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Modelled spatiotemporal variability of outdoor thermal comfort in local climate zones of the city of Brno, Czech Republic

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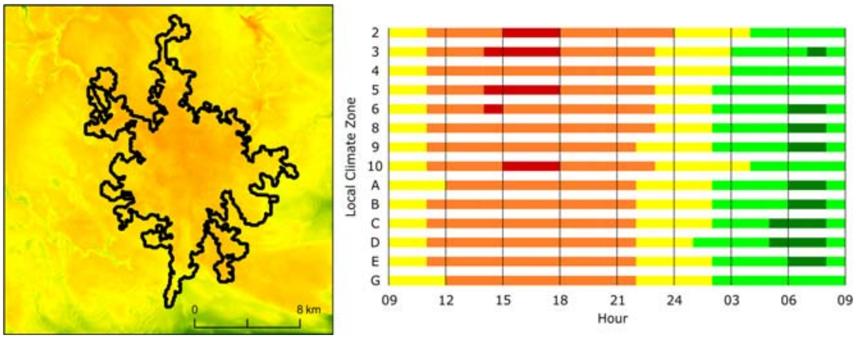
HIGHLIGHTS

- MUKLIMO_3 model was suitable for spatiotemporal thermal comfort simulations.
- Significant outdoor thermal comfort differences exist among the majority of LCZs.
- The most uncomfortable areas of the city were LCZs 2, 3, 5, 8 and 10.
- The most comfortable areas were land-cover types from A to G and LCZ 9.
- Air humidity increased HUMIDEX values in “green” and “blue” research areas.

GRAPHICAL ABSTRACT



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ABSTRACT

This study uses the MUKLIMO_3 urban climate model (in German, *Mikroskaliges Urbanes KLImaMOdell in 3-Dimensionen*) and measurements from an urban climate network in order to simulate, validate and analyse the spatiotemporal pattern of human thermal comfort outdoors in the city of Brno (Czech Republic) during a heat-wave period. HUMIDEX, a heat index designed to quantify human heat exposure, was employed to assess thermal comfort, employing air temperature and relative humidity data. The city was divided into local climate zones (LCZs) in order to access differences in intra-urban thermal comfort. Validation of the model results, based on the measurement dates within the urban monitoring network, confirmed that the MUKLIMO_3 micro-scale model had the capacity to simulate the main spatiotemporal patterns of thermal comfort in an urban area and its vicinity. The results suggested that statistically significant differences in outdoor thermal comfort exist in the majority of cases between different LCZs. The most built-up LCZ types (LCZs 2, 3, 5, 8 and 10) were disclosed as the most uncomfortable areas of the city. Hence, conditions of great discomfort (HUMIDEX >40) were recorded in these areas, mainly in the afternoon hours (from 13.00 to 18.00 CEST), while some thermal discomfort continued overnight. In contrast, HUMIDEX values in sparsely built-up LCZ 9 and non-urban LCZs were substantially lower and indicated better thermal conditions for the urban population. Interestingly, the model captured a local increase of HUMIDEX values arising out of air humidity in LCZs with the presence of more vegetation (LCZs A and B) and in the vicinity of larger bodies of water (LCZ G).

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1. Introduction

With the growing number of available data sources, burgeoning computing capabilities and new methodological approaches, urban climatology is undergoing change from descriptive, empirical work to realistic climate modelling (Mills, 2014). At the same time, intensified urbanization together with global climate change raise awareness that control of the microclimate in the urban environment is very important, as it can reduce heat stress and contribute to a better living environment in cities (Mutani and Fiermonte, 2017). The problem of increased heat stress in urban areas as a consequence of what has become known as the urban heat island (UHI) is therefore of direct concern to those municipal authorities that recognize that the well-being of their inhabitants is vital, in many ways, to the well-being of the whole city. Researchers have responded to, or anticipated, such concern about modelling of urban climate processes and various small-grid scale models and frameworks for (numerical) modelling have recently been developed.

The first, most obvious, approach to urban climate modelling is to use regional meteorological or climate models. However, these typically operate at horizontal resolutions of in the order of hundreds of meters to tens of kilometres, and urban processes are addressed by means of bulk parameterizations or single-/multi-layer urban canopy models (e.g. Kusaka et al., 2001; Martilli et al., 2002). Thus, these models are much better suited to assessing the influence of urban environments within larger-scale meteorological surveys.

Stand-alone parameterized models, e.g. the SOLWEIG model (Lindberg et al., 2008), RayMan (Matzarakis et al., 2010), the TUF-3D model (Krayenhoff and Voogt, 2007), the TUF-IOBES model (Yaghoobian and Kleissl, 2012, based on TUF-3D), TEB (Masson, 2000), or SUEWS (Järvi et al., 2011) are also available. These involve certain physical processes (e.g. radiation, latent heat flux, water balance), while they parameterize air flow by means of statistical and climatological models or meteorological measurements.

The most exhaustive approach consists of a group of computational fluid dynamics (CFD) models. The explicit simulation of turbulent flow is computationally demanding; thus, various techniques have to be adapted to make calculations feasible, usually based on limiting the range of the length scales and time-scales of the turbulent flow to be resolved. Most such CFD models applied in current urban climatology studies are based on the Reynolds-averaged Navier-Stokes (RANS) equations, e.g. ENVI-met (ENVI-met, 2009), MITRAS (Schlünzen et al., 2003), MIMO (Ehrhard et al., 2000), and MUKLIMO_3 (Sievers, 2012; Sievers, 2014). In RANS models, the entire turbulence spectrum is parameterized, and thus only mean flow is predicted. This allows the use of relatively large time-steps, leading to moderate computational demands, but physical limitations are inevitable since the interactions of turbulent eddies within the urban canopy cannot be approached explicitly. Large-eddy simulation (LES) models may be employed to overcome this deficiency. These use scale separation to resolve the bulk of the turbulence spectrum explicitly, while parameterizing only the smallest eddies at a "subgrid-scale" model; some examples are PALM (Maronga et al., 2015; Resler et al., 2017) and DALES (Heus et al., 2010).

This study is based on MUKLIMO_3, one of the most advanced models to employ the RANS equations, developed by Deutscher Wetterdients (Sievers, 1995; Sievers, 2012), to simulate the spatiotemporal variability of HUMIDEX (more precisely air temperature and relative humidity). This model was applied to Brno, the Czech Republic's second-largest city, and its surroundings.

HUMIDEX is a relatively simple thermal comfort index based on air temperature and humidity (see Section 2.3 for more details) developed by Masterton and Richardson (1979) of Canada's Atmospheric Environment Service. Its results are directly comparable with dry temperature in degrees Celsius and its values are associated with corresponding degrees of thermal comfort, rendering the index widely understandable.

HUMIDEX does not incorporate any of the other main factors affecting heat stress (e.g. wind speed and mean radiant temperature). These limitations have been addressed by, for example, d'Ambrosio Alfano et al. (2011). However, in the context of modelling and model validation, its main advantage compared to more complex indices (e.g. the universal thermal climate index [UTCI] and the physiological equivalent temperature [PET]) lies in its wider availability of a representative input sample. In particular, the high accessibility of validation data for HUMIDEX (e.g. in situ air temperature and humidity measurement in contrast to mean radiant temperature usually calculated from another sub-model) has much to recommend it. HUMIDEX is therefore widely used in studies addressing large-scale and/or long-trend analyses (Dankers and Hiederer, 2008; Błażejczyk and Twardosz, 2010; Mekis et al., 2015). The application of HUMIDEX to urban climate research is also widespread (Błażejczyk and Twardosz, 2010; Bokwa and Limanówka, 2014; Giannopoulou et al., 2014; Oleson et al., 2015; Středová et al., 2015). In recent urban climate modelling, Hamdi et al. (2016) used HUMIDEX with a 1-km-resolution dynamic downscaling technique to perform simulations within the A1B scenario of the ARPEGE-Climate global climate model for Brussels, Belgium. Further, Ho et al. (2016) modelled the spatial distribution of HUMIDEX in the greater Vancouver area using a regression model validated in terms of a network of urban weather stations and found that in some areas (particularly sparsely built-up) the apparent temperature based on HUMIDEX may exceed air temperature by >5 °C.

Moving on from the above contributions, this study applies the concept of local climate zones (LCZs) in order to obtain representative spatial units for analyses of HUMIDEX differences between various types of urban neighbourhood and LULC. As defined by Canadian urban climatologists Stewart and Oke (2012), LCZs are areas of uniform surface cover structure, material, and human activity. They may cover areas ranging from hundreds of meters to several kilometres on the horizontal scale. The classification of LCZs was designed to be generic and from its nature is immediately intelligible to a wider range of specialists involved in urban areas (local policy-makers, urban specialists, architects, ecologists, and others). LCZs are now used in most major UHI studies (e.g. Alexander and Mills, 2014; Stewart et al., 2014; Leconte et al., 2015; Unger et al., 2017). LCZs have also been employed in recent urban climate modelling (e.g. Alexander et al., 2015; Bokwa et al., 2015; Geletič et al., 2016).

The particular aims of this study underscore our intention to provide the results of a validated urban climate model that will be intelligible the wider community of those who shape the environment in city of Brno (Czech Republic), thus: i) to simulate and validate the spatiotemporal pattern of HUMIDEX in Brno during the heat wave that occurred in August 2015, employing the MUKLIMO_3 model; ii) to analyse the spatiotemporal pattern of thermal comfort and differences within it in various urban neighbourhoods, using the widely-recognized LCZ classification; and iii) to evaluate the extent to which humidity might affect the spatiotemporal pattern of outdoor thermal comfort when compared to air temperature in a central European city.

2. Data and methods

2.1. Study area

The study area of Brno and surroundings is situated in the south-eastern part of the Czech Republic (Fig. 1). Brno is a regional capital with 400,000 inhabitants. The Land Registry area is 230 km^2, of which 125 km^2 is classified as compact urban development (Lehnert and Geletič, 2017). The urban structure of Brno has a clearly-defined historical core surrounded by residential buildings, followed by industrial areas. Large areas with mid-rise and high-rise prefabricated concrete housing estates usually form separate cells of compact development outside the city centre. On the outskirts, there are large areas of shopping malls and warehouses. The landscape south-east of the city is of