Assessing Pedestrian Accessibility to Urban Land Surface Temperature Cold Spots in Bavarian Cities

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1 ABSTRACT

As climate change intensifies, European cities must adapt to increasingly frequent and severe heatwaves. Urban heat is not only an environmental concern but a key challenge for spatial justice, public health, and long-term resilience. For sensible adaptation strategies, planners require spatially detailed and comparable information to understand where heat accumulates, where cooling potential exists, and how equitably these cool spaces are accessible to different population groups. Recent advances in Earth observation and the availability of the German Census data at a spatial gridding of 100-m offer opportunities to integrate high-resolution environmental and demographic data into planning processes in a way that is consistent across cities of very different sizes and spatial configurations.

This study presents a scalable framework that combines satellite-derived Land Surface Temperature (LST) with population data to analyse urban heat patterns and the accessibility of naturally cool areas (cold spots) across all cities in Bavaria, ranging from small historic towns and medium-sized regional centres to large urban municipalities. Multi-year Landsat composites are processed to the harmonised 100-m grid aligned with the national census grid, enabling consistent and methodologically comparable cross-city analyses. Local Getis–Ord Gi* statistics are used to identify spatial clusters of unusually warm and cool surfaces within each city, creating a coherent thermal surface vulnerability indicator which can be compared across different urban systems.

To contextualize the spatial distribution of cold spots, we link them to sociodemographic data from the census grid and to walking-time accessibility. For each city, we derive population-weighted indicators that quantify how well different social groups (such as elderly people, children, and immigrants) can reach cold spots. These indicators reveal how accessibility inequalities vary not only between socio-demographic groups but also between various city sizes. This allows us to identify where targeted planning interventions are needed.

By applying this workflow to the full set of Bavarian cities, the study offers a state-wide, high-resolution comparison of urban heat structures and socially differentiated access to cooling. The results demonstrate how remote sensing, geospatial analyses, and census microdata can strengthen evidence-based planning, support climate-resilient urban design, and contribute to more equitable access to cooling in cities of all sizes.

Keywords: walking accessibility, land surface temperature, climate change, cold spots, Bavaria

2 INTRODUCTION

Climate change represents one of the most pressing societal challenges of the 21st century and its impacts are becoming increasingly evident in urban areas (IPCC, 2022). According to the European State of the Climate Report of the Copernicus Climate Change Service, 2024 was the warmest year on record since the beginning of systematic meteorological observations and the year with the second highest number of heat-stress days in Europe (C3S, 2025).

Currently, approximately 56% of the world's population lives in urban areas (United Nations, 2018), where exposure to extreme weather events such as floods, storms, wildfires, and heatwaves is particularly high (C3S, 2025). Compared to rural regions, the high degree of soil sealing, dense built environments, and limited vegetation in cities significantly reduces the capacity to mitigate the impacts of such events (Stewart & Oke, 2012). Among these hazards, heatwaves affect urban populations more severely than those in surrounding rural areas, as cooling locations are often scarcer and less accessible (Lan, 2022).

Heat has been identified as the most significant and urgent climate-related risk to human health in Europe by the European Climate Risk Assessment of the European Environment Agency (EEA, 2024). A lack of centrally located, easily accessible cool places poses substantial challenges for everyday activities, particularly for vulnerable population groups such as older adults, people with disabilities, and families with young children. Increased thermal stress, adverse health outcomes, and rising heat-related mortality rates are among the major risks associated with increasing temperatures and extreme heat events in Europe (IPCC, 2023). Recent studies suggest that these trends will persist in the future (Taubenböck et al., 2024), with climate change progressing particularly rapidly in European cities (Friesen & Taubenböck, 2025). Projections indicate that under the SSP5-8.5 scenario, average temperatures in European cities could in avaerage increase by 4 °K by the end of the century.

A prerequisite for effective climate adaptation in cities is the availability of up-to-date, spatially detailed temperature data. Satellite observations offer considerable advantages in this regard due to their regular temporal coverage and their retrospective availability dating back to the late 1970s. A widely used indicator for identifying thermally warm and cool urban areas is Land Surface Temperature (LST). LST derived from satellite data allows surface temperatures to be captured at spatial resolutions of up to 30 meters across the entire Earth's surface. It provides valuable insights into where cities tend to heat up most intensely during summer – and, crucially, where comparatively cool areas persist.

Land Surface Temperature (LST) is one of the currently 55 Essential Climate Variables (ECVs) defined by the Global Climate Observing System (GCOS). It describes the thermal radiation emitted by the Earth's surface and constitutes a key indicator for identifying thermal hot and cold spots across both sealed (impervious) and natural surfaces (GCOS, 2025). It is important to note, that LST captures radiative emissions; i.e. it does not capture the near-surface factors that contribute to the heat that is actually experienced by people such as air temperature, humidity, radiation or wind (Oke et al., 2017). However, it has been shown that correlations exist and that under the conditions that one is aware of what LST data shows and what not, it is valuable as a proxy with consistent and area-wide data (e.g. Leichtle et al., 2022). LST is widely applied in studies of the hydrological cycle (Wang, 2009), drought assessment (Karnieli, 2010), and even research on vector-borne diseases (Anyamba, 2014), but it is particularly relevant for analyzing heat-induced stress on urban populations (Malakar et al., 2018; Massaro et al., 2023).

LST can be measured either by in situ meteorological stations, which allow for detailed temporal analyses at fixed locations, or by satellite-based remote sensing. Due to their global coverage, regular revisit times, and high spatial resolution, satellites are the primary data source for LST measurements at regional (Friesen, Leichtle & Taubenböck, 2025) to global scales (Good et al., 2022; Massaro et al., 2023). Using thermal infrared (TIR) sensors, satellite-derived LST captures spatial patterns of urban surface heat and cooling phenomena (Bechtel et al., 2019) and is frequently employed in the literature to characterize the Surface Urban Heat Island (SUHI) effect (e.g., Choi et al., 2012; Isufi et al., 2021; Lemus-Cánovas et al., 2020; Xue et al., 2022).

In recent years, an increasing number of studies have focused on LST cold spots, which represent the thermal counterpart to SUHI hot spots. These areas play a crucial role in enhancing urban climate resilience and supporting climate adaptation strategies due to their cooling effects (Mavrakou et al., 2018; Xue et al., 2022; Choi et al., 2012). Although definitions of cold spots vary across studies, they are consistently characterized by lower surface temperatures relative to their surroundings. Cold spots in cities are most commonly associated with green spaces and water bodies, as well as with areas of low imperviousness, low building density, and good ventilation conditions (Bechtel et al., 2019; Xue et al., 2022; Weng, 2009).

Against this background, this study investigates LST cold spots in Bavarian cities as critical yet underexplored elements of surface urban heat adaptation. While previous research on Bavaria has primarily focused on identifying thermal hot spots and the Surface Urban Heat Island effect (e.g. Heldens et al., 2013;

Leichtle et al., 2023; Friesen, Leichtle & Taubenböck, 2025), comparatively little attention has been paid to the spatial distribution, accessibility, and social context of urban cooling areas. By integrating satellite-derived LST with high-resolution socio-demographic data and pedestrian network information (Weigand et al., 2023; Droin et al., 2024), this study aims to assess not only where LST cold spots are located, but also who can access them. Focusing on all 317 municipalities classified as cities in Bavaria, the central research question is: Which socio-geographical patterns can be identified in the spatial distribution and pedestrian accessibility of land surface temperature cold spots across Bavarian cities? In doing so, the study contributes to a more socially informed understanding of urban cooling potential.

3 CONCEPTUAL FRAMEWORK

This study follows a conceptual framework that links the urban surface thermal environment with pedestrian accessibility and socio-demographic characteristics.

Land surface temperature (LST) patterns within cities give rise to spatially distinct cold spots, which represent areas of comparatively lower surface temperatures and potential cooling benefits. However, the contribution of these cold spots to surface urban heat adaptation depends not only on their presence but also on their spatial distribution and accessibility by foot, i.e. by spatial proximity.

At the same time, socio-demographic characteristics influence heat exposure and vulnerability, shaping who benefits from available cooling opportunities. By jointly considering LST cold spots, pedestrian accessibility, and socio-demographic patterns across Bavarian cities, the framework enables an assessment of spatial inequalities in access to urban cooling and their implications for climate adaptation.

4 STUDY AREA & DATA

This study covers the entire federal state of Bavaria (Germany) and includes all 317 municipalities that are classified as cities according to the official census definition (Fig. 1, left). The spatial extent of each city is defined by its administrative municipal boundary, which serves as the analytical frame for all subsequent processing steps. By considering the complete set of census-defined cities rather than a limited number of case studies, the analysis enables a systematic and comparable assessment of thermal patterns and accessibility conditions across a wide range of urban contexts, including small, medium-sized, and large cities.

To support intra-urban analyses and ensure consistency with population data, each city is represented using a regular grid with a spatial gridding of 100 m × 100 m, clipped to the corresponding administrative boundary. This resolution was chosen to match the spatial structure of the available census grid (Destatis, 2024). All thermal, spatial-statistical, and accessibility indicators are derived and evaluated at this grid-cell level, allowing population-weighted aggregation and cross-city comparisons.

Land Surface Temperature (LST) was derived from Landsat 8 and Landsat 9 thermal infrared observations and processed as a spatially continuous raster dataset covering the entirety of Bavaria at 30 m spatial resolution. Only scenes with a nominal cloud cover below 50% were included in the analysis. Due to frequent cloud contamination over large parts of the study area, shorter time periods were insufficient to obtain robust spatial coverage of all cities. For this reason, the temporal extent of the dataset was expanded to a four-year period from 1 November 2020 to 31 October 2024. This ensures adequate data availability across all municipalities and avoids short-term anomalies by focusing on a long-term trend.

For all eligible scenes within the study period, LST values were aggregated on a per-pixel basis to compute a multi-year temporal mean at 30 m spatial resolution. This aggregation captures long-term average thermal conditions and highlights spatially persistent temperature patterns at the land surface. The temporal mean LST, expressed in degree Celsius, was selected as a robust indicator of urban surface thermal characteristics, as maximum LST values showed strong heterogeneity within cities due to differing acquisition dates of individual satellite scenes. Using the mean reduces artificial temperature discontinuities caused by short-term meteorological variability while preserving meaningful spatial contrasts between warmer and cooler urban areas. The resulting raster thus provides a harmonized representation of urban surface temperatures suitable for comparative analysis across cities.

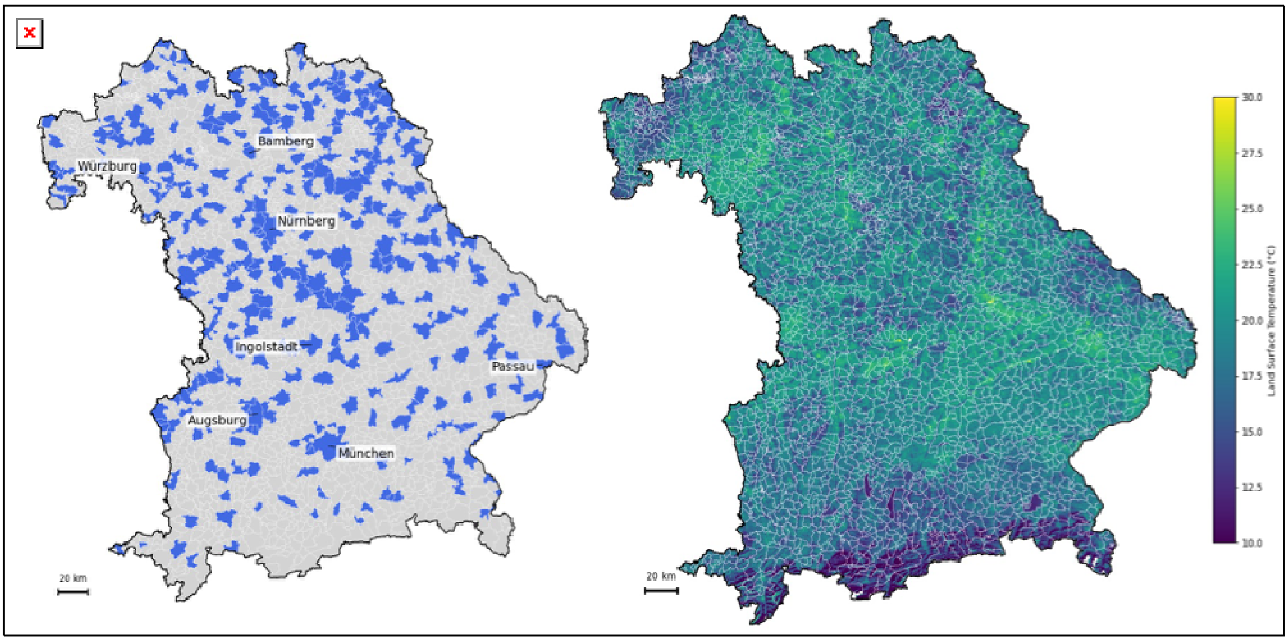

Fig. 1. Left: In blue the analysed municipalities (cities) in Bavaria. Right: Median Land Surface Temperature derived from Landsat 8 and Landsat 9 over four entire years from 2020 to 2024.

5 METHODS

5.1 Grid-based aggregation and identification of thermal hot and cold spots

To enable city-scale and intra-urban analyses, the 30 m land surface temperature (LST) raster was spatially aggregated to the 100 m analysis grid defined for each city (Fig. 2, upper row). Zonal statistics were computed by intersecting the LST raster with the grid-cell polygons and calculating the mean LST value per cell. The resulting grid-based LST values were stored as attributes of the city-specific analysis grids.

Based on the aggregated grid-level LST values, spatial clustering of relatively high and low surface temperatures within each city was assessed using the local Getis–Ord Gi* statistic. This local indicator of spatial association identifies areas where grid cells with similar surface temperature values cluster more strongly than would be expected under spatial randomness. The analysis was conducted separately for each city to account for differences in urban extent, morphology, and thermal variability.

Spatial relationships between grid cells were modeled using a Queen contiguity spatial weights matrix, in which neighboring cells share either an edge or a corner. Only grid cells with valid LST values were included in the analysis.

Rather than applying fixed significance thresholds, a relative, quantile-based classification was used to define thermal hot and cold spots. Grid cells with Gi* z-scores in the lowest 20% of the city-specific distribution were classified as cold spots, while those in the highest 20% were classified as hot spots. This approach facilitates comparison across cities with differing sample sizes and thermal contrasts and ensures a consistent identification of relative thermal surface extremes within each urban system. The resulting binary cold-spot classification forms the primary input for the subsequent pedestrian accessibility analysis.

5.2 Pedestrian accessibility to cold spots

Pedestrian accessibility to thermal cold spots was assessed using a network-based routing approach grounded in OpenStreetMap (OSM) data (Fig. 2, lower row). For each city, a walkable street and path network was extracted using OSMnx. The network was projected to a metric coordinate system, and each edge was assigned a travel time based on its geometric length and an assumed constant walking speed of 4.5 km/h.

Cold spots were represented by the centroids of all grid cells classified as cold spots, which were spatially matched to the nearest nodes in the OSM network. Similarly, centroids of all census grid cells were mapped to their nearest network nodes. To efficiently compute walking times from all populated locations to the nearest cold spot, a multi-source Dijkstra algorithm was applied, treating all cold-spot nodes as simultaneous sources. This yields the minimum travel time along the pedestrian network from each network node to the closest cold spot.

For each census grid cell, the travel time associated with its nearest network node was extracted and stored in both seconds and minutes. This procedure results in a spatially explicit representation of pedestrian access to cool locations across the entire urban fabric of each city.

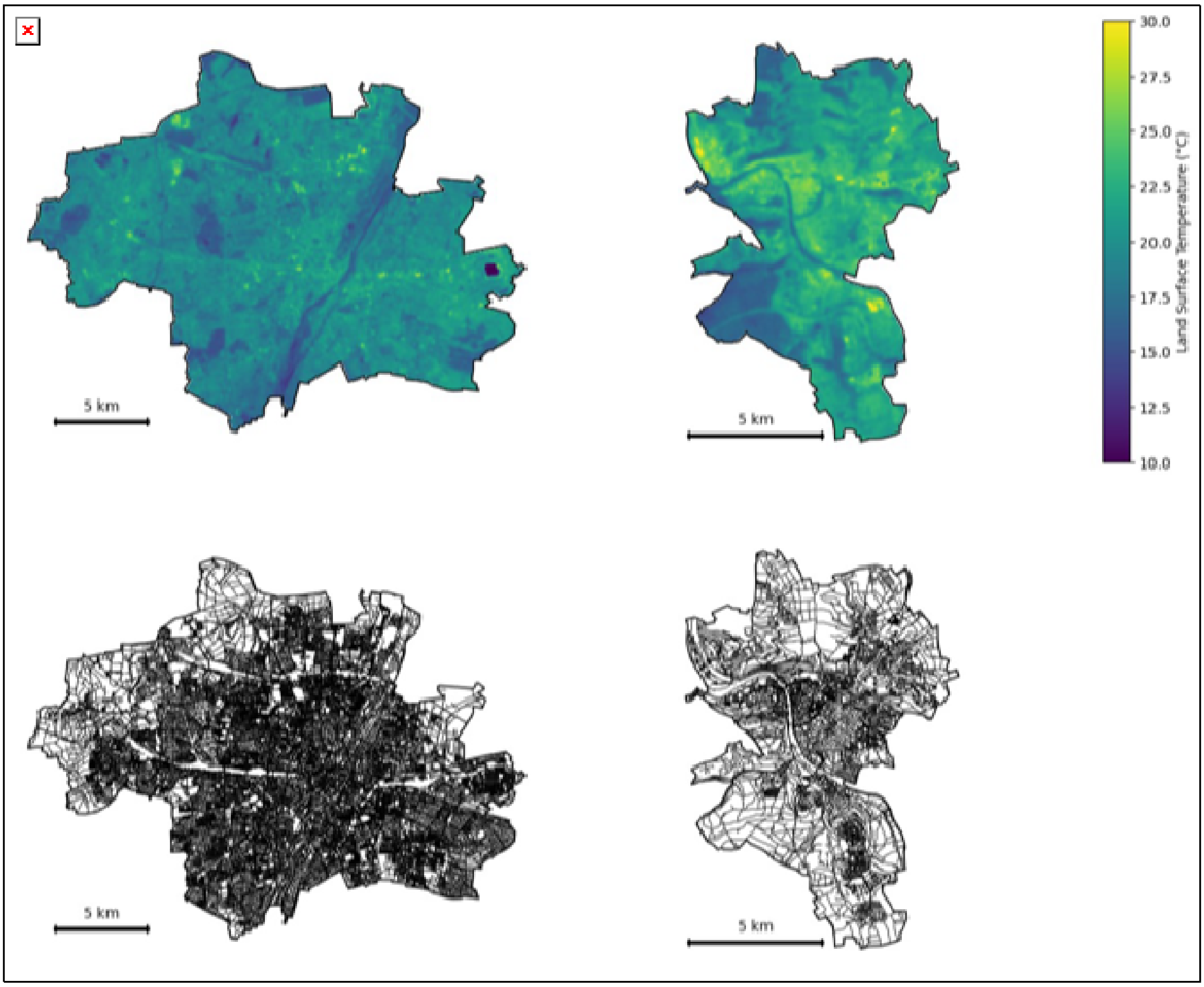

Fig. 2: Upper row: Land surface Temperature for the cities of Munich (left) and Würzburg (right). Lower row: Pedestrian network for the cities of Munich (left) and Würzburg (right)

5.3 Population-weighted exposure and relative risk analysis

Population exposure to limited cold-spot accessibility was evaluated using the 100 m census grid. For each cell, total population counts as well as subgroup attributes (population under 18 years, population aged 65 years and older, and the share of foreign residents) were considered. These groups are considered to suffer most during extreme heat events (Depietri et al., 2013).

Accessibility outcomes were summarized at the city level by calculating the population-weighted share of residents whose walking time to the nearest cold spot exceeds 10, 20, and 30 minutes. These thresholds were selected to reflect increasingly constrained pedestrian access in a particular urban context.

To assess social disparities in access to cooling opportunities, a relative risk (RR) metric was computed for a long-walking-time condition defined as more than 20 minutes to the nearest cold spot. For each population group g, relative risk was calculated as $RRg=P(t>20|g) / P(t>20|all)$ where $P(t>20|g)$ denotes the proportion of group g living in census cells with walking times exceeding 20 minutes, and $P(t>20|all)$ represents the corresponding proportion for the total population (Friesen, Georganos and Haas, 2025). Values $RRg > 1$ indicate that a group is disproportionately affected by limited pedestrian access to thermal cold spots compared to the city population as a whole.

6 RESULTS

6.1 Intra-urban thermal structure: hotspots and coldspots

Across the 317 cities included in the analysis, mean land surface temperatures (LST) show relatively limited variation, with a median of 18.9 °C (Inter quantile range IQR: 18.1–19.9 °C). In contrast, substantial differences emerge when comparing thermally extreme surface areas within cities. Hotspots exhibit a median LST of 21.7 °C (IQR: 21.1–22.6 °C), while coldspots are markedly cooler, with a median of 15.7 °C (IQR: 14.9–16.5 °C).

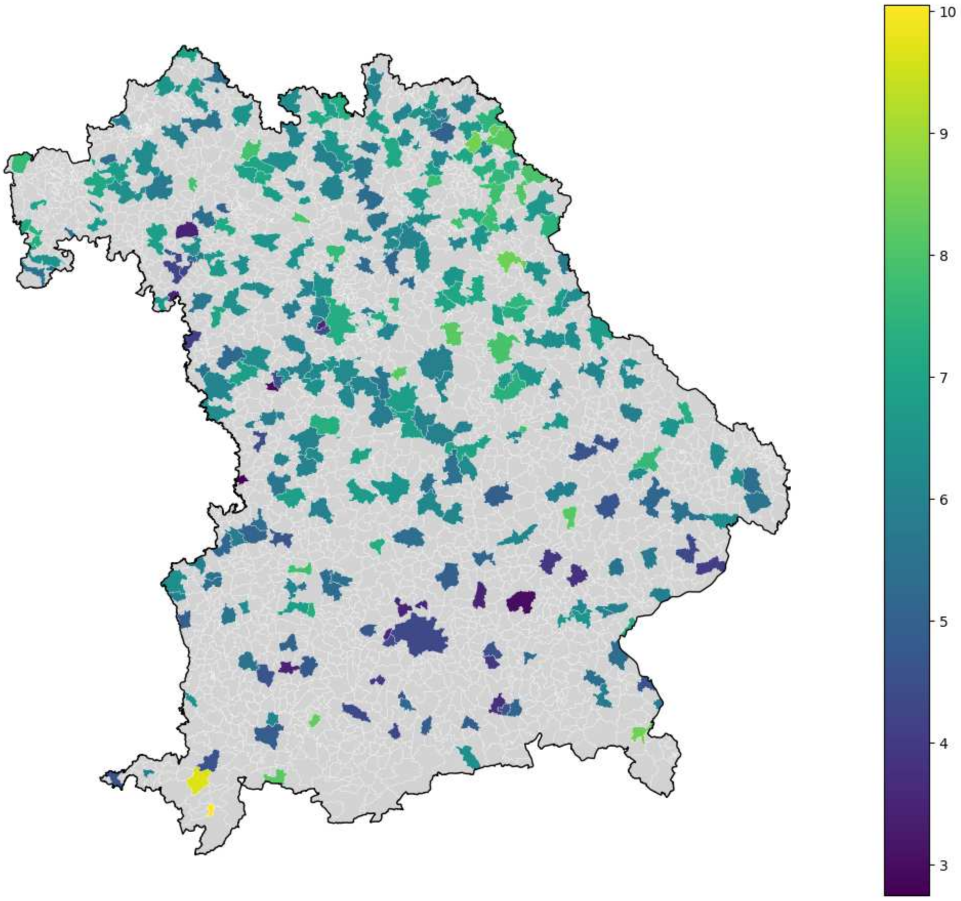

Fig. 3: Temperature differences in °K between hot- and coldspots in Bavarian cities.

The resulting hotspot–coldspot temperature contrast varies considerably across cities and across the state. Cities in the notheastern part show higher temperature differences than cities in the south and west. The median difference amounts to 6.1 °K, with an interquartile range from 5.4 °C to 6.8 °K. At the lower end, some cities show contrasts below 3 °K, indicating relatively homogeneous thermal conditions, whereas others exceed 10 °K, reflecting pronounced thermal segregation.

6.2 Accessibility of cooling areas

Accessibility to coldspots differs strongly both within and across cities. The median walking time to the nearest coldspot is 14.6 minutes (IQR: 11.7–18.9 minutes). It can therefore be stated that at the aggregated city level in Bavaria, the planning idea of the 15-minute city (Allam et al., 2022), i.e. being able to reach central functions for everyday needs on foot in less than 15 minutes, is just about fulfilled for cold spots. But of course there are many places at the intra-urban level that have much better or worse accessibility.

A median of 79.0 % of residents live more than 10 minutes away from the nearest coldspot. For stricter thresholds, the median share of the population living more than 20 minutes away is 32.8 %, while 2.2 % live more than 30 minutes away. However, the upper quartiles reveal much higher exposure levels: in 25 % of cities, more than 55.7 % of the population is located beyond the 20-minute threshold, and in some cities the entire population exceeds this distance.

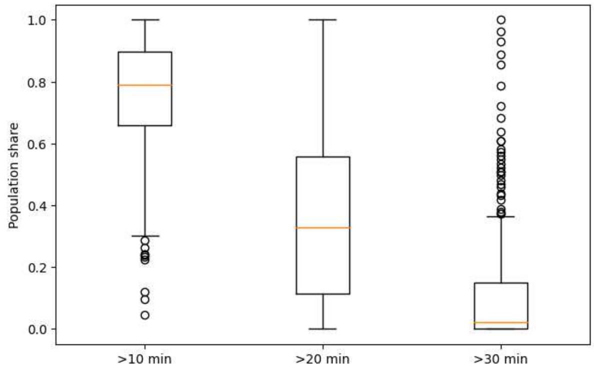

Fig. 4: Boxplots representing the accessibility to coldspots above 10, 20 and 30 minutes for Bavarian cities.

Large cities such as Augsburg illustrate the upper end of this distribution, with 84 % of the population with more than 20 minutes walking time to the next coldspot, whereas more compact cities like Abenberg or Altdorf show substantially shorter travel times for most residents. Nevertheless, similarly high accessibility deficits are also observed in smaller cities with dispersed settlement patterns.

6.3 Coupling of thermal contrast and cooling accessibility

Cities with stronger intra-urban thermal contrasts (Fig. 3) tend to exhibit poorer access to cooling areas. Fig. 5,a highlights, that the hotspot–coldspot LST difference correlates moderately with the share of the population living more than 20 minutes from a coldspot (ρ = 0.51).

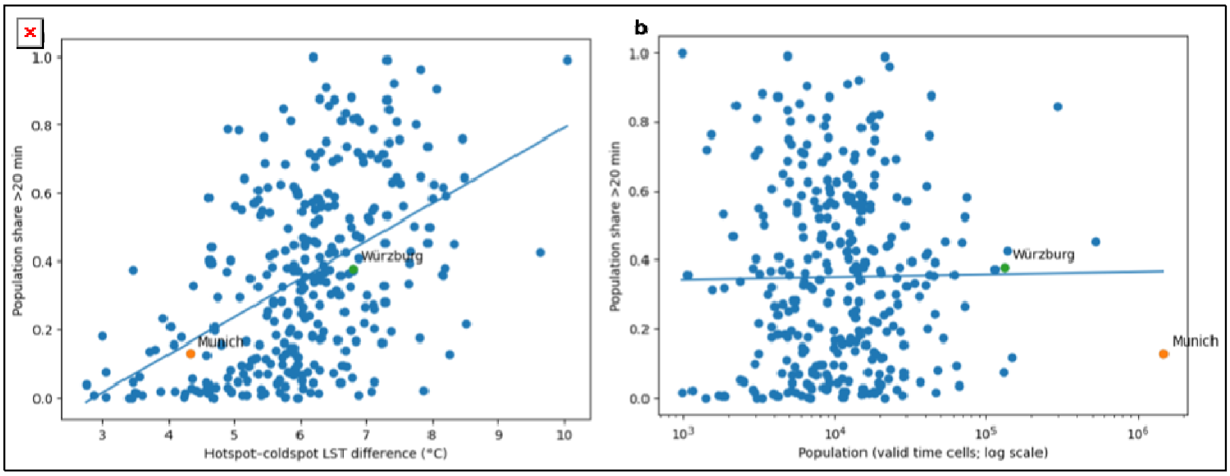

Fig. 5: a: Relationship between population share with more than 20 minutes walking time to cold spots for the analyzed cities. b: Relationship between population share with more than 20 minutes and population within the analyzed city.

While these relationships are intuitively plausible, their consistency across more than 300 cities suggests that they reflect structural characteristics of urban form and land-use configuration rather than isolated local conditions.

In contrast, total city population shows no meaningful correlation (Fig. 5, b) with either thermal contrast or accessibility indicators (|ρ| < 0.1). This finding indicates that cooling accessibility challenges are not primarily driven by city size but occur across the full urban hierarchy, from small towns to large regional centers.

6.4 City-level exemples: Munich and Würzburg

The detailed maps of Munich and Würzburg (Fig. 2 and Fig. 6) show how the aggregated patterns illustrated above occur on a city-wide scale. In both cities, coldspots are spatially coherent and closely linked to vegetated areas or bodies of water, while hotspots correspond to densely built-up zones. However, their accessibility patterns differ.

Munich, with moderate hotspot–coldspot thermal contrasts (see Fig. 5, left), exhibits relatively moderate median walking times to coldspots, with a more dispersed pattern of cold and hotspots.

By contrast, Würzburg exhibits a more compact spatial structure, with hotspots in the highly dense structures of the old town and the surrounding highly dense block developments and coldspots on the periphery, near local forests. This, in combination with a less dense network for walking due to topography, leads to localised accessibility deficits. It is important to mention, that some of the city's local parks (e.g. Ringpark in the center of Würzburg) that are supposed to be cold spots do due to our data and threshold approach not appear as cold spots.

6.5 Distributional impacts and relative risks

Relative risk (RR) analysis reveals systematic disparities in cooling accessibility across population groups (Fig. 7) and thus spatial inequality.

For residents with a foreign nationality background, the median RR is 1.07 (IQR: 0.80–1.26). In 59.3 % of cities, RR values exceed 1, indicating that this group is more likely than the general population to live more than 20 minutes from the nearest coldspot. In 25.2 % of cities, RR exceeds 1.25, and in 10.1 % it exceeds 1.5, pointing to substantial overrepresentation in a non-negligible subset of cities. In extreme cases, RR values approach 8, reflecting highly uneven spatial distributions.

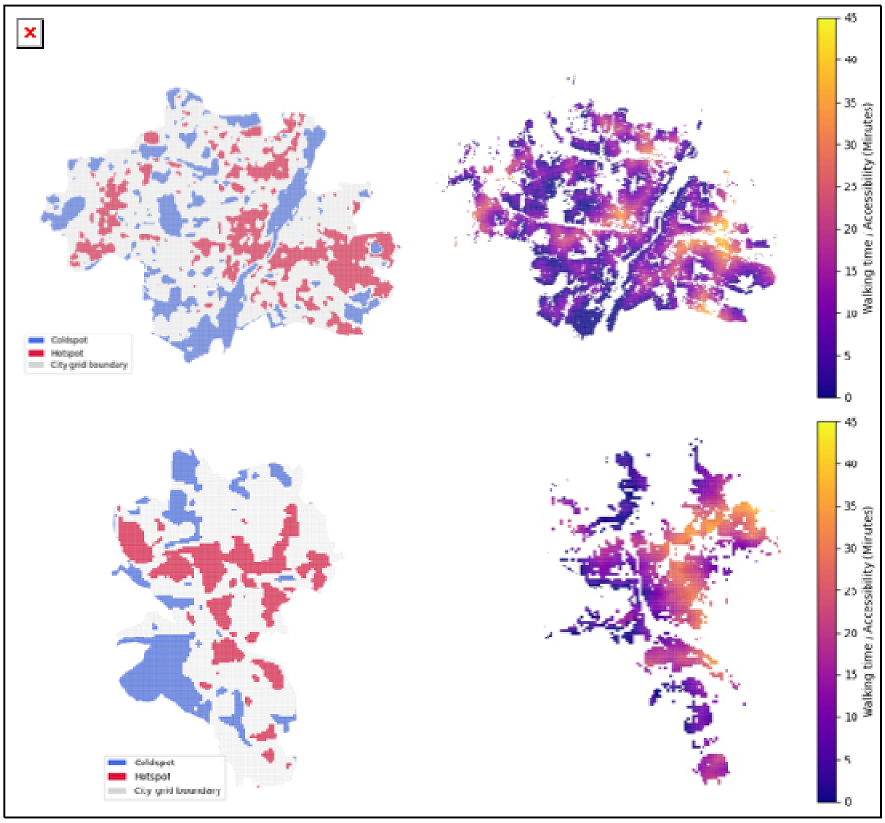

Fig. 6: Spatial distribution of cold- and hotspots (left column) and accessibility (right column) for Munich (upper row) and Würzburg (lower row).

For children and adolescents under 18 years, the median RR is close to parity (1.00, IQR: 0.95–1.06). Although RR values exceed 1 in 52.1 % of cities, stronger disadvantages are uncommon: only 5.7 % of cities exceed an RR of 1.25, and 1.6 % exceed 1.5.

A similar pattern is observed for residents aged 65 years and older. The median RR is 1.00 (IQR: 0.92–1.06), with RR > 1 in 50.2 % of cities. However, elevated values above 1.25 occur in fewer than 5 % of cases, and values above 1.5 are rare.

Comparing across groups, residents with a foreign nationality background consistently exhibit both the highest frequency and the highest magnitude of disadvantage. While slight deviations from parity are common across all groups, pronounced inequities are largely concentrated in this population group.

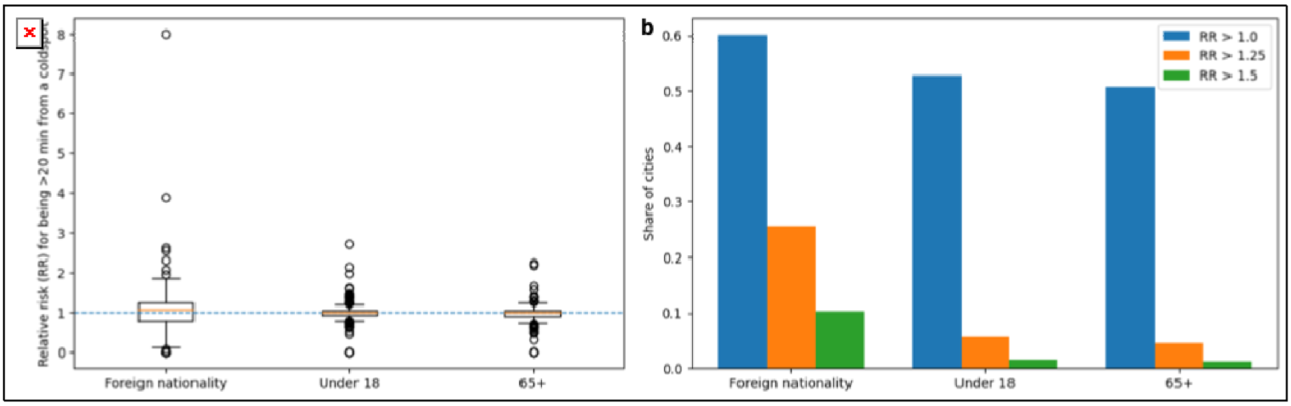

Fig. 7: (a) Relative risk (RR) for different social groups to have worse access to cooling space than the rest of the population and (b) share of cities exceeding a specific threshold of RR. The time threshold used for this analysis is 20 minutes.

7 DISCUSSION

This study demonstrates that pronounced thermal surface heterogeneity is a common feature of cities across Bavaria, extending well beyond large metropolitan areas. Across municipalities, the median difference in land surface temperature (LST) between hotspots and coldspots clusters around approximately 6 °K, with interquartile ranges between roughly 5.4 and 6.8 °K. These magnitudes confirm that even small and medium-sized cities exhibit strongly differentiated internal thermal surface structures rather than spatially uniform surface heat exposure.

The observed intra-urban contrasts are consistent with previous urban heat island research highlighting the role of land cover, vegetation, and impervious surfaces in shaping local thermal environments. Importantly, the lack of association between hotspot–coldspot contrast and total population size suggests that thermal differentiation is driven more by urban form and land-use configuration than by city size per se.

The Bavaria-wide comparison reveals that high thermal surface contrasts are not restricted to large urban centers. Several small and medium-sized municipalities exhibit hotspot–coldspot surface differences comparable to, or even exceeding, those of larger cities. This finding underscores that challenges related to urban surface heat exposure and cooling provision are regionally pervasive and should not be framed solely as metropolitan issues. From a planning perspective, it reinforces the need to consider heat adaptation and cooling infrastructure across the full spectrum of city sizes.

While thermal surface contrasts provide insight into the existence and intensity of coldspots, accessibility metrics reveal how unevenly these cooling resources are distributed relative to residential urban populations. Across cities, a substantial share of residents – around one third at the median – lives more than 20 minutes walking distance from the nearest coldspot, with upper quartiles exceeding 50%. At a more conservative 30-minute threshold, accessibility is given in most cities, indicating that coldspots are generally present but often spatially distant from everyday residential environments.

Another finding of this study is the positive association between hotspot–coldspot thermal surface contrast and poor cooling accessibility. Cities with larger thermal surface differences tend to have a higher proportion of residents living far from coldspots. While this relationship is moderate and not deterministic, it suggests that strong thermal surface heterogeneity may coincide with spatial concentration of cooling resources rather than their integration into the urban fabric. In other words, cities may exhibit substantial cooling potential without providing widespread, walkable access to it.

City-specific patterns illustrate how analytical choices and urban morphology jointly shape these outcomes. In cities such as Augsburg and Würzburg, large forested areas located within administrative boundaries dominate the coldspot classification due to the high temperature differences between the urban forests and the urban fabric. These specifics by the adminsitrative units influence the coldspot classification. For Würzburg this leads to comparatively low accessibility for large parts of the population in our analysis (Fig. 6). These cases highlight that coldspots are not purely physical entities but analytically defined spatial units whose extent and location influence observed accessibility patterns.

Importantly, not all cities with large thermal contrasts exhibit poor accessibility. This variation indicates that urban layout, connectivity, and the spatial distribution of green infrastructure mediate the relationship between thermal patterns and effective cooling access. Walking networks, permeability (c.f. r.g. Droin et al., 2024), and the placement of small-scale green spaces appear to play a critical role in translating cooling potential into practical heat mitigation benefits.

Beyond average accessibility, the relative risk (RR) analysis reveals systematic but heterogeneous inequities in access to cooling. In approximately 60% of cities, residents with foreign nationality are overrepresented among populations living more than 20 minutes from a coldspot. For children and older adults, the proportion of cities with RR values greater than 1 is slightly above 50%, indicating weaker but still widespread inequities. While median RR values across cities remain close to 1 for all groups, the distribution for residents with foreign nationality shows a pronounced upper tail, with RR values exceeding 1.25 and, in some cases, substantially higher.

These patterns suggest that cooling accessibility inequities are highly context-dependent and shaped by local residential segregation and urban structure. The relative measures (relative risk) mentioned in the study are robust measures for capturing inequality in access to cold spots, as are the absolute values, since, as already indicated above, these are sensitive to the definition of cold spots. As a result, while absolute accessibility measures reflect conditional exposure patterns influenced by analytical choices, the observed relative inequities point to more robust social gradients in access to cooling resources.

Taken together, the findings suggest that surface urban heat adaptation strategies should not focus solely on increasing the total amount of green space or cooling capacity. Cities characterized by large, spatially concentrated coldspots but poor accessibility may benefit more from distributed, small-scale interventions (such as street trees, pocket parks, and shaded pedestrian corridors) than from further expansion of already extensive green areas. Integrating accessibility considerations into urban climate adaptation planning is therefore critical for translating cooling potential into thermal relief.

The observed equity patterns further highlight the importance of evaluating cooling interventions not only in terms of average benefits but also in terms of who gains access. Place-specific diagnostics that combine thermal (surface) patterns, accessibility, and socio-demographic characteristics can help ensure that cooling infrastructure contributes to reducing, rather than reinforcing, existing social inequalities.

Overall, this study should be interpreted as identifying indicative patterns of relative thermal surface exposure and cooling accessibility rather than providing precise estimates of individual-level heat risk. The sensitivity of results to coldspot definitions and boundary choices highlights the need for future work to systematically test the robustness of accessibility and equity patterns across alternative conceptualizations of urban cooling, including absolute temperature thresholds, usability-based criteria, and alternative delineations of urban areas such as functional urban areas. Despite these challenges, the consistent spatial and social patterns observed across cities demonstrate the value of the proposed approach as a comparative framework for understanding how thermal environments, accessibility, and equity intersect in urban heat adaptation.

7.1 Limitations

The following limitations should be considered when interpreting the results of this study, particularly with respect to data sources and modeling assumptions.

First, land surface temperature (LST) estimates were derived from multi-scene Landsat composites using median values. While this approach increases robustness against cloud contamination and scene-specific artifacts, it may underestimate thermal extremes that are most relevant for acute heat-related health impacts. Peak temperatures during extreme heat events are likely higher than the reported values, and their spatial patterns may differ. Although this limitation affects absolute temperature levels, it is less likely to substantially alter relative hotspot–coldspot contrasts within cities, which form the basis of the comparative analysis. It has also to be taken into account, that LST is just a proxy for thermal comfort and further studies on ambient air temperature, humidity radiation or wind (Oke et al., 2027) are needed to better understand to what extent the findings of this study relate to heat stress.

Second, pedestrian accessibility was modeled using OpenStreetMap (OSM) street networks. Despite generally high coverage in urban areas, OSM data quality varies with respect to pedestrian connectivity, access restrictions, and the representation of informal or recently developed pathways. Such inconsistencies may introduce spatial biases in estimated walking times, particularly in areas with complex access conditions. However, as accessibility calculations were performed consistently across cities, these uncertainties primarily affect absolute values rather than relative comparisons between population groups within the same city.

Third, accessibility modeling assumed a uniform walking speed across all population groups and spatial contexts. This simplification does not account for differences related to age, health status, terrain, or environmental conditions, which may disproportionately affect vulnerable populations such as older adults or individuals with mobility impairments. Consequently, estimated walking times should be interpreted as generalized indicators of spatial proximity rather than precise measures of experienced accessibility.

Fourth, the analysis focused on spatial proximity to coldspots without explicitly accounting for their functional characteristics or usability. Coldspots differ substantially in size, public accessibility, amenities, and their capacity to provide effective thermal relief (e.g., tree canopy density, shaded seating, or water features). The presence of a coldspot within walking distance therefore does not guarantee that it functions as an accessible or effective cooling resource for all residents.

Finally, population characteristics were analyzed at the 100 m grid-cell level using aggregated census attributes. This spatial aggregation may mask intra-cell heterogeneity and does not capture temporal dynamics such as daily mobility, diurnal population shifts, or differences between daytime and nighttime exposure. As a result, the analysis reflects residential accessibility patterns rather than dynamic individual exposure.

Taken together, these limitations suggest that the results should be interpreted as indicative patterns of relative thermal exposure and cooling accessibility rather than precise estimates of individual-level heat risk. Nevertheless, the consistent application of methods across cities and the robustness of relative risk patterns support the validity of the comparative insights and provide a foundation for future studies using more detailed, temporally resolved, or context-specific data.

8 CONCLUSION

This study shows that strong intra-urban thermal surface heterogeneity is a widespread feature of cities across Bavaria, extending well beyond large metropolitan areas. Substantial hotspot–coldspot contrasts are common even in small and medium-sized municipalities. In many cities, a significant share of the population lives at considerable walking distances from coldspots, and stronger thermal contrasts tend to coincide with poorer accessibility. These patterns indicate that urban surface heat risk is shaped not only by the intensity of heating but also by how cooling opportunities are distributed within the urban fabric.

The analysis further reveals context-dependent but systematic social inequities in cooling accessibility, particularly affecting residents with foreign nationality. While absolute accessibility measures are sensitive to analytical choices and urban morphology, relative risk patterns are more robust, highlighting persistent social gradients in who benefits from urban cooling. Together, these findings underscore that effective urban surface heat adaptation requires attention to spatial distribution and walkable access, not only the amount of green space availability. The proposed framework demonstrates the value of integrating thermal data, accessibility analysis, and equity metrics to support more targeted and socially just climate adaptation planning, while also providing a basis for future robustness and sensitivity analyses.

9 ACKNOWLEDGEMENTS

The Free State of Bavaria funded this research via the Bavarian State Ministry of Economic Affairs, Regional Development and Energy and the German Aerospace Center (DLR) as part of the "Earth Observation Innovation Laboratory for Climate Adaptation and Mitigation" project (www.EO4CAM.de).

10 REFERENCES

Allam, Z., Nieuwenhuijsen, M., Chabaud, D., & Moreno, C.. The 15-minute city offers a new framework for sustainability, liveability, and health. The Lancet Planetary Health, 6(3), e181-e183, 2022.

Anyamba, A.; Small, J. L.; Britch, S. C.; Tucker, C. J.; Pak, E. W.; Reynolds, C. A.; Linthicum, K. J.: Recent weather extremes and impacts on agricultural production and vector-borne disease outbreak patterns. In: PLOS ONE, Vol. 9, Issue 3, e92538, 2014.

Bechtel, B.; Benz, S. A.; Wicki, A.: Einsatz von Satelliten zur Analyse des Stadtklimas, 2019.

Calvin, K.; et al.: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2023.

Choi, H.-A.; Lee, W.-K.; Byun, W.-H.: Determining the Effect of Green Spaces on Urban Heat Distribution Using Satellite Imagery. In: Asian Journal of Atmospheric Environment, Vol. 6, Issue 2, pp. 127–135, 2012.

Copernicus Climate Change Service (C3S): European State of the Climate 2024, 2025.

Statistisches Bundesamt (Destatis): Zensus 2022 – Ergebnisse. URL: https://www.zensus2022.de/, 2024.

Depietri, Y., Welle, T., & Renaud, F. G. (2013). Social vulnerability assessment of the Cologne urban area (Germany) to heat waves: Links to ecosystem services. International Journal of Disaster Risk Reduction, 6, 98-117.

Droin, A., Wurm, M., Weigand, M., Gawlas, C., Köberl, M., & Taubenböck, H. How does pedestrian permeability vary in and across cities? A fine-grained assessment for all large cities in Germany. In: Computers, Environment and Urban Systems, 110, 102115, 2024.

European Environment Agency (EEA): European Climate Risk Assessment, 2024.

Friesen, J.; Georganos, S.; Haas, J.: Differences in walking access to healthcare facilities between formal and informal areas in 19 sub-Saharan African cities. In: Communications Medicine, Vol. 5, Issue 1, Article 41, 2025.

Friesen, J.; Leichtle, T.; Taubenböck, H.: How much urban green do Bavarian cities need to cool by 1 degree? In: The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. 48, pp. 7–12, 2025.

Friesen, J.; Taubenböck, H.: The world’s largest cities under climate change and their adaptive capacity to rising heat. In: Scientific Reports, Vol. 15, Issue 1, Article 32671, 2025.

Global Climate Observing System (GCOS): Land Surface Temperature – Essential Climate Variable, 2025.

Good, E. J.; Aldred, F. M.; Ghent, D. J.; Veal, K. L.; Jimenez, C.: An Analysis of the Stability and Trends in the LST_cci Land Surface Temperature Datasets Over Europe. In: Earth and Space Science, Vol. 9, Issue 9, 2022.

Heldens W, Taubenböck H, Esch T, Heiden U, Wurm M.: Analysis of thermal patterns in relation to urban structure types – a case study for the city of Munich. In: Künzer C & Dech S (Eds.): Thermal Infrared Remote Sensing. pp. 475-494, 2013.

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2022 – Impacts, Adaptation and Vulnerability. Working Group II Contribution to the Sixth Assessment Report, 2023.

Isufi, F.; Berila, A.; Bulliqi, S.: Measuring Urban Heat Island Using Landsat 8 OLI and TIRS Data with NDVI and NDBI. In: Disaster Advances, Vol. 14, pp. 25–36, 2021.

Karnieli, A.; Agam, N.; Pinker, R. T.; Anderson, M.; Imhoff, M. L.; Gutman, G. G.; Goldberg, A.: Use of NDVI and land surface temperature for drought assessment: Merits and limitations. In: Journal of Climate, Vol. 23, Issue 3, pp. 618–633, 2010.

Lan, T.; Liu, Y.; Huang, G.; Corcoran, J.; Peng, J.: Urban green space and cooling services: Opposing changes of integrated accessibility and social equity along with urbanization. In: Sustainable Cities and Society, Vol. 84, Article 104005, 2022.

Lemus-Cánovas, M.; Martin-Vide, J.; Moreno-García, M. C.; López-Bustins, J. A.: Estimating Barcelona’s Metropolitan Daytime Hot and Cold Poles Using Landsat-8 Land Surface Temperature. In: Science of the Total Environment, Vol. 699, 2020.

Leichtle T, Kühnl M, Beck C, Hiete M, Droin A & Taubenböck: Exposure to urban heat – Citizen Science and remote sensing for the measurement and modeling of indoor and outdoor temperatures and its influencing factors. Urban Climate. vol. 49, 2023.

Malakar, N. K.; Hulley, G. C.; Hook, S. J.; Laraby, K.; Cook, M.; Schott, J. R.: An Operational Land Surface Temperature Product for Landsat Thermal Data: Methodology and Validation. In: IEEE Transactions on Geoscience and Remote Sensing, Vol. 56, Issue 10, pp. 5717–5735, 2018.

Massaro, E.; Schifanella, R.; Piccardo, M.; Caporaso, L.; Taubenböck, H.; Cescatti, A.; Duveiller, G.: Spatially-optimized urban greening for reduction of population exposure to land surface temperature extremes. In: Nature Communications, Vol. 14, Issue 1, Article 2903, 2023.

Mavrakou, T.; Polydoros, A.; Cartalis, C.; Santamouris, M.: Recognition of Thermal Hot and Cold Spots in Urban Areas in Support of Mitigation Plans to Counteract Overheating. In: Climate, Vol. 6, Issue 1, 2018.

Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. Urban climates. Cambridge university press, 2017.

Stewart, I. D., & Oke, T. R.: Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93(12), 1879–1900, 2012.

Taubenböck H, Mast J, Geiß C, Wurm M, Esch T & Seto K.: Global differences in urbanization dynamics from 1985 to 2015 and outlook considering IPCC climate scenarios. Cities. vol. 151, 2014.

United Nations, Department of Economic and Social Affairs, Population Division. World urbanization prospects: The 2018 revision. https://www.un.org/en/desa/201 8-revision-world-urbanization-prospects, 2018.

Wang, L.; Koike, T.; Yang, K.; Yeh, P. J. F.: Assessment of a distributed biosphere hydrological model against streamflow and MODIS land surface temperature in the upper Tone River Basin. In: Journal of Hydrology, Vol. 377, Issues 1–2, pp. 21–34, 2009.

Weigand M, Wurm M, Droin A, Stark T, Staab J, Rauh J & Taubenböck H (2023): Are public green spaces distributed fairly? A nationwide analysis based on remote sensing, OpenStreetMap and census data. Geocarto International.

Weng, Q.: Thermal Infrared Remote Sensing for Urban Climate and Environmental Studies: Methods, Applications, and Trends. In: ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 64, Issue 4, pp. 335–344, 2009.

Xue, X.; He, T.; Xu, L.; Tong, C.; Ye, Y.; Liu, H.; Xu, D.; Zheng, X.: Quantifying the Spatial Pattern of Urban Heat Islands and the Cooling Effect of Blue–Green Landscapes. In: Science of the Total Environment, Vol. 843, 2022.