Academic Article

The role of soil water content for microclimatic effects of green roofs and urban trees – a case study from Berlin, Germany

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ABSTRACT

Stormwater can have negative influences on receiving systems and could be used to transpire water in order to improve urban climate and thermal comfort within an urban area. Especially during warm sunny days, people in cities can suffer in certain areas under extreme temperatures and very strong heat stress. Green roofs and trees could be measures to use the benefits from stormwater. In this study the three-dimensional distribution of wind and temperature was simulated with a micro-scale model for a city quarter in Berlin to study the effects of those two measures. Under optimal soil water conditions the green roof on a large low warehouse lowers the temperature in 2 m height at noon within 100 m downstream 0.5 – 3 K. The thermal comfort, here evaluated by the Universal Thermal Climate Index (UTCI), is also improved by the same amount. The potential cooling effect of the trees is almost limited to the area of their shadow. The air is at noon about 3-4 K cooler and the UTCI is 7 K lower. After 14 days without precipitation the soil water content is much lower and the green roof does not transpire soil water anymore. This halves the effects of the green roof. They are now only caused by changes in the albedo and heat flux into the underlying medium. The effects of the trees are almost the same for both soil water content situations, as it relies mainly on the solar radiation shielding under their canopy.

Key Words : urban climate, thermal comfort, soil water content, green roof, stormwater

1. Introduction

Stormwater runoff from sealed surfaces and roof tops can have strong impacts on the sewer system and receiving lakes / rivers. It influences them regarding hydraulics(1), toxic impacts(2) and water quality(3). The positive potential of rain water is traditionally not often used for building services(4) and improving thermal comfort(5) in cities. Especially in larger urban areas a heat island effect is observed and leads to higher temperatures than in the surrounding rural area(6). This is caused by a reduced wind speed between buildings and other obstacles, changes in the radiation budget, heat storage in build-up materials and impervious surfaces that alter the water balance. The surface energy budget is overall different. The meteorological conditions of a typical summer day with low wind speeds and no cloud cover can lead to heat stress and make it unpleasant for people to live there.

To reduce the negative effect of sealed surfaces and improve the urban climate, a number of measures can be applied at building level (e.g., green roofs, rain water use) and city quarter level (e.g., de-paving of impervious areas)(7). In the following the effects of two urban greenery measures on the urban climate and human thermal comfort are investigated during a heat wave. The dependence of those effects on the availability of water for transpiration is examined for two different soil water contents (SWC).

2. Methods

The wind and temperature distribution in a city district is simulated with the micro-scale model ASMUS (Ausbreitungs- und Strömungs Modell für Urbane Strukturen). It is based upon the Navier-Stokes equations, the continuity equation, the first law of thermodynamics and an equation for specific humidity. Buildings and trees are represented by impermeable or semipermeable grid volumes. Their surface temperatures are calculated depending on their specific orientation and physical properties by a surface energy budget(8). The model equations, boundary conditions for ground and building surfaces, including green roofs and trees are described by Gross(9).

The calculation of the latent heat flux is modified after Bruse[10] to take the SWC and solar radiation via stomata resistance into account.

$$Q_V = L_s \rho J_{f,trans}, \quad (1)$$

where L_s is the latent heat, ρ the air density and $J_{f,trans}$ the transpiration part of water vapor fluxes. Evaporation is neglected and rain fall only interacts with the SWC.

$$J_{f,trans} = \left\{ \begin{matrix} (r_a + r_s)^{-1} \Delta q; if \Delta q \geq 0 \\ 0 \quad ; if \Delta q < 0 \end{matrix} \right\}, \quad (2)$$

with aerodynamic resistance r_a, stomata resistance r_s and difference between saturation humidity at leaf temperature and air humidity Δq. Stomata resistance can be calculated with[11]

$$r_s = r_{s,min} \left[\frac{R_{kw,max}}{0.03 R_{kw,max} + R_{kw}} + f_{wilt} \right] \quad (3)$$

and depends on the minimal stomata resistance $r_{s,min}$ (different for each vegetation type, here: for grass 200, for deciduous trees 400)[12], the possible daily maximum of shortwave radiation $R_{kw,max}$ and the availability of water f_{wilt}.

$$f_{wilt} = \left(\frac{\Theta_{wilt}}{\Theta} \right)^2 \quad (4)$$

is the ratio between SWC at wilting point and the actual SWC in the root zone[11].

2.1 Hydrology model

ASMUS was extended by a hydrology model that is described by Chen and Dudhia[13] and verified against measurements[14]. It is used to simulate the changes in soil water under the ground surface and within green roofs dependent on transpiration and precipitation. Short vegetation on the ground and on green roofs only interacts with the hydrology model at the top layer (here: 5 cm depth) and directly under the greenery. Trees (here: only tilia cordata / small-leaved lime) take water from deeper layers (here: in depths up to 3 m) and from a larger horizontal area[15].

2.2 The superimposed forcing

The domain of the micro scale model is embedded in the atmospheric boundary layer. The time-dependent external forcing above the domain has to be prescribed to study the diurnal variation of the effects of urban greenery measures. A one-dimensional boundary layer model[16] simulates the atmosphere up to 2000 m height with 45 grid levels and grid levels of 10 m near the ground and up to 100 m at the top of the domain. The surface temperature at the lower boundary is calculated by a surface energy budget for a green field. The hourly results of the lowest 1000 m are used to force the micro scale model. They are linear interpolated to match the time step and vertical grid resolution of the mirco-scale model.

The reservoir capacities of the soil for water make it necessary to consider its long-term behavior. Because of the high computing time for the micro-scale model the SWC is calculated separately for a longer time period starting before the main simulation (here 2 months). It is simulated for a grass surface, for a grass surface with a nearby tree of 10 m height and a green roof.

The different green surfaces of the micro scale model are initialized with the resulting SWC of the hydrological model. Hourly observations, linear interpolated, from nearby meteorological stations provide the necessary data (precipitation, air temperature in 2 m height, soil temperature, wind and cloud cover for the one-dimensional, the hydrological and the micro scale model).

3. Setup of the numerical experiments

For the numerical experiments, GIS-data (Geographical Information System) of the city quarter Schöneberg in Berlin, Germany and hourly data from the weather station of the german weather service (DWD) at Berlin-Tempelhof is used from 1.6.2003 to 14.8.2003. The whole time period was simulated with the hydrology model and the last day was simulated with the micro-scale model with two different SWC under the same weather conditions. The simulation area has a size of 458 m x 458 m and is 1000 m high. The horizontal grid resolution inside a square of 202 m x 202 m in the center of the domain is 2 m, on

Fig. 1 Simulation area in Berlin-Schöneberg (Google Earth, 2014). Inside the red square 2 m x 2m horizontal grid resolution and outside 8 m x 8 m. The green area in the middle shows the position of the green roof as measure number one and the yellow dots the 13 trees as measure number two.

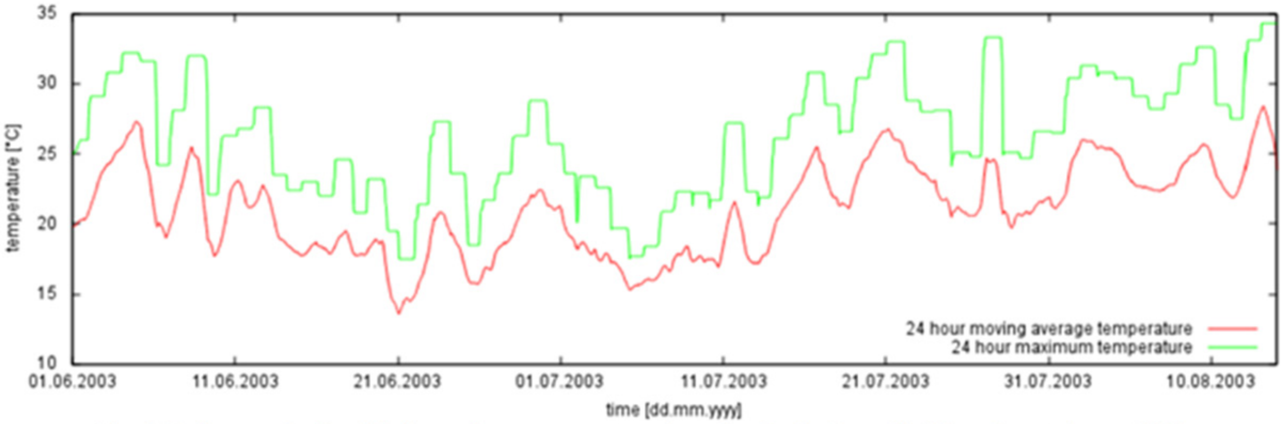

Fig. 2: Daily mean (red) and daily maximum temperatures (green) at Berlin-Tempelhof from June to August 2003

the outside 8 m (Fig. 1). The vertical resolution is 2 m from the ground up to 40 m height and then increases up to 150 m at the top of the domain.

3.1 The synoptic situation

From 1st of august until 14th of august 2003 the daily average temperatures at the meteorological station were between 20 °C and 28 °C with daily maximum temperatures between 27 °C and 34 °C (Fig. 2). There were light winds with up to max. 2- 3 m/s in 10 m height from the east and during daytime strong solar radiation. The rain water total in June and July at Tempelhof was 105 mm and almost no precipitation in the first two weeks of August 2003 (Fig. 2).

3.2 Geographical data

The geographical data is from different databases and includes high resolution information about building and vegetation heights, green roofs, degree of the sealing and tree positions. The city quarter is in the southwest of Berlin and consists of perimeter development with inner yards and small public parks. It has a less dense population than in the center of Berlin (Berlin-Mitte). The average building has a height of 20 m, except for the large warehouse in the center of the domain that is 4 m high (Fig. 1). Flat roofs are assumed for all buildings and inclined or sloping surfaces were ignored. The average vegetation / tree is about 10 m high and their overall coverage is about 30 % of the area. Short vegetation on the ground and on green roofs is assumed to be grass and covers about 15 % of the ground surface (excluding additional measures). Other ground surfaces are assumed to be sealed. A sandy soil was assumed for all ground surfaces with a SWC at field capacity of 0.236 m^3/m^3, soil saturation at 0.339 m^3/m^3 and wilting point at 0.01 m^3/m^3. For the green roofs a one-layer sandy loam soil with a higher SWC at field capacity (0.312 m^3/m^3), at soil saturation (0.476 m^3/m^3) and at wilting point (0.084 m^3/m^3) was assumed.

3.3 Scenarios

In order to study the effects of measures for stormwater management on the urban climate and human thermal comfort two measures are defined and simulated for one day under the weather conditions described above (3.1). The first measure is a green roof (albedo 0.2)[17] on the central warehouse. It has an assumed heat conductivity of 2.2 W/(m*K)[9] and a size of about 9600 m^2, is 4 m high and originally has a black mat surface (albedo 0.13)[17]. The heat conductivity was set to 0.7 W/(m K)[18]. The transpiration rate of the green roof depends on the SWC that is saved in the growing medium from previous rain falls. The second measure are 13 trees of 10 m height and a ball shaped crown with a diameter of 8 m. They are located on the parking lot (that is now unsealed) in the south of the warehouse (Fig. 1). They use the soil water in their environment for transpiration.

The SWC at the beginning of the simulation with the micro scale model takes two possible values: SWC at field capacity ("high") or as simulated with the hydrological model until 14th of August 2003 ("low") (see 4.1).

4. Results and discussion

The effects on urban climate are described by changes in the surface temperature and air temperature at 2 m height. The Universal Thermal Climate Index (UTCI) is used to characterize the thermal comfort. The UTCI depends like the PMV (Predicted Mean Vote) on several meteorological parameters (wind speed, mean radiation temperature, air temperature and humidity), activity and clothing of people. There are some differences between UTCI and PMV which lead to advantages and disadvantages, nevertheless is the correlation between both indices still very high[19]. A comparison of the effects on thermal comfort based upon PMV would also have been possible.

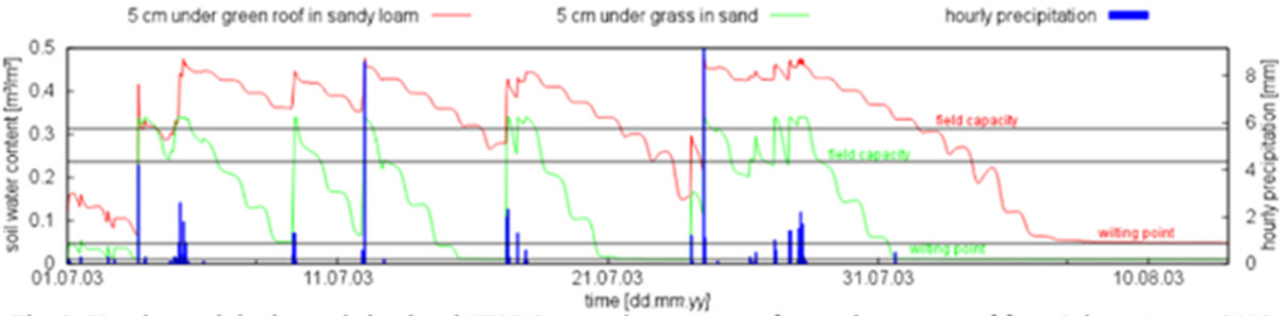

Fig. 3: Hourly precipitation and simulated SWC 5 cm under a grass surface and a green roof from July to August 2003

4.1 Soil water content

Fig. 3 shows the simulated SWC under a grass surface and a green roof in a depth of 5 cm. The precipitation and evaporation has a strong influence on the SWC in the top layers and is reduced in deeper layers. After rain fall the SWC at the top layer reaches its maximum value and is limited to SWC at saturation. Within one day the SWC at those layers is reduced to SWC at field capacity. This matches the scenario with "high" SWC. At mid-August 2003, during the heat wave with two weeks of almost no precipitation, the SWC reaches wilting point at the top layers and minimum values in deeper layers under both types of surfaces ("low" SWC scenario).

4.2 Diurnal variation of latent heat flux and water consumption

The daily maximum latent heat flux over the grass covered green roof measure varies between 0 W/m² for "low" SWC and 270 W/m² for "high" SWC (not shown here). Overall up to 4.0 l/m² of soil water are transpired per day under optimal conditions with high SWC.

The trees of measure two have a mean maximum latent heat flux of 105 W/m² for the "low" SWC and 180 W/m² for the "high" SWC (not shown here). Each tree has a surface of 194 m² and transpires between 300 l to 500 l soil water per day dependent on the SWC scenario. Because of their size and shape the trees simulated in this study consume about 2.7 l/m² to 4.4 l/m² per day. The water consumption of the two measures per square meter soil is similar, but trees also take soil water from deeper layers, access a greater water reservoir directly and are therefore less dependent on short-term rain events.

The simulated latent heat flux depends strongly on the amount of solar radiation and is only sensitive to extremely low SWC. The order of magnitude for the daily water consumption for both measures is in the range of literature values[20].

4.3 Temperatures and thermal comfort in the built-up area

Fig. 4 shows a perspective view from south west of the simulated surface temperatures at noon for the inner domain with both measures and "high" SWC. At this time south

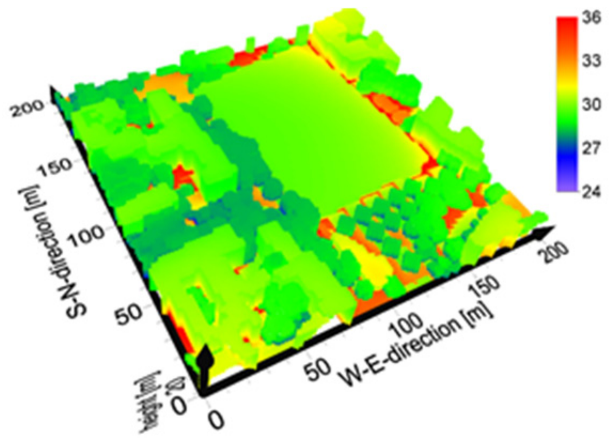

Fig. 4 Perspective view from southwest of surfaces temperatures in °C at noon with both measures and "high" SWC

orientated surfaces and the ground receive the largest values of solar radiation and temperatures of bare ground reach temperatures up to 36 °C. The temperature of other surfaces are much lower (≤ 24 °C) dependent on their orientation, presence of shadow, surrounding wind speeds and, as the case may be, transpiration.

The surface temperature of the warehouse roof is lower during daytime if it is covered with a green roof (not shown here). The maximum difference is at noon and depends on the SWC. It ranges from -2 ("low" SWC) to -3 K ("high" SWC). This is caused by transpiration (for the "high" SWC scenario), a different albedo and heat flux through the underlying medium. In the early morning around 4 a. m. the green roof surface is 1.5 K warmer than the bare roof for both SWC scenarios, caused by a stronger surface heat flux from the underlying medium.

The surface temperature of the ground under the trees is at noon up to 4.5 K lower than without this measure (not shown here). This is mainly caused by the shadow of the trees and does not significantly change with the SWC.

The maximum differences between the surfaces temperatures at daytime with and without green are much smaller than simulated by Gross[9] (10 - 15 K) or measured by Wong[21] (8 – 10 K). Reasons could be a different wind and temperature profile and lower solar radiation.

In the following the focus of this study is on the evaluation of the potential cooling effect of the two measures.
At noon the simulated air temperature in 2 m height ranges from 27 °C, in the shadow of buildings and vegetation to 36 °C, near south orientated walls and areas without vegetation and bare surfaces for the reference situation with “low” SWC (Fig. 5). The temperature distribution for the reference situation with “high” SWC is almost the same (not shown here), because of the small fraction of distributed short vegetation that transpire significantly more water and have a different surface temperature.
The green roof effects the air temperature in 2 m height in a large area in wind direction, which covers almost the whole inner domain, when there is “high” SWC. Near the warehouse the potential cooling can reach up to -3 K. In a distance of 100 m the effect is much smaller (still more than -0.5 K) (Fig. 6). Wong[22] measured a similar potential cooling effect 1 m above of a green roof (max. –4.2 K). The maximum potential cooling effect of the green roof is much lower for the “low” SWC scenario when the roof does not transpire water (max. -0.5 K) and diminishes within the inner domain (Fig. 7). The potential cooling of the trees does not significantly depend on the SWC and has its maximum within their shadows with -4 K but vanishes within a distance of 20 m (Fig. 8). Shashua-Bar[23] calculated a similar potential cooling effect for this kind of tree at noon, ranging from -1.2 to -3.4 K.
The UTCI is divided in heat and cold stress categories, e.g.: 26 °C - 32 °C = moderate heat stress and 32 °C - 38°C = strong heat stress. It is very sensitive to the mean radiation temperature, which is about 30 K cooler without direct solar radiation. Because of this the heat stress is only moderate in the shadow of trees and buildings within the inner domain. Near south orientated walls over bare ground with no shadow, strong heat stress is caused, e. g. in the south of the warehouse (Fig. 9).
The green roof on the warehouse changes the UTCI within the inner domain by up to -2 to -3 K (Fig. 10) because of the lower air temperature dependent on the SWC scenario (not shown here). The effect of the tree measure on the UTCI is locally much stronger (up to -8 K) (Fig. 10). This measure lowers the heat stress at noon by one category from strong to moderate heat stress. The increased air humidity, caused by the transpiration of two measures or between the “high” and “low” SWC scenarios, do not decrease thermal comfort significantly.

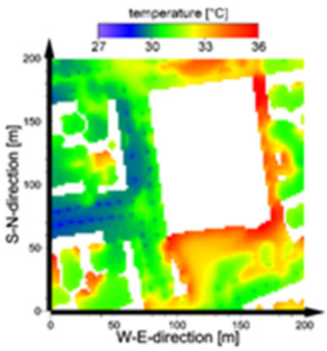

Fig. 5 Simulated air temperature at noon in 2 m height in °C without both measures and “low” SWC.

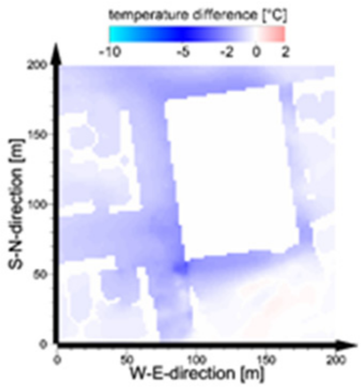

Fig. 6 Effect on air temperature in 2 height of the green roof measure in K with “high” SWC.

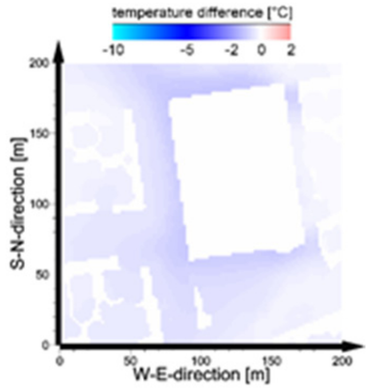

Fig. 7 Effect on air temperature in 2 height of the green roof measure in K with “low” SWC.

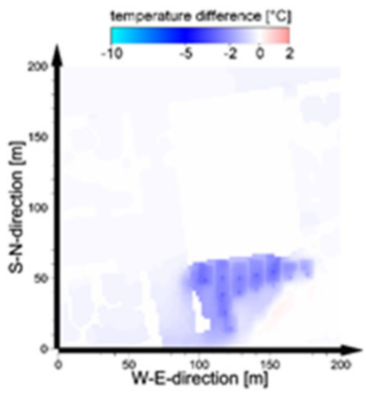

Fig. 8 Effect on air temperature in 2 height of the tree measure in K with “low” SWC.

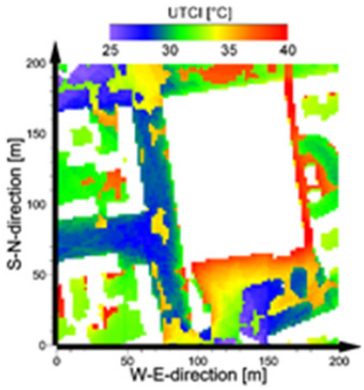

Fig. 9 Simulated air temperature at noon in 2 m height in °C without both measures and “high” SWC.

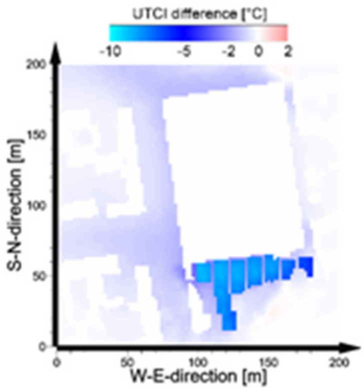

Fig. 10 Effect on UTCI for both measures with “low” SWC.

5. Conclusions

The urban climate benefits from both measures. Only the shadow of the trees has a strong impact on the thermal comfort. A 14 day long period without precipitation causes a SWC at wilting point in the top surface layers of the green roof. This limits its cooling effect. A more realistic and extensive green roof with different substrate layers and better water storage properties could improve the urban climate by transpiration for a longer time period. The potential warming effect of the green roof at night, caused by a higher surface temperature, could increase the urban heat island effect, but the benefits from the green roof are still larger than the possible negative impacts. The SWC in deeper layers is effected much less by single precipitation events. The trees transpire water in both scenarios. Nevertheless their benefit to the urban climate and especially thermal comfort is mainly caused by their solar radiation shielding effect that should be a priority to improve thermal comfort under sunny and warm weather conditions.

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