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Analysis of the subsurface urban heat island in Oberhausen, Germany

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ABSTRACT: Soil temperature (t_B) was determined down to 2 m below ground level at 8 locations in the city of Oberhausen, Ruhr area, Germany, between August 2010 and July 2011 to investigate the subsurface urban heat island (SUHI) and its impact on drinking water quality. The soil temperatures obtained in Oberhausen demonstrate typical location-dependent behaviour. At the depth of drinking water pipes (1 to 2 m subsurface), the daily average soil temperature ranges from 3°C in the winter (at the coldest location) to 24°C in the summer (at the warmest location). A maximum SUHI (70 cm below ground level) of almost 9 K on hourly average was found between the city centre station and the open country station. Soil temperatures were measured to be >20°C at the drinking water pipeline level in the city centre over the course of 89 d, which could have an impact on drinking water quality.

KEY WORDS: Urban climate · Subsurface urban heat island · SUHI · Urban heat island · UHI · Urban surface parameters · Soil temperature · Drinking water quality · Climate change

1. INTRODUCTION

Urban areas are warmer than the surrounding countryside, resulting in the formation of urban heat islands (UHIs). UHIs include not only the urban boundary layer of the near-surface atmosphere (Arnfield 2003), but also the soil in urban areas (called a subsurface urban heat island, or SUHI), in some cases down to considerable depths (20 to 40 m; Ferguson & Woodbury 2007, Taniguchi et al. 2007, Zhu et al. 2010).

Modifications of the micro- and meso-climate caused by urbanisation have been observed and quantified for a large number of cities throughout the world (e.g. Wienert & Kuttler 2005). For example, the effects of varying degrees of sealing with anthropogenic materials on soil temperature were examined by Halverson & Heisler (1981); the study compared soil temperatures below planted and sealed parking spaces at low depths (15 to 60 cm) in New Brunswick, New Jersey, USA. Asaeda et al. (1993) analysed the temperature differences influenced by the type of substrate (asphalt, concrete, gravel, sand and natural soil) up to 20 cm below the surface in Saitama, Japan. Not only do anthropogenic surface and substrate materials influence the soil temperature, but the energy loss from buildings and underground traffic routes also contributes to more intensive heating of urban soil (Ferguson & Woodbury 2004, Menberg et al. 2013).

Tang et al. (2011) studied the effects of urbanisation by comparing soil profiles at urban and rural locations in Nanjing, China, at a depth of 25 cm and found a difference of 1.2 K on annual average. A study conducted by Yamashita (1990) observed summer (>4 K) and winter (>3 K) SUHI temperatures at a depth of 90 cm in Tokyo, Japan. Long-term measurements and model calculations have confirmed the role of climate change in both past and future soil temperature increases (e.g. Savva et al. 2010); thus, urbanisation and climate change are considered to be the main causes of SUHI formation.

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However, thus far, there have not been any studies conducted concerning urban soil heating at the level of drinking water systems (normally between approximately 1 and 2 m below ground level in the Ruhr area, Germany, in accordance with MUNLV 2010) as a function of land use. Considering that most drinking water pipeline systems in Germany are operated without disinfection (Uhl et al. 2002), drinking water quality can be jeopardised at temperatures >20°C in pipes (LGL 2006). To prevent the propagation of pathogenic organisms, drinking water should not exceed this temperature. As the data from some extremely hot summer periods show that this value can potentially be exceeded more often as a result of climate change (LGL 2006), this study was conducted to obtain further information on the causes and characteristics of the SUHI and its potential impact on drinking water quality.

2. MATERIALS AND METHODS

2.1. Investigation area and measurement stations

From 1 August 2010 to 31 July 2011, soil climate parameters were measured based upon the framework of the *dynaklim*-project (www.dynaklim.de) in the immediate vicinity of drinking water shafts in different climatopes (in accordance with VDI 2003, Stewart 2011) at 8 representative locations in the city of Oberhausen, North Rhine-Westphalia, Germany (77 km^2, 210 000 inhabitants; www.it.nrw.de/statistik/a/daten/bevoelkerungszahlen_zensus/zensus_reg1.html). Table 1 provides detailed descriptions of the locations and the characteristic features of the climatopes that affect soil temperature.

Each station was classified as 1 of 4 different soil types; these soil unit types comprise approximately

Table 1. Description of the measurement stations in Oberhausen, Germany. Climatopes are based on VDI (2003), and for comparative purposes, the more commonly known local climate zones (LCZ, in parentheses; after Stewart 2011) are also given. Depth of horizon limits (+: end of horizon not reached during sampling) was defined by on-site soil profile uptake (drilling). Soil texture was classified based on pipette analysis after Köhn (DIN 1973 or DIN ISO 2002). Soil texture and horizon designation abbreviations in accordance with AG Boden (1994): Lts = sandy-clayey loam, S = sand, Sl2 = slightly loamy sand, Sl3 = medium loamy sand, Sl4 = strongly loamy sand, Su2 = slightly silty sand, Ut3 = medium clayey silt, A = terrestrial topsoil, C = terrestrial bedrock, G = semi-terrestrial soil layer influenced by ground water, R = mixed layer, S = terrestrial sublayer influenced by backwater, d = confining impermeable layer, e = eluvial/bleached, h = humus, j = anthropoogenically restored natural substrate, l = unconsolidated substrate, o = oxidised, r (prefixed) = relict, r (suffixed) = deoxidised, w = backwater, y = anthropogenically restored artifical substrate, II = indicates a change of substrate layers

Stn no.	Climatope (LCZ)	Stn abbreviation	Depth of horizon limits (cm)	Humus content (mass %)	Soil texture	Soil type (horizon designation) [soil unit]	Characteristic features
1	City centre, highly sealed (compact midrise)	CH	Road surface — no sampling possible			[Sandy soil]	Severely sealed
2	City centre, (compact midrise)	CC	0–15 15+	3–6 0	Sl2 S	Regosol (jAh–jC) [sandy soil]	Severely sealed, little grass, few shrubs, district heating pipeline in vicinity
3	Urban park (open midrise)	UP	0–57 57+	7–13 3–6	Sl3 Sl2	Rigosol (R–Ah–jC) [sandy soil]	Flowerbed, surrounded by tall deciduous trees
4	Commercial area (large lowrise)	CA	0–6 6–25 25+	3–6 3 3	Ut3 Ut3 Sl2	Regosol (Ah–jAh/C–jC) [no soil unit]	Mown lawn, car park, no trees providing shade
5	Suburban area (open lowrise)	SA	0–40 40–115 115–133 133+	3–6 2–3 <1 0	Sl3 Sl4 S Su2	Regosol on gley (jAh/C–IIC–rGo–rGr) [clayey loam]	Houses, road, gardens, deciduous trees, some shade
6	Water body (sparsely built)	WB	0–29 29–43 43–52 52–63 63+	2–4 0 0 0 0	Sl2 Sl2 Su2 Su2 Sl2	Regosol of sandy humus material (jAh– jAh –jlCv–yC–yjC) [clayey loam]	Roads, car park, gardens, deciduous trees, canal 40 m away, shaded
7	Forest (dense trees)	FO	0–43 43–53 53–90 90–160	7–13 0 0 0	Sl3 Sl2 Sl3 Lts	Pseudogley, podsol-like brown earth (jAh–Sew–Sw–Swd) [clayey sandy soil]	Woodland, trails, gardens, intense shade for the most part
8	Open country (low plants)	OC	0–20 20–150 150+	3–6 1 0	Sl3 Sl3 Lts	Gley (Ah–Go–Gr) [sandy soil]	Woods, road, some shade

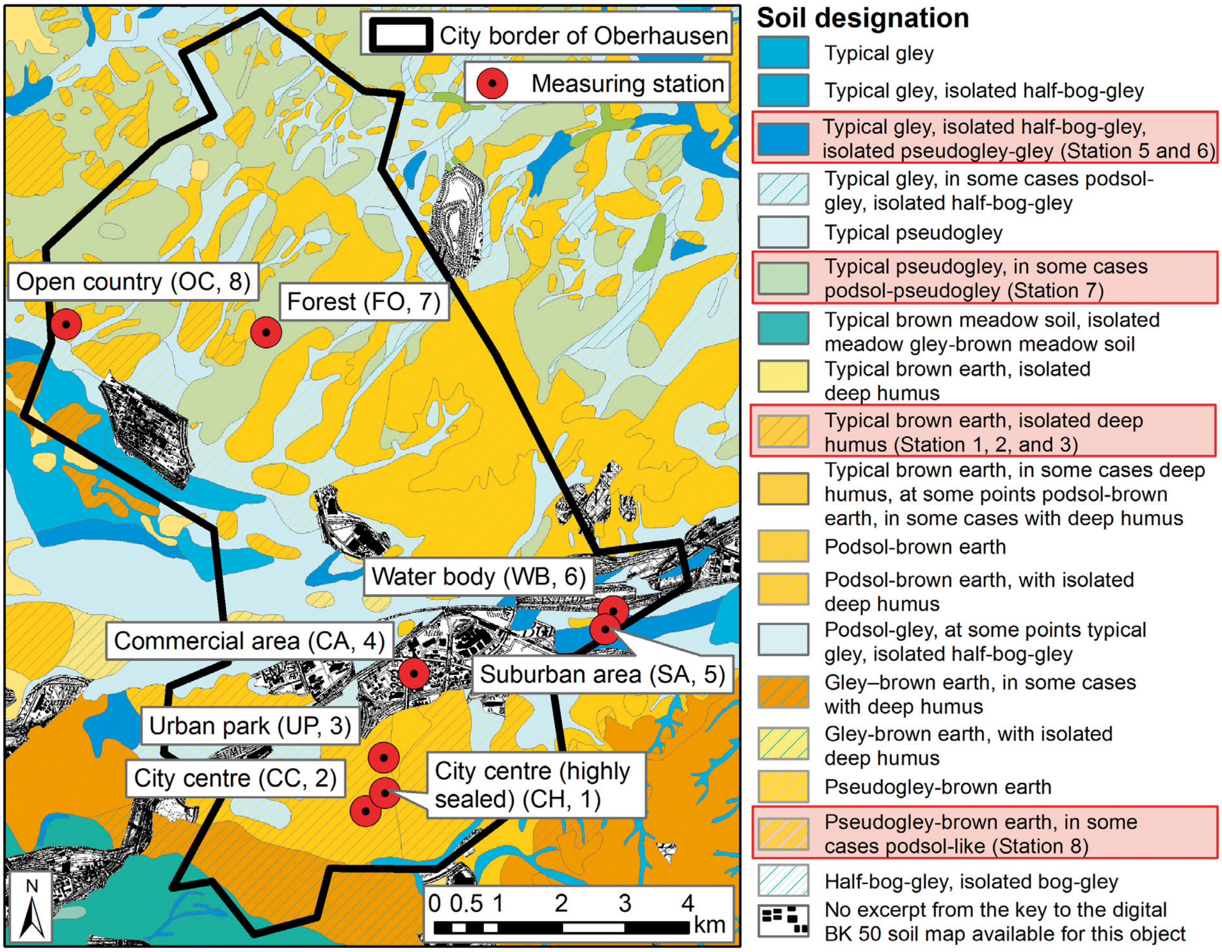

Fig. 1. Measurement stations and soil types in Oberhausen, Germany, based on the 1:50 000 soil map of the North Rhine-Westphalian Geological Service (IT NRW 2011) (soil types at the measurement sites are highlighted by red frames in the legend)

40 % of the total area of Oberhausen (Fig. 1). It was not possible to characterise the profile at the city centre (CH, 1), as it is located in a fully sealed pedestrian precinct. In the case of the commercial station (CA, 4), it was not possible to assign a soil unit, as this is a former industrial site with a technogenic substrate (Hiller & Meuser 1998) (Fig. 1, Table 1).

2.2. Measurement parameters and equipment

A total of 50 soil temperature probes (Pt 100, manufacturer: Friedrichs) were installed in the 8 climatope sampling sites to record the soil temperature (t_B) in each soil horizon from the surface to the depth of the drinking water system (between 1 and 2 m) (normally, 5 probes were used; Table 2). The soil temperature measurement sensors were inserted horizontally into the soil through the walls of the drinking water system maintenance shafts, approximately 40 cm from the wall of the shaft (Fig. 2). The soil humidity was determined at 2 locations (Table 2) by soil sampling in the field once per week and gravimetric analysis in the laboratory following the methods of Löffler (2012). The soil moisture at 70 cm depth varied between 2 and 16 % by volume at CC (2) and between 4 and 37 % at OC (8) over the course of the year; soil humidity was not analysed in more detail. Apart from the soil climate measurements, an aboveground meteorological measurement network collected data 3.5 m above ground level at the same locations (ambient air temperature [t_a, relative humidity, wind speed and wind direction, and radiation balance]). Therefore, clear and calm weather situations could be derived.

Because t_a was not just recorded in the urban canopy layer but also in the shaft ($t_{a\ shaft}$), it was possible to consider the impact of $t_{a\ shaft}$ on the soil measurements. As the correlation between $t_{a\ shaft}$ and the soil temperature at a depth of 70 cm ($t_{B\ 70\ cm}$) ($r^2 \geq 0.95$)

Table 2. Measuring depths and parameters at the 8 stations in Oberhausen, Germany. t_B: soil temperature (recorded as 3 min averages, aggregated to hourly mean values); $t_{a\ shaft}$: air temperature in the shaft, measured 50 to 130 cm below ground level; $t_{B\ DWPL}$: soil temperature at the drinking water pipeline level, with sample depth indicated; Θ: soil moisture content (determined by gravimetric method in layers of 10 cm thickness of a 100 cm soil profile sampled in the field once per week). Station abbreviations see Fig. 1

	CH (1)	CC (2)	UP (3)	CA (4)	SA (5)	WB (6)	FO (7)	OC (8)
$t_{B\ 1\ cm}$		✓						✓
$t_{B\ 10\ cm}$		✓						✓
$t_{B\ 15\ cm}$		✓		✓	✓	✓	✓	✓
$t_{B\ 30\ cm}$			✓		✓	✓	✓	✓
$t_{B\ 45\ cm}$	✓	✓		✓	✓	✓	✓	✓
$t_{B\ 55\ cm}$	✓							
$t_{B\ 58\ cm}$						✓		
$t_{B\ 70\ cm}$	✓	✓	✓	✓	✓	✓	✓	✓
$t_{B\ 85\ cm}$			✓					
$t_{B\ 125\ cm}$	✓			✓				
$t_{B\ DWPL}$	110 cm	145 cm	115 cm	195 cm	115 cm	110 cm	115 cm	145 cm
$t_{a\ shaft}$	✓	✓	✓	✓	✓	✓	✓	
Θ		✓						✓

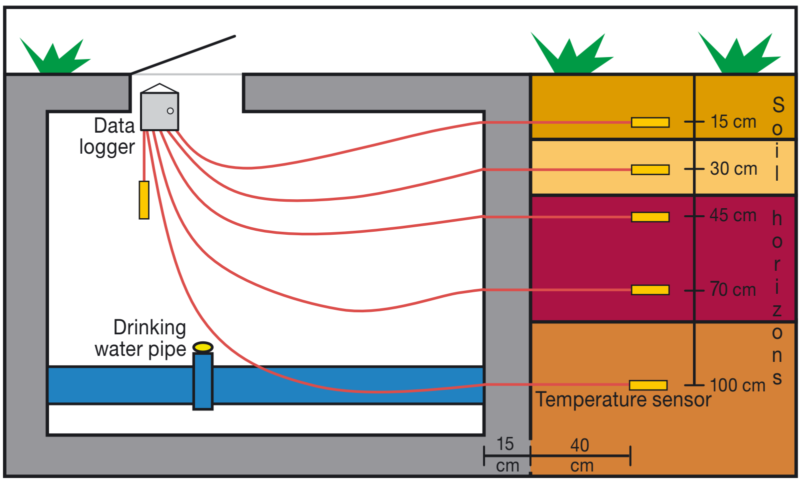

Fig. 2. Schematic overview showing the general design of the soil temperature measurement network in Oberhausen, Germany

was clearly higher than the correlation between $t_{a\ shaft}$ and t_a ($r^2 \leq 0.73$) and the correlation between $t_{B\ 70\ cm}$ and t_a ($r^2 \leq 0.65$) (Table 3), the influence of air temperature in the shaft on the soil temperature measurements was excluded.

3. RESULTS

3.1. Climatic assessment of the measurement period

The long-term average t_a of the 30 yr period 1961–1990 in the investigation area was 10.9°C, with July (18.9°C) as the warmest and January (3.1°C) as the coldest month (DWD 2011). The monthly average values measured during the 1 yr measuring period are in line with the long-term averages, fluctuating between −1.4°C in December and 17.8°C in August, with an annual average of 10.7°C. Deviations in air temperature, with respect to long-term averages, were observed in April (data not shown), which was considerably warmer than the long-term average (plus 4.3 K), and in December, which was 5.5 K colder than the long-term average. In comparison with the long-term average precipitation (767 mm), precipitation rates in the measurement period were slightly higher, at 878 mm (H. Augustin, Emschergenossenschaft/Lippeverband [EGLV], pers. comm.). Two other uncharacteristic periods should be mentioned here: the dry spring of 2011, during which there was only 20 to 30% of the mean precipitation, and the wet August of 2010, during which there was double the long-term average precipitation. With reference to the 30 yr climate normal values, the data found over the 1 yr measurement period are representative.

3.2. Soil temperature variations among climatopes

The drinking water pipeline level (DWPL) was different for the various stations. For this reason, the measurement depth of 70 cm rather than the actual DWPL was used in the comparison of the annual course of soil temperatures between climatopes, as this was available for all stations and was therefore comparable. Fig. 3 provides an overview of the annual course of soil temperatures for the various stations and climatopes. The plot of soil temperatures at all of the stations over the year shows a typical sinusoidal course, with the highest soil temperatures obtained in the summer (June to August) and the lowest in the winter (December to February). Weather conditions illustrated by the course of the air temperature (Fig. 3) have a considerable impact on soil temperature; this

Table 3. Coefficient of determination of the correlation between the air temperature in the shaft ($t_{a\ shaft}$), soil temperature at a depth of 70 cm ($t_{B\ 70\ cm}$) and the air temperature 3.5 m above ground level (t_a) at all stations in Oberhausen, Germany, from 1 August 2010 to 31 July 2011, based on hourly average values. (–) no values available. Station abbreviations see Fig. 1

Stn	$t_{a\ shaft}$ and $t_{B\ 70\ cm}$	t_a and $t_{B\ 70\ cm}$	$t_{a\ shaft}$ and t_a
CH (1)	0.99	0.63	0.65
CC (2)	0.99	0.65	0.68
UP (3)	0.98	0.61	0.69
CA (4)	0.99	0.65	0.66
SA (5)	0.95	0.59	0.73
WB (6)	0.98	0.56	0.62
FO (7)	0.99	0.49	0.58
OC (8)	–	0.54	–

is indicated by fluctuations in the soil temperature curves, which show short-term maximum and minimum values during summer. This impact of weather conditions is also evident in winter, when periods of snow cover with gradual temperature changes are interspersed with periods of strong rises and falls of the soil temperature (Fig. 3).

Temperature ranges varied among stations. The city centre station (CH, 1) was the warmest, reaching values of nearly 25°C (August 2010) and cooling to approximately 3°C in the winter (January 2011). The forest station (FO, 7) showed daily maximum values of nearly 16°C in the summer (August 2010) and minimum soil temperatures of approximately 5°C in the winter (January 2011). This results in a difference of nearly 9 K between the coldest and warmest stations in the summer. In the winter, the difference was only 2 K. The city centre station (CC, 2) was a special case, as it did not undergo the same cooling as the other stations in the winter months. The winter temperatures at this station ranged from 5 to 9°C, as there was a district heating pipeline only approximately 1 m from the station; at the other sites, the winter temperatures ranged from 3 to 7°C.

Fig. 3 shows the thermal differentiation between the stations, classifying them into 2 groups. Group I consists of the city centre (CH, 1 and CC, 2) and commercial (CA, 4) stations, which are characterised by strong anthropogenic heating effects. Group II is comprised of the park (UP, 3), suburban (SA, 5), water body (WB, 6), forest (FO, 7), and open country (OC, 8) stations, which were less affected by anthropogenic impacts, resulting in lower soil temperatures, which is especially apparent in the summer (Apr–Nov). In the winter, there is less difference between the soil temperatures at the various stations and lower thermal differentiation of the climatopes.

The average annual $t_{B\ 70\ cm}$ varied between 13.6°C (CH, 1) and 10.4°C (FO, 7), resulting in a considerable temperature difference of >3 K between these sites (Table 4). The stations most impacted by anthropogenic effects (Group I) were the warmest, followed by the urban park station (UP, 3). Because the park only has an area of approximately 1 ha, it is strongly affected by the densely built surroundings (86% of the surroundings in a 25 ha grid square are sealed). The highest annual ranges of soil temperatures were measured at the city centre station (CH, 1) and the commercial station (CA, 4), at 21.3 and 18.5 K, respectively. The forest station (FO, 7) had the lowest temperature range (11.3 K), which is likely a result of the local climate (highly affected by shading, transpiration and interception) and the relatively moist soil.

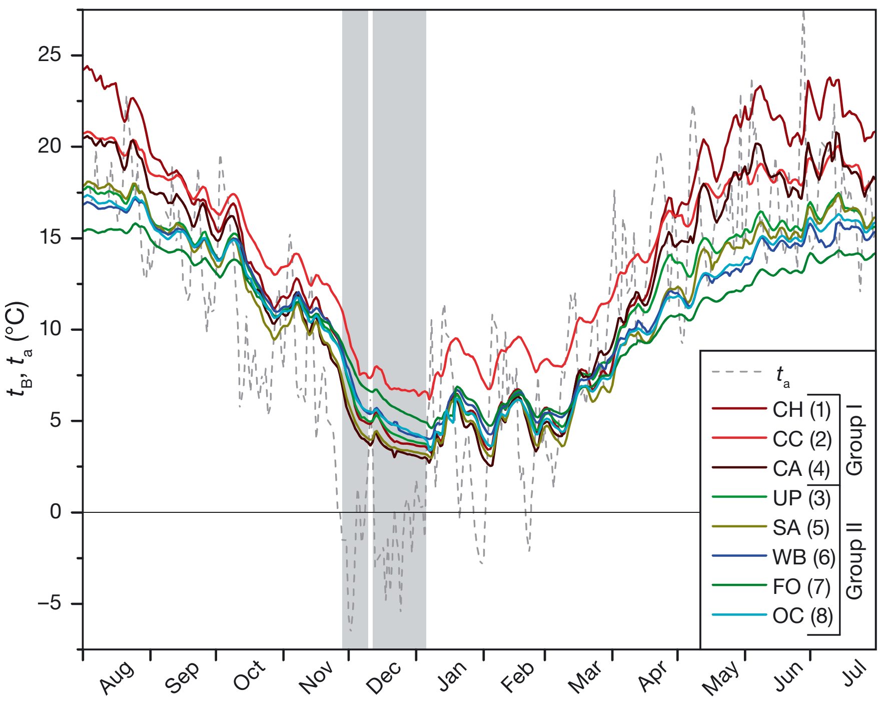

Fig. 3. Daily average soil temperatures (measured at 70 cm depth) at all stations and the station average of air temperature (t_a) for all stations in Oberhausen, Germany, from 1 August 2010 to 31 July 2011, based on hourly average values (period with snow cover is shown by grey shading; Group I includes anthropogenic stations, while Group II includes the near-natural stations). Station abbreviations see Fig. 1

Table 4. Annual mean, maximum, minimum and range of the soil temperature (t_B) at 70 cm depth at all sites in Oberhausen, Germany, from 1 August 2011 to 31 July 2011, based on hourly average values. Station abbreviations see Fig. 1

Stn	$t_{B\ mean}$ (°C)	$t_{B\ max.}$ (°C)	$t_{B\ min.}$ (°C)	$t_{B\ range}$ (K)
CH (1)	13.6	24.5	3.2	21.3
CC (2)	14.0	20.8	6.1	14.7
UP (3)	11.3	18.0	3. 5	14.5
CA (4)	12.1	21.0	2.5	18.5
SA (5)	10.7	18.1	2.9	15.2
WB (6)	11.0	17.2	4.0	13.2
FO (7)	10. 4	15.8	4.6	11.2
OC (8)	10.8	17.4	3.2	14.2

Rankings of annual average soil temperatures ($t_{B\ mean}$) at the various stations compared with those of annual average air temperatures ($t_{a\ mean}$) for the various climatopes were very similar (Table 5). For example, the 2 city centre stations (CH, 1 and CC, 2) were the 2 warmest stations and the forest station was the coolest station, both in terms of annual average soil and air temperatures. The similar rankings of climatopes on the basis of soil (subsurface layer) and air (urban canopy layer) temperatures confirm the close relationship between climatope and soil temperature.

The soil temperature differences between the climatopes can be observed at all measurement depths. The variation in the annual soil temperature course of daily mean values at different measuring depths is shown in Fig. 4 and is best exemplified for the city centre station (CH, 1) and the open country site (OC, 8) (as examples of Groups I and II, respectively), which are also used to define SUHI in Section 3.2. Fig. 4 shows that the short-term fluctuations in soil temperature are much smaller than those in air temperature at both sites. The daily fluctuations, as well as the annual soil temperature ranges, are continually reduced with increasing depth (Fig. 4, Table 6).

Table 5. Ranking of the climatopes by annual average soil temperatures ($t_{B\ mean}$, measured at 70 cm depth) (left columns) and annual average air temperatures $t_{a\ mean}$ (measured at 3.5 m above ground level) (right columns) for all stations in Oberhausen, Germany, from 1 August 2010 to 31 July 2011, based on hourly average values. Station abbreviations see Fig. 1

Soil (subsurface layer) Ranking	$t_{B\ mean}$	Air (urban canopy layer) Ranking	$t_{a\ mean}$
CC (2)	14.0	CH (1)	11.3
CH (1)	13.6	CC (2)	11.1
CA (4)	12.1	CA (4)	10.8
UP (3)	11.3	UP (3)	10.7
WB (6)	11.0	SA (5)	10.6
OC (8)	10.8	WB (6)	10.5
SA (5)	10.7	OC (8)	10.3
FO (7)	10.4	FO (7)	10.2

The near-surface soil temperature at a depth of 1 cm ($t_{B\ 1\ cm}$) at the open country station (OC, 8) is subject to a lower annual average soil temperature range than at the comparatively deep depth of 45 cm ($t_{B\ 45\ cm}$) in the city centre (CH, 1). These results can be seen as an indication of the anthropogenic effects at the city centre station (CH, 1). Especially in the summer, the daily average soil temperatures at the city centre site (CH, 1) reach almost the daily average air temperature, whereas the daily average soil temperatures at the open country station (OC, 8) stay far below the daily average air temperature values. A phase delay between the air and soil temperatures occurs at both sites and can be observed most notably for the short-term maximum and minimum temperature values (fluctuations) of the annual course; however, it is not pronounced in the case of the daily mean values for different depths (Fig. 4).

The annual average soil temperatures at CH (1) and OC (8) are approximately the same at all measurement depths (Table 6). In contrast, there are significant differences between the minimum and maximum values at different depths. For example, the maximum soil temperature decreases with increasing depth in both climatopes. Conversely, the minimum soil temperature rises with increasing depth. The maximum soil temperature range is therefore also reduced with increasing depth. At the anthropogenically affected city centre station (CH, 1), the ranges of soil temperatures at different measuring depths are more pronounced than at the rural open country station (OC, 8), as a comparison of the values for the 2 measurement depths of 45 and 70 cm shows (Table 6).

At the open country site (OC, 8), there were very small differences between the soil temperatures measured at the DWPL (145 cm deep) and at a depth of 70 cm (Fig. 4b). At the city centre station (CH, 1), differences between the temperatures at the DWPL (110 cm deep) and 70 cm depth were slightly higher (Fig. 4a). Overall, the differences in soil temperatures at 70 cm depth for different stations (climatopes) may be regarded as representative of the differences in the soil temperature at the DWPL.

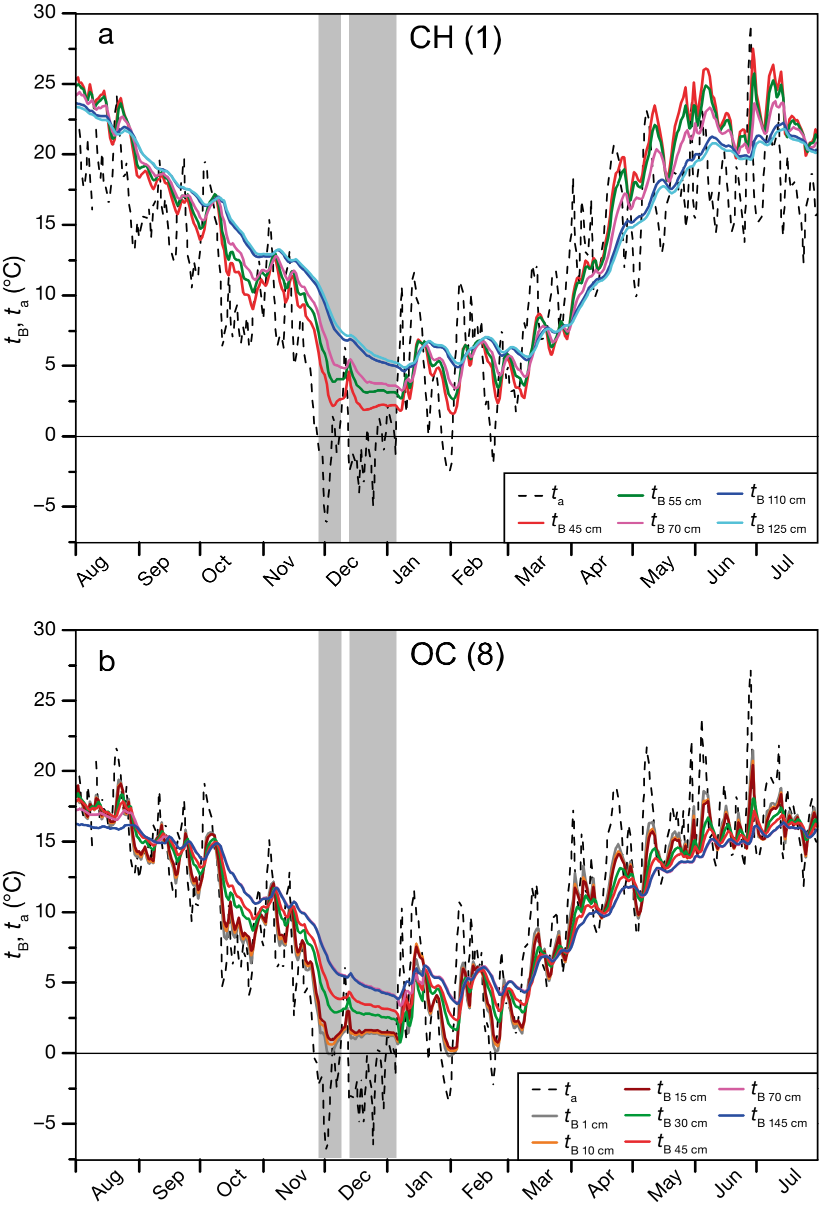

Fig. 4. Daily average soil temperatures (t_B) at different measuring depths, as exemplified by (a) the city centre (CH, 1) and (b) the open country sites (OC, 8) in Oberhausen, Germany, from 1 August 2011 to 31 July 2011, based on hourly average values. t_a: average air temperature; period with snow cover is shown by grey shading

3.2. Interactions between subsurface (SUHI) and above-ground heat islands (UHI)

Differences in soil and air temperatures between the city centre station (CH, 1) and the open country station (OC, 8) were used to calculate SUHI and UHI, respectively. Fig. 5 indicates the daily intensity of minimum and maximum SUHI values at 70 cm depth and UHI values 3.5 m above ground level on the basis of hourly mean values.

There were scarcely any differences between $SUHI_{min}$ and $SUHI_{max}$, whereas there were remarkable differences between UHI_{min} and UHI_{max} over the course of the day. The SUHI was pronounced in the summer of 2010, with $SUHI_{min}$ and $SUHI_{max}$ values of almost 7 K. The SUHI intensity declined markedly during autumn and winter, reaching a minimum in mid-December. In the winter, UHI_{max} reached a short-term maximum of almost 7 K in clear and calm weather. Beginning in the spring, the highly sealed soil gained more energy compared with the open country location, as observed from the gradient of the temperature curve at CH (1), which is approximately double that of the temperature curve for OC (8) (see Fig. 3). In May, UHI_{max} reached its annual maximum (8.5 K). The SUHI, however, still increased, supported by the delay in soil heating. The SUHI annual maximum was reached in early June 2011, at 8.6 K. Fig. 5 shows that the UHI is not determined by the SUHI and vice versa, as the maximum values of the 2 effects occur at very different times. While atmospheric conditions directly affect UHI intensity, they exert a delayed impact on SUHI intensity.

3.3. Effects of soil temperature on drinking water quality

To investigate the impact of the SUHI on the drinking water quality, the city centre station (CH, 1) and the open country station (OC, 8) were once again taken as examples of Groups I and II. In Fig. 6, soil temperature frequency distributions at the DWPL at both stations show a tri-modal distribution, reflecting the annual pattern of severe heating and cooling in the spring and autumn, respectively, and plateaus in the summer and winter (Figs. 3 & 4). In this study, an hourly average value of 20°C is considered critical for drinking water quality based on literature evaluation (Uhl et al. 2002, Rohn & Mälzer 2010; for more details see 'Discussion').

This study obtained soil temperatures that may be critical for drinking water quality at the city centre

Table 6. Mean, maximum, minimum values and ranges of soil temperature (t_B) at all measurement depths at the city centre station (CH, 1) and the open country site (OC, 8) in Oberhausen, Germany, from 1 August 2011 to 31 July 2011, based on hourly average values

Depth (cm)	$t_{B\ mean}$ (°C)	$t_{B\ max.}$ (°C)	$t_{B\ min.}$ (°C)	$t_{B\ range}$ (K)
CH (1)				
45	13.2	27.5	1.6	25.9
55	13.4	25.7	2.7	23.0
70	13.3	24.4	3.3	21.1
110	13.5	23.6	4.6	19.0
125	13.4	23.4	4.9	18.5
OC (8)				
1	10.0	21.5	−0.2	21.7
10	10.0	20.8	0.2	20.6
15	10.0	20.5	0.4	20.1
30	10.3	18.5	0.7	17.8
45	10.4	18.0	2.1	15.9
70	10.6	17.4	3.4	14.0
145	10.6	16.4	3.5	12.9

station (CH, 1). Soil temperature values of ≥20°C were measured at the DWPL at this station over a total of 2055 h (89 d) (Figs. 4 & 6). In particular, the critical temperature was continuously exceeded from 1 August to 2 September 2010, 31 May to 21 June 2011 and 28 June 2011 until the end of the measurement period (31 July 2011). In contrast, the temperature distribution at the open country station (OC, 8) even failed to exceed 17°C (Fig. 6). However, as most drinking water lines are laid under sealed surfaces, i.e. under traffic routes, hygiene risks to the drinking water quality are likely to increase in the future.

4. DISCUSSION AND CONCLUSION

With With site-specific variations, the data collected show a sinusoidal soil temperature pattern over the course of the year (cf. Fig. 3) and a reduction in soil temperature amplitude with increasing depth (Table 6). Furthermore, the anthropogenic effects on soil temperatures were demonstrated; the measurement results show a clear split between the stations, into a more anthropogenic/warmer group (Group I) and a more natural/cooler group (Group II). The effect of urbanisation on soil temperature varies by climatope, and thus climatope can be used as a factor for classification (Table 5).

These results agree with those from other studies on SUHIs (e.g. Ferguson & Wood bury 2007, Menberg et al. 2013). The equalisation of soil temperature conditions at anthropogenic and near-natural locations in the winter was also observed by Pagel et al. (1993) in Hanover, Germany, and by Halverson & Heisler (1981) in New Brunswick, New Jersey, USA. Turkoglu (2010) identified the vicinity of anthropogenic heat sources and artificial surface coverings as a further cause of urban soil overheating, especially in the summer. Menberg et al. (2013) confirmed higher subsurface/ground water temperatures at densely built-up city centre locations in several German cities, as well as at industrial sites and near known local heat sources (e.g. underground system, land fill), in contrast to near-natural locations.

Nevertheless, the differences between the anthropogenic and near-natural climatopes are not

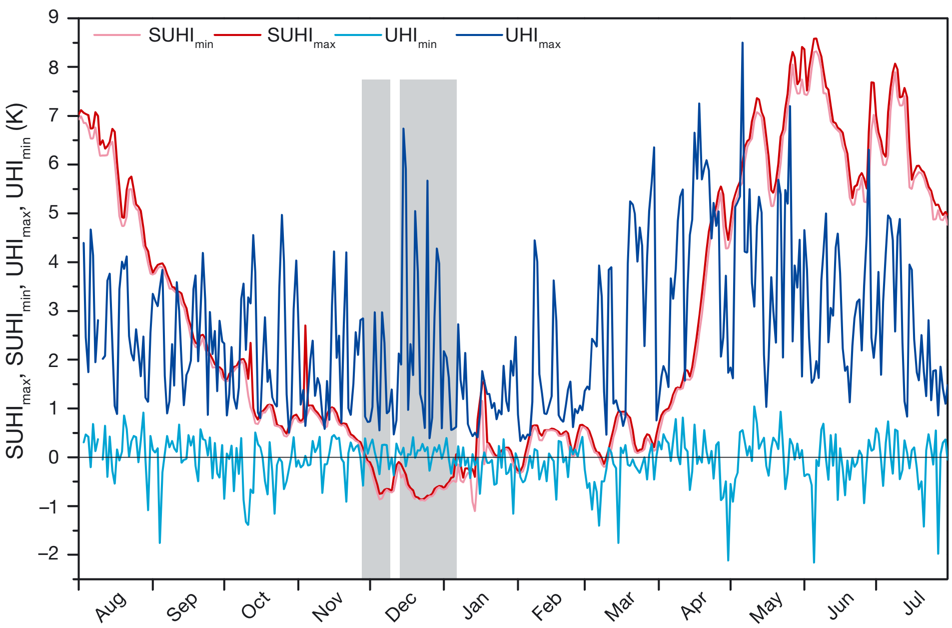

Fig. 5. Daily minimum and maximum subsurface urban heat island (SUHI) values and urban heat island (UHI) values (as soil and air temperature differences between the city centre [CH, 1] and the open country [OC, 8] stations at 70 cm depth and 3.5 m above ground level, respectively) in Oberhausen, Germany, from 1 August 2010 to 31 July 2011, based on hourly average values; period with snow cover is shown by grey shading

only due to anthropogenic effects, but may also be influenced by soil properties. In the Oberhausen measurement network, more humid soils (e.g. gley at the open country station [OC, 8]) coincide with the more natural climatopes, so soil humidity/soil moisture content was not further analysed. But Savva et al. (2010) showed a connection between urban/rural temperature differences and larger summer differences in soil moisture conditions and thermal conductivity. Furthermore, studies in Nanjing, China, show that urban soils tend to be drier than rural soils (Liu et al. 2011, Tang et al. 2011). The higher soil water content in the near-natural climatopes (Group II) may therefore contribute to the cooling of the soil (cf. Table 2); however, the relationship between soil temperature, soil water content and thermal conductivity is complex, and other influencing factors (e.g. porosity) have to be considered, as has been indicated by other studies (see Cosenza et al. 2003, Sakaguchi et al. 2007).

Therefore, as a result of a variety of factors, a pronounced SUHI and a UHI have been formed in Oberhausen. The low SUHI values, which may even be negative in winter (Fig. 5) in this study, are due to the open country station (OC, 8) being covered by snow, whereas at the city centre station (CH, 1), which lies in a pedestrian precinct, snow was partly cleared, thus effectively removing the thermal isolation of the snow cover and cooling the soil. In May, UHI_{max} reached its annual maximum (8.5 K) as a result of the clear weather conditions found in the spring of 2011. The $SUHI_{max}$ reached its annual maximum in early June due to delay in soil heating compared to air temperatures. The annual average soil temperature differences of 3 K found in Oberhausen between the city centre and the surrounding countryside are comparable with those measured in other subsurface temperature studies. For example, Mount & Hernandez (2002) found a horizontal temperature difference of 3.1 K in New York, USA; Turkoglu (2010) found a difference of 2.1 K in Ankara, Turkey; and Savva et al. (2010) found a difference of 1.4 K in Baltimore, USA.

Drinking water quality may be impaired by increased propagation of bacteria due to rising soil temperatures as a result of climate change and SUHI effects. As most drinking water pipeline systems in Germany are operated without disinfection systems (Uhl et al. 2002) and are lying in rather shallow depths of 1 to 2 m, the risk of bacterial contamination during prolonged heat waves is elevated. Reasoner et al. (1989) demonstrated increased concentrations of bacteria at water temperatures >16°C. Similarly, Uhl et al. (2002) found that the concentration of bacteria in drinking water samples incubated at 20°C was 10 times higher than that for an incubation temperature of 10°C. Assuming that soil temperatures >20°C may result in such critical water temperatures leading to bacterial contamination, these conditions were measured over approximately 2050 h during the measurement period in the city centre of Oberhausen (CH, 1), corresponding to approximately 90 d yr^{-1}. In the future, the number of hours with critical soil temperatures may continue to increase due to climate change (LGL 2006, Rohn & Mälzer 2010). Therefore, adaptation measures are required, e.g. by means of land use and land cover using near-natural materials in urban areas whenever possible or by means of technical development, e.g. installing disinfection systems in drinking water pipes.

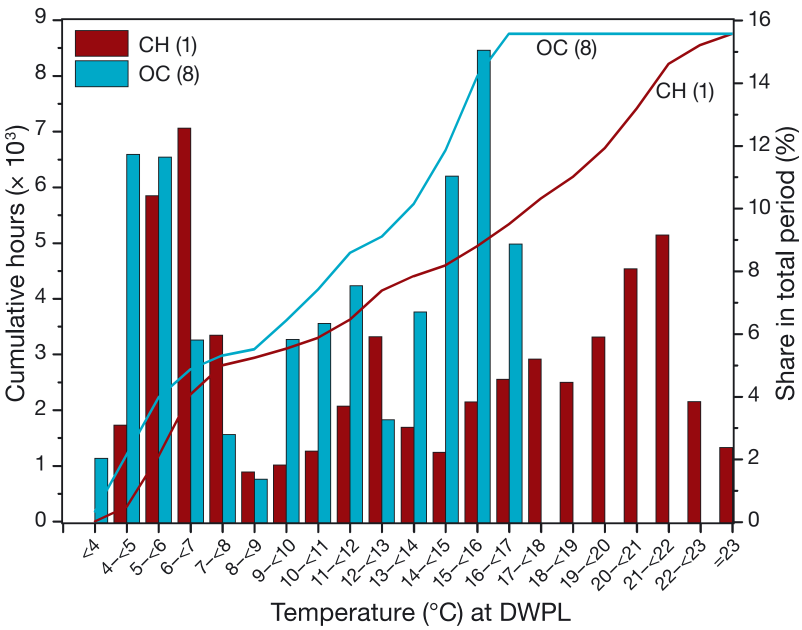

Fig. 6. Frequency distribution of soil temperature at the drinking water pipeline level (DWPL) at the city centre (CH, 1; 110 cm depth) and the open country stations (OC, 8; 145 cm depth), with cumulative frequency curves (lines) and the share in overall hours (bars) from 1 August 2010 to 31 July 2011 in Oberhausen, Germany, based on hourly average values

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