Science of the Total Environment 584–585 (2017) 145–153

Contents lists available at ScienceDirect

Science of the Total Environment

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

Identifying anthropogenic anomalies in air, surface and groundwater temperatures in Germany

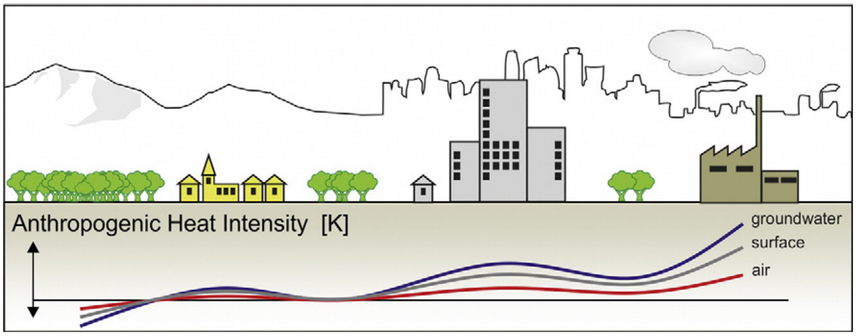
Susanne A. Benz [a,*], Peter Bayer [b], Philipp Blum [a]

[a] Karlsruhe Institute of Technology (KIT), Institute for Applied Geosciences (AGW), Kaiserstr. 12, 76131 Karlsruhe, Germany
[b] Ingolstadt University of Applied Sciences, Institute of new Energy Systems (InES), Esplanade 10, 85019 Ingolstadt, Germany

HIGHLIGHTS

- Anthropogenic temperature anomalies are quantified in Germany.
- Temperatures in air, surface and groundwater correlate with nighttime lights.
- Groundwater temperature anomalies are most extreme.
- Heat anomalies in air and groundwater are mainly caused by artificial surfaces.
- Surface urban heat islands are observed in settlements with only 5000 inhabitants.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 20 January 2017
Accepted 20 January 2017
Available online 29 January 2017

Editor: Dr. D. Barcelo

Keywords:
Anthropogenic heat
Surface air temperature
Groundwater temperature
Land surface temperature
Germany
Urban Heat Island

ABSTRACT

Human activity directly influences ambient air, surface and groundwater temperatures. The most prominent phenomenon is the urban heat island effect, which has been investigated particularly in large and densely populated cities. This study explores the anthropogenic impact on the thermal regime not only in selected urban areas, but on a countrywide scale for mean annual temperature datasets in Germany in three different compartments: measured surface air temperature, measured groundwater temperature, and satellite-derived land surface temperature. Taking nighttime lights as an indicator of rural areas, the anthropogenic heat intensity is introduced. It is applicable to each data set and provides the difference between measured local temperature and median rural background temperature. This concept is analogous to the well-established urban heat island intensity, but applicable to each measurement point or pixel of a large, even global, study area. For all three analyzed temperature datasets, anthropogenic heat intensity grows with increasing nighttime lights and declines with increasing vegetation, whereas population density has only minor effects. While surface anthropogenic heat intensity cannot be linked to specific land cover types in the studied resolution (1 km × 1 km) and classification system, both air and groundwater show increased heat intensities for artificial surfaces. Overall, groundwater temperature appears most vulnerable to human activity, albeit the different compartments are partially influenced through unrelated processes; unlike land surface temperature and surface air temperature, groundwater temperatures are elevated in cultivated areas as well. At the surface of Germany, the highest anthropogenic heat intensity with 4.5 K is found at an open-pit lignite mine near Jülich, followed by three large cities (Munich,

---

* Corresponding author.
E-mail address: susanne.benz@kit.edu (S.A. Benz).

http://dx.doi.org/10.1016/j.scitotenv.2017.01.139

Düsseldorf and Nuremberg) with annual mean anthropogenic heat intensities >4 K. Overall, surface anthropogenic heat intensities >0 K and therefore urban heat islands are observed in communities down to a population of 5000.

1. Introduction

Climate and temperature are strongly affected by humans (IPCC, 2013). The main cause of global climate change is additional greenhouse gas emission that alters the Earth's atmospheric composition (Karl and Trenberth, 2003). However, human activity also affects temperatures on a smaller, local scale. Alterations of surface cover and land use influence the ambient thermal regime (Rhee et al., 2014; Rotem-Mindali et al., 2015; Skinner and Majorowicz, 1999), and, in most cases, cause spatial heat anomalies. These local temperature anomalies are primarily described within the bounds of large urban settlements, where urban temperatures are elevated compared to their rural surrounding and form so-called urban heat islands (UHI) (Hung et al., 2006; Peng et al., 2012). These UHIs have a tremendous impact on human life, energy consumption and the urban ecosystem (Yow, 2007). In France, for example, most consequences of the heat wave in August 2003 occurred in Paris, where an increase of 130% in expected mortality was observed (Dhainaut et al., 2004). Furthermore, the cooling demand of buildings within a city center is approximately 13% higher than in similar buildings in rural areas (Santamouris, 2014). UHIs also change urban phenology: plants tend to develop up to a few weeks earlier in cities compared to their rural surrounding (Jochner and Menzel, 2015). However, with the current research mainly focusing on large city clusters, only little is known about the impact smaller communities and industrial sites have on ambient temperatures (Doyle and Hawkins, 2008; Hinkel et al., 2003) and thus on phenology, energy consumption, and human health.

Urban heat islands can be detected in the atmosphere (Chow and Roth, 2006; Giannopoulou et al., 2011) (e.g. surface air temperature, SAT), at the surface (Pongracz et al., 2010) (land surface temperature, LST) and in the subsurface (Menberg et al., 2013a) (groundwater temperature, GWT). However, the interplay between these different layers is not yet fully understood. A comparison of surface and subsurface UHIs in four German cities showed that, while surface and subsurface temperatures correlate, GWTs are elevated compared to LSTs (Benz et al., 2016). This is due to multiple sources of anthropogenic heat flux into the subsurface, such as the thermal energy release from buildings and reinjection of thermal wastewater (Benz et al., 2015). UHIs in the surface and atmosphere were compared for the city of Leipzig, Germany by Schwarz et al. (2012). They revealed that air temperature and LSTs are related, even so, the UHI in the air was less pronounced.

Urban heat islands are often quantified using the urban heat island intensity (UHII), which is the difference between rural background temperatures and highest urban temperatures (Oke, 1973). A critical component is the rural background temperature, which is not well defined yet and hence differs among presented studies (Martin-Vide et al., 2015; Stewart and Oke, 2012). Both the MODIS Land Cover Product (Peng et al., 2012) and the ASTER land use land cover data (Rajasekar and Weng, 2009) are currently used to differentiate rural areas. Some studies include elevation as an additional parameter for deriving rural background temperatures (Pongracz et al., 2010). In a study by Weber et al. (2014) the distance to the city center was additionally considered. While all of these approaches generally result in an improved understanding of urban heat islands, the variabilities of these results also prevent the comparability. Furthermore, use of non-standard measuring equipment can significantly increase the observed urban heat island magnitudes (Santamouris, 2015) and assessing UHIs becomes rather ambiguous.

The key drivers of urban heat island intensity (UHII) are comprehensively studied (Hoffmann et al., 2012; Menberg et al., 2013b; Ward et al., 2016). However, the results of these studies do not always agree. Oke (1973), for example, found that a cities' atmospheric UHII increases with its population, P. In Europe, this dependency is expressed with the following fit: $UHII = 2.10\ K \cdot \log P - 4.06\ K$ ($R^2 = 0.74$). In contrast, Peng et al. (2012) found no evidence of population density driven surface UHII. They also showed only a modest correlation (R^2 of 0.0 to 0.18) between surface UHII and nighttime lights. Only recently though, Zhang et al. (2014) published results indicating a correlation R^2 of 0.83 to 0.85 between summer daytime surface urban heat islands and nighttime light anomalies. Most studies however agree on the effects of vegetation on UHII: within a park or green area, the average temperature difference to the urban surrounding is −0.94 K at the ground level (Bowler et al., 2010).

In this study, the human impact on ambient temperatures is quantified for three different compartments in Germany: air, surface and groundwater. Because above- and below-ground temperatures are influenced differently by seasonal temperature variations (Kurylyk et al., 2014; Smerdon et al., 2006), we chose to analyze annual mean temperatures to ensure comparability. As a universal parameter to quantify anthropogenic heat anomalies, the anthropogenic heat intensity (AHI) is introduced. It is closely related to the UHII, but determined for each pixel (for satellite-derived LST) or measurement point (for SAT and GWT) individually, regardless of land use and location. Hence, it provides the unique and novel opportunity to a) compare the anthropogenic impact on temperatures in air, surface and subsurface, b) to find main instances of anthropogenic temperature anomalies in Germany, and c) to study the impact of smaller settlements or industrial sites on ambient temperatures.

2. Material and methods

2.1. Material

2.1.1. Surface air temperature

Annual mean (2015) surface air temperature (SAT), measured 2 m above ground, was determined in 464 measurement points by taking the arithmetic mean of monthly mean values provided by the German Weather Service (Deutscher Wetter Dienst, DWD, n.d) through their Climate data center (Fig. 1a). SAT is on average 0.26 K colder than land surface temperatures at the same location. The Pearson correlation coefficient between the two is 0.81 (Fig. S1).

2.1.2. Land surface temperature

Annual mean (2015) land surface temperature (LST) was determined from level-5 MODIS daily products MOD11A1 and MYD11A1 (Wan and Dozier, 1996), as obtained from NASA's TERRA and AQUA satellites, courtesy of the NASA Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, https://lpdaac.usgs.gov. LST can only be determined for cloud-free days. As Germany has significantly less cloud-cover in summer than in winter, there is more LST data available for this period of the year. Following the approach by Benz (2016), the annual mean was determined from monthly mean temperatures to eliminate this seasonal bias. This calculation was performed in Google Earth Engine, 2015. The results were then exported at a resolution of approximately 1 km × 1 km (0.009° × 0.009°) (Fig. 1b).

2.1.3. Groundwater temperature

Groundwater temperature (GWT) data are only available for the province of Baden-Württemberg in the southwest of Germany. We