Supplementary Information to "Contrasting changes of urban heat island intensity during hot weather episodes"

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Supplementary Discussion

D1. Selection of time intervals

For the identification of hot weather episodes (HWEs) and following analyses, air temperature and urban heat island intensity (UHII) for each station was aggregated to an arithmetic mean value for a daytime (13 – 16 h UTC+1) and a night-time (01 – 04 h UTC+1) interval each day. Several aspects motivated this choice, aiming at:

(1) Obtaining results not only valid for a single point in time, but to cover a longer period of time during the day and night.
(2) Including many crowdsourced citizen weather stations (CWSs). CWS data often have missing values for individual hours. These are typically due to server errors during data collection, if a station has no wireless connection for data upload, or the result of the data quality assessment during which individual values are filtered out. By aggregating over an interval more stations can be included in the analyses (note that at least three valid values per interval and station, i.e., 75 %, had to be present to calculate the mean for this interval).
(3) Retaining temporal consistency between identification and analysis intervals, which would not be possible by using, e.g., daily maximum and minimum air temperature for the identification of HWEs, and then analysing an interval.
(4) Retaining temporal consistency between all stations for identification and analysis (also a reason against using daily maximum and minimum air temperature).
(5) Inclusion of time during the day when daily maximum air temperature typically occurs in Berlin (for daytime interval), which is also the time when UHII is usually around zero.
(6) Inclusion of time during the night when daily minimum air temperature typically occurs in Berlin (for night-time interval) and when UHII is strong.

Different lengths of the intervals, and different start and end times per interval were tested to find out whether changing these parameters had an effect onto results. Generally, longer intervals lead to less distinct results, while shorter intervals or single hourly values even produced clearer signals if positioned at the right time, but with fewer stations proving valid data. The selected four-hourly intervals are a balance between having a longer period of time for analyses (and identification), including many CWSs, but obtaining distinct signals. Moving the intervals to other start and end times (while maintaining the exclusion of sunrise for the night-time interval) lead to slightly differing values of UHII and UHII change than those presented, but main results and conclusions were not altered (not shown).

The months May to September were analysed as this is often analysed in hot weather/heat wave investigations, thus keeping comparability to other studies. Further, these months typically show highest UHII in Berlin (Fenner et al 2014, 2017). To investigate a possible influence of the annual cycle in the analysed weather variables, it was tested if differences between HWEs and normal conditions in weather conditions are sensitive to the choice of study period (not shown). Analysing only summer months June, July, and August leads to slightly altered values, but changes in weather variables have the same sign, as well as showing statistical significance for the same variables and for the same intervals (daytime/night-time) as if analysing the months May to September, thus leading to the same conclusions.

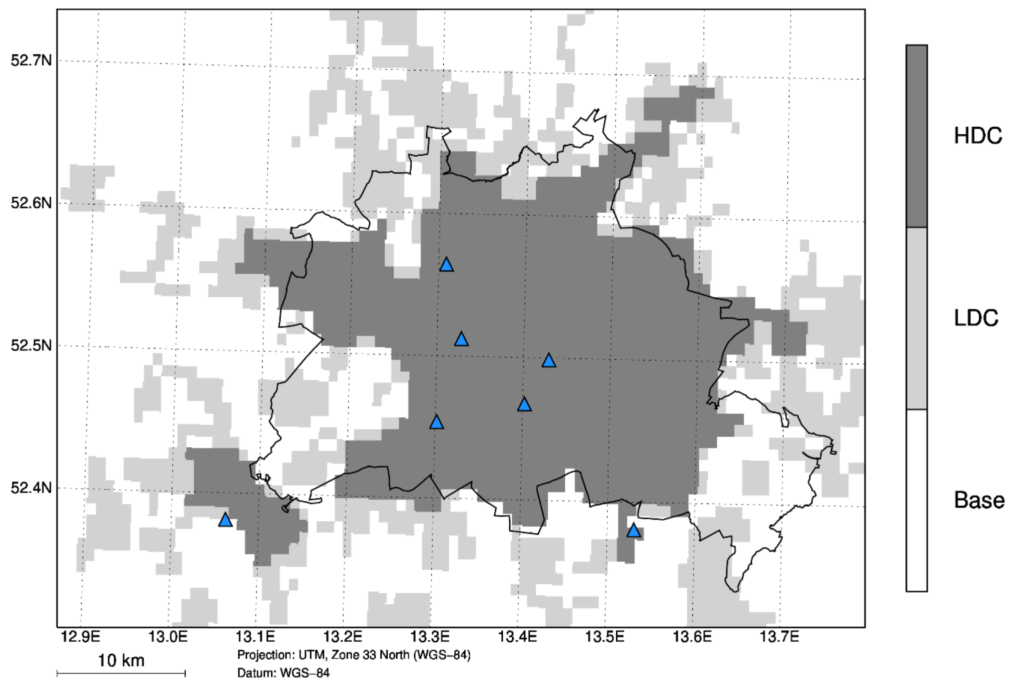
D2. Selection of definition for hot weather episodes

The applied method to identify HWEs (using the 90th percentile of the distribution as threshold) was motivated by the following aspects:

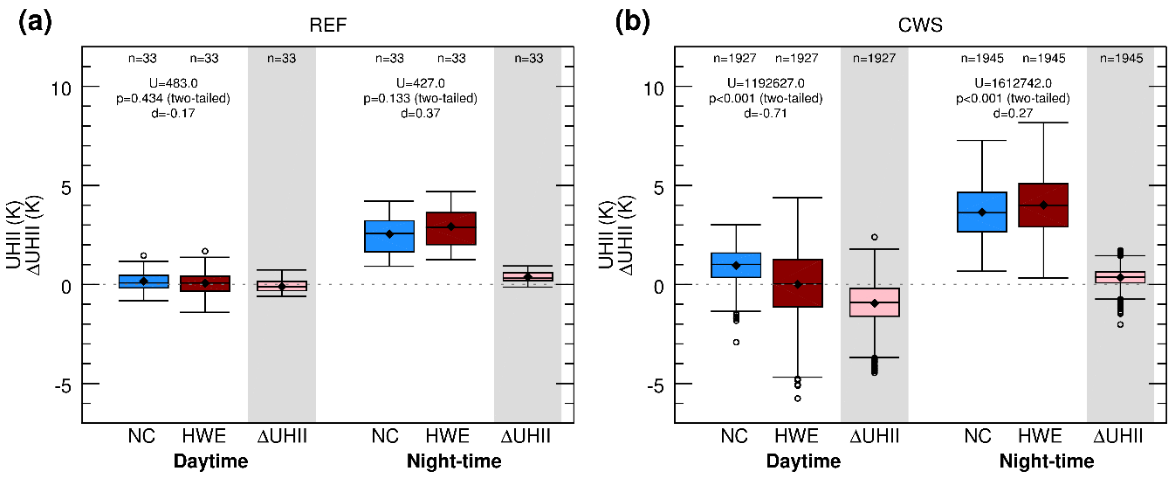
(1) Since the temporal evolution of the UHI is strongly driven by weather conditions on a day-to-day basis, it was decided to use a method that is based on a daily basis and that does not require that air temperature is above a certain threshold for a longer period of time. Common among heat wave definitions is that air temperature has to remain above a certain threshold for an extended period of time usually longer than one day. These heat wave definitions often aim at capturing and assessing the impact of prolonged heat onto certain societal systems rather that investigating physical processes in the urban atmosphere.
(2) To make the analyses as systematic as possible, the sample size for daytime and night-time conditions, as well as for urban and rural locations had to be similar. By applying a percentile-based threshold, we ensured these criteria. Limiting the study period to the months May to September ensured that hot episodes (in absolute terms) were identified when applying the percentile-based threshold.
(3) The applied threshold and identification method follow the climate extreme indices “TX90p” (daytime) and “TN90p” (night-time), developed by the CCl/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) (https://www.climdex.org/learn/indices/). These indices are widely known and applied in scientific studies to study heat extremes world-wide. However, deviating from the indices TX90p and TN90p, HWEs in this study were (a) not calculated using daily minimum or maximum temperature, and (b) not identified relative to the calendar day distribution of air temperature in the 1961 – 1990 reference period. This was done to (a) fulfil the criteria detailed in section D1, and (b) since rural and urban stations used in this study do not provide data for the 30-year reference period.

It was tested whether changing the threshold for identification to a higher percentile (95th and 98th percentile) lead to different results. Though individual values varied, overall conclusions remained the same. Only for urban hot days using the highest threshold tested (only thirteen nights analysed) mean night-time ΔUHII is slightly negative with a very small effect size for CWSs and unchanged for REFs (not shown). This is due to increased cloud cover and wind speed, and precipitation developing in the afternoon and evening, typical indication of convective precipitation events during these extremely hot days.

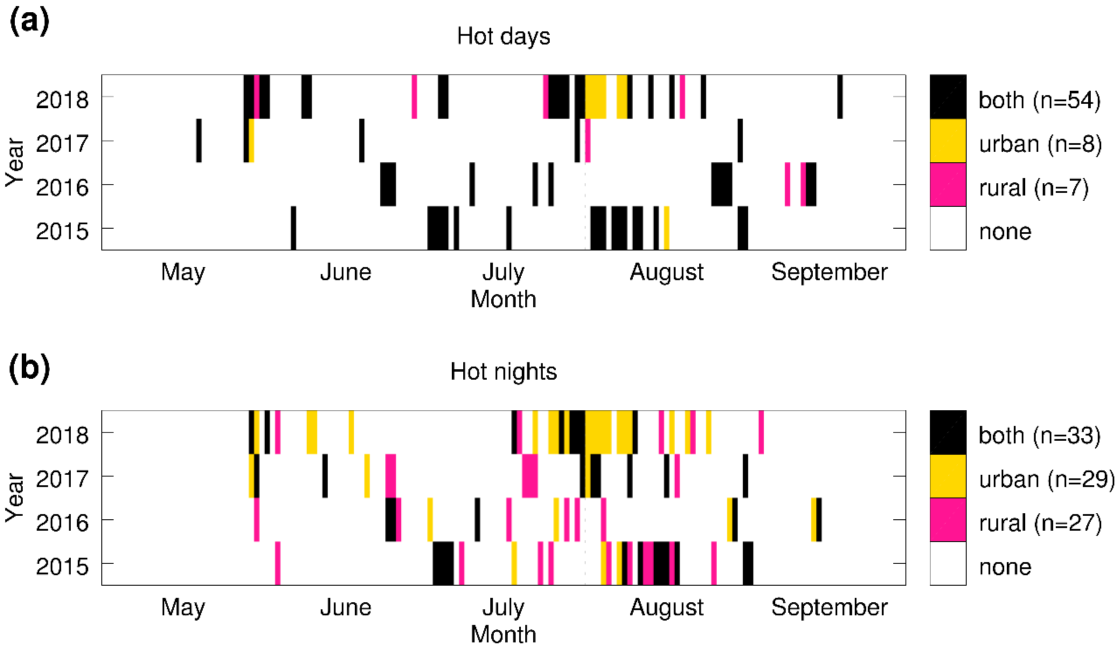
Supplementary Figures



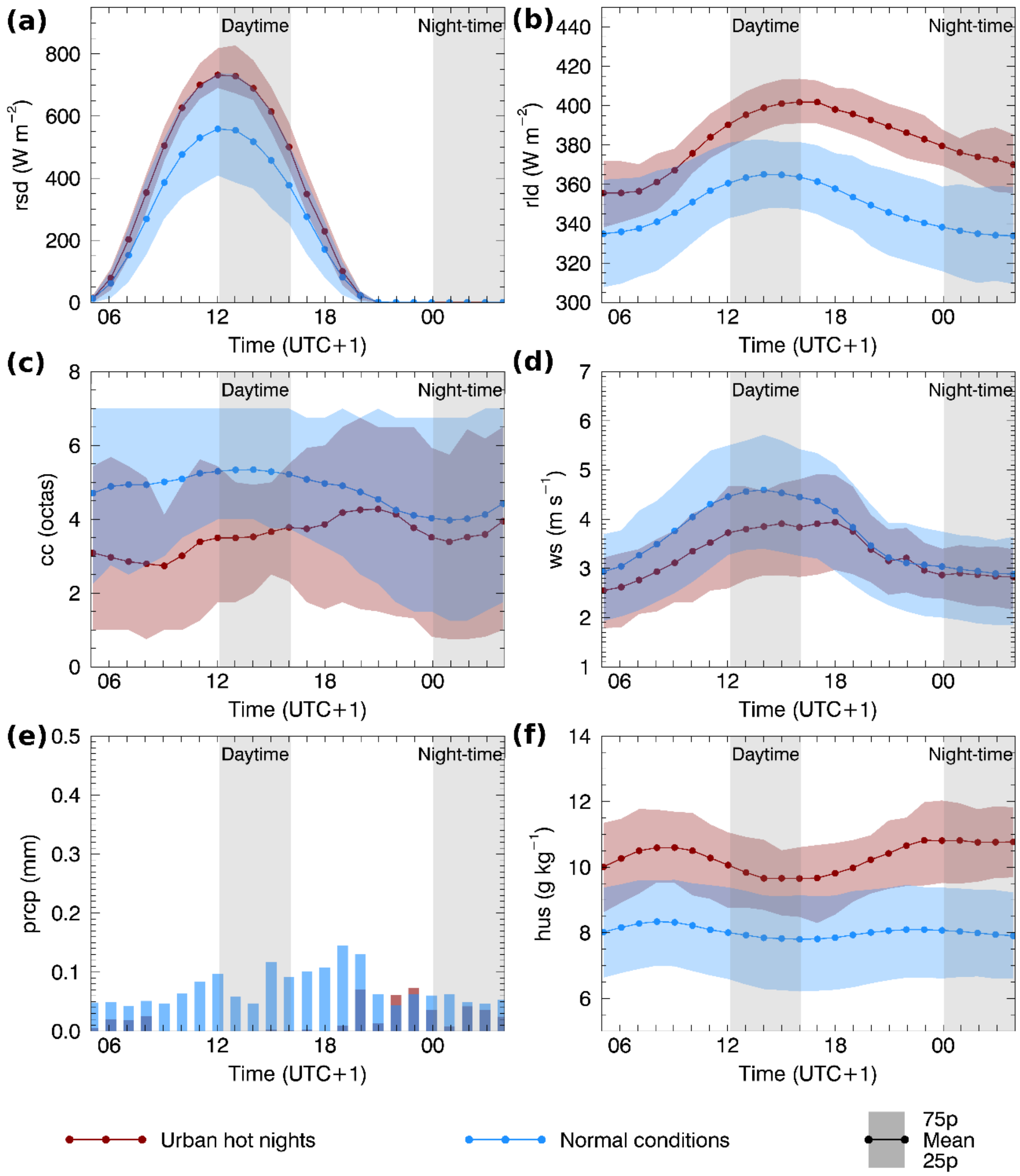
Supplementary Figure S1: Location of measurement sites to characterize weather conditions in the Berlin region. The black line displays the city border of Berlin. Background map: Global Human Settlement product "GHS S-MOD" (Pesaresi and Freire 2016). HDC: High Density Cluster, LDC: Low Density Cluster, Base: rural cells.



Supplementary Figure S2: UHII and UHII change (ΔUHII) during normal conditions and urban hot days during 2015 – 2018, May – September. UHII quantification using (a) high-quality reference stations (REFs) and (b) citizen weather stations (CWSs) during daytime (13-16 h UTC+1) and night-time (01-04 h UTC+1). Each box contains temporal mean values for each station, the Mann-Whitney-U test was applied to determine statistical significance of difference in UHII between normal conditions (NC) and hot weather episodes (HWE). Effect size of mean differences was determined using Cohen's d. The number of stations providing valid data is displayed above each box. Boxes range from 1st to 3rd quartile, median is denoted as horizontal line, mean as diamond, whiskers indicate 1.5-fold inter quartile range from upper and lower boundary, or the maximum and minimum, respectively. Values outside that range are displayed as circles.



Supplementary Figure S3: Occurrences of (a) hot days and (b) hot nights. The colour indicates whether a hot day/night was identified exclusively at urban or rural locations, or at both. The number of each case (n) is displayed next to the colour bars.



Supplementary Figure S4: Weather conditions during urban hot nights and normal conditions during 2015 – 2018, May – September, (a) downwelling shortwave radiation (rsd), (b) downwelling longwave radiation (rld), (c) cloud cover fraction (cc), (d) wind speed (ws), (e) precipitation (prcp), (f) specific humidity (hus). Percentiles for shading correspond to the respective probability distribution function during hot days and normal conditions. Measurement data from seven sites used (cf. section 2.2, Supplementary Figure S1, Supplementary Table S2), averaged across available sites.

Supplementary Tables

Supplementary Table S1: Location and station information of high-quality reference stations used in UHII analyses. Operator: DWD – German Meteorological Service, FUB – Freie Universität Berlin, TUB – Technische Universität Berlin. LCZ – Local Climate Zone (Stewart and Oke 2012). Data availability refers to the percentage of hourly data for the months May – September in 2015 – 2018. All presented sites are located in High Density Cluster (HDC) of Global Human Settlement product "GHS S-MOD" (Pesaresi and Freire 2016), except rural reference sites Berlin-Kaniswall and dahlemerfeld, located in base/rural grid cells (marked with asterisk *).

Site (operator)	Longitude (° E)	Latitude (° N)	Altitude SRTM (m above mean sea level)	LCZ (mapped as in Fenner et al 2017)	Measurement height (m above ground level)	Setup	Date start	Date end	Data availability (%)
albrecht (TUB)	13.348607	52.444594	42	6	2.0	1	01 May 2015	30 Sep 2018	99.4
bamberger (TUB)	13.337552	52.496494	47	2	2.5	1	01 May 2015	30 Sep 2018	98.0
Berlin-Alexanderplatz (DWD)	13.405400	52.519798	48	2	2.0	2	01 May 2015	30 Sep 2018	96.7
Berlin-Buch (DWD)	13.502200	52.630900	61	6	2.0	2	01 May 2015	30 Sep 2018	99.8
Berlin-Dahlem (DWD)	13.301700	52.453700	52	6	2.0	2	01 May 2015	30 Sep 2018	100.0
Berlin-Kaniswall (DWD) *	13.730900	52.404000	33	B	2.0	2	01 May 2015	30 Sep 2018	99.5
Berlin-Marzahn (DWD)	13.559800	52.544700	60	4	2.0	2	01 May 2015	30 Sep 2018	99.8
Berlin-Schoenefeld (DWD)	13.530600	52.380700	43	D	2.0	2	01 May 2015	30 Sep 2018	100.0
Berlin-Tegel (DWD)	13.308800	52.564400	31	D	2.0	2	01 May 2015	30 Sep 2018	100.0
Berlin-Tempelhof (DWD)	13.402100	52.467500	45	D	2.0	2	01 May 2015	30 Sep 2018	98.9
biesdorf (FUB)	13.550515	52.519089	55	6	2.0	3	01 May 2017	30 Sep 2018	50.0
buckower (FUB)	13.387509	52.409286	46	8	2.0	3	01 May 2017	30 Sep 2018	50.0
dahlemerfeld (TUB) *	13.225339	52.477623	54	B	2.0	1	01 May 2017	30 Sep 2018	98.6
dessauer (TUB)	13.378300	52.504670	38	2	3.5	1	01 May 2015	30 Sep 2018	86.8
fasanen (FUB)	13.333798	52.511238	34	2	2.0	4	01 May 2015	30 Sep 2017	73.3
fichtenberg (FUB)	13.310109	52.457924	71	6	2.0	5	01 May 2015	30 Sep 2018	97.7

galvani (FUB)	13.317342	52.519638	34	2	2.0	3	01 May 2017	30 Sep 2018	48.9
jagow (FUB)	13.333493	52.522907	39	2	2.0	6	01 May 2017	30 Sep 2018	48.8
landsberger (FUB)	13.491102	52.533649	57	4	2.0	3	01 May 2017	30 Sep 2018	50.0
martinhoffm (FUB)	13.456027	52.494888	37	4	2.0	3	01 May 2017	30 Sep 2018	50.0
marzahnwuhle (FUB)	13.585976	52.547962	47	4	2.0	6	01 May 2015	30 Sep 2018	92.5
montan (FUB)	13.354542	52.579922	44	8	2.0	3	01 May 2017	30 Sep 2018	50.0
motard (FUB)	13.262133	52.534580	35	8	2.0	3	01 May 2017	30 Sep 2018	50.0
petit (FUB)	13.414712	52.605988	49	6	2.0	3	01 May 2017	30 Sep 2018	50.0
pichelsdorf (FUB)	13.196944	52.507870	31	G	2.0	6	01 May 2015	30 Sep 2018	99.2
potsdamneuga (TUB)	13.063573	52.411510	36	6	2.0	7	01 May 2016	30 Sep 2018	73.8
rothenburg (TUB)	13.315827	52.457232	52	6	2.0	1	01 May 2015	30 Sep 2018	98.8
schiller (FUB)	13.320117	52.510925	41	2	2.0	3	01 May 2017	30 Sep 2018	50.0
schlosscharl (TUB)	13.294496	52.521343	34	6	2.0	7	01 May 2016	30 Sep 2018	71.8
spandauer (TUB)	13.158442	52.536388	30	5	2.0	1	01 May 2015	30 Sep 2018	99.4
swinemuender (TUB)	13.396834	52.543095	45	5	2.0	1	03 Jun 2015	30 Sep 2018	94.0
tiergarten (TUB)	13.363593	52.514492	36	A	2.0	1	01 May 2015	30 Sep 2018	100.0
waldschule (FUB)	13.256679	52.502827	56	6	2.0	3	01 May 2017	30 Sep 2018	50.0
zerpensch (FUB)	13.371320	52.605087	50	8	2.0	3	01 May 2017	30 Sep 2018	50.0
zoo (FUB)	13.344800	52.510349	33	4	2.0	3	01 May 2017	30 Sep 2018	49.1

1: Campbell Scientific CS215, white radiation shield (actively ventilated during sunlit periods, otherwise naturally ventilated), ±0.4 K (5 – +40 °C); 2: Eigenbrodt LTS 2000; white radiation shield (actively ventilated), ±0.2 K (-30 – +40 °C); 3: Rotronic HC2-S, white radiation shield (naturally ventilated), ±0.1 K (-40 – +60 °C); 4: Lambrecht Pt-100, stainless steel radiation shield (naturally ventilated), ±0.1 K (-30 – +50 °C); 5: Thies Hygro-Thermo Transmitter compact, ±0.1 K (-30 – +70 °C); 6: Thies Pt-100, white radiation shield (naturally ventilated), ±0.1 K (-30 – +50 °C); 7: Vaisala WXT536, white radiation shield (naturally ventilated), ±0.3 K (-52 – +60 °C)

Supplementary Table S2: Location of measurement sites and available variables used to characterise weather conditions in the Berlin region. Operator: DWD – German Meteorological Service, TUB: Technische Universität Berlin. cc – cloud cover fraction, hus – specific humidity, prcp – precipitation, rld – downwelling longwave radiation, rsd – downwelling shortwave radiation, ws – wind speed.

Site (operator)	Longitude (° E)	Latitude (° N)	Variable
Berlin-Dahlem (DWD)	13.3017	52.4537	cc, hus, prcp
Berlin-Schoenefeld (DWD)	13.5306	52.3807	cc, hus, prcp, ws
Berlin-Tegel (DWD)	13.3088	52.5644	cc, hus, prcp, ws
Berlin-Tempelhof (DWD)	13.4021	52.4675	hus, prcp, ws
Potsdam (DWD)	13.0622	52.3813	cc, hus, prcp, rld, rsd, ws
tumainroof (TUB)	13.3279	52.5123	rld, rsd
wiener (TUB)	13.4292	52.4987	rld, rsd

Supplementary References

Fenner D, Meier F, Bechtel B, Otto M and Scherer D 2017 Intra and inter 'local climate zone' variability of air temperature as observed by crowdsourced citizen weather stations in Berlin, Germany *Meteorol. Z.* **26** 525-547. DOI: 10.1127/metz/2017/0861

Fenner D, Meier F, Scherer D and Polze A 2014 Spatial and temporal air temperature variability in Berlin, Germany, during the years 2001-2010 *Urban Clim.* **10** 308-331. DOI: 10.1016/j.uclim.2014.02.004

Pesaresi M and Freire S 2016 GHS-SMOD R2016A - GHS Settlement grid, following the REGIO model 2014 in application to GHSL Landsat and CIESIN GPW v4-multitemporal (1975-1990-2000-2015). European Commission, Joint Research Centre (JRC), GHS S-MOD, PID: http://data.europa.eu/89h/jrc-ghsl-ghs_smod_pop_globe_r2016a

Stewart I D and Oke T R 2012 Local climate zones for urban temperature studies *Bull. Amer. Meteor. Soc.* **93** 1879-1900. DOI: 10.1175/BAMS-D-11-00019.1