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Subsurface urban heat islands in German cities

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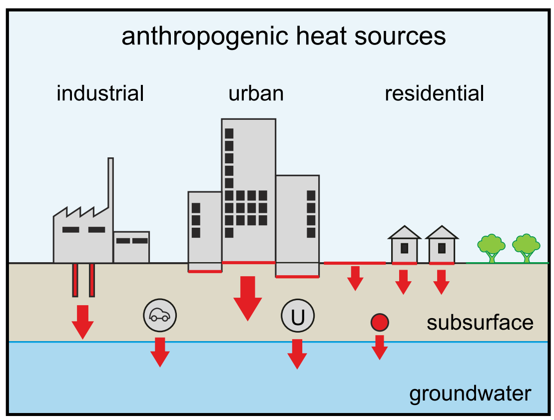
HIGHLIGHTS

- ► Positive temperature anomalies under German cities.
- ► Local heat sources cause hot spots > 30 °C in Frankfurt.
- ► Superposition of various heat sources leads to a significant regional warming.
- ► Subsurface urban heat island (UHI) intensities range between 1.9 and 2.4 K.

GRAPHICAL ABSTRACT



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ABSTRACT

Little is known about the intensity and extension of subsurface urban heat islands (UHI), and the individual role of the driving factors has not been revealed either. In this study, we compare groundwater temperatures in shallow aquifers beneath six German cities of different size (Berlin, Munich, Cologne, Frankfurt, Karlsruhe and Darmstadt). It is revealed that hotspots of up to +20 K often exist, which stem from very local heat sources, such as insufficiently insulated power plants, landfills or open geothermal systems. When visualizing the regional conditions in isotherm maps, mostly a concentric picture is found with the highest temperatures in the city centers. This reflects the long-term accumulation of thermal energy over several centuries and the interplay of various factors, particularly in heat loss from basements, elevated ground surface temperatures (GST) and subsurface infrastructure. As a primary indicator to quantify and compare large-scale UHI intensity the 10–90%-quantile range $UHII_{10-90}$ of the temperature distribution is introduced. The latter reveals, in comparison to annual atmospheric UHI intensities, an even more pronounced heating of the shallow subsurface.

1. Introduction

The phenomenon of urban heat islands (UHI) in the atmosphere is widely known and has been a focus of environmental research for several decades (Landsberg, 1956; Kratzer, 1956). UHI formation is caused by the manifold changes in cities due to urbanization, such as artificial surface cover and anthropogenic heat loss. These factors cause changes in the

Abbreviations: GST, ground surface temperature; GWT, groundwater temperature; UHI, urban heat island; UHII, urban heat island intensity; SST, subsurface temperature; SUHII, surface urban heat island intensity.

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atmospheric radiation balance and the urban energy balance, which leads to an urban microclimate and more specifically, to the warming of air temperature (Landsberg, 1981; Oke, 1988). Oke (1973) defined the maximum difference in surface air temperature (SAT) between the urban city center and the rural area as the urban heat island intensity (UHII). The latter is the highest in clear and windless summer nights and can reach values of up to 12 K. He also demonstrates a positive correlation between UHII and city population. Wienert and Kuttler (2005) suggested a relationship between UHII, the geographical latitude and accordingly, the primary energy use of the city. However, Landsberg (1981) pointed out that the UHI effect represents a heterogeneous and site-specific sum of many microclimatic changes. As a consequence, the overall effect can only be inadequately described by a single parameter.

In the subsurface, the temperature (subsurface temperature, SST) is mainly governed by the heat flow from the Earth's interior and the ground surface temperature (GST) (Huang et al., 2009). Variation in GST propagates into the subsurface mainly by thermal diffusion. Especially close to the ground surface, additional local factors may influence the thermal regime, such as advective heat transport from interaction of aquifers with surface water, and any type of direct anthropogenic stimulation (Molina-Giraldo et al., 2011; Saar, 2011). Many studies used vertical borehole temperature profiles to examine paleoclimate conditions or to back-track recent climate changes (Birch, 1948; Lachenbruch and Marshall, 1986; Pollack et al., 1998; Bodri and Cermak, 1997; Kohl, 1998; Huang et al., 2000; Beltrami et al., 2002). Taniguchi (1993) analyzed temperature-depth profiles for detecting regional groundwater flow systems. Alterations of surface covers also influence the SST and the measured temperature profiles (Taylor and Stefan, 2009). For example, increases in soil temperature of several degrees after deforestation were found by Taniguchi et al. (1999) and Nitoui and Beltrami (2005).

In the urban subsurface environment, the temperature regime is more complex than in rural, less disturbed environments. Similar to the UHI in the atmosphere, urbanization leads to a warming of the subsurface environment (Taniguchi et al., 2007), and the observed thermal conditions are always revealed to be specific. Increased SST in fast growing Asian megacities are well documented by numerous studies (e.g. Taniguchi and Uemura, 2005; Taniguchi et al., 2009). Others scrutinized the UHI effect in the subsurface of Northern American cities (e.g. Changnon, 1999; Ferguson and Woodbury, 2007), and elevated SST are reported from several large European cities. Yalcin and Yetemen (2009) inspected shallow soil temperatures at different points in time in two districts of Istanbul. It was revealed that temperatures rise by 3.5 K in built-up areas. However, shallow soil temperature varies seasonally following GST oscillation, and thus fixed-time measurements are not representative for an annual average temperature. In London, Headon et al. (2009) identified regional temperature differences of up to 5 K. However, this temperature anomaly is apparently triggered by variations in the natural geothermal heat flux. Zhu et al. (2010) investigated the spatial distribution of groundwater temperatures below Cologne, Germany, with the highest temperatures under the city center. Similar to the experience from Asian megacities and in North America, intensified vertical heat flux due to urbanization was suspected the main reason.

The factors and processes that cause the subsurface urban warming are not yet comprehensively understood. Taniguchi et al. (2007) and Huang et al. (2009) explored the relationship between SST and SAT. However, the temperature anomalies in the subsurface cannot be explained only by the increase of urban air temperatures. Ferguson and Woodbury (2004) calculated the heat loss from non-insulated buildings in an urban area. This effect is only noticeable within hundred meters from the heated structure. Thus, it cannot fully explain the vast regional increase in SST. In addition, the urban subsurface environment is influenced by a vast amount of other anthropogenic structures, such as subway networks or injections of thermal wastewater, which were not considered in previous studies.

The objective of this study is to evaluate the spatial distribution of groundwater temperatures (GWT) under several German cities, to find commonalities and differences, and to identify the main influencing factors that stimulate warming of urban aquifers. As most investigations of UHIs in the subsurface were conducted in Asian megacities, the question remains if extensive warming of GWT is a phenomenon characteristic mainly for fast growing cities with a large population, or if also smaller cities with nearly constant populations and a different history share similar thermal features. In contrast to related work on borehole climatology that uses subsurface temperature to assess the effects of climate change, this study focuses on the present state and potential sources of subsurface warming in urban areas.

The present study carefully analyzes the GWT beneath six German cities with different population numbers in order to detect the diverse anthropogenic and natural heat sources. While most previous studies focused on individual factors, we consider the interplay of various potential heat sources. For the evaluation of the UHI effect in the subsurface specific city characteristics, such as population and population density are correlated against the UHII and the spatial relationship between GWT and SAT is examined. In the following, first the cities are introduced with special focus on the geological conditions, and the utilized temperature information is shown. Then the thermal subsurface conditions and the dominant urban heat sources are compared for the different cases. This is complemented by contrasting the subsurface conditions with the above ground UHI in two selected cities, Karlsruhe and Berlin.

2. Material and methods

2.1. Study areas

The locations of the studied German cities are shown in Fig. 1. In Table 1 various data are listed providing an overview on the studied cities and showing available geographical, hydrogeological and statistical information. In order to cover a certain range of different population numbers, the selected cities include both large cities with more than one million inhabitants, as well as smaller cities with a population of less than half a million people (Table 1). All cities have a moderate climate and share a similar urban design, with densely built-up city centers, suburban/residential areas and separated industrial areas. Furthermore, below all studied cities, shallow aquifers are present that are prone to be heated by intensified downward heat fluxes. In the following, the hydrogeological and geological conditions for each city are explained in more detail. Then the findings from case-specific temperature measurements and spatial analyses are reported.

Fig. 1. Geographical locations of the studied German cities.