Report by UWI doctoral researcher Stenka Vulova (W3)

Project number: W3

First and last name of doctoral researcher: **Stenka Vulova**

(Working) title of doctoral project: **Heat and vapour fluxes of urban vegetation patterns – a remote sensing based approach**

Name of supervisors: Prof. Dr. Birgit Kleinschmit (TUB), Prof. Dr. Doerthe Tetzlaff (IGB, HU), Prof. Dr. Chris Soulsby (University of Aberdeen, IGB, TUB)

2. Description of doctoral project and research results achieved to date:

State of the art

Water resources planning and management, which is essential for human and ecological sustainability, demands a deeper understanding of water flows. Water flows can be partitioned into blue-water flows, which flow through rivers and recharge groundwater, and green-water flows, constituting transpiration from plants and evaporation from soil and other surfaces (Falkenmark & Rockström 2006). While research has traditionally focused on blue water flows, understanding the partitioning of rainfall into blue- and green-water flows across spatial and temporal scales is increasingly important for water resources management (Falkenmark & Rockström 2006). Vegetation is therefore a key component of the water cycle, driving water flow across the soil-plant-atmosphere interface and responding to fluctuations in water availability (Damm et al. 2018).

Urban green spaces refer to a variety of vegetated open areas in cities, including public parks, residential gardens, green roofs, and street trees (Nouri et al. 2013a). The benefits of urban green spaces have been well-documented, with effects on air temperature, air quality, biodiversity, building energy consumption, and soil stabilization (Nouri et al. 2013a). Vegetation reduces the land surface temperature by providing shade and absorbing radiation energy via transpiration and photosynthesis (Wang et al. 2018; Bowler et al. 2010). In urban environments, vegetation is generally spatio-temporally heterogeneous, with variations in vegetation type, species, vegetation density, vegetation height, leaf area, microclimate, water accessibility, and soil and water characteristics (Nouri et al. 2013a).

Evapotranspiration (ET) is a crucial parameter with a high dynamic component in the urban water and energy regime, yet a sufficient understanding of the role of vegetation in the urban water cycle is still lacking. Quantifying ET accurately is a necessity in order to understand and manage climate change, irrigation, water use, and land use (Nouri et al. 2013b). As the majority of studies investigating ET have thus far focused on rural and agricultural regions, the estimation of ET in urban environments with heterogenous land cover remains is a critical area of research (Bartesaghi Koc et al. 2018). Unravelling the resulting complex feedbacks and interactions between the plant-water system and environmental change is essential for any modelling approaches and predictions, but still inadequately understood due to currently missing observations (Damm et al. 2018).

Currently, large scale observations of plant-water relations are still emerging and not fully matured (Damm et al. 2018). Combined observational and modelling approaches incorporating remote sensing offer the potential to advance the understanding of heat and vapor fluxes at the soil-vegetation-atmosphere interface (Damm et al. 2018). ET estimation using remote sensing technology is the most efficient and cost-effective method that can be utilized for large spatial areas (Nouri et al. 2013a). Remote sensing is particularly well-suited for heterogeneous vegetated areas, due to its capacity to quantify spatio-temporally variable vegetation characteristics (Nouri et al. 2013a). Remote sensing can improve existing ET estimation methods, provide broad spatio-temporal coverage and facilitate continuous updates (Nouri et al. 2013a; Nouri et al. 2013b).

Motivation

In urban environments, ET is one of the most significant components of energy balance and the water budget, yet also one of the least-studied aspects of urban hydrology (Qiu et al. 2017). Thus far, estimation of ET has been predominantly conducted in rural areas and in an agricultural context (Bartesaghi Koc et al. 2018). Despite a high number of promising technologies, ET estimation of urban green areas remains insufficient due to the high complexity and heterogeneity of urban vegetation cover (Nouri et al. 2013b). Thus, the estimation of ET in an urban context with heterogeneous vegetation is an understudied and promising direction for research (Nouri et al. 2013b; Bartesaghi Koc et al. 2018).

A review of research on urban green spaces recommended that future research should incorporate functional (ET, photosynthetic activity), structural (size, type, height), and configurational parameters of urban vegetation in order to more fully assess the thermal effect of green spaces (Bartesaghi Koc et al. 2018). The first research phase will help fill this research gap by incorporating 3D vegetation data, biotope types, and vegetation indices in a study of land surface temperature (LST) across diurnal and seasonal temporal scales in a mid-latitude city. As the majority of previous studies of vapor and heat fluxes of urban vegetation were conducted at the meso scale using low and medium spatial resolution imagery, incorporating high resolution UAV technology in future studies is highly recommended for future research (Bartesaghi Koc et al. 2018). The second research phase will utilize drone-based high-resolution imagery to further understanding of ET at a local scale. The third research phase will apply advanced methods of modeling ET in an urban environment (e.g. radiative transfer models and machine learning).

The dynamic spatial and temporal heterogeneity of green spaces has thus far been overlooked in the literature (Bartesaghi Koc et al. 2018). This study will further the understanding of this research field by contributing a study of the seasonal and diurnal variability of heat and vapor fluxes in a mid-latitude city across spatial scales (Nouri et al. 2013b). By combining observational, remote sensing, and modelling approaches to estimating ET, this study will advance the knowledge of the soil-vegetation-atmosphere interface in an urban context.

Planned Research

Topic 1: Spatial and temporal variability of thermal behaviour of different urban green types

The work carried out in this project is divided into three different phases. The first phase will comprise a landscape-level study of the thermal behaviour of urban green spaces in Berlin. The key question investigated for this research topic will be how LST and vegetation parameters of different types of biotopes vary temporally (seasonally and diurnally). Landsat 8 Thermal Infrared Sensor (TIRS) data will be used to characterize LST at a higher resolution (see Fig. 1). Diurnal variability can be assessed using both MODIS day and night 8-day composite products (see Fig. 2).

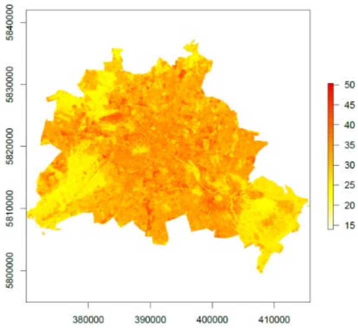

Figure 1: LST in Berlin (23 July 2018), derived from Landsat 8 imagery using Wang et al. (2015)'s mono-window algorithm

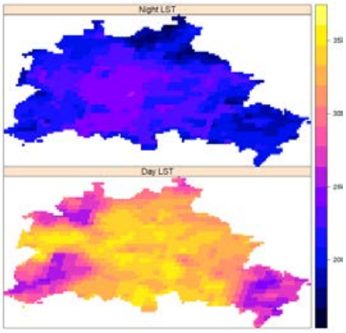

Figure 2: Day and night LST in Berlin (20-28 July 2018), provided by MODIS (MOD11A2.006 Terra Land Surface Temperature and Emissivity 8-Day Global 1km)

A biotope type map provided by the Berlin Environmental Atlas of the Berlin Senate Department for Urban Development and Housing will be used to provide GIS data for the biotope types in Berlin (see Fig. 3). The relationship between LST and the biotope types and its spatio-temporal variation will be investigated. Vegetation indices will be used to assess the relationship between the state of the vegetation and LST. The normalized difference vegetation index (NDVI) derived from a Landsat 8 image is shown in Figure 4. 3D laser scan data will be used to investigate the relationship between vegetation height and LST. The dataset contains vegetation and building height as raster data with a 5-meter resolution. For this research topic, the following questions will be addressed: 1) How does LST of different urban green biotope types vary in a mid-latitude city spatially and temporally (seasonally and diurnally)?; 2) Which vegetation related indicators are appropriate to describe the quantitative relationship?; and 3) Are the indicators scale sensitive?

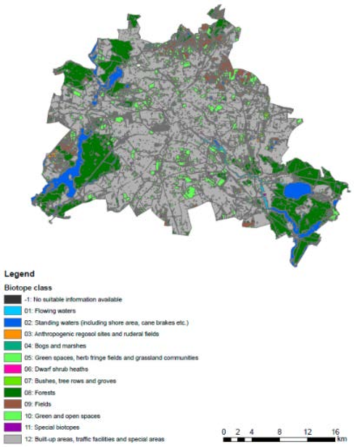

Figure 3: Biotope classes in Berlin, as provided by the Berlin Environmental Atlas

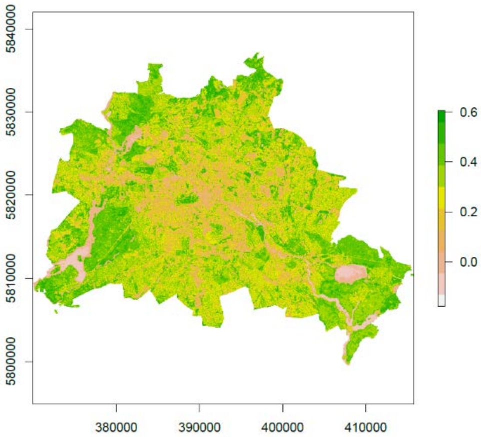

Figure 4: NDVI in Berlin (23 July 2018), derived from Landsat 8 imagery

Topic 2: Thermal behaviour and vapor fluxes at the local level
The second phase of this project will focus on the thermal behaviour of urban green spaces at the local level. In this research phase, 2-3 remote sensing-based ET measurement techniques will be assessed in comparison to conventional ET estimation methods. The measuring period will last from March of 2019 until winter of 2019. 2-3 intensive field campaigns are planned. Measurements will be conducted regularly in the study site of TU Berlin in Steglitz in order to characterize vegetation at different phenological stages. Hydrometeorological monitoring will be conducted with the eddy flux tower at Steglitz and the eddy flux tower of IGB. A thermal camera will be mounted on the Steglitz tower, and drone flights with hyperspectral and thermal cameras will be conducted. Various biophysical parameters, including leaf area index (LAI), water content, biomass, hydrological and soil moisture parameters, will be measured. The canopy leaf area index (LAI) is defined as a unitless quotient attained when green leaf area is divided by the ground area covered by the tree canopy (Hardin & Jensen 2007). With LI-6800, a portable photosynthesis system equipped with leaf fluorometer, the photosynthetic activity and gas exchange (transpiration) of vegetation will be measured (Guha et al. 2018). Validation of remote sensing-derived ET data can be conducted with measurements conducted in collaboration with the W1 team (isotope sampling, sap flow measurements, eddy covariance) and our own LI 6800 measurements. Maps from UAV flights at different parts of the same day can be created, showing the spatial distributions of LST and ET. These maps can be used to assess the diurnal variation of vegetation types in LST and ET. For this research topic, the following questions will be addressed: 1) How does the thermal behavior (LST, ET) differ between different vegetation types typical for urban environments? (lawns, bushes, trees, ruderal); 2) How does vertical structure affect LST and ET?; and 3) How do LST and ET vary diurnally and seasonally for different vegetation types?

Topic 3: Modelling evapotranspiration of typical urban vegetation types
The third phase of this project will broadly focus on modelling evapotranspiration of typical urban vegetation types by including structural vegetation parameters and their seasonal variability in urban EP models. With the knowledge gained from local observations in the second project phase, the field measurements will be upscaled to the sub-catchment scale using remote sensing-based regression and radiative transfer models. One component of this phase will focus on model optimization with remote sensing data. The SCOPE (Soil Canopy Observation, Photochemistry, and Energy fluxes) model, for instance, can be applied to the data collected in the second phase of the project (van der Tol et al. 2009). The SCOPE model is a vertical (1-D) integrated radiative transfer and energy balance model linking water, heat, and carbon dioxide fluxes to visible to thermal infrared radiance spectra (van der Tol et al. 2009). Machine learning approaches could also be utilized to identify non-linear relationships between green cover spatial parameters and urban LST and ET in an urban environment (Berlin). The modelled ET from machine learning approaches could be compared to ET derived from other models and also to ET derived from in-situ instruments. A potential output of the third research phase will be a joint paper comparing the ET model results from IGB (in collaboration with the W1 UWI project) and machine learning results (TU Berlin). For this research topic, the following questions will be addressed: 1) How can we enhance evapotranspiration modelling in urban environments with remote sensing techniques?; 2) What role does the spatial and seasonal variability play?; and 3) How can non-linear modelling techniques (machine learning algorithms) be applied to estimate LST and ET in an urban environment (Berlin)? Which machine learning approaches can best simulate the relationships between land parameters (e.g. vegetation indices) and LST/ ET?

Collaboration
The research will be conducted in close collaboration with the W1 UWI project (“Ecohydrological controls on urban groundwater recharge: an isotope-based modelling approach”). Various biophysical parameters, including LAI, water content, biomass, hydrological and soil moisture parameters, will be available through collaboration with Prof. Dr. Dieter Scherer (Chair of Climatology, Institute of Ecology, TUB). An external collaboration with Professor Chris Soulsby (University of Aberdeen) is also planned. Soulsby is an expert in tracer-aided ecohydrological modelling at different spatial scales and isotope laboratory analyses.

3. Comments on the qualification programme and supervision strategy:

Participation in the following Research Training Group events:

1. Core courses
    - I – Urban interface processes – fluxes, transport, interactions (3 ECTS)
    - II – Modelling and measuring concepts of interface processes (3 ECTS)
    - III – Urban freshwater ecology (3 ECTS)

Research stays or internships at other research institutions both at home and abroad.

Participation in conferences, congresses, etc., at home and abroad:

2019:

- European Geosciences Union (EGU) General Assembly (07. – 12.04.2019, Vienna, Austria)
- Joint Urban Remote Sensing Event (JURSE) 2019 (22. – 24.05.2019, Vannes, France)

References

1. Bartesaghi Koc,C., Osmond,P., & Peters,A. (2018): Evaluating the cooling effects of green infrastructure: A systematic review of methods, indicators and data sources. Solar Energy, 166, 486–508.
2. Bowler,D.E., Buyung-Ali,L., Knight,T.M., & Pullin,A.S. (2010): Urban greening to cool towns and cities: A systematic review of the empirical evidence. Landscape and Urban Planning, 97(3), 147–155.
3. Damm,A., Paul-Limoges,E., Haghighi,E., Simmer,C., Morsdorf,F., Schneider,F.D., van der Tol,C., Migliavacca,M., & Rascher,U. (2018): Remote sensing of plant-water relations: An overview and future perspectives. Journal of plant physiology, 227, 3–19.
4. Falkenmark,M., & Rockström,J. (2006): The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. Journal of Water Resources Planning and Management, 132(3), 129–132.
5. Guha,A., Han,J., Cummings,C., McLennan,D.A., & Warren,J.M. (2018): Differential eco-physiological responses and resilience to heat wave events in four co-occurring temperate tree species. Environmental Research Letters, 13(6), 65008.
6. Hardin,P.J., & Jensen,R.R. (2007): The effect of urban leaf area on summertime urban surface kinetic temperatures: A Terre Haute case study. Urban Forestry & Urban Greening, 6(2), 63–72.
7. Nouri,H., Beecham,S., Kazemi,F., & Hassanli,A.M. (2013a): A review of ET measurement techniques for estimating the water requirements of urban landscape vegetation. Urban Water Journal, 10(4), 247–259.
8. Nouri,H., Beecham,S., Kazemi,F., Hassanli,A.M., & Anderson,S. (2013b): Remote sensing techniques for predicting evapotranspiration from mixed vegetated surfaces. Hydrology and Earth System Sciences Discussions, 10(3), 3897–3925.
9. Qiu,T., Song,C., & Li,J. (2017): Impacts of Urbanization on Vegetation Phenology over the Past Three Decades in Shanghai, China. Remote Sensing, 9(9), 970.
10. van der Tol,C., Verhoef,W., Timmermans,J., Verhoef,A., & Su,Z. (2009): An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy bal-ance. Biogeosciences, 6(12), 3109–3129.
11. Wang,X., Cheng,H., Xi,J., Yang,G., & Zhao,Y. (2018): Relationship between Park Composition, Vegetation Characteristics and Cool Island Effect. Sustainability, 10(3), 587.