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The temperature recorded by simulated mobile receptors is an indicator for the thermal exposure of the urban inhabitants

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ABSTRACT

We propose a framework for simulating the individual-specific exposure as an indicator for the environmental quality of urban regions. Adopting the perspective of a moving individual we combined maps of urban temperature with algorithms simulating human mobility. The former were derived from thermal-scan data gathered with an aeroplane and calibrated with air temperatures observed at 1.5 m height. The agent-based mobility models utilize different forms of random movement and agenda-driven movement and comprise potential field controlled walk (PTW), reference point mobility model (RPM), RPM with a pre-defined daily agenda of targets (RPMA), and truncated Lévy flights (TLF).

Defining the distribution of exposure increments (temperature exposure at every time step; in K/min) as an indicator, we studied its dependence on both mobility and urban spatial temperature distribution by help of simulation models. We found that the mobility algorithms PTW and TLF can generate non-ergodic trajectories, i.e., a runner performing many consecutive journeys and an ensemble of walkers have different distributions of exposure increments. Thus, the temperature-exposure of individuals highly depends on their mobility patterns. This result is consistent with a previous benzene-study that generated likewise very different levels of personal exposure depending on the type of mobility. For both maps the PTW algorithm has the potential to generate unique movement patterns that can result in individual-specific exposure.

A conclusion is that the temperature recorded by mobile receptors is a suitable indicator for the thermal exposure of people living in an urban region. Heat maps may show significant differences with respect to individual exposure. The cumulative distribution of temperature exposure provides information about the hazard of heat for individuals living in the studied environment. We suggest mobile measurements for an exploration of the urban environment, as they involve individual-specific mobility in a natural way and provide records of how much of an environmental agent arrives directly at human receptors.

1. Introduction

Thermal conditions in urban areas have significant impact on the buildings' energy consumption, the vegetation dynamics, the urban air quality, as well as the thermal comfort. In recent research, the urban heat island effect (UHI; Mirzaei and Haghighat, 2010) has been a particular focus of attention. The UHI causes a local alteration of atmospheric stability (Santese et al., 2007) and is one of the most well-known forms of localized anthropogenic climate modifications. Classically the UHI is measured by the difference between the air temperature in the urban system and the air temperature recorded at the closest meteorological station situated in the countryside (Oke, 1987). During recent years many alternative indicators for the UHI have been developed for air temperatures as well as for land surface temperatures, the latter representing the surface urban heat island (SUHI; Schwarz et al., 2011, 2012). The UHI results from a spatially smoothed consideration of the urban thermal conditions and aggregates temperature patterns for a given urban region. However, it does not capture the variations of thermal conditions at the short distances experienced by inhabitants.

Direct impact of urban climate and urban environmental conditions on people can be severe (Krüger et al., 2011; Krüger and Rossi, 2011). Here we draw attention to the fact that thermal perception as well as heat-related adverse health effects occur in individual persons. The exposure experienced by a person often varies dramatically within minutes and hours depending on his/her location in the urban area. That means general data of an UHI provide superficial and generalized information about the burden of urban inhabitants and do not reflect actual personal exposure profiles.

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Besides this, studies on the vulnerability of people towards heat stress tend to consider the urban space in a rather static manner. Due to the availability of data, they focus on residences of people, e.g. when heat disturbs night sleep or elderly are exposed to health risks in their homes (García-Herrera et al., 2010; Klinenberg, 2002). However residents of various age groups perceive heat also as stressful – sometimes even more stressful – outside their homes when they work and are on the way to and from work, during daily shopping, child care and other obligations that respondents find especially stressful (Franck et al., 2013; Großmann et al., 2012).

For that reason we suggest a novel indicator for the thermal conditions in a city that involves both the urban temperature field as well as the mobility of individuals, i.e., individuals are considered as receptors. Receptor-oriented indicators have been previously developed for air pollutants utilizing activity-based models (e.g., Beckx et al., 2009; Hertel et al., 2001; McNally, 2000). The personal exposure approach presented here is in line with two scientific developments. Firstly, environmental health researchers currently recognize the importance of the complex individual-specific exposure of a person and develop the novel "exposome" approach for studying and preventing non-communicable diseases (Rappaport and Smith, 2010). Secondly, novel information and communication technologies provide the basis for small and simple devices that make personal monitoring easy (Hyvärinen and Saltikoff, 2010). For example, a mobile phone carried by an individual during his/her daily routine offers the best proxy to capture human trajectories and this yields in interesting novel aspects in the understanding of human mobility patterns (González and Barabási, 2007; Hidalgo and Rodriguez-Sickert, 2008). Most recently, mobile phones are combined with miniature sensors for personal exposure measurements (Chen et al., 2012; Negi et al., 2011; Rodes et al., 2012).

In this paper we suggest a personal temperature exposure indicator on the basis of simulated movements of receptors in an urban region. The receptors represent human individuals, synonymously cited as 'runners' or 'walkers'. The suggested personal exposure indicator has two aspects: it represents the health relevant exposure of individuals and it provides a measure for the urban temperature conditions on the basis of a simulated mobile exploration. To assess the utility of such an individual-specific indicator for the urban exploration, we performed simulations and studied the association of the mobility of persons and the spatial distribution of temperature in an urban area with the resulting cumulative temperature exposure of individuals. We elaborated in what way the mobility algorithm and the spatial temperature field are represented by this indicator. We consider our modelling exercise not as an attempt to reproduce real observations as exactly as possible, but as a kind of 'toy model' to understand the basic mechanisms that map, by dint of mobile individuals, the urban spatial conditions into human exposure and vice versa.

In this study we applied different movement algorithms (Sections 2.2 and 2.3) in an agent-based model implemented in C# software, simulated movement paths and calculated the distribution of exposure using temperature maps derived from thermal scans recorded by an aeroplane (Section 2.1). Characteristics of the simulated trajectories (Section 2.4) were used for an evaluation (Section 3) of the implemented algorithms. Conclusions (Section 4) are drawn for the utility of the suggested indicator and its relevance for the urban inhabitants.

2. Data and methods

Our study is exemplified for temperature data measured in Leipzig, Germany, in September 2010. The used spatiotemporal resolution is a compromise between data availability and the need to realistically describe the individual-specific temperature exposure. For that purpose, the simulation area (urban region of Leipzig) was mimicked using a generalized map of 806 × 748 pixels. The pixel side length is 28 × 28 m^2 so that a pedestrian who walks with 3 km/h crosses approximately 2 pixels in 1 min. The simulated temperature exposure was compared with simulated exposure to benzene that is based on a benzene map of the same resolution (annex C in supplementary material).

2.1. Temperature maps

For the spatial distribution of temperature we utilized surrogate data provided by a thermal remote sensor mounted at an aeroplane. The two flights covered an area of 30,250 m × 24,700 m with the left upper edge at E 12°8′42.9″ and N 51°27′0.324″ and were made after sunset and at the verge of sunrise. The evening flight was on September 22nd (19:30–21:00 CEST, called "evening" for the remainder of this paper) and the morning flight was on September 23rd (05:00–06:30 CEST, called "morning" throughout the paper); time values are given in Central European Summertime (CEST = UTC + 2 h). During these days there was autochthone high-pressure weather with a clear sky in the region. The winds were very weak (German Weather Service observations at Leipzig-Schkeuditz weather station: air pressure: 1006 hPa, mean air temperature 2 m above ground 14.7 °C (min: 8.0 °C, max: 21.4 °C), relative air humidity 78.1%, average wind 2 Bft, wind gusts 4 Bft, sunshine duration 11.2 h, no precipitation).

The applied recording procedure ensured that the registered thermal radiation was indeed emitted by the surface and no solar radiation was reflected to the thermal scanner. The thermal scans registered surface temperatures (as digital numbers between 0 and 255) in pixels of 5 × 5 m^2. Surface temperatures varied between 5.5 and 18.5 °C, calculated from a calibration of the thermal scans with the temperatures of black bodies at the ground.

These thermal maps were resampled to a grid size of 28 × 28 m^2 and trimmed to fit our simulation region. Downsampling procedures reduce the noise of an image, but can alter the appearance of the image and become contaminated by aliasing especially when the Nyquist–Shannon sampling theorem is violated. To test the impact of the downsampling method we comparatively applied nearest neighbour, bilinear, cubic and majority resampling in ArcGIS®.

For the present study we did not use the surface temperatures associated with the thermal images, but calibrated the thermal scans with measurements of air temperature gathered in the urban area at ten fixed sites 1.5 m above ground at the same time (see weather stations in Fig. 1 and Schwarz et al., 2012).

Every minute, temperature and humidity were recorded and stored in data loggers (OPUS 10, company Lufft GmbH, Germany, accuracy: ±0.1 K and ±2.5% relative humidity), each assembled in a ventilated shed protecting the measuring probe against rain and solar radiation. Measurements at 20:00 and 05:30 CEST, respectively, were used for the calibration (Fig. 2). The requirements for the performed calibration and a performance test of this procedure are discussed in annex A (supplementary material).

In this temperature field we simulated the movement of receptors in successive time steps. An ideal model would involve temporal changes of the temperature field. However, such data were not available. To derive maximum information from the data at hand we calculated in addition to the morning and the evening maps a map from the geometric mean temperature ($T_{gm} = \sqrt{T_{evening} \times T_{morning}}$, in K). The T_{gm} is high only at locations where both morning and evening temperatures are high (Fig. 3) and this map is able to represent a thermal burden during the night. For the simulation study, the range of temperature was partitioned into 10 categories in each map.