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Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration

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ABSTRACT

This paper reports on temporal and spatial variability of local climate and outdoor human thermal comfort within the Rotterdam agglomeration. We analyse three years of meteorological observations (2010–2012) from a monitoring network. Focus is on the atmospheric urban heat island (UHI); the difference in air temperature between urban areas and rural surroundings. In addition, we calculate the Physiologically Equivalent Temperature (PET) which is a measure of thermal comfort. Subsequently, we determine the dependency of intra-urban variability in local climate and PET on urban land-use and geometric characteristics. During a large part of the year, UHI-intensities in densely built areas can be considerable, under calm and clear (cloudless) weather conditions. The highest maximum UHI-values are found in summer, with 95-percentile values ranging from 4.3 K to more than 8 K, depending on the location. In winter, UHI-intensities are generally lower. Intra-urban variability in maximum UHI-intensity is considerable, indicating that local features have an important influence. It is found to be significantly related to building, impervious and green surface fractions, respectively, as well as to mean building height.

In summer, urban areas show a larger number of discomfort hours (PET > 23 °C) compared to the reference rural area. Our results indicate that this is mainly related to the much lower wind velocities in urban areas. Also intra-urban variability in thermal comfort during daytime appears to be mainly related to differences in wind velocity. After sunset, the UHI effect plays a more prominent role and hence thermal comfort is more related with urban characteristics.

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1. Introduction

In the coming decades, sustainable urban planning faces two major challenges: first, the impact of climate change and the necessity for adaptation measures to mitigate the consequences, and second, that of urbanization and the necessity of balancing the various conflicting spatial demands. Climate change projections suggest that European summer heat waves will become more frequent and severe during this century, consistent with the observed trend of the past decades [1]. This will also be true for northwest Europe, including the Netherlands [2]. While urban areas will generally be exposed to the same change in regional

climate as the surrounding area, the urban setting can exacerbate the impact of this exposure on a local scale. In addition, urbanization will continue in the next decades. Future projections for the Netherlands show a large expansion of the urban landscape, particularly in the western and central parts, of up to 20% in the next decades [3,4]. Both developments may significantly influence future urban climate conditions, thermal comfort of citizens and liveability of urban areas. Recent results indicate that outdoor thermal comfort and heat stress will likely become a critical issue in many urban areas in the Netherlands [5].

The presence of many buildings and artificial surfaces at the expense of open ground, open water and vegetation creates unique local climates altering temperature, moisture, wind patterns, and radiation. Consequently, local climate may vary considerably within cities. To ensure an effective and coherent development of adaptation strategies aimed at improvement of the urban thermal environment, a better understanding of the spatial and temporal

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variability in local climate (intra-urban variability), and the influence of urban features thereon is needed.

To date, relatively few long-term observational data on the spatial variability of local climate within cities are available [6]. The climatological description of a city is often based on one or a few fixed meteorological stations, usually located in the city centre, or at the airport, and therefore not representative of the whole city. Information about the spatial variability in local climate usually applies to a limited period of time (for example based on observations obtained in dedicated measuring campaigns).

A distinct feature of urban climate is the urban heat island (UHI). A distinction can be made between surface UHI, the difference in surface temperatures between the urban and rural area, and the atmospheric urban heat island, the corresponding differences in air temperature. Furthermore, two types of atmospheric UHI can be distinguished, that of the Urban Boundary Layer (UBL) and that of the Urban Canopy Layer (UCL) [6].

For outdoor thermal comfort the UCL-UHI is the most important one since people live in the urban canopy layer. Therefore, the UCL-UHI is the most commonly observed of the two atmospheric types and often the one referred to in discussions of urban heat islands. In contrast to the surface UHI, the atmospheric UHI is mainly a nocturnal phenomenon; it often weak during the late morning and throughout the day and becomes more pronounced after sunset due to the slow release of heat from urban infrastructure. So, maximum UHI intensities (UHI_{max}) are usually reached after sunset as a result of slower cooling down of the urban areas as compared to the rural surroundings [7].

Outdoor thermal comfort is often implicitly linked with the UHI phenomenon [6]. However, human thermal comfort not only depends on air temperature but on the combined effect of air temperature, wind speed, air humidity and radiation [8]. Recent results of Ketterer and Matzarakis [9] indicate that air temperature alone is not an appropriate measure to quantify the intra-urban spatial variability of climate with respect to human thermal comfort.

The impact of land cover buildings, impervious and green surfaces, on local air temperatures has been well documented (see Ref. [10] for a literature review). An increase of the built-up area at the expense of natural surfaces like vegetation, open ground or water causes a change in the surface energy balance resulting into higher surface and air temperatures. Conversely, heating of urban areas may be lowered by increasing the vegetation area [11–15]. Urban geometry relating to the height and spacing of buildings is considered to be another important feature determining local climate because of its effect on radiation and air flow. Important parameters are the surface albedo, mean building height, ratio between mean building height and mean street width (height-to-width ratio or aspect ratio), and the sky view factor (SVF) [16–18].

In many studies, the influence of one or a few of the aforementioned urban landscape parameters has been examined. However, only a limited number of studies have applied a more integrative assessment, taking all urban landscape parameters into account [11,15,19–21]. Consequently, the relative importance of the urban landscape parameters in affecting local climate is unclear.

This paper reports on the urban climate within the Rotterdam agglomeration, the second largest city in The Netherlands. Results from earlier meteorological observations indicate the existence of a considerable UHI in densely built areas with values reaching up to 8 K or more [22,23]. The municipality of Rotterdam wishes to anticipate on current and future challenges for human thermal comfort by mainstreaming adaptation measures in the reconstruction of older neighbourhoods and development of new urban areas. In this context, a monitoring network has been established in 2009 [24]. It currently consists of 14 fixed Automatic Weather Stations (AWS).

In our study, we analyse three years of meteorological observations (2010–2012). All meteorological variables relevant for thermal comfort (that is, air and globe temperature, humidity, wind speed, radiation) are monitored by the monitoring network. As such also an indication about the intra-urban variability in human thermal comfort can be obtained. We focus on the conditions in the UCL. For this layer, we evaluate the UHI and calculate the Physiologically Equivalent Temperature (PET). The latter is a sophisticated measure of thermal comfort based on the energy balance of the human body [8].

The study has been carried out in the framework of Climate Proof Cities (CPC) [25]. The main objectives are: 1) to assess the temporal and spatial variability of local climate and human thermal comfort, and 2) to quantify the dependency of this intra-urban variability on the various urban features.

The main research questions are: 1) how large is the intra-urban variability in local climate and that of outdoor thermal comfort, and to what extent are these two linked, 2) to what extent is this variability determined by local features, and 3) what is the relative importance of the urban landscape parameters in explaining local climate and thermal comfort?

The results of the study give important insight into the potential effectiveness of adaptation measures in city design aimed at mitigating the impact of climate change on the UHI and outdoor thermal comfort in urban areas in the Netherlands.

The paper is organised as follows. After a description of the material and methods (Section 2), we first discuss the intra-urban variability in local climate with a focus on UHI (Section 3.1). Next the intra-urban variability in outdoor thermal comfort for the summer months (June, July and August) is discussed (Section 3.2). We examine to what extent UHI and thermal comfort are connected. In Section 3.3, we discuss the dependence of intra-urban variability in UHI and that in thermal comfort on the various urban landscape parameters. This is done for the summer results; results obtained for the other seasons are presented in the [Supplementary Material](#). Section 4 discusses remaining issues and areas for further research and Section 5 concludes the paper. Impressions of the areas surrounding the monitoring stations in the Rotterdam agglomeration are given in the [Supplementary Material](#).

2. Material and methods

2.1. Study area

The Rotterdam agglomeration is located at the North Sea, at the mouth of the rivers Meuse and Rhine, in the Southwest of the Netherlands. The agglomeration is the industrial heart of the Netherlands and is home to one of the World's largest ports. It covers approximately 782,43 km² of land surface and has 1,175,477 inhabitants [26]. The city of Rotterdam itself has more than 600,000 inhabitants (2011 UN data) and covers 319 km². The municipality consists of 22 districts, which are again subdivided into 88 neighbourhoods. Most of the area lies several meters below sea level, and is situated on a sandy plain. The area, like the rest of the Netherlands, experiences a rather mild maritime climate with average minimum and maximum temperatures during winter of about 1 °C and 6 °C respectively, and average minimum and maximum temperatures during summer of about 12 °C and 22 °C respectively [27].

2.2. Monitoring network and data collection

The monitoring network became operational in August 2009 with 4 automatic weather stations (AWS) and was extended to a total of 14 AWS in 2010 (operational in June 2010). Thirteen of the

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