Urban Climate 20 (2017) 33–45

Contents lists available at ScienceDirect

Urban Climate

journal homepage: http://www.elsevier.com/locate/uclim

A neighbourhood-scale estimate for the cooling potential of green roofs

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ARTICLE INFO

Article history:
Received 5 May 2016
Received in revised form 14 November 2016
Accepted 17 February 2017

Keywords:
Green roofs
Urban heat island
Urban energy balance
cooling potential

ABSTRACT

Green roofs offer the possibility to mitigate multiple environmental issues in an urban environment. A common benefit attributed to green roofs is the temperature reduction through evaporation. This study focuses on evaluating the effect that evaporative cooling has on outdoor air temperatures in an urban environment. An established urban energy balance model was modified to quantify the cooling potential of green roofs and study the scalability of this mitigation strategy. Simulations were performed for different climates and urban geometries, with varying soil moisture content, green roof fraction and urban surface layer thickness. All simulations show a linear relationship between surface layer temperature reduction ΔT_s and domain averaged evaporation rates from vegetation *mmW*, i.e. $\Delta T_s = e_W \cdot mmW$, where e_W is the evaporative cooling potential with a value of ~−0.35 Kdaymm^{-1}. This relationship is independent of the method by which water is supplied. We also derive a simple algebraic relation for e_W using a Taylor series expansion.

1. Introduction

The fast growth of global population, mainly in urban areas (UNFPA, 2012) and the concurrent increase in likelihood of extreme weather events (IPCC, 2014) force cities to prepare for water scarcity and heat spells. The fact that cities are several degrees warmer than the surrounding rural environment, known as the urban heat island effect, amplifies this risk (Rosenzweig et al., 2015). Simultaneously, heavy precipitation and flooding are expected to become more likely in many European cities (Rojas et al., 2012). As a consequence, the integrated management of water becomes an increasingly important part of urban planning both in terms of flood and urban heat island risk mitigation (Niemczynowicz, 1999).

Green roofs are often discussed as a possible remedy for these problems. The vegetation and soil of green roofs can retain water and delay discharge after rainfall events, thereby reducing the flood risk. Evaporation of the stored water over time leads to lower roof temperatures by converting sensible into latent heat (Getter and Rowe, 2006). This also lowers indoor temperatures and reduces the energy demand for cooling (Castleton et al., 2010). The water availability depends on the local climate as well as green roof design. Tools to assess the benefits of such installations are thus needed for better planning urban development. Central questions an urban planner may have are thus 1) how much cooling can be achieved by green roofs given the available amount of water in a city and 2) how much water is required to achieve a certain amount of cooling.

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http://dx.doi.org/10.1016/j.uclim.2017.02.007
2212-0955/

Quantifying the cooling effect of green roofs on outdoor air temperatures is difficult and various studies suggest only a small temperature reduction on street level (Li et al., 2014; Gromke et al., 2015, Yang et al., 2016). Roofs with a high albedo, so-called “cool roofs”, reflect a larger proportion of solar radiation than conventional roofs and may excel in reducing outdoor temperatures (Mackey et al., 2012; Georgescu et al., 2014; Santamouris, 2014), but they lack the additional benefits for ecology and water management that green roofs provide (Oberndorfer et al., 2007). Yet, to significantly improve thermal comfort both cool and green roof strategies need to be implemented on a large scale. This also brings up the question how efficiently the implementation of green roofs can be scaled up. Li et al. (2014) and Sun et al. (2016) describe a linear decrease of air temperature with green roof fraction, Mackey et al. (2012) compare temperature reduction to the normalised difference vegetation index (NDVI) from satellite measurements and also find a linear relationship. However, this dependency is not well understood. If this relation holds in general, a fast way of determining the slope coefficient depending on urban characteristics will be of great support for decision makers and urban planners.

This paper establishes a simple relation to estimate the cooling potential of green roofs for known urban properties and climate. Specifically we 1) quantify the cooling of green roofs on an urban scale taking the urban energy balance (UEB) model approach (Oke, 1988; Grimmond et al., 2010); 2) examine how the cooling relates to the evaporation rates; and 3) derive a relatively simple equation for the cooling potential for a given amount of water to evaporate. The paper is organised as follows. In Section 2 the original UEB model and the changes we made for simulating green roofs in an urban environment are discussed. In Section 3 we will present steady and unsteady diurnal cases simulated with the new model and study the effect of surface layer thickness, urban geometry, method of water supply and evaporation from green roofs on the surface layer temperature. In Section 4 we derive an algebraic equation to predict the cooling from green roofs and compare it to the findings in Section 3. Finally in Section 5 we discuss our findings and set them into context of application in real cities.

2. Model description

2.1. Town Energy Budget

The coupling of numerical weather prediction models with the (urban) surface is usually achieved by using land surface modules such as the Town Energy Budget (Masson, 2000, TEB) used by the French national weather service (Météo-France) or the Joint UK Land Environment Simulator (Best et al., 2011; Clark et al., 2011, JULES) by the UK Met Office. These models are based on a surface energy balance. Urban areas exchange energy in various forms, such as incoming and outgoing longwave ($L^{\downarrow}, L^{\uparrow}$) and shortwave radiative fluxes ($S^{\downarrow}, S^{\uparrow}$), the turbulent sensible heat flux (H), the turbulent latent heat flux (E), ground heat flux (G) and the net heat storage per unit time ($\Delta Q \equiv dQ/dt$). These fluxes have to balance and the surface energy balance equation is expressed as

$$\Delta Q = (L^{\downarrow} - L^{\uparrow}) + (S^{\downarrow} - S^{\uparrow}) - (H + E + G), \tag{1}$$

where all the terms have unit $\mathrm{Wm^{-2}}$. Additional heat sources could be added if necessary, e.g. anthropogenic heating. UEB models solve a set of ordinary differential equations describing the evolution of heat and water on urban surfaces such as roads, walls and roofs. Air movement is not modelled explicitly; instead aerodynamic resistances are used to describe the turbulent heat and moisture transport in the atmosphere.

We used the open source TEB as starting point for our UEB model. Here we summarise the principles underlying TEB, for a detailed description see Masson (2000). The urban geometry in TEB is represented as a generic street canyon, including a single conventional roof (R), wall (w) and road (r) surface (Fig. 1a). The scheme assumes isotropy for the street and house distribution on a large horizontal scale. Equations describing directional process such as radiation are thus integrated horizontally over 360°. TEB therefore does not represent single buildings, but rather the average over a large domain. The canyons are represented by mean building height (h), building width (b) and road width (l). Grimmond et al. (2010) have previously shown that more complex UEB models do not necessarily yield more accurate results. Three distinct energy budgets are considered for the roof, wall and road. The TEB scheme thus takes the form of five coupled differential equations, three for the temperatures and two for the water reservoirs on the roof and the road. The evolution of temperature with time is described as

$$c_{\star} d_{\star} \frac{dT_{\star}}{dt} = S_{\star} + L_{\star} - H_{\star} - E_{\star} - G_{\star}, \tag{2}$$

where $T_{\star}$ [K] represents the roof, wall or road temperature, respectively. The corresponding heat capacity is c [$\mathrm{Jm^{-3}K^{-1}}$] and the layer thickness d [m]. The water (W) budget on the roof and road is

$$\frac{dW_{\star}}{dt} = P - \frac{E_{\star}}{L_v} - R, \tag{3}$$