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Assessment of evaporative water loss from Dutch cities

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ABSTRACT

Reliable estimates of evaporative water loss are required to assess the urban water budget in support of division of water resources among various needs, including heat mitigation measures in cities relying on evaporative cooling. We report on urban evaporative water loss from Arnhem and Rotterdam in the Netherlands, using eddy covariance, scintillometer and sapflow observations. Evaporation is assessed at daily to seasonal and annual timescale. For the summer half-year (April–September), observations from Arnhem and Rotterdam are consistent regarding magnitude and variability of evaporation that typically varies between 0.5 and 1.0 mm of evaporation per day. The mean daily evaporative cooling rate was 20–25 $\mathrm{W m^{-2}}$, 11–14% of the average incoming solar radiation. Evaporation by trees related to sapflow was found to be a small term on the water budget at the city or neighbourhood scale. However, locally the contribution may be significant, given observed maxima of daily sap flows up to 170 l per tree. In Arnhem, evaporation is strongly linked with precipitation, possibly owing to building style. During the summer season, 60% of the precipitation evaporated again. In Rotterdam, the link between evaporation and precipitation is much weaker. An analysis of meteorological observations shows that estimation of urban evaporation from routine weather data using the concept of reference evaporation would be a particularly challenging task. City-scale evaporation may not scale with reference evaporation and the urban fabric results in strong microweather variability. Observations like the ones presented here can be used to evaluate and improve methods for routine urban evaporation estimates.

1. Introduction

Evaporation links the energy budget to the water budget of urban regions. This link implies that evaporation can help to prevent heating of cities, since the energy used to evaporate water is not available anymore for warming the urban fabric or atmosphere. Lack of evaporation in cities due to replacement of natural soil and green cover by impervious structures like buildings and streets has since long been known to contribute to the Urban Heat Island (UHI) effect [1]. Inversely, many surveys have demonstrated cooling effects of vegetation in the urban microclimate [2], even in the temperate maritime climate of the Netherlands [3–5]. Improving green infrastructure by planting or maintaining vegetation, including application of green roofs, has become a popular measure to mitigate heat in cities and increase human thermal comfort [2,6,7]. Trees may be particularly effective in this respect because they not only provide cooling by evaporation, but also by shading [2,8]. Although open water in the city also contributes to urban evaporation, the effect of water bodies on mitigating heat in the city is less clear [3,5,9].

Mitigating heat in cities and at the same time reducing urban water consumption is an extremely challenging task. Cooling by evaporation obviously requires ample water supply, especially if vegetation is involved. At the same time urban water use may have to be reduced in the near future because more drought events are expected under climate change [10]. Reliable estimates of evaporative water loss are required in support of appropriate water management, especially during hot conditions when water has to be divided among various needs, including general water supply to citizens, evaporative cooling of cities and survival of urban vegetation. Monitoring evaporation is expected to become more urgent in the future because of urbanisation, climate change and their

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impact on outdoor thermal comfort [11]. In the Netherlands, evaporation is at present estimated mainly in support of regulation of groundwater levels. Unfortunately, hardly any information is available on evaporation from Dutch cities, in spite of its importance regarding specific Dutch problems linked to the urban water budget, including salt water intrusion in coastal areas and decay of wooden foundations upon lowering the groundwater level [12].

The objective of this paper is to assess evaporation from urban areas in The Netherlands. We analyse observations carried out in two cities in the framework of "Climate Proof Cities" (CPC) [13]. In Arnhem, evaporation was measured using the eddy covariance technique. In Rotterdam, evaporation was derived from scintillometer observations and sapflow observations were carried out to examine water use of individual urban trees. These various estimates of evaporation are complemented by meteorological observations that enable us to compute the so-called reference evaporation (see Section 2.5) in both cities. In agriculture, this quantity has often been used as a starting point for estimates of crop water requirements when direct observations of evaporation are not feasible [14].

Given the lack of information on evaporation from Dutch cities, the first research question underlying the present study is: how much water evaporates from Dutch cities? Quantification of urban evaporative water loss helps to assess avoided heating of cities and is interesting for water managers, notably the Dutch Water Boards and larger municipalities that are responsible for water management in the Netherlands. Our analyses of the data will mainly focus on observations from the summer half-year (April–September) because of the link with heat in the city.

The second research question is: what fraction of precipitation received in the urban areas evaporates again? Estimating the relation between evaporation and precipitation including the amount of recycled water supports water management issues, while also improving understanding of the role of urban design in the water budget. To overcome water shortage during hot periods harvesting as much water from precipitation as possible may become crucial in order to refill depleted water reservoirs [10]. Buildings and sealed soils may render cities quite efficient in recycling water to the atmosphere since they can act as an interception reservoir from which water easily evaporates. However, urban characteristics generally prevent infiltration and promote rapid transport of water away from cities via stormwater networks and sewage systems.

The third research question is: to what extent can the concept of reference evaporation be used to derive city evaporation on a routine basis? Direct and indirect specialized routine observations of evaporation from cities are scarce in spite of the expanding network of urban flux observations [11,15]. There is a need for relatively simple methods that allow routine monitoring of evaporation in support of water management. In agricultural practice estimations of crop water requirements have been derived from the reference evaporation with reasonable success [14]. In particular on dry days, urban evaporation is largely due to city vegetation [16]. Therefore, and because the concept of reference evaporation can be linked with remote sensing observations quite easily [17], applying the method used in agriculture but adjusted to the urban setting is sometimes considered a practical way to estimate urban evaporation, at least from vegetated parts [11], with promising results at specific urban green spots [18,19]. However, given the agricultural background of the methodology, application of the concept in the urban environment is far from trivial because of the impact of the urban fabric on local weather conditions. Thus, it is not clear if the concept allows reliable routine evaporation estimates at the neighbourhood to city scale, which is the relevant scale for many Dutch water managers.

2. Site description and methods

2.1. City characteristics

Observations were performed in Arnhem and Rotterdam (see Ref. [13] for a map showing their location). Characteristics of these cities relevant to urban evaporation are provided first. More specific characteristics of the measurement locations are given in the subsections that follow, or described elsewhere in this issue [3].

Arnhem is located near a forested area in the Netherlands. The total area of the municipality of Arnhem is 102 km^2 and the number of residents is just over 150,000 [20]. The share of impervious surface, including streets and buildings, is 44% [21]. In 2009, the municipality had a relatively large share of green space, covering 77 km^2 or over 75% of the city area. However, in the city centre the green fraction is much less (~12%, see Section 2.2). Almost one million (±983,500) trees are present in Arnhem, of which 56,500 in parks and estates and 47,000 distributed as city trees. The total area of surface water within the municipality is 4.5 km^2, of which 1.9 km^2 is occupied by the River Rhine [22]. The average annual temperature (1981–2010) measured at a weather station operated by the Royal Netherlands Meteorological Institute (KNMI) about 8.5 km North of Arnhem is 9.8 °C. The average maximum temperature in the summer months (June, July, August) is 21.9 °C, the average minimum temperature 11.5 °C. The mean annual precipitation is 861 mm, of which on average 224 mm is received during the summer months [23].

The city of Rotterdam covers a total area of 319 km^2 and hosts nearly 615,000 residents. The share of impervious surface is 45%. Over 30% of the Rotterdam area, 114 km^2, is surface water [20]. In 2003, the total area covered with vegetation was estimated to be about 52 km^2, or about 16% of the city area (25% of the land area) [21]. Of course, these numbers vary widely across the city [3]. The number of trees within the municipality is almost 600,000, of which 450,000 are located in parks and about 150,000 in streets [24]. The mean annual temperature measured at the KNMI airport weather station near the city is 10.4 °C. During the summer months, the average maximum temperature is 21.5 °C, the average minimum temperature 12.2 °C. The mean annual precipitation sum is 856 mm, of which on average 220 mm is received during the summer months [23].

2.2. Eddy covariance measurements

In Arnhem, actual evaporation was determined using the eddy covariance (EC) method. An EC station was set up in the heart of the city (N51.9847, E5.9183), on the roof of a 6-storey building. The height of the roof is 36 m ASL, the building height is about 18 m. The EC equipment was mounted on top of a mast extending 5 m above the flat roof so that the EC measurements are carried out at 23 m above ground level. The impact of spurious eddies created by wind flow past this building on the EC measurements is assumed to be negligible.

The EC technique yields direct evaporation estimates at the scale of a hectare to a few square kilometres, depending on the observation height, the atmospheric conditions and the surface characteristics [25]. A first-order analysis of the footprint of the flux measurements [26] shows that in our case city parts within 1 km from the tower usually contribute to the measured flux well over 80%. A map of the building height within a circular zone with radius 1 km around the site is shown in Fig. 1. The average building height in this footprint of the flux measurements, z_H (m), is nearly 11 m. Thus, the measurement height is 2.1 times z_H, implying that effects of individual buildings have largely been blended [27]. A few isolated tall buildings in the area are located at least 800 m away from