **31,** 471-505.

Ennos, R., 2011: Quantifying the cooling benefits of urban trees. *Trees, people and the built environment* Birmingham, UK, Forestry Commission.

Forster, M. A., 2014: How significant is nocturnal sap flow? *Tree Physiology*.

Granier, A., 1985: A NEW METHOD OF SAP FLOW MEASUREMENT IN TREE STEMS. *Annales Des Sciences Forestieres*, **42,** 193-200.

Hari, P., A. Maekelae, E. Korpilahti, and M. Holmberg, 1986: Optimal control of gas exchange. *Tree Physiology*, **2,** 169-175.

Holmer, B., S. Thorsson, and J. Lindén, 2013: Evening evapotranspirative cooling in relation to vegetation and urban geometry in the city of Ouagadougou, Burkina Faso. *International Journal of Climatology*, **33,** 3089-3105.

Jacobs, C. M. J., 1994: Direct impact of atmospheric CO2 enrichment on regional transpiration, PhD thesis, Agricultural University Wageningen,Wageningen.

Krueger, E., and R. Emmanuel, 2013: Accounting for atmospheric stability conditions in urban heat island studies: The case of Glasgow, UK. *Landscape and Urban Planning*, **117,** 112-121.

Lindén, J., 2011: Nocturnal Cool Island in the Sahelian city of Ouagadougou, Burkina Faso. *International Journal of Climatology*, **31,** 605-620.

Liu, J., and S. Schweighoefer, 2011: A New Type of Sap Flow Sensor. *8th international Workshop on Sap Flow*.

Moore, G. W., J. R. Cleverly, and M. K. Owens, 2008: Nocturnal transpiration in riparian Tamarix thickets authenticated by sap flux, eddy covariance and leaf gas exchange measurements. *Tree Physiology*, **28,** 521-528.

Qiu, G.-y., H.-y. Li, Q.-t. Zhang, W. Chen, X.-j. Liang, and X.-z. Li, 2013: Effects of Evapotranspiration on Mitigation of Urban Temperature by Vegetation and Urban Agriculture. *Journal of Integrative Agriculture*, **12,** 1307-1315.

Resco de Dios, V., J. Roy, J. Ferrio, J. Alday, Landais D., A. Milcu, and A. Gessler, 2015: Processes driving nocturnal transpiration and implications for estimating land evapotranspiration. *Scientific Reports, in print*.

Spronken-Smith, R. A., and T. R. Oke, 1998: The thermal regime of urban parks in two cities with different summer climates. *International Journal of Remote Sensing*, **19,** 2085-2104.

Zeppel, M., D. Tissue, D. Taylor, C. Macinnis-Ng, and D. Eamus, 2010: Rates of nocturnal transpiration in two evergreen temperate woodland species with differing water-use strategies. *Tree Physiology*, **30,** 988-1000.

Zeppel, M. J. B., J. D. Lewis, N. G. Phillips, and D. T. Tissue, 2014: Consequences of nocturnal water loss: a synthesis of regulating factors and implications for capacitance, embolism and use in models. *Tree Physiology*, **34,** 1047-1055.