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Towards a city-wide analysis of mean radiant temperature at high spatial resolution – An example from Berlin, Germany –

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1. Introduction

Heat stress is expected to increase in the future due to global climate change. Many epidemiological studies show the close link between elevated air temperature and increased morbidity and mortality, which are not restricted to subtropical and tropical regions but also common in cities at higher latitudes like Berlin (52.5° N). Heat-stress risks are particularly high in urban regions, since urban climate modifications of regional weather conditions tend to increase heat-stress hazards.

In order to analyse heat-stress risks and hazards within a city, the mean radiant temperature (T_{mrt}) is an important variable as it sums up long- and short-wave radiation that reaches the human body (Höppe 1992). Thus, T_{mrt} along with air temperature, atmospheric humidity, wind speed and personal factors such as clothing, metabolic rate, sex etc., is used for the calculation of many biometeorological indices. In urban environments T_{mrt} is highly variable due to the shadow patterns of objects. To calculate the mean radiant temperature, urban structures such as trees, bushes, courtyards, street canyons and buildings need to be parameterized or explicitly included. The former reduces the computation demand, but limits the possibility to derive planning measures to reduce heat stress. In addition, weather and climate influence the variability of the mean radiant temperature, because the atmospheric conditions are heterogeneous in large urban areas.

Therefore, the aim of this study is to calculate the mean radiant temperature for the case of Berlin while considering both micro-scale urban structures and meso-scale atmospheric conditions. For computing T_{mrt} we apply a version of the SOLWEIG model (Lindberg and Grimmond 2011a) that is able to use gridded meteorological input data. Results from a meso-scale atmospheric model coupled with an Urban Canopy Model (UCM) serve as input of meso-scale atmospheric conditions. Firstly, we assess the sensitivity of T_{mrt} to these spatially distributed meteorological input data in order to discuss, if it is necessary to consider meso-scale atmospheric conditions (Section 3.1). Secondly, we will discuss the spatial pattern and variability found in this simulation (Section 3.2).

2. Material and methods

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 interfere with the formation of the urban heat island (UHI). As an exemplary weather situation, we selected one day (5 August 2003) during an extreme heat event. This day was characterized by high air temperatures (on average 22.0 °C) and cloud-free.

2.1 Incorporation of meso-scale atmospheric conditions

We used results from an UCM that has already been applied and found as plausible in Berlin by Schubert & Grossman-Clarke (2013). The simulations of the urban atmosphere were conducted with the meso-scale atmospheric model COSMO-CLM with Double Effect Parameterization Scheme (DCEP) (Rockel et al. 2008, Schubert et al. 2012). The dataset has a spatially resolution of 1×1 km², but we interpolated it with the nearest-neighbour method to the building-resolving resolution (5 m).

2.3 Incorporation of micro-scale urban structures

To simulate T_{mrt}, we applied the radiation model SOLWEIG, which estimates T_{mrt} and long-wave and short-wave radiation of the six directions (upward, downward and the four cardinal points) (Lindberg and Grimmond, 2011a; Lindberg et al., 2008). Therefore meteorological input data of air temperature, relative humidity and global radiation is required, as well as spatial information of building and vegetation heights represented by digital surface models (DSM). In this study, we applied a new subversion of the SOLWEIG 2013a model that is able to use gridded meteorological input data to represent weather situations and urban climate more realistic. DSMs of buildings and vegetation with a spatial resolution of 5 m provide the height of the micro-scale urban structures (Senate Department for Urban Development and Environment Berlin, 2014). We applied the following parameters: albedo=0.20, transmissivity of shortwave radiation through vegetation=0.05, emissivity of the walls=0.9 and emissivity of ground=0.95.

2.3 Analyses

We performed two experiments tor analysing the effect of spatially distributed meteorological data on T_{mrt}. The first experiment represents a standard simulation without gridded meteorological input data. Gridded meteorological data are usually unavailable with an appropriate resolution at a city-scale. In many cases meteorological input data are only available from observational sites of national climate services, which provide air temperature, relative humidity and global radiation. Thus, the standard approach (STD) used ungridded air temperature, relative humidity and global radiation from one grid point of the UCM closest to the weather station at the former airport Berlin-Tempelhof.

3. Results and discussions

3.1 Influence of meso-scale atmospheric conditions on T_{mrt}

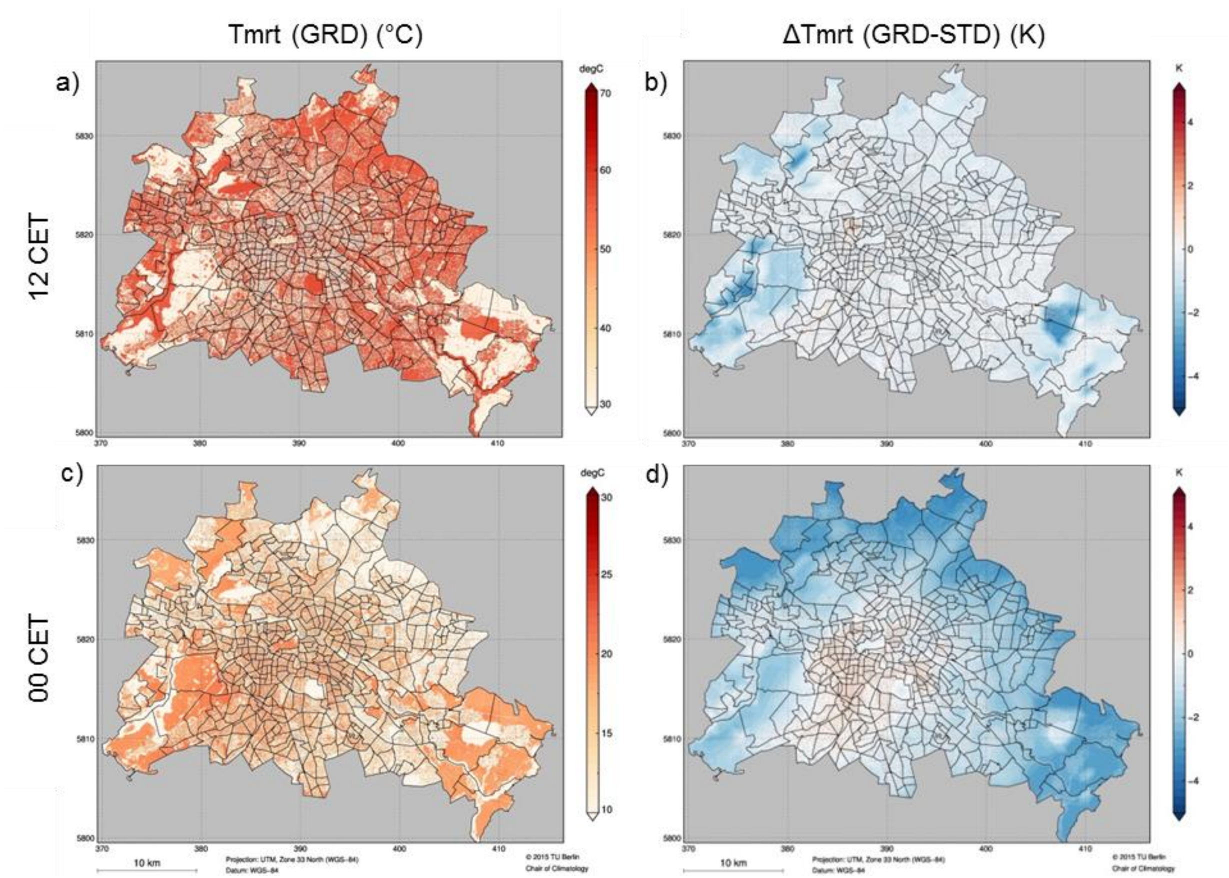

Fig. 1 Spatial variability of T_{mrt} (GRD) during midday (a) and midnight (c) at 5 August 2003; and differences in T_{mrt} between standard setting (STD) without and new setting (GRD) with spatially resolved meteorological input data during midday (b) and midnight (d).

We examined the influence on meso-scale atmospheric conditions by analysing the differences between one experiment without (STD) and one with (GRD) gridded meteorological input data. With this approach we examined that T_{mrt} was sensitive to spatially resolved air temperature, relative humidity and short-wave radiation. Both during day and night, spatially distributed air temperature (GRD) showed clear modifications of T_{mrt} compared to STD (Fig. 1 b, d). During midday, T_{mrt} decreased close to water surfaces, such as the large lakes in the suburban areas, whereas during night an effect of UHI was visible.

Owing to this sensitivity, we concluded that spatial distribution of variables relevant for calculating T_{mrt} should be considered when simulating night time T_{mrt} for an entire city. During the day the influence of gridded meteorological input data is negligible in Berlin. In addition, the influence of spatially distributed air temperature might by different and probably high in other cities, because Berlin has no altitudinal gradient of air temperature due to its shallow terrain and thus only relative few variability of air temperature during the day.

For deriving building-resolving and city-wide analysis of T_{mrt} the applied method of combining SOLWEIG with gridded atmospheric data served well. Currently drawbacks of this method were high demands of data storage and computational time. Other methods to derive building-resolving and city-wide T_{mrt} are possible as well (e.g. suggestions by Yi et al. 2015, Lindberg et al. 2015, Onomura et al. 2015).

3.2 Spatial variability and pattern of T_{mrt} in Berlin

After we demonstrated that spatially distributed meteorological data is important for simulating T_{mrt} city-wide, we will analyse spatial variability and patterns of T_{mrt} in Berlin based on the experiment GRD with gridded meteorological input data. Spatial variability of T_{mrt} was high both during day and night on 5 August 2003 with a large range of values (Fig. 1 a, c), which is typical for T_{mrt} (Thorsson et al. 2011, Lindberg et al. 2014).

During the day, T_{mrt} patterns differentiated in sunlit and shaded areas, whereby the cause of shadow – either of built-up or wooded areas – was of small importance. Thus, an urban cool island of T_{mrt} established during the day with highest values at open inner-city areas (e.g. airports and water surfaces) as well as at sparsely built-up suburban areas, which was also mentioned by Lau et al. (2015). Furthermore, we detected that city-wide pattern of T_{mrt} characterized by highest values at daytime in suburbs and open. Particular at sparsely built-up areas, planting trees to increase shaded area would be effective to reduce heat stress as already discussed (Lindberg and Grimmond, 2011b; Thorsson et al., 2011).

The pattern reversed from day to night. In the night, open areas showed lowest T_{mrt} due to higher emitted long-wave radiation. Large wooded areas tended to have higher T_{mrt} than the urban areas in the simulation, which seems implausible. This phenomenon could be caused by underestimation of heat storage released by buildings and impervious surfaces, or underestimation of cold-air production and transport. Evaluation with observational data during the night would enable clarification.

The large range of T_{mrt} demonstrated that building-resolving and city-wide analyses are necessary to describe intra-urban variability of heat stress hazards. This variability caused by micro-scale urban geometry, local-scale effects of urban climate and meso-scale weather conditions needs to be included to identify hazardous spaces within a city.

4. Conclusion

All in all, we showed that the coupling of SOLWEIG with spatially resolved meteorological data is feasible and useful for simulating T_{mrt} city-wide. We detected that the intra-urban variability of air temperature and short-wave radiation should be considered for simulating T_{mrt} to incorporate micro- to local scale urban modifications and meso-scale weather conditions.

Moreover, we conclude that city-wide, building-resolving T_{mrt} analyses could be highly beneficial for assessing intra-urban heat stress hazards and to identify priority areas for actions to reduce heat stress, because of large spatial variability. In a next step the quality of the simulated T_{mrt} should be evaluated to provide a reliable basis for climate-sensitive urban planning.

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