Received: 22 June 2023 | Revised: 11 November 2023 | Accepted: 11 December 2023

DOI: 10.1002/gdj3.237

DATA ARTICLE

Geoscience Data Journal RMetS WILEY

High-resolution dataset of nocturnal air temperatures in Bern, Switzerland (2007–2022)

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Funding information
FAIRNESS (FAIR NEtwork of micrometeorological measurements), Grant/Award Number: CA20108; University of Bern Oeschger Centre for Climate Change Research

Abstract

To prepare for a hotter future, information on intra-urban temperature distributions is crucial for cities worldwide. In recent years, different methods to compute high-resolution temperature datasets have been developed. Such datasets commonly originate from downscaling techniques, which are applied to enhance the spatial resolution of existing data. In this study, we present an approach based on a fine-scaled low-cost urban temperature measurement network and a formerly developed land use regression approach. The dataset covers mean nocturnal temperatures of 16 summers (2007–2022) of a medium-sized urban area with adapted land cover data for each year. It has a high spatial (50 m) and temporal (daily) resolution and performs well in validation (RMSEs of 0.70 and 0.69 K and mean biases of +0.41 and −0.19 K for two validation years). The dataset can be used to examine very detailed statistics in space and time, such as first heatwave per year, cumulative heat risks or inter-annual variability. Here, we evaluate the dataset with two application cases regarding urban planning and heat risk assessment, which are of high interest for both researchers and practitioners. Due to potential biases of the low-cost measurement devices during daytime, the dataset is currently limited to night-time temperatures. With minor adaptions, the presented approach is transferable to cities worldwide in order to set a basis for researchers, city administrations and private stakeholders to address their heat mitigation and adaptation strategies.

KEYWORDS

daily temperature fields, land use regression, low-cost air temperature measurement network, urban heat island

Dataset Identifier: https://doi.org/10.48620/316

Creator: Moritz Burger, Moritz Gubler, Stefan Brönnimann

Title: High-resolution dataset of night-time temperatures in Bern (2007–2022)

Publisher: BORIS Portal

Publication year: 2023

Version: 1

1 | INTRODUCTION

Global surface temperatures over land have increased more than 1.5°C since the end of the 19th century, which lead to an aggravation of hot extremes in almost all regions of the globe since the 1950s (IPCC, 2021). This change in mean and extreme temperatures particularly affects the population of densely built-up areas, as they have to cope with even higher temperatures caused by the urban heat island (UHI) effect (Oke et al., 2017). City administrations thus need to address the consequences of the continuing global warming at local scales (He et al., 2020). To do so, detailed information about the intra-urban spatial variability of air temperatures is key to plan and monitor adequate adaptation measures and strategies (Köllner et al., 2017).

Scientific efforts to model fine-scaled temperature variabilities and to provide high-resolution datasets have augmented in recent years. One main approach thereby is dynamical–statistical downscaling from coarser scaled datasets, such as ERA5-Land (Muñoz-Sabater et al., 2021) or the UERRA European reanalysis (Schimanke et al., 2020). The final products include urban climate data at 100 m resolution (Hooyberghs et al., 2019) or indicators of heat with a resolution of 1 km^2 for various cities in Europe (Urban SIS, 2018). Alternative approaches include the use of satellite-based land surface temperature (LST) data, such as MODIS and Landsat imagery (Zhou et al., 2019). Although the resolution in time and space (up to 30 m for Landsat) of the remote sensing products is promising, land surface UHIs differ substantially in shape and characteristic compared to air temperature UHIs (further referred as UHIs; Parlow et al., 2014).

The advantages of downscaling and remote sensing approaches are the existence and the accessibility of the input data and the lower costs compared to measurement campaigns (Muller et al., 2013). With such datasets, current (and future) UHI patterns of cities can be investigated, mostly analysing seasonal or annual averages (i.e. Andrade et al., 2023; Chakraborty & Lee, 2019). However, variabilities within summers (caused by meteorology) or changes in land use between different summers are usually not investigated (Andrade et al., 2023). Another limitation is the dependency on the input data, that is, in terms of spatial or temporal resolution or insufficient representativeness of the sparse validation sites (Mussetti et al., 2020).

In recent years, several urban climate networks focussing on fine-scaled temperature variations have been established, that is in Tainan (Chen et al., 2019), Birmingham (Chapman et al., 2015), Rennes (Foissard et al., 2019) or Bern (Gubler et al., 2021). Such networks offer the possibility of analysing urban temperature variabilities with novel approaches. One cost-effective and promising method is land use regression (LUR) modelling (Hoek et al., 2008), which has already been successfully applied in different cities around the world, such as in Hongkong (Shi et al., 2018), Rennes (Foissard et al., 2019), Houston (Zhou et al., 2014) or Bern (Burger et al., 2021; Burger, Gubler, & Brönnimann, 2022).

For Bern, a LUR model aiming to estimate the urban temperature distribution of every night of a summer was developed (Burger, Gubler, & Brönnimann, 2022). For the study presented here, we implemented that model and computed a high-resolution urban temperature dataset with annually adjusted land use data, which enables fine-scaled statistical investigations in space and time and extends the potential of current datasets. The outcome is a dataset ranging from 2007 to 2022 containing mean nighttime temperatures at a spatial resolution of 50 m for every night of a summer period (June–August). The aim of this study was to explain the computation of the dataset and to evaluate it with application cases. Furthermore, we want to assess the potential of transferability of the approach to other cities and discuss limitations and future developments of such datasets and the technique in general.

2 | METHODS

2.1 | Study area

The modelled area covers 122.5 km^2 (11.45 km east to west/10.7 km north to south) over the capital of Switzerland, including the densely populated city of Bern and its adjacent agglomeration with a population of approximately 250,000 in the year 2021 (BFS, 2022; Figure 1). The local topography is characterized by several hills and valleys and the River Aare, which crosses the study area from southeast to northwest. The elevation ranges from 481 (basin of the Aare River in the northwest) to 937 m.a.s.l. (pre-alpine hillslopes in the South; Figure 1). Summers (June–August) in Bern are usually warm humid (Kottek et al., 2006) with temperatures reaching 18°C on average and a total precipitation amount of 322 mm for the reference period 1991–2020 (MeteoSwiss, 2021a). Two professional measurement stations exist in the city of Bern: The official measurement station (operated by the Federal Office of Meteorology and Climatology, MeteoSwiss) is located about 5 km north of the city centre in Zollikofen (hereafter ZOLL, Figure 1) in a rural, agricultural zone in a slightly concave topographical position (local climate zone [LCZ] D, Stewart & Oke, 2012). The second station (AFU) is located in the suburban (LCZ 5) eastern part of the city and is maintained by the city administration for protection on the environment (Gubler et al., 2021; Figure 1).

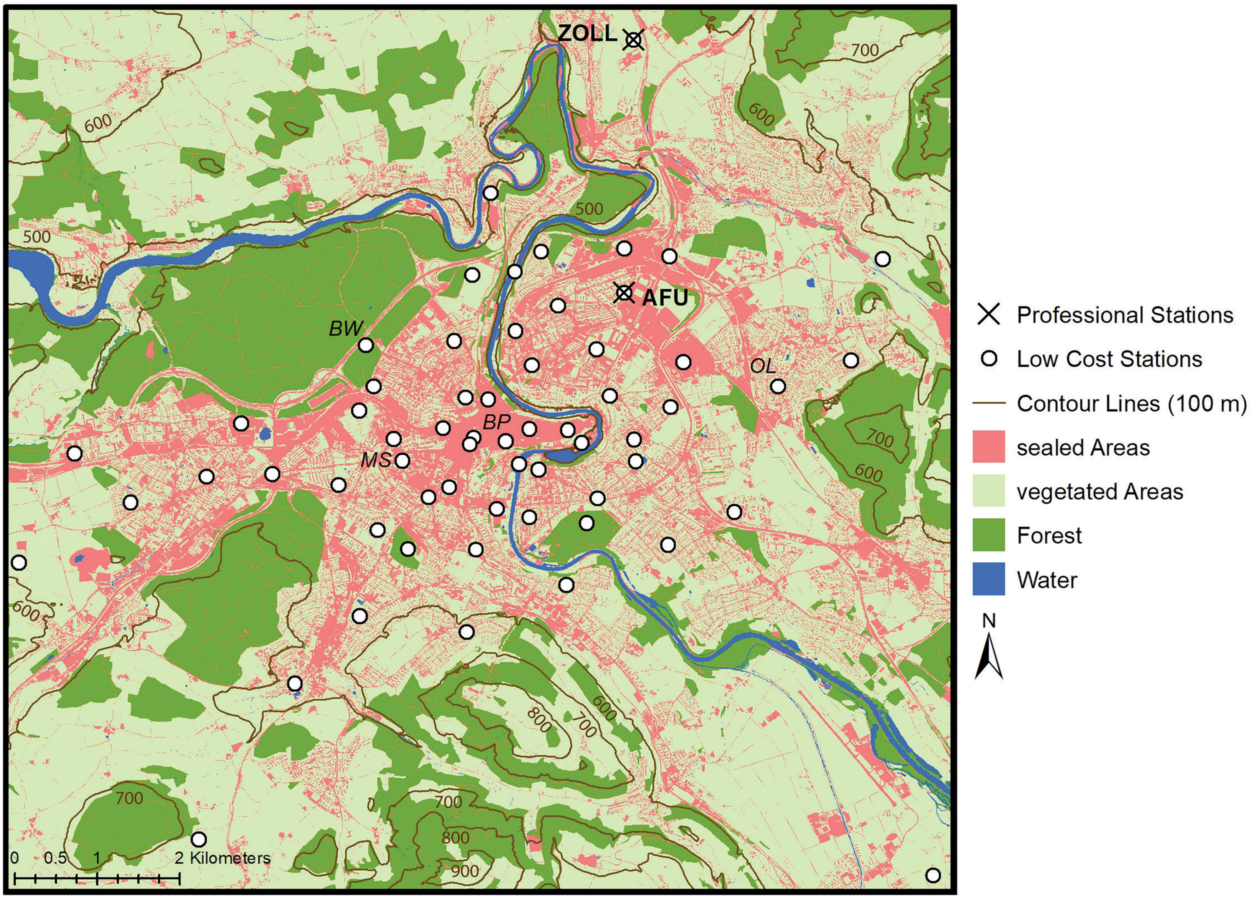

FIGURE 1 Overview on the study area. The colours indicate the land cover, the contour lines the topography. The 61 low-cost measurement stations used for the calibration of the model (white circles) as well as the two professional stations of Bern (black crosses) with their abbreviations are shown. Four low-cost measurement stations, which are analysed in the validation Section (3.2), are additionally marked (BW, MS, BP and OL). A picture of these four stations is furthermore provided in the supplementary material (Figure S2).

TABLE 1 Selected model structure and final model for the computation of the dataset (adapted from Burger, Gubler, & Brönnimann, 2022).

Model structure
$T_{Sji} - T_{Zi} = \left(\sum_{t=1}^{n} a_t \times \mathrm{M}_{ti}\right) + \left(\sum_{s=1}^{m} b_s \times L_{sj}\right) + \left(\sum_{t=1}^{n} \sum_{s=1}^{m} c_{ts} \times \left(M_{ti} \times L_{sj}\right)\right)$
Final model
(0.007 × G – 0.49 × SWI – 1.0 × NR) + (0.6 + 1.01 × BUL – 0.72 × FO – 0.29 × GA – 0.61 × AC – 0.03 × VH – 0.001 × AD – 0.001 × TPI) + (0.005 × (G × BUL) – 0.006 × (G × FO) – 0.002 × (G × GA) – 0.01 × (G × AC) – 0.0001 × (G × VH) + 0.00005 × (G × AD) + 0.00006 × (G × TPI) – 0.48 × (SWI × BUL) + 0.37 × (SWI × FO) + 0.35 × (SWI × AC) – 0.008 (SWI × VH) – 0.001 (SWI × AD) + 1.24 × (NR × FO) + 0.33 (NR × GA) + 1.63 × (NR × AC) + 0.02 × (NR × VH) - 0.006 (NR × AD) – 0.006 (NR × TPI))

Note: T_{Sij} represents the observed air temperature at station *j* of the urban temperature network for the night *i*. T_Z represents the observed night-time air temperature at the reference station ZOLL. *M* denotes the temporal and *L* the spatial variables of which *n* and m exist. a_t represents the slopes of the temporal, b_s the slopes of the spatial and c_{ts} the slopes of the combined predictors. The abbreviations of the final model variables can be found in Table 2.

2.2 | Applied LUR modelling

2.2.1 | Model structure

Land use regression modelling is a geostatistical method that has been applied in urban studies at first mainly in the field of air pollution modelling (Hoek et al., 2008), but that recently has been increasingly introduced into small-scale air temperature variability modelling (i.e. Burger et al., 2021; Burger, Gubler, & Brönnimann, 2022; Foissard et al., 2019; Shi et al., 2018; Zhou et al., 2014). The aim of this modelling approach was to combine (and explain) observational data with predictor variables derived from a set of different land use, topography or socio-economic variables (Hoek et al., 2008), and to estimate the mean exposure level in areas without measurement

TABLE 2 Variables used in LUR model containing their unit, data source and available period.

Variable (abbreviation)	Unit	Data source	Available period
Urban temperature measurements (explanatory variable)			
Temperature difference from ZOLL	Night-time mean (K)	Urban temperature network of Bern	2018–2022
Meteorological data (predictor variables)			
Global solar radiation (*G*)	Daily mean (Wm^{-2})	MeteoSwiss	2006–2022
Precipitation during night (NR)	yes/no	MeteoSwiss	2006–2022
Wind from South (SWI)	Night-time mean (ms^{-1})	MeteoSwiss	2006–2022
Land use data (predictor variables)			
Buildings (BUL)	% (250 m)	Cadastral survey	2007–2022
Open space garden (GA)	% (25 m)	Cadastral survey	2007–2022
Open space agriculture (AC)	% (750 m)	Cadastral survey	2007–2022
Open space forest (FO)	% (1000 m)	Cadastral survey	2007–2022
Altitude difference (AD)	m (25 m)	Swisstopo	2020
Vegetation height (VH)	m (150 m)	WSL	2013 and 2021
Topographic Position Index (TPI)	Number (500 m)	Swisstopo	2020

Note: The buffer radii (area of influence) of the spatial predictors are added in the column 'Unit'.

stations (Shi et al., 2018). In Bern, two different types of LUR models with a differing degree of complexity were computed. First, an approach to estimate the UHI effect during heatwave periods that did not incorporate meteorological variables (Burger et al., 2021). Then, a more complex approach aiming to model nocturnal urban temperatures for every night of a summer, which implied that meteorological variables were included in the modelling process (Burger, Gubler, & Brönnimann, 2022). Three different mathematical combinations of meteorological and land use variables were tested in that study, resulting that an integrative structure showed the most appropriate results (Burger, Gubler, & Brönnimann, 2022, Table 1). We therefore use that model structure to compute the dataset. In the following subchapters, the explanatory and predictor variables used in the modelling are shortly described (see Burger et al., 2021 and Burger, Gubler, & Brönnimann, 2022 for more details). To provide an overview of the entire workflow of developing the model and the dataset, a flowchart including the main steps of the former (Burger, Gubler, & Brönnimann, 2022) and the present study is provided in the supporting information (Figure S1).

2.2.2 | Urban temperature measurements

To calculate the explanatory variable in the model, measurements of the urban temperature network in the city of Bern were used. This network has been operated since 2018 and consists of 70–90 self-built, low-cost and passively ventilated measurement devices that are installed at free-standing poles at 3 m height (Figure S2). Validation with professional weather station data during summer 2018 revealed that the stations have a potential positive mean bias during daytime (06:00–22:00, CEST) of 0.61–0.93 K, while during night (22:00–06:00), no systematic offset was found (mean bias: −0.12 to 0.23 K; Gubler et al., 2021). We defined the mean night-time (22:00 to 06:00, CEST) temperature difference from the reference station ZOLL as explanatory variable in the models (Burger, Gubler, & Brönnimann, 2022, Table 2). For the calibration of the LUR model, we used 61 stations that were placed at the same location from summer 2018 to 2020 (Figure 1). Fifty-four of these stations were again installed in summer 2021 and 2022 and were used for the evaluation (Section 3.3.1).

2.2.3 | Meteorological data

As meteorological predictor variables, we used data from the professional measurement station ZOLL (Figure 1). Out of five variables tested, global radiation (*G*), winds originating from South (SWI) and night-time precipitation (NR) were identified as significant meteorological drivers of the small-scale night-time temperature variation in Bern (Burger, Gubler, & Brönnimann, 2022; Table 2).

2.2.4 | Land use data

Regarding the land use data, a total of 18 variables were tested during the modelling process of the former study,

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of which seven were selected for the final models (Burger, Gubler, & Brönnimann, 2022). For every variable, a best fitting buffer radius was calculated, estimating the area of influence of a land use variable (Table 2; Burger et al., 2021). Since the formation of cold air drainage is an important feature of the local climate in Bern (Mathys et al., 1980), four different models with varying cold air drainage variables were tested in that study. They showed, however, very similar performances (Burger, Gubler, & Brönnimann, 2022). For the computation of the dataset, we used the model with the cold air drainage variable 'Topographic position index' (TPI, Tables 1 and 2). This variable represents a comparison of the height of a pixel with the average height of the 500-m buffer around the pixel. A positive value indicates a convex (hilltop) and a negative value a concave (valley) topographical position of the pixel (Burger, Gubler, & Brönnimann, 2022).

2.3 | Compiling the dataset

The main process for compiling the dataset is to get data from a model for single nights (Burger, Gubler, & Brönnimann, 2022) to continuous data for several years, which incorporates the prevailed meteorological conditions and the land use change over time. For this computation, the availability of the input data over the entire period is required (Table 2). Concerning the meteorological data, the official reference station of Bern was displaced several times since its establishment in 1864. Within the last 50 years, it was shifted from the city centre to a southwestern location in 1978 and then to the current location in 2005 (Burger, Gubler, Brönnimann, Vicedo-Cabrera, et al., 2022). The first available complete summer series of its current location (ZOLL) is available for summer 2006.

Regarding the land use data, two out of seven variables (AD and TPI; Table 2) rely on topography and are computed with a digital elevation model of 2020 (Swisstopo (Federal Office of Topography), 2020). Since these variables are independent from land cover change, they are held constant over time. The variables BUL, GA, AC and FO are computed using the cadastral survey of the canton of Bern (Amt für Geoinformation des Kantons Bern, 2022; Table 2). The data were first published in 2006, are updated regularly and can be downloaded directly on the cantons data portal. To obtain historical data, we requested the responsible office and obtained one dataset from every year (2007–2022). One municipality published their first version of the data only in 2011. For this small municipality ('Kehrsatz'; located southeast of Bern), we used the data of 2011 also for the years 2007–2010. The last land use variable VH is obtained from the 'Vegetation height model NFI' database of the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), which contains Switzerland-wide data on vegetation height (VH; Ginzler & Hobi, 2015; Table 1). Two different datasets exist, representing the VH of the study area in 2013 and in 2021. The data of the 2013 model were used for the timespan 2007–2020, the 2021 data for the years 2021 and 2022.

Regarding the spatial resolution, we use the same grid size (50 m) as in the former study (Burger, Gubler, & Brönnimann, 2022). We again focussed on night-time means, due to the radiative bias of the daytime data (Burger, Gubler, & Brönnimann, 2022; Gubler et al., 2021). In addition, the dataset contains absolute values in °C obtained by summing the mean night-time temperature of ZOLL with the output of the model (temperature difference from ZOLL). In consideration of the data availability constraints mentioned above, we were able to conduct a dataset from 2007 to 2022 containing mean night-time temperatures with a resolution of 50 m for every night of a summer.

3 | RESULTS AND EVALUATION

3.1 | Nocturnal mean temperatures for every night in the summers of 2007–2022

Figure 2a,c shows the outputs of every night of the coldest (2014) and the hottest (2022) summer in the covered period (MeteoSwiss, 2014, 2022). Overall, the mean temperatures are estimated to be 1.4–3.7°C higher during summer 2022 than during 2014. Since summer 2022 was also much sunnier and drier than 2014, nights with strongly pronounced UHIs could more often form during 2022 (MeteoSwiss, 2014, 2022; Figure 2a,c). To get a closer look at the maps, the individual outputs of 11 July are shown in more detail (Figure 2b,d). While 11 July 2014 is estimated to be a night with practically no urban excess heat, a strong UHI is modelled for the same date in 2022 (Figure 2d).

3.2 | Temperature time series for individual locations

In addition to daily maps of the whole study area, also time series of individual locations can be retrieved from the dataset. Figure 3 shows the mean measured (green) and modelled (yellow) night-time temperatures for four locations (BP, MS, BW and OL; Figure 1; Figure S2) throughout summer 2022 as well as the recorded temperatures at the official reference station ZOLL (black). The temperatures and UHIs (difference to ZOLL) vary not only depending on the site but also from night to night.

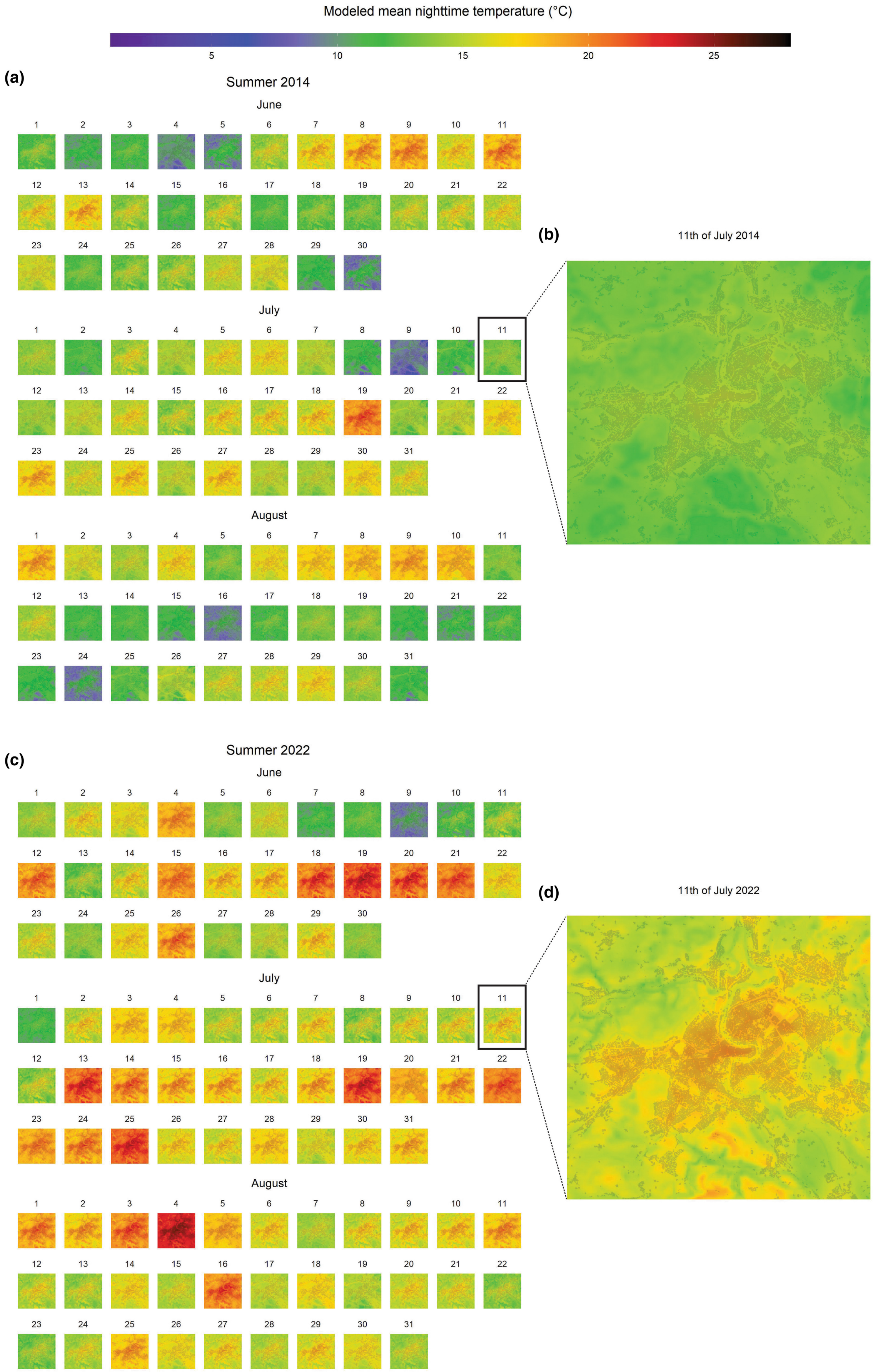

FIGURE 2 Modelled mean temperatures for the region of Bern during all the nights of the summers of 2014 (a) and 2022 (c) with the night of the 11th of July shown more in detail ((b) for 2014 and (d) for 2022).

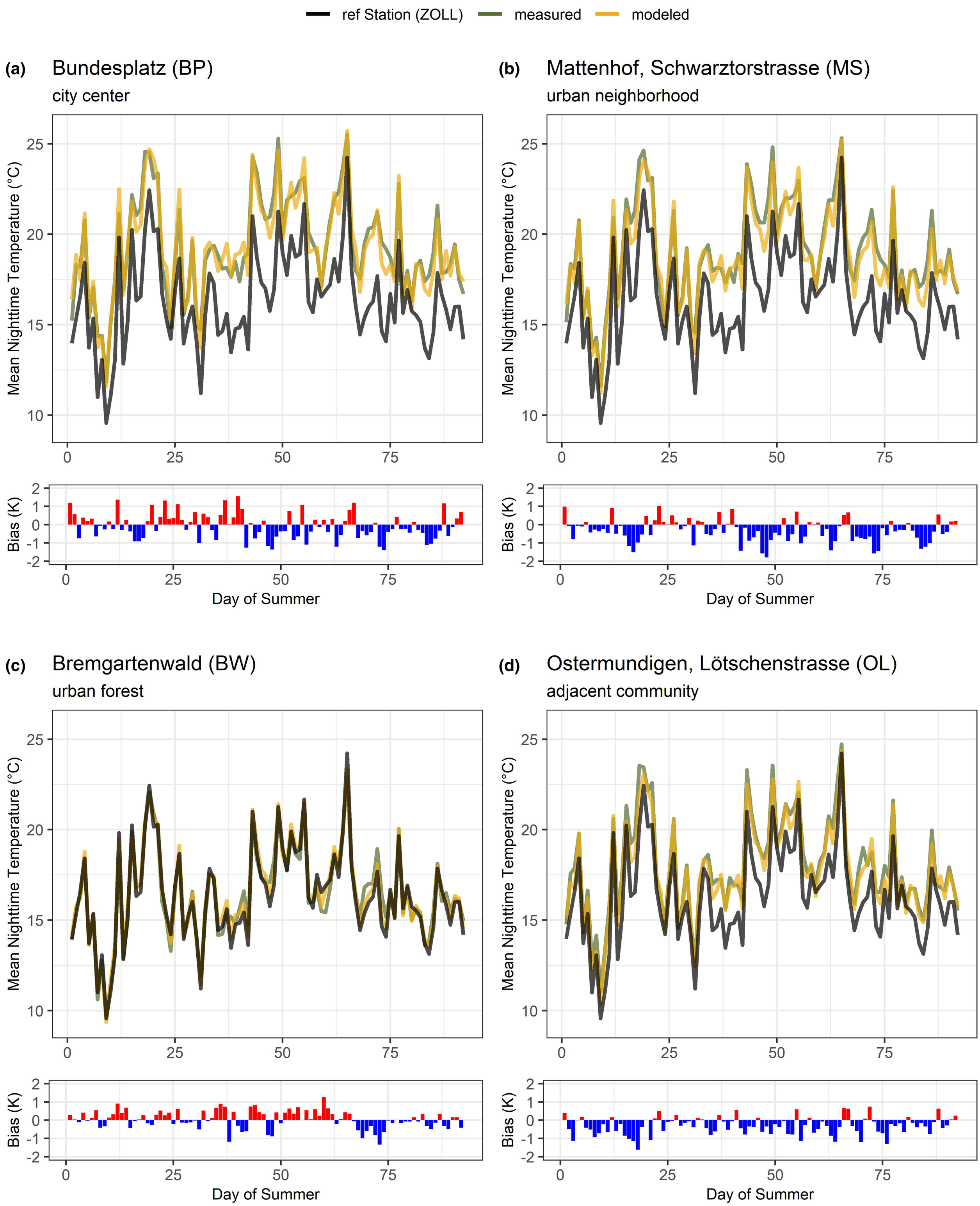

FIGURE 3 Measured (green) and modelled (yellow) mean night-time temperatures and bias of the model (modelled minus measured) during summer 2022 at four locations (a = city center, b = urban neighborhood, c = urban forest, d = adjacent community) in Bern. The black lines show the temperatures at the reference station ZOLL. Red bars show nights, which were modelled too warm, and blue bars nights, which were modelled too cold. The location of the stations are shown in Figure 1. A picture of the stations is provided in Figure S2.

The results show that even in the city centre, nights with almost no additional UHI occur (Figure 3a) and that in the urban forest, negative UHI intensities are measured and modelled during some nights (Figure 3c). The bias of the model for these four stations is usually within 1 K and never exceeds 2 K (Figure 3).

3.3 | Evaluation

3.3.1 | Comparison with station data

Since the LUR model is calibrated with data of the years 2018–2020, the additional data of the years 2021 and 2022 can be used for validation. Those summers differed substantially regarding the meteorology: 2021 was relatively cool and rainy, while 2022 was very hot and dry (MeteoSwiss, 2021b, 2022). The explained variance (R^2) for the summer 2021 was already calculated in Burger, Gubler, & Brönnimann, 2022, showing that 67% of the temperature variations of the remaining 54 calibration stations could be explained by the LUR model. For the summer 2022, an even higher value is achieved (75%; Table 3). As an additional validation approach, we compared the LUR output with professional stations data. Therefore, we analysed root mean square errors (RMSEs) and mean biases (MBs) of the remaining stations in 2021 and 2022, if either one of the professional stations (ZOLL or AFU; Figure 1) or the LUR model is chosen as a predictor for the temperature at these locations.

The analysis shows that the median of the RMSE is the lowest for both years in the LUR model and that the MB is closest to zero in 2021 and only marginally further away than AFU in 2022 (Figure 4; Table 3). The spreads of the RMSE and MB are much smaller in the LUR models than those of the station data. The RMSE and MB for the rural station ZOLL are substantially larger during the hot and dry summer 2022 than during the rainy summer 2021 (Figure 4; Table 3).

3.3.2 | Application of the dataset

In order to evaluate the implementation of the dataset in research and practice, two applications are presented in the following.

Risk of warm nights

One of the most important threats of urban heat is the negative effects on health (IPCC, 2021). Warm nights, in combination with hot days, deteriorate the recovery quality while sleeping and might thus have an impact on morbidity and mortality rates (Laaidi et al., 2012), as well as on mental health (Bundo et al., 2021). Having a fine-scale dataset on urban temperatures might thus give valuable information on the exposure to heat in a city.

For this analysis, we define the threshold for a 'warm night' (WN) as temperatures exceeding the 99th percentile of mean night-time temperatures experienced at ZOLL in the summers of 2007–2022 (22.15°C; Figure 5). We then apply this threshold to the dataset and calculate the percentage (risk) of a WN for every 50 m x 50 m pixel of the study area for the timespan 2007–2022.

The results indicate that the risk of experiencing a WN during summertime lies for many rural locations below 1% (Figure 6). For densely populated agglomeration communities or neighbourhoods in the outskirts of Bern, the calculated risk increases to 3%–5%. Even higher values are found in the northeastern as well as in the centre part of Bern with calculated risks of 7% up to 11% (Figure 6). This implies that 6–10 WN must be expected for those highly built-up regions of Bern during an average summer in the period 2007–2022.

Depicting the influence of land use change

Since the land use data are adapted for every year in the dataset, different states of land cover can be investigated with the dataset. To test this, we combine the land use data of 2007 and the meteorological data of 20 July 2022 and compare it with the outputs using land use data of

TABLE 3 Validation metrics applied to the LUR model (R^2, RMSE and MB) and station data (RMSE and MB).

Validation metric	Statistical variable	ZOLL (LCZ D) 2021	ZOLL (LCZ D) 2022	AFU (LCZ 5) 2021	AFU (LCZ 5) 2022	LUR model 2021	LUR model 2022
R^2	–	–	–	–	–	0.67	0.75
RMSE	Median	1.14 K	2.10 K	0.78 K	0.85 K	0.70 K	0.69 K
	Spread	2.06 K	3.01 K	2.80 K	4.06 K	0.84 K	1.19 K
MB	Median	−0.66 K	−1.80 K	+0.56 K	+0.17 K	+0.41 K	−0.19 K
	Spread	3.25 K	4.85 K	3.25 K	4.85 K	1.09 K	1.66 K

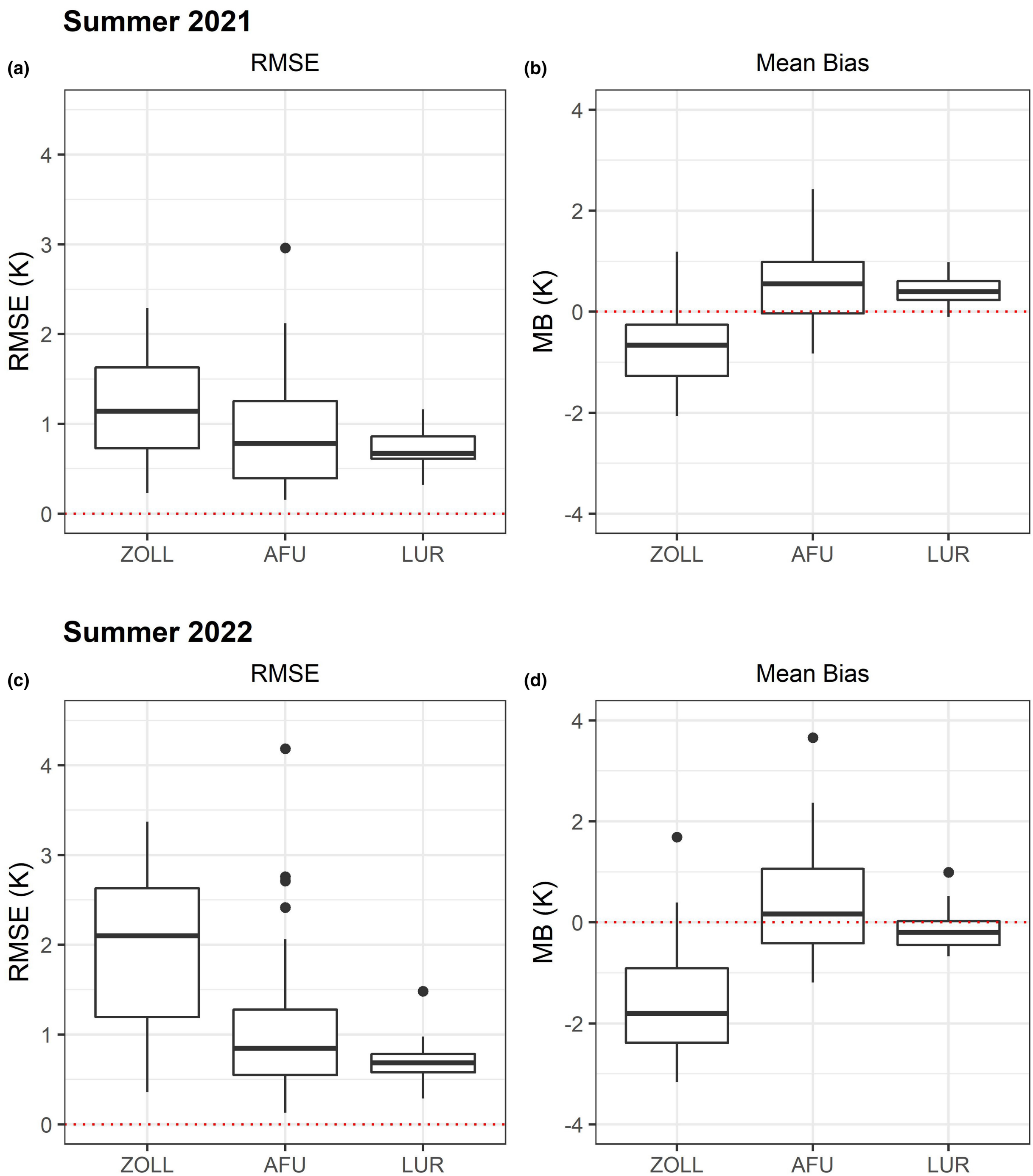

FIGURE 4 Validation metrics for the LUR model (LUR) compared with professional station data (ZOLL and AFU) for the summers 2021 (a, b) and 2022 (c, d). The boxes show the interquartile range (IQR) with the 25th (bottom) and 75th (top) percentile and the median value (black line within the box). The vertical lines refer to the minimum (bottom) and maximum (top) value of the data within $\pm 1.5 \times$ IQR. The black dots denote outliers. The red dotted lines mark the 0 K lines, which implies for both validations metrics the best possible result. The location of the professional stations can be found in Figure 1.

2022. During the night of 20 July 2022, good meteorological conditions to form urban heat were prevailed.

The comparison reveals that in many locations, land use change has caused additional warming in Bern in the last 16 years (Figure 7; Figure S3). Most of the warming is induced by the growth of the city and its adjacent agglomeration in the outer boundaries of the study area. A study analysing a western district of Bern (Bern-Brünnen, Figure 7) found out that under meteorologically favourable urban heat conditions, night-time temperatures increased by about 1 K in addition to overall warming due to the local land use change from agricultural land to a residential

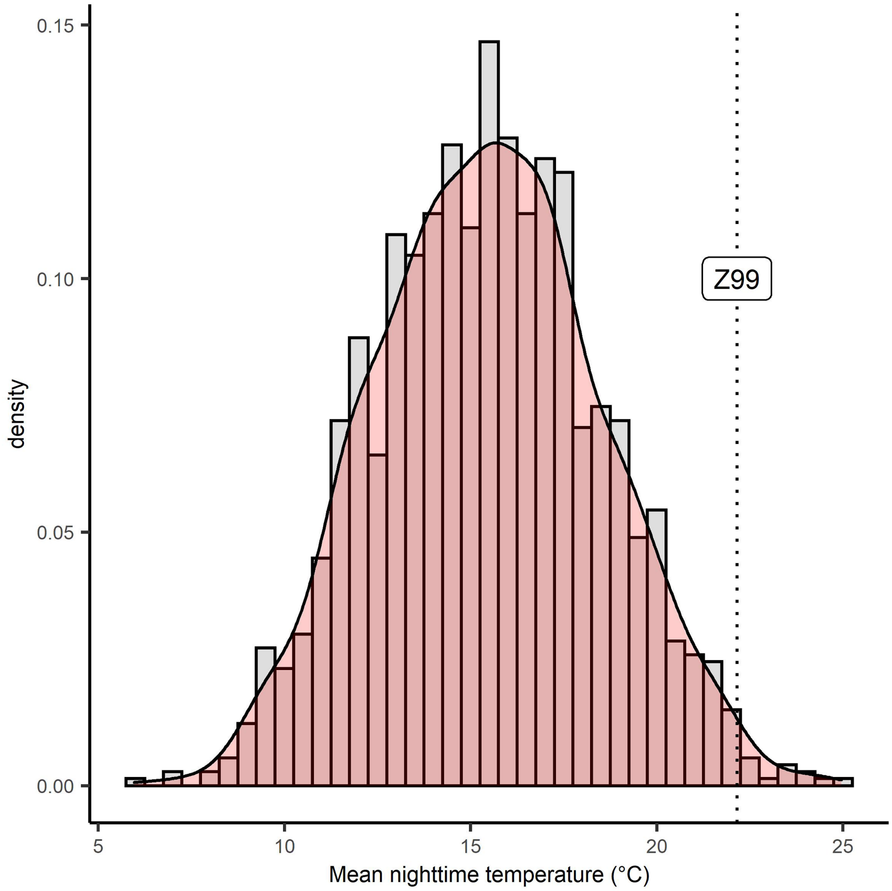

FIGURE 5 Distribution (bars) and density function (red area) of the mean summer night-time temperatures at ZOLL from 2007 to 2022. The vertical dotted line represents the 99th quartile of the distribution, which is 22.15°C.

area (Burger, Gubler, Brönnimann, Vicedo-Cabrera, et al., 2022). The outputs of the dataset show a similar warming signal for Bern-Brünnen in the last 16 years (Figure 7). Large differences are furthermore estimated in the forest, where some areas were lumbered and others restocked (Figure 7; Figure S3). These features can however only hardly be validated as the existing measurement stations are located at the edges of the forests, which have not been affected by lumbering recently (Figure 1). Most of the other small-scale cooling areas arise from land use change from sealed or agricultural to garden areas (Table 2). A particular cooling signal driven by such land use change is the urban park 'Liebefeld', which was built in 2009. However, since some of the previously agricultural land was changed to residential area, a warming signal surrounds the cooling feature of the urban park (Figure 7).

4 | DATASET LOCATION AND FORMAT

The dataset can be downloaded with an open access licence (CC-BY 4.0) from the Bern Open Repository and Information System (BORIS) Portal (https://doi.org/10.48620/316). The data are provided in a geoTIFF format (.tif) with the coordinate system WGS_84. For every year, a folder with 92 files exists. The files are named 'NightTempBern_xx_yy', in which 'xx' indicates the year (07=2007) and 'yy' the day of the summer (1=1 June; 92=31 August).

5 | DISCUSSION

5.1 | Potential of the presented dataset

With the presented dataset, it is possible to investigate the fine-scaled temperature variability of a medium-sized urban region with a high degree of confidence. The evaluation with data from 54 urban measurement stations showed that the errors of the LUR model are smaller than if data from single official stations are used: For summer 2022, LUR model outputs showed a median RMSE of 0.69 K compared to 0.85 K (AFU) and 2.10 K (ZOLL) and a spread of 1.19 K compared to 4.06 K (AFU) and 3.01 K (ZOLL). This implicates that the uncertainties about the temperatures at a certain location are distinctly smaller if the LUR model

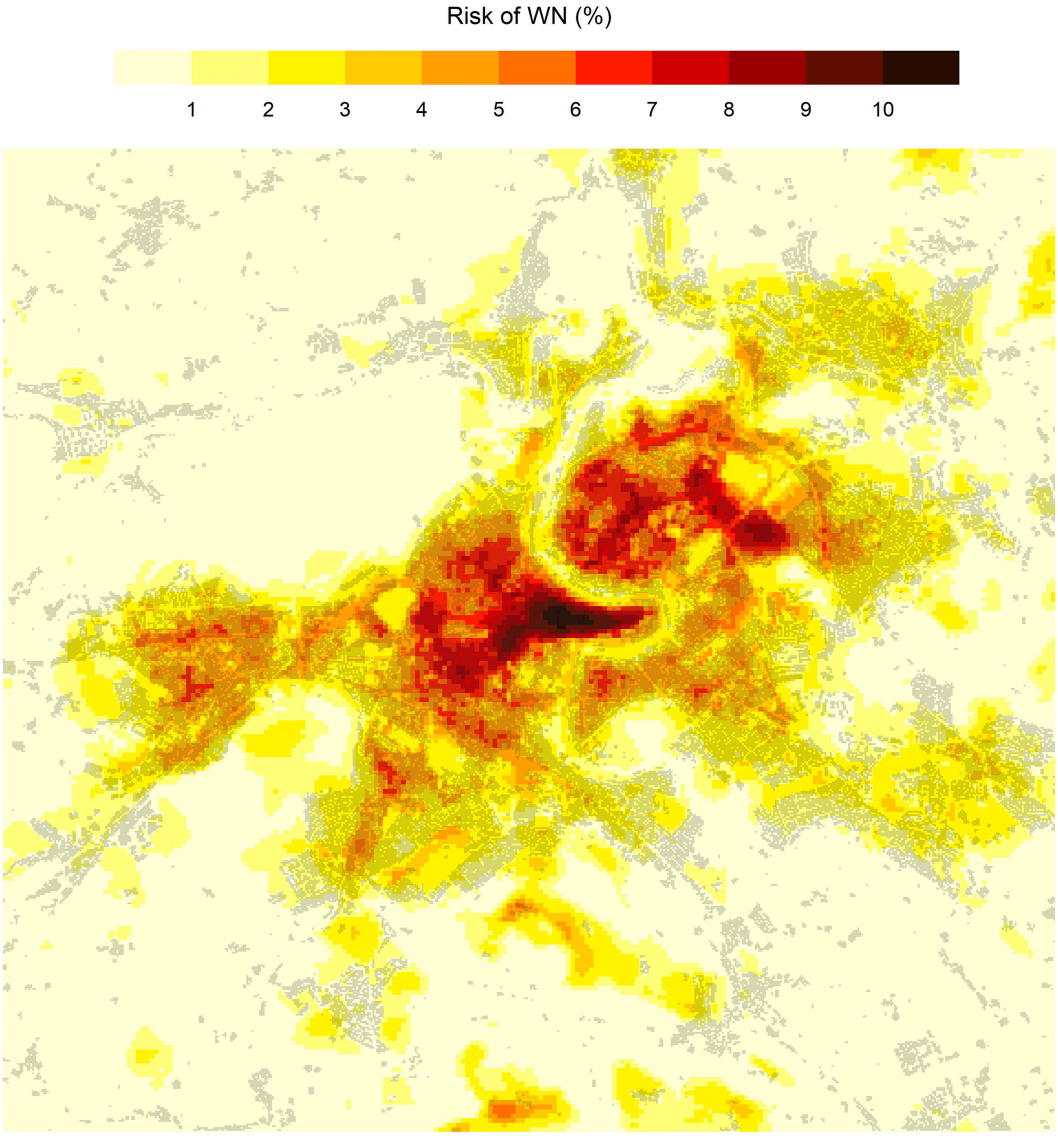

FIGURE 6 Risk of warm nights in Bern during summers 2007–2022.

output is taken as a predictor instead of data of an official measurement station. The large differences of the spreads furthermore indicate that very different urban conditions can be reproduced using this modelling approach, which is not possible when using data from single stations (Figures 3 and 4; Table 3). The lower MB (spread) values additionally show that systematic biases (over- or underestimations of locations) are clearly reduced when using the model outputs. Finally, the two very different summers have been modelled with a similar performance in the LUR model, while particularly ZOLL shows larger bias during an unusual hot summer, due to the differences getting larger between the rural location of ZOLL and the urban stations (Figure 4; Table 3). These findings support the already established assumption that the heterogeneity of a city can be hardly reproduced and recorded only with the differentiation in 'urban' and 'rural' stations (Stewart & Oke, 2012).

The dataset was then evaluated with two applications, showing its great value and usability, especially for local city administrations and decision-makers. Spatial statistics, such as the 'risk of warm nights' (Figure 6), could also be conducted for more detailed research questions, such as: 'At which date is the first WN per year on average experienced at a certain location?' or 'what is the longest period of successively WNs at a certain location?' Such detailed statistics in time and space would not be possible with coarser datasets, retrieved with current downscaling or remote sensing methods. Since the input land use data used for the modelling are furthermore very precise (resolution ≤1 m; Burger, Gubler, & Brönnimann, 2022), the spatial resolution of the dataset could even be enhanced to 1 m, which might be of interest if land use change in a certain area is analysed more in detail than shown here (Figure 7). Another advantage of the LUR method is that

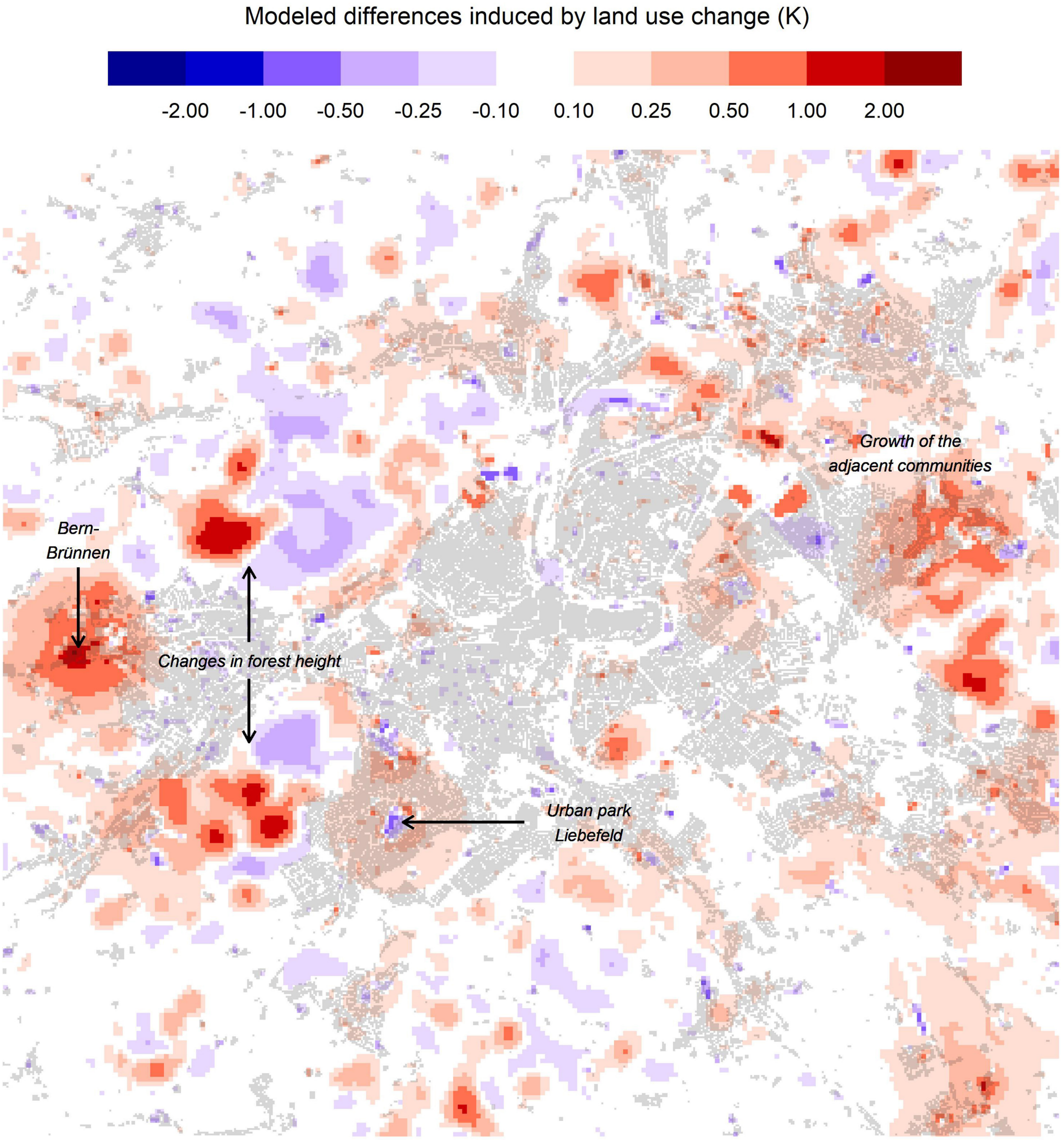

FIGURE 7 Modelled differences in temperatures due to land use change from 2007 to 2022 at 20 July 2022. Red areas mark regions where the land use change between 2007 and 2022 has caused warming, blue areas mark regions where land use change has caused cooling at the example day in the model.

the locations of the measurement stations and land use data used for modelling can be selected by the project leaders. This means that specific locations can be chosen for validation and that depending on the purpose, different land use datasets (with different spatial resolutions) can be selected, which makes this approach more flexible than downscaling or remote sensing approaches.

5.2 | Limitations and further developments

It is important to mention that several applications are not possible with the current dataset. The most obvious limitation is the lacking daytime data. Although the UHI is less pronounced during the day, data on daytime temperatures would be important to provide a more detailed understanding of small-scale temperature variabilities in a city. Due to the bias of the low-cost sensors (chapter 2.2.2), a LUR model of the daytime situation would have been erroneously calibrated. This issue could be solved by using expensive professional temperature stations. In Bern, however, a new series of low-cost devices with an integrated ventilator are currently tested. Since the radiation error of the stations can be modelled reasonably well, parallel measurements of the two generations of low-cost devices will potentially enable a retrospective debiasing of the daytime data in the future (Gubler et al., 2021).

Another limitation is the rather short time span of 16 years back to the year 2007. Since the meteorological series of ZOLL only started in 2006, in-depth data homogenization efforts would be needed to use data before 2006. Since the former station was located in the southwest of the topographically complex city, especially the homogenization of the wind direction could be challenging. Another possibility might be the use of reanalysis data, such as ERA 5, as meteorological input data. Both approaches might be tested in the future.

Land use data before 2007 are also lacking. Land use change importantly influences the night-time temperatures (Figure 7) and can thus not be neglected. Since the original land cover data from the cadastral survey are reduced from a set with 25 different attributes to a database with only six variables (Burger et al., 2021; Table 2), it might be possible to retrieve such a database from old digitized and georeferenced maps or satellite images. The estimation of the VH before 2007 could, however, be an even more complex task.

Finally, it is important to be aware of the computation of the dataset, which is a static, geostatistical approach. Dynamic patterns, such as cold air streams or intra-urban air flows at sub-local scales cannot be included in the model. This leads to the limitation that some indicators such as the orientation of buildings are not reproduced.

5.3 | Transfer to other cities

An important topic is the potential of transferring the method to other cities. In Switzerland, the same land use data exist for all (urban) areas. For the transfer to other European cities, the urban atlas data could be used. This is a land use database which has been compiled for 788 European urban areas with more than 50,000 inhabitants (EEA (European Environment Agency), 2021). Although the data are not at the same spatial resolution as the data used for the compilation of the presented dataset, it would be possible to extract very similar spatial variables. If that data and multiple local meteorological reference stations could be used, the modelling approach seems transferable to urban areas all over Europe. On a global scale, data from WUDAPT (world urban database and access portal tools, https://www.wudapt.org/) and from USGS Earth Explorer (https://earthexplorer.usgs.gov/) could be used. WUDAPT contains freely accessible information on urban data (Ching et al., 2018) and includes a tool to derive standardized LCZ maps for all cities around the world (Demuzere et al., 2021). A combination of such urban data with vegetation (e.g. NDVI map derived from satellite data, Grover & Singh, 2015) and topographic data (digital elevation model to calculate AD and TPI, Table 2), which can be downloaded from the USGS earth explorer, could be used to calculate spatial variables similar to those presented here. Nevertheless, similar LUR models in Switzerland, Europe and all over the world would need to be calibrated with local-specific urban temperature networks in the study area, since local aspects might be crucial for the results of the modelling process. In Bern, the complex topography of and the proximity to the Alps lead to a complex local wind system, which exerts an important influence on the intra-urban temperature variability (Burger, Gubler, & Brönnimann, 2022; Mathys et al., 1980). Following from that, an important question is which spatial coverage and temporal resolution urban networks should have in order to be able to compile such a dataset. In Bern, data of 61 stations maintained throughout three summers were used for the calibration, which led to a very good performance of the model (Burger, Gubler, & Brönnimann, 2022). However, depending on the size and the complexity of the city, it might also be possible to use smaller networks during shorter periods to derive reasonably well models. Since currently many cities in Europe are mounting or planning urban temperature networks, research regarding this issue would be an important step to be able to validate the potential of LUR approaches for compiling fine-scaled urban temperature datasets more in detail.

6 | CONCLUSION

In this study, we presented a spatially and temporally high-resolution dataset of mean night-time temperatures in a medium-sized city in Switzerland. To conduct that dataset, LUR modelling was applied to combine temperature data of a fine-scaled measurement network with detailed land use and meteorological data. The dataset was validated with station data and for two different application scenarios, illustrating the value of such a dataset regarding both, research and nonacademic fields. For the advancement and refining of the presented approach, the compilation of similar LUR datasets with differing input data (amount of stations, timespan or land use data) would be of great interest.

ACKNOWLEDGEMENTS

We thank the city of Bern and Energie Wasser Bern for the collaboration regarding the low-cost measurement network in Bern. Additionally, we would like to thank the three anonymous reviewers for their valuable comments on an earlier version of this manuscript.

FUNDING INFORMATION

This project is funded by a grant from the Oeschger Centre for Climate Change Research (OCCR) and the FAIRNESS (FAIR NEtwork of micrometeorological measurements, CA20108) project.

OPEN RESEARCH BADGES

This article has been awarded Open Data Badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. Data is available at [https://boris.unibe.ch/161882/].

DATA AVAILABILITY STATEMENT

The dataset can be downloaded under an open access licence (CC-BY 4.0) using the following identifier: https://doi.org/10.48620/316. Additionally, the raw data of the urban temperature measurement network of Bern can be downloaded from https://boris.unibe.ch/161882/ with the same open access licence (CC-BY 4.0).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Burger, M., Gubler, M. & Brönnimann, S. (2024) High-resolution dataset of nocturnal air temperatures in Bern, Switzerland (2007–2022). *Geoscience Data Journal*, 00, 1–15. Available from: https://doi.org/10.1002/gdj3.237