Urban Climate 15 (2016) 83–98

Contents lists available at ScienceDirect

Urban Climate

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

Towards city-wide, building-resolving analysis of mean radiant temperature

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ARTICLE INFO

Article history:
Received 16 July 2015
Revised 22 October 2015
Accepted 4 November 2015

Keywords:
Heat stress
Human bioclimate
SOLWEIG
Berlin
Mean radiant temperature

ABSTRACT

This study presents a method to simulate T_{mrt} building-resolving while considering both micro-scale urban structures and meso-scale atmospheric conditions. We extended the model SOLWEIG, one of the few methods to derive mean radiant temperature (T_{mrt}) building-resolved and city-wide, to include spatial patterns of meteorological input. Based on a day within an extreme heat event (2003) in Berlin, Germany, we examined the effect of the new method on T_{mrt}, which uses gridded meteorological input data from a mesoscale weather model, compared to a standard set-up using ungridded data. Results indicted a considerable effect of spatially resolved air temperature (up to 3.2 K) during midnight. Furthermore, we detected high sensitivity of T_{mrt} to the partitioning of direct and diffuse short-wave radiation. The spatial pattern of T_{mrt} revealed that at midday the city centre exhibited low values compared to open areas. We conclude that considering meso-scale atmospheric conditions and urban structure for simulating T_{mrt} city-wide can lead to a more appropriate description of heat-stress hazards and might also be valuable for climate-sensitive urban planning.

1. Introduction

Heat-stress hazards are particularly high in cities due to effects of urban climate like Urban Heat Island (UHI) (Hajat and Kosatky, 2010; Mishra et al., 2015). During heat waves, mortality rates are also higher in cities such as Berlin, Germany compared to their rural surroundings (Gabriel and Endlicher, 2011). But, even within one city, intra-urban variability towards heat stress can be high (Scherber et al., 2014). To analyse intra-urban heat stress hazards, rational biometeorological indices or the mean radiant temperature (T_{mrt}) are essential (Jendritzky et al., 2012; Ketterer and Matzarakis, 2014) since air and surface temperature are insufficient for assessing human bioclimate. T_{mrt} is the most important variable describing the human heat balance under sunny conditions, as it sums up long- and short-wave radiation that reaches the human body (Höppe, 1992; Kántor and Unger, 2011; Thorsson et al., 2014, 2007). Yet T_{mrt} is highly variable due to urban structures such as trees, bushes, street canyons and buildings (Lindberg et al., 2014). Moreover, weather and climate (e.g. air temperature and radiative fluxes) influence the spatial pattern of T_{mrt}, because the atmospheric conditions are heterogeneous in large urban areas (Endlicher and Lanfer, 2003; Fenner et al., 2014; Stewart et al., 2014).

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http://dx.doi.org/10.1016/j.uclim.2015.11.003

High spatial resolution is as important as an appropriate hazard description to understand the effects of heat stress and to implement suitable adaptation measures. In this study, we use the term 'building-resolving' to describe a grid spacing that is capable to explicitly resolve buildings as well as the spaces between buildings. The spacing, needed for this purpose, varies between different cities due to different street and building width. Many previous studies concentrated on the variability of T_{mrt} at a building-resolving resolution for streets, neighbourhoods or districts (e.g. Bruse and Fleer, 1998; Chen et al., 2014; Ketterer and Matzarakis, 2014; Lindberg et al., 2008). In contrast, little attention has been paid to the combination of building-resolving along with city-wide analyses. This requirement is nevertheless inevitable for effective climate-sensitive urban planning, which requires high-resolution analysis for case-specific adaptation measures as well as a comprehensive overview to identify priority areas within a city (e.g. Dütemeyer et al., 2013; Mills et al., 2010; Norton et al., 2015). Such analyses can help to identify areas with high heat-stress hazards (potential 'priority areas') during heat waves and to develop reasonable actions to reduce heat stress.

Various methods are available for city-wide analyses on the one hand and building-resolving resolutions on the other hand. The combination of both methods offers new insights, however, its implementation is a big challenge. City-wide analyses are frequently carried out with atmospheric numerical models coupled with urban canopy scheme. These models are in general reliable and widely used, even if some issues remain unsolved (e.g. Ching, 2013; Grimmond et al., 2010; Martilli, 2007). These meso-scale models are not yet able to resolve explicitly mirco-scale urban structures, such as buildings and vegetation. In contrast, building-resolving studies are often performed with models focusing on human bioclimate, such as ENVI-met, RayMan or SOLWEIG. These models perform well in the micro- to local-scale (Chen et al., 2014; Jänicke et al., 2015; Kántor and Unger, 2011). CFD models, such as ENVI-met, are not able to represent an entire city due to high computational demands (Bruse and Fleer, 1998). RayMan produces results only for one point (Matzarakis et al., 2007). SOLWEIG is in principle able to simulate T_{mrt} for large areas with a high spatial resolution (Lindberg and Grimmond, 2011a; Lindberg et al., 2008), but the standard version applies meteorological input data, including air temperature, relative humidity and short-wave downward radiation, only based on one point for spatial–temporal calculations. Hence, meteorological conditions might become unrealistic when the model domain is very large. In summary, it is to our knowledge with existing models not possible to simulate T_{mrt} building-resolving for an entire city while considering both meso-scale weather situation and urban modifications.

The aim of this study is to introduce and analyse sensitivities of a method that closes this gap. We analysed T_{mrt} during one day (5 August 2003) of an extreme heat event in Berlin. We incorporated the meso-scale weather situation and urban modifications from results of a regional climate model (RCM) coupled with an urban canopy scheme (UCM), whereas we simulated the effects of micro-scale urban structures on T_{mrt} with a new subversion of the SOLWEIG model. In the new subversion, we applied gridded meteorological input data from the meso-scale model instead of only one-dimensional data. Firstly, we assess results from the coupled RCM/UCM against in-situ observations regarding variables required for calculating T_{mrt} (Section 3.1). Then, we study the sensitivity of the new SOLWEIG subversion to urban structures (Section 3.2), partitioning of direct and diffuse short-wave radiation (Section 3.3) and gridded meteorological input data (Section 3.4). As a step towards climate-sensitive urban planning, we finally analyse the spatial pattern of T_{mrt} in Berlin to discuss implications for identifying priority areas during an extreme heat event (Section 3.5).

2. Materials and methods

2.1. Study area and period

Berlin (52°31′N, 13°24′O) is the largest city in Germany, with 3.5 million inhabitants. We chose Berlin as a test bed for a large mid-latitude city, because its urban climate is not directly influenced by mountains or oceans, which can interfere with the formation of UHI. Furthermore, heat stress had already been identified as a serious threat there (Gabriel and Endlicher, 2011; Scherber et al., 2014; Scherer et al., 2014).

As exemplary weather situation, we selected one day (5 August 2003) during an extreme heat event (from 1 to 13 August, 2003) in Berlin (see Schubert and Grossman-Clarke (2013) for the definition of extreme heat events and thresholds). The heat wave of 2003 was one of the most disastrous extreme heat events in modern European history, with the highest temperature since the beginning of record in many regions and around 40,000 associated extra deaths across the continent (García-Herrera et al., 2010). In Berlin, the mortality rates also increased strongly during this extreme heat event (Gabriel and Endlicher, 2011). The 5th August 2003 was characterised by high air temperature, with an average of 22.0 °C and nearly cloud-free. Above Berlin and other parts of Germany a stable anticyclone existed that brought mixed subtropical air masses from Western Europe (Verein Berliner Wetterkarte, 2003). We chose this nearly cloud-free day to minimise uncertainty regarding cloud parameterization of the meso-scale model. Additionally, we used a longer period (3–18 August 2003) in Section 3.1 for evaluating the RCM/UCM.

2.2. Simulation approach

For simulating T_{mrt} building-resolving and city-wide, we combined two different models. The coupled RCM/UCM provided meteorological input data to be used in the micro-scale model SOLWEIG. SOLWEIG is then used to simulate micro-scale modifications of radiation fluxes due to urban geometry and hence estimate T_{mrt} at building-resolving resolution.