

The unrelenting global expansion of the urban heat island over the last century

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Abstract

The past century has seen dramatic increases in global temperatures and mounting urbanization. As a result of these events, the urban heat island (UHI) effect has received growing attention in scientific research worldwide. A global search was initially conducted using a scientific literature database to collect all available relevant publications to understand how the UHI has been expanding worldwide and affecting more cities across different latitudes and altitudes. Subsequently, a semantic analysis was performed to extract city names. The literature search and analysis combined resulted in 6,078 publications in which UHI was investigated in 1,726 cities worldwide in the 1901 to 2022 time period. The cities were grouped into ‘first appearance’ and ‘recurrent appearance’. Results show that UHI was studied in only 134 cities during the 90-year period from 1901 to 1992, with a remarkable growth over time in the number of cities where interest in UHI increased. Interestingly, the number of first appearances was always notably higher than the number of recurrent appearances. The Shannon evenness index was employed to identify the spatial locations (hotspots) across the globe where UHI-related research has been concentrated in multiple cities over the last 120 years. Finally, Europe was selected as a testbed for conducting an analysis to shed light on how economic, demographic, and environmental factors can impact UHI. Our study is unique for having demonstrated not only the rapid growth of cities affected by UHI globally but also the increasing and unrelenting expansion of UHI occurrences across different latitudes and altitudes over time. These novel findings will undoubtedly be of interest to scientists

55 investigating the UHI phenomenon and its trends. Stakeholders will acquire a broader
56 perspective and deeper understanding of UHI in order to engage in more effective
57 urban planning to offset and mitigate the phenomenon's adverse effects in the context
58 of increasing climate change and urbanization.

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60 **Keywords:** Urban heat island; Latitude; Altitude; Literature database; Climate;
61 Vegetation

1. Introduction

Dramatic global climate change and urbanization, which are regrettably advancing at a rapid pace, are among the most important global trends of the 21st century (Marcotullio et al., 2021). According to the Intergovernmental Panel on Climate Change (IPCC) assessment report, the global mean air and surface temperature have significantly increased over the last century, and by the end of the 21st century will have increased by 1°C to 3.7°C (IPCC, 2013). At the same time, the world is urbanizing rapidly, and people living in cities have outnumbered rural dwellers (Yang and Zhao 2022). More than half of the global population will be living in urban settlements by 2030 (United Nations 2018). The end result will be a higher rise of temperatures in built-up areas (Radhi, et al., 2013) compared to their suburban counterparts, which defines what is commonly known as the urban heat island (UHI) effect (EPA, 2022). Of these events, UHI has received growing attention in scientific research worldwide (Balany et al., 2020; Mohajerani et al., 2017; Peng et al., 2012; Radhi et al., 2013).

The largest number of contributions to UHI-related research come from meteorology atmospheric sciences and environmental sciences (Huang & Lu, 2018). With regard to meteorology atmospheric sciences, investigations of the urban climate date back to the early 19th century. Hundreds of studies on the “urban temperature effect” or “heat island effect” have been published in the academic literature (Stewart, 2019), since Howard (1833) first suggested that the temperature difference between London and its countryside was proportional to urban density and development. The

continuous exploration and development of theories, methods, and techniques (e.g., Arnfield, 2003; Balchin & Pye, 1947; Huang & Ye, 2015; Oke, 1995; Schwarz et al., 2012; Stewart, 2011; Zhou et al., 2019) by scientists and scholars in urban climatology have allowed UHI to grow in popularity from its modest beginnings into a research topic of prominent academic interest. Its negative effects (Akbari et al., 2001; Donovan & Butry 2009; Hirano & Fujita 2012; Lowry, 1977), spatiotemporal patterns (Jin et al., 2015; Ren et al., 2007) and causes (Akbari et al., 2001; Doulos et al., 2004; Mohajerani et al., 2017; Rossi et al., 2014) have been extensively reported.

The majority of contributions to the environmental sciences, on the other hand, demonstrate that increasing vegetation and green spaces in cities have proven to be a way to address the root causes of the UHI issue (Gill et al., n.d.; Givoni, 1991; Norton et al., 2015; Peng et al., 2012; Shi et al., 2021). Scientists from specific disciplines, such as environmental management, landscape ecology, ecological restoration and urban forestry, have investigated the impact factors (Barbierato et al., 2019; Radhi et al., 2013; Ren et al., 2013; Zhou et al., 2014) and mitigation measures of UHI (Broadbent et al., 2018; Oliveira, 2011; Tan et al., 2010). It has also been suggested that controlling population size and GDP growth per capita may help to mitigate the UHI effect (Li et al., 2020). Correspondingly, most secondary sources (review articles) have not only focused on causes (Mohajerani et al., 2017; Ward et al., 2016) and mitigation measures (Aleksandrowicz et al., 2017; Balany et al., 2020; Bowler et al., 2010; Santamouris, 2013) but also on UHI evaluation methods (Neinavaz et al. 2021; Ward et al. 2016). In the early literature, the UHI was determined by measuring

urban air temperature using various methods, such as sensors mounted on bicycles (Budel & Wolf, 1933), motorcars (Fukui, 1941; Oke, 1976; Schmidt, 1927) and climate stations (Besson, 1931). Subsequently, the developments in remote sensing technology and spatial science have greatly incremented UHI research based on land surface temperature (e.g., Chen et al., 2022; Kong et al., 2014; Ren et al., 2013; Zhou et al., 2022), with an exponential growth trend beginning in 2005 (Zhou et al., 2019).

Viewed from another perspective, very few studies have dealt with the expansion of the UHI phenomenon. However, with the increased impact of climate change on cities (Gill et al., n.d.) and enhanced public awareness (Brondizio et al., 2021), various disciplines and interdisciplinary research areas focusing on climate change have been emerging (Lemos et al., 2019), thus expanding the UHI research trend. Oke (1982) had previously argued that there is a relative wealth of research on UHIs in temperate climates but a paucity of studies on heat islands in equatorial, tropical, subpolar and polar settlements. In contrast, 20 years later, Arnfield (2003) suggested that the areas studied for UHIs have included equatorial wet climates, tropical wet-dry and monsoonal climates, tropical highland climates, tropical deserts, subtropical climates and high latitude locations. Since then, another 20 years have passed and scientific research on the UHI effect continues to grow exponentially (e.g., Balany et al., 2020; Qi et al., 2019; Santamouris, 2013). However, this body of literature still does not provide evidence of UHI occurrence expanding to geographical regions worldwide.

The overarching goal of this study is to demonstrate how the UHI has been affecting an increasing amount of cities globally over a century and beyond (from here on referring to 120 years). The specific objectives of this study are to: (i) analyze the spatial distribution of cities where UHI has been investigated as well as the growth ratio of these cities over time; (ii) investigate the trend of UHI expansion in latitude and altitude; (iii) identify the spatial locations (i.e., hotspots) across the globe where UHI-related research is concentrated in multiple cities; and (iv) explore the economic, demographic and environmental drivers underlying the distribution of hotspots and non-hotspots with a focus on the European continent.

This singular study will greatly benefit urban planners and urban forestry research as well as offer scientists with important insights to deepen their understanding of the UHI phenomenon and its unrelenting and increasing worldwide trend. It will open the window of opportunity to policy makers and diverse stakeholders to engage in more skillful urban planning to offset and mitigate UHI's impacts on society and the environment at a time in history when global temperatures are dangerously increasing and the world's cities are rapidly urbanizing.

2. Materials and methods

To conduct our research, a large database (i.e., Scopus) of scientific literature focusing on the UHI phenomenon was accessed. For the purpose of including as many publications related to the UHI effect as possible in the study, (i) we used *climate* and *vegetation* as two main domains in the search query (see Section 2.1); (ii) followed up

the search by conducting a semantic extraction to restrict the publications to the urban area (see Section 2.2); and (iii) performed a subsequent data analysis with the extracted city information (Fig. 1) (see Section 2.3). Overall, the publications collected in this work focus on climate and vegetation in an urban context and will be referred to from here on as UHI-related research.

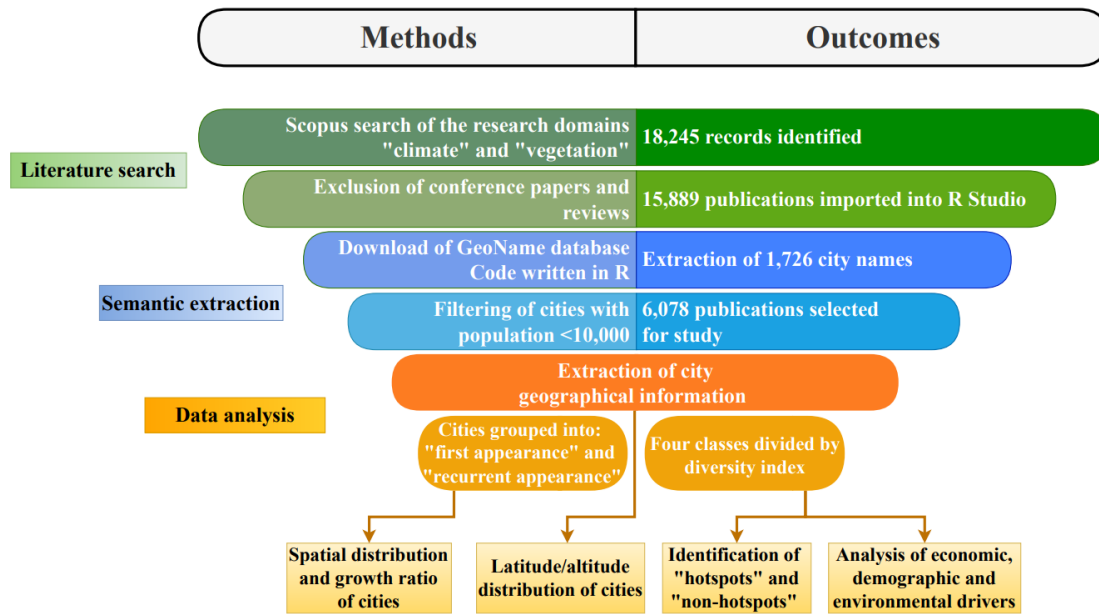


Figure 1. Flowchart of the literature search and analytical process.

2.1. Literature search

To search publications in which UHI has been investigated at the global level, we performed a selection of keywords focusing on the two main research domains as follows (asterisks replace all possible characters at the end of a word):

- **Climate:** “urban heat island*” OR “UHI*” OR “land surface temperature” OR “microclimate”, and
- **Vegetation:** “urban forest*” OR “green space” OR “green infrastructure” OR

“vegetation” OR “tree*” OR “nature-based solution*” OR “canopy cover” OR
“biomass”.

2.2. Semantic extraction

An additional filtering step focusing on UHI-related research conducted in the urban area was performed by means of semantics. Firstly, BibTeX files were imported from the identified literature and downloaded from Scopus into an R statistical environment (Version 4.1.2). Secondly, the GeoNames (2009) database was downloaded, as it contains more than 25 million geographical names (cities, provinces, regions) and their respective latitude, longitude, and altitude. Thirdly, the code was written in R for the semantic analysis of publications to automatically extract city names from the title and abstract based on GeoNames. Cities with a population of less than 10,000 were filtered out to avoid incorrect matching with common names. For example, Shannon (Quebec, Canada) and William (California, USA) are names of cities with populations of 6,423 and 5,642, respectively, which more often refer to names of individuals. In addition, a further analysis was conducted on abstract records. The analysis involved identifying the frequency of terms related to air temperature, local climate zone, land surface temperature, and land use. A Venn diagram was designed to represent the presence and intersection of terms found in each abstract. The same analysis was performed for four different timeframes to gain insight into the research history of each category. The analysis provides a comprehensive view of the research on UHI and related parameters, and highlights the importance of considering multiple

parameters in urban climate studies (see Supplementary Material, Fig. S1 and Table S1).

2.3. Data analysis

In our study, the probability density function (shown below) was used to standardize and compare the latitude and altitude distributions of cities between different timeframes,

$$F(x) = P(a \leq x \leq b) = \int_a^b f(x)dx = 1 \quad (\text{Eq. 1})$$

where probability (P) is the integration of the density function $f(x)$ from $x = a$ to $x = b$.

The integer was set at 1 to compare multiple functions across time. The Shannon evenness index (Eq. 3), which is based on Shannon diversity (Shannon 1948) (Eq. 2), was used to analyze the spatial distribution of UHI-related research on a global scale over a period of 120 years. For the scope, we divided the globe into equal grids by overlapping a fishnet polygon (size $1 \times 1^\circ$) and calculated the evenness index for each grid. The formula is shown as follows:

$$H' = - \sum_{i=1}^S (p_i \ln p_i) \quad (\text{Eq. 2})$$

where p_i and S are, respectively, the proportion of appearances belonging to the i -th city and the total number of cities within each cell of the grid for which UHI-related research has been conducted. The Shannon evenness index is defined as:

$$E = \frac{H'}{H'_{\max}} \quad (\text{Eq. 3})$$

where H' represents the number derived from the Shannon diversity index and $H'_{\max}$

is the maximum possible value of H' ; E is constrained between 0 and 1.

To illustrate the behavior of the index included in our analysis, a schematic sample is given in Figure 2. Grids belonging to different classes with cities (indicated by black dots) and their respective appearances in the grid are shown on the right. For example, the grid in panel (b) contains 4 cities which appeared 8, 7, 3 and 2 times, respectively. Therefore, S is the total number of cities in the grid ($N = 20$), while p_i is the proportion of appearances belonging to the i -th city, which are respectively 0.4, 0.35, 0.15, 0.1, and H' is 1.249. The probability of H'_{max} in this grid, which is the equal number of appearances of the four cities, is 0.25 for all p , and H'_{max} is 1.386; thus, the Shannon evenness index equals 0.9.

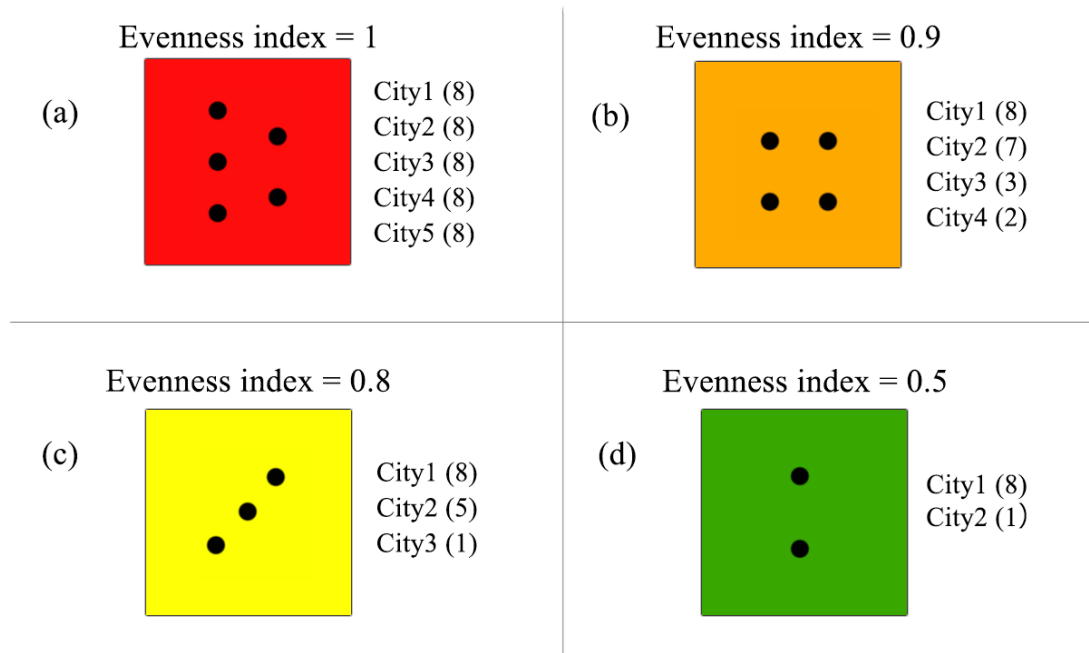


Figure 2. Schematic sample of the Shannon evenness index grids of different classes: (a) 0.96-1; (b) 0.83-0.96; (c) 0.59-0.83; and (d) 0-0.59 extracted from the global map of Figure 8.

Finally, we explored the economic, demographic, and environmental drivers underlying the distribution of hotspots and non-hotspots with a focus on the European

continent for a specific timeframe: 2000-2021 (KC & Ruth, 2015). The selection of Europe and the above timeframe is motivated by the availability of consistent data, both spatially and temporally, for all cities in Europe. Gross Domestic Product (GDP) and population density data were retrieved from the Organisation for Economic Cooperation and Development (OECD) Regional Statistics Database (Anon, n.d.). Temperature data for summer (June, July and August) were sourced from WorldClim (www.worldclim.org).

3. Results

The Scopus search for scientific literature containing keywords from both domains – climate and vegetation – revealed 18,245 publications altogether from 1901 to 2022. Conference papers were excluded, which reduced the total number of publication records to 15,889 (most recent update: September 29, 2022). Subsequent to the semantic extraction strategy, 6,078 publications were finally included in our study for further analysis (Fig. 1). The statistics were visualized using Tableau (Version 2022.1) and the ggplots package (Wickham 2016) in R studio.

3.1. The spatial distribution and growth ratio of cities in UHI-related research

After running the code for semantics filtering, a total of 1,726 cities with 8,257 appearances in 6,078 publications were extracted in the last 120 years. The 120 years of research were divided into four timeframes: 1901-1992; 1993-2002; 2003-2012; and 2013-2022 (1901-1992 constituted one timeframe due to the small amount of

246 literature, while the others were grouped per decade). The appearance of each city is
247 indicated by a dot on a map, while a further division of the cities into ‘first
248 appearance’ and ‘recurrent appearance’ is represented by blue and orange dots,
249 respectively (Fig. 3). In other words, the same city was identified as a first occurrence
250 in the earliest timeframe that was extracted, and then as a reoccurrence if it was
251 extracted in other timeframes. The results of a further analysis performed on abstract
252 records are also shown on a map (Fig. 4), with the different colored dots representing
253 the analysis conducted in that city for air temperature (AT), land surface temperature
254 (LST), air temperature and land surface temperature (AT+LST), or other studies
255 which did not mention AT or LST (Other). Results show a remarkable growth over
256 time in the number of cities in which the UHI effect was studied (Figs. 3 and 4).

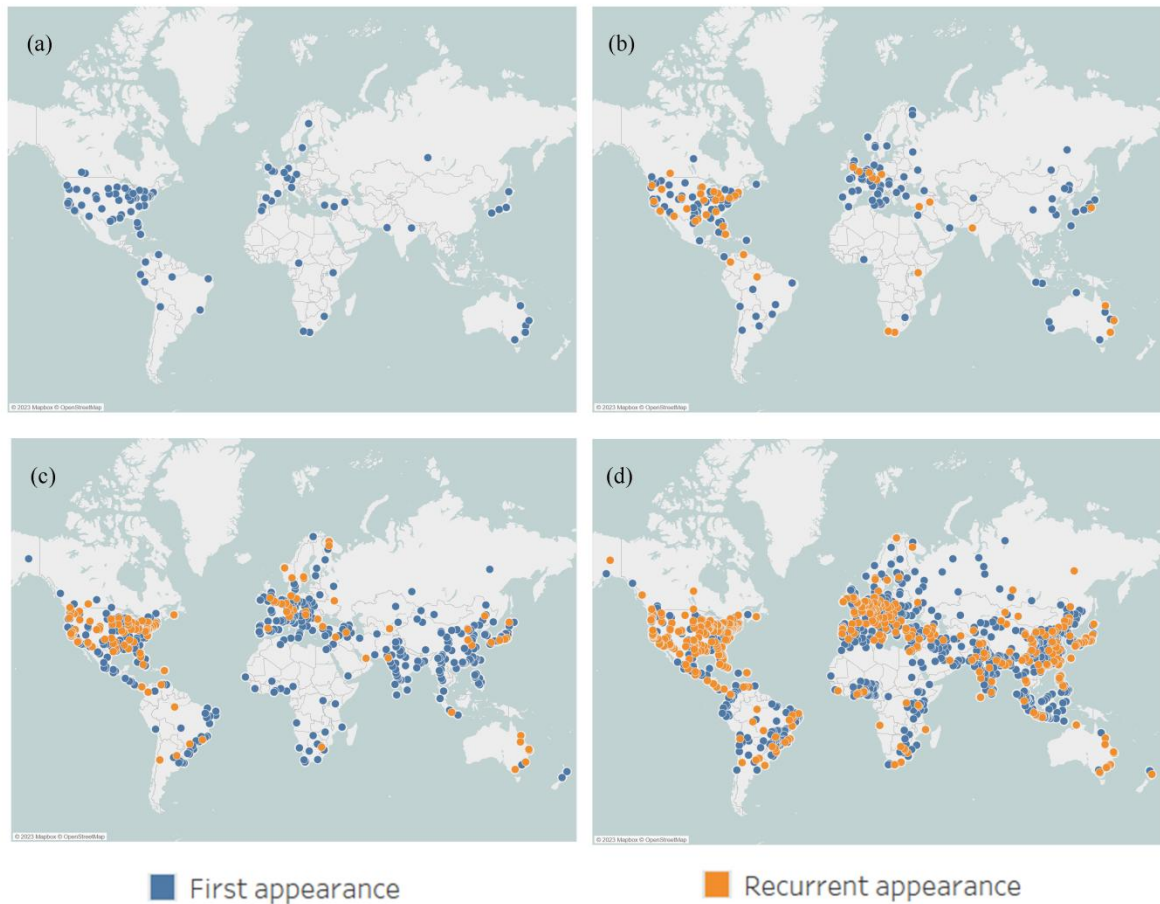


Figure 3. Cities that appear in publications in which the UHI effect was studied. The blue and orange dots represent the first appearance of cities and the recurrent appearance of cities, respectively, for the timeframes (a) 1901-1992, (b) 1993-2002, (c) 2003-2012, and (d) 2013-2022.

Over the past century, new cities have been continuously included in research related to UHI worldwide, indicating that an increasing number of cities are affected by UHIs and, more specifically, that the UHI is becoming a growing phenomenon in the majority of cities where it has never occurred before. At the same time, the number of cities which have been repeatedly studied has also grown (see Fig. 3), although these (recurrent appearances) have been outnumbered by the new cities (first appearances). This secondary finding proves that the UHI effect has long captured the interest of scientists. Furthermore, research of the early timeframes (1901-2002) on

the UHI specifically investigating AT and LST shows that the number of appearances of both terms was more similar than in the latest timeframes (2003-2022), where scientists tended to focus on LST more frequently due to the global availability of thermal infrared satellite images.

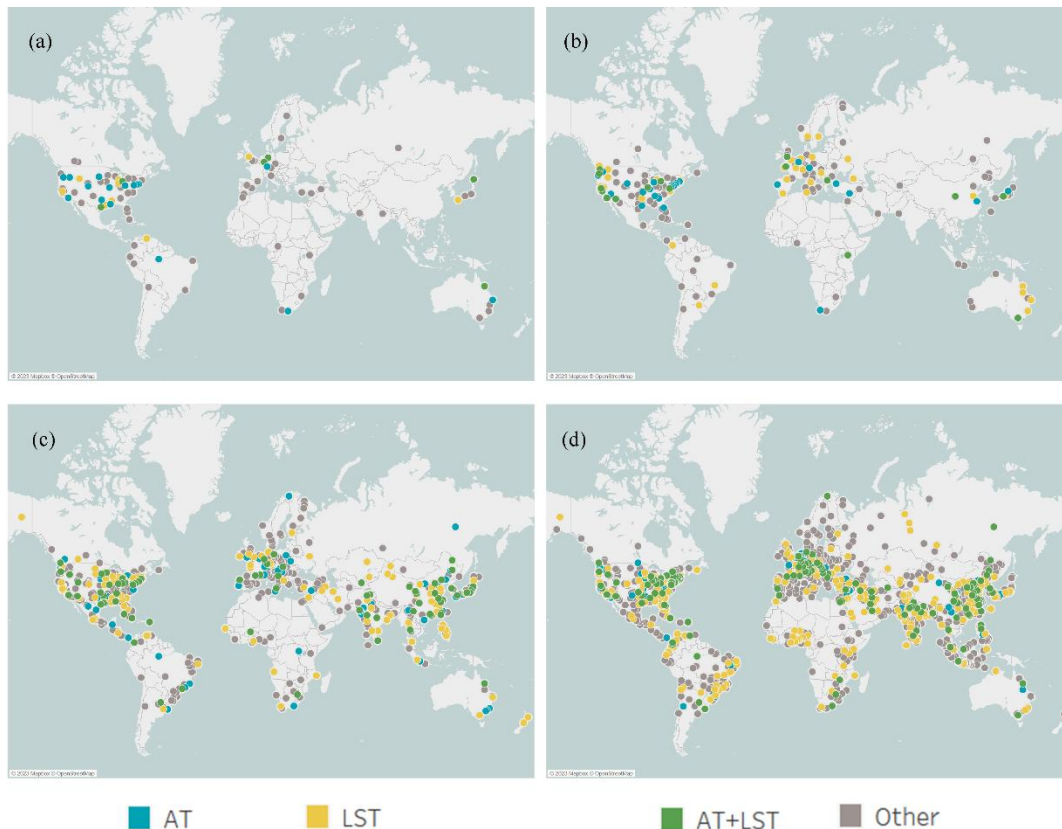


Figure 4. Cities that appear in publications in which the UHI effect was studied. The sky-blue, yellow, green and gray dots represent the cities where the research included air temperature (AT), land surface temperature (LST), air temperature and land surface temperature (AT+LST), but not AT or LST (Other), respectively, for the timeframes (a) 1901-1992, (b) 1993-2002, (c) 2003-2012, and (d) 2013-2022.

After examining the spatial distribution of the cities studied in the UHI, we proceeded to explore the number of these cities and the proportion of their growth over time (Fig. 5). The results of our analysis show that the number of cities that appeared for the first time in publications was consistently higher than the number of

cities that appeared repeatedly (n = 187 vs. 49, 1993-2002 timeframe; n = 440 vs. 143, 2003-2012 timeframe; n = 965 vs. 431, 2013-2022 timeframe). The difference in this number was consistently more than double, except for the first timeframe where no cities were considered to be recurrent (n = 134 vs. 0, 1901-1992 timeframe). In the 2003-2012 and 2013-2022 timeframes, the percentage increase in recurring cities was even more striking, at 191.8% and 201.4%, respectively. At the same time, the growth ratio of first appearance cities never fell below 100%, except for the 1993-2002 timeframe, indicating that scientists have never lost interest in studying the UHI effect.

Meanwhile, the term LST was always used more often than the term AT, except in the first timeframe (Fig. 5), where scientists focused more on AT. Also, the growth ratio of LST appearance was constantly higher than the appearance of all other terms, except the last timeframe, which may be due to the rapid development of remote sensing technology and its application in the field of urban forestry. Although the number of studies investigating AT+LST was always the lowest, the results show that scientists have worked on combining AT and LST in conducting UHI research.

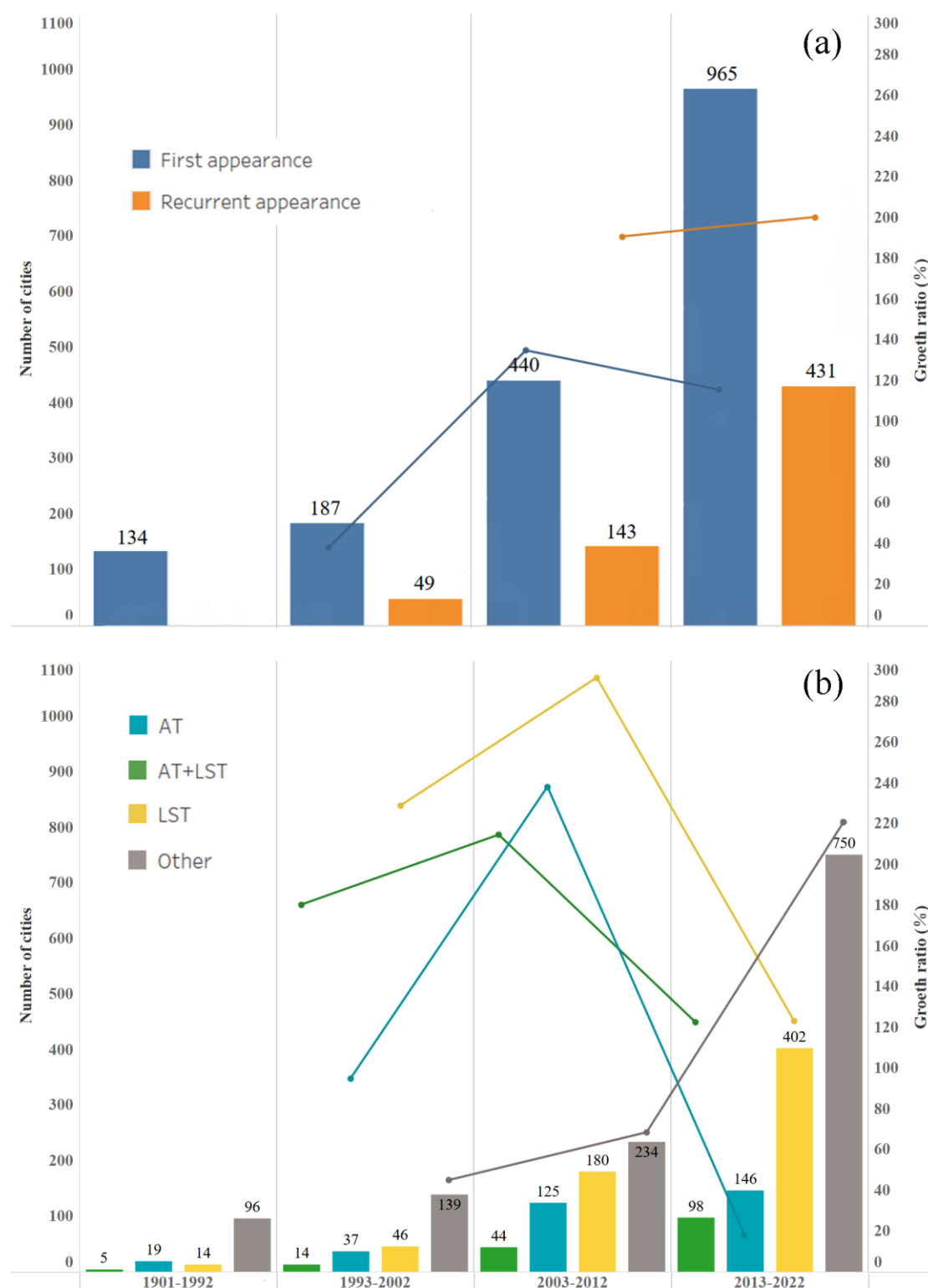


Figure 5. Number and growth ratio of cities with different times of appearance (a) and different terms (b) in the four timeframes under study (1901-2022). AT, air temperature; LST, land surface temperature; AT+LST, air temperature and land surface temperature; and Other, other studies which did not mention AT or LST.

3.2. The latitude and altitude distribution of cities in UHI-related research

The latitudes of cities where scientists conducted UHI-related research during different timeframes were compared in a probability density diagram (Fig. 6). The density curve as a whole was negatively skewed, with skewness increasing over time (Table 1). This indicates that most of the cities extracted from the publications are distributed in the northern hemisphere and vary in decreasing latitude with time. The peaks of the density plot (Fig. 6) display where the values are concentrated over the intervals. The overall shape of the curve illustrates that the density distribution patterns of the latitudes of cities in the publications for all timeframes are single-peaked, concentrating around the 40° latitude. The standard deviation trended upward from 1901-1992 to 2013-2022 (Table 1), indicating that the latitudes of cities are gradually separating from the mean. This outcome implies that the latitudinal range of cities where scientists have conducted UHI-related research is expanding. The two curves representing the 1901-1992 and 1993-2002 timeframes, respectively, are the steepest. Over different timeframes, the height of the remaining curves decreased while their width increased, suggesting an increment in the differences in latitude between cities. In other words, more cities of different latitudes globally are being included in studies relating to UHI. Contrarily, the curve of the 2013-2022 timeframe is the lowest, implying that in the last decade the latitude range of cities has been the widest, and further confirming the above finding that at decreasing curve height a greater number of cities at different latitudes are being included in UHI-related research.

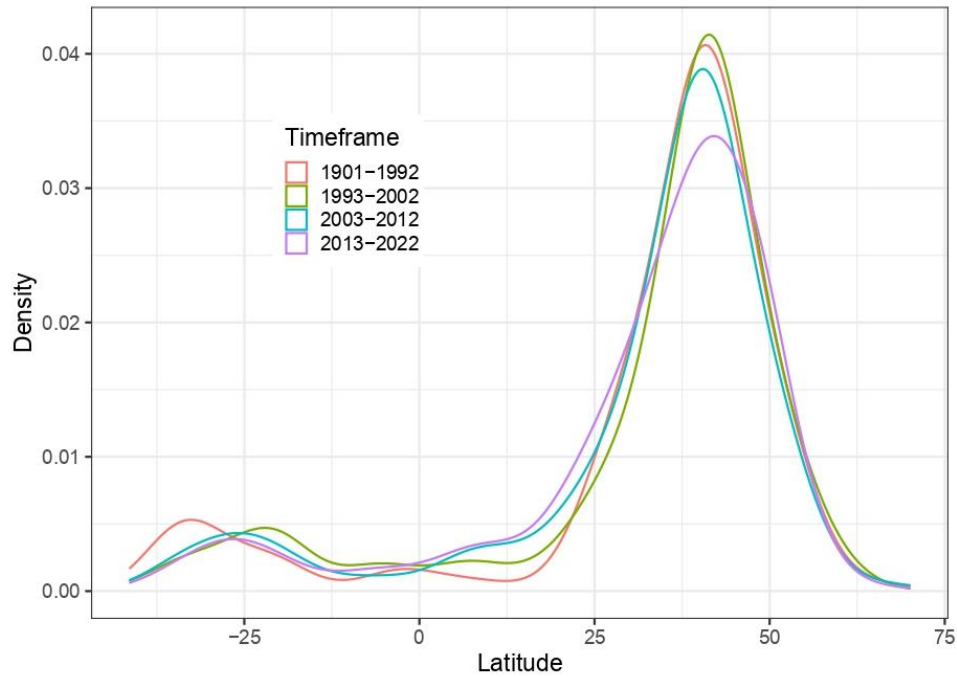


Figure 6. Latitude distribution by timeframe of cities mentioned in UHI-related research.

Table 1. Metrics of the latitude probability distribution of cities in UHI-related research.

Timeframe	Mean	StdDev	Kurtosis	Skewness
1901-1992	32.02	23.09	2.81	-1.95
1993-2002	32.42	21.99	2.27	-1.79
2003-2012	31.69	21.51	2.50	-1.79
2013-2022	31.97	20.85	2.48	-1.75

The same increasing trend over time observed for latitude can be observed for altitude ranges (Fig. 7), except for the 1901-1992 timeframe, which is likely due to the long time span and small amount of data. The density curves were positively skewed overall, with most of the data concentrated in the lower altitude range and the

skewness decreasing over time (Table 2). This indicates that the altitude of cities extracted from publications gradually extends to a higher range. The kurtosis of the altitude distribution (Table 2) was always greater than the kurtosis of the latitude (Table 1), implying a greater degree of difference between the steepness of its distribution pattern and that of the Gaussian distribution. This is explained by the fact that most of the world's cities are concentrated at low altitudes and do not follow the Gaussian distribution. Our research on the UHI effect in the two timeframes of 2003-2012 and 2013-2022 involves cities in a wider altitude range (Fig. 7). In addition to the height concentration observed for the 0- to 500-m altitude range, some peaks can be noted at other altitudes. For example, peaks around 700 m depicted in red representing the 1901-1992 timeframe and in green representing the 1993-2002 timeframe (Fig. 6) are due to the fact that cities in this altitude range (600-700 m), exemplified by Madrid, appear 11 and 22 times, respectively, in publications related to the UHI. Cities at the same altitude were studied 56 and 163 times in the 2003-2012 and 2013-2022 timeframes, respectively, without showing significant peaks, which proves that there are more publications related to the UHI phenomenon in the last two decades.

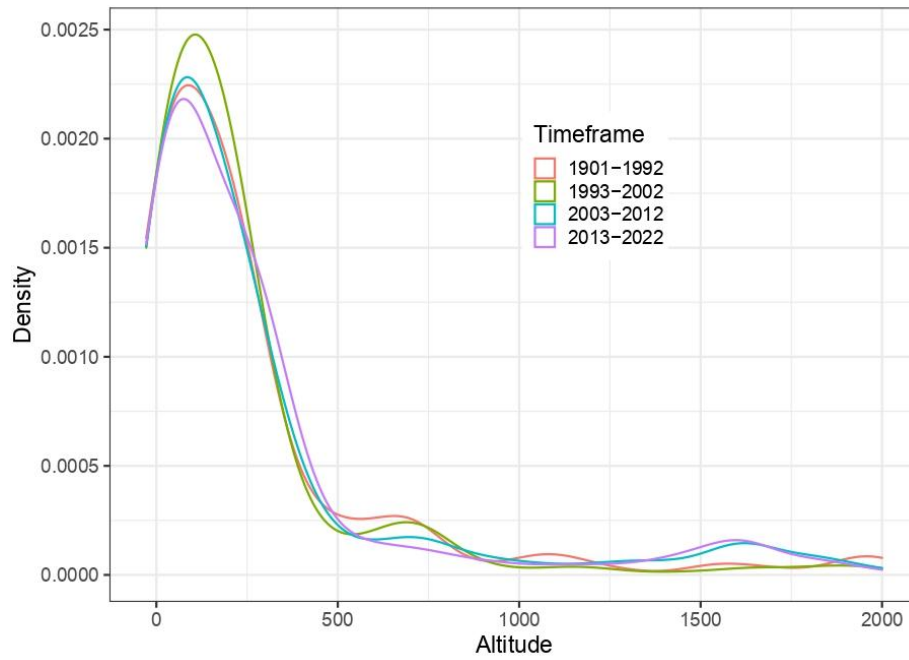


Figure 7. Altitude distribution density by timeframe of cities mentioned in UHI-related research.

Table 2. Metrics of the altitude probability distribution of cities in UHI-related research.

Timeframe	Mean	StdDev	Kurtosis	Skewness
1901-1992	326.49	552.61	13.64	3.37
1993-2002	269.62	434.14	11.77	3.32
2003-2012	361.28	568.68	6.29	2.51
2013-2022	326.65	513.28	9.42	2.84

From 1901 to the present day, most studies in which the UHI has been investigated have focused on cities at latitudes between 30° and 50° and at altitudes below 500 m. One possible reason is that the world's population is mainly distributed at this latitude and altitude range (Cohen & Small, 1998; Bill Rankin, 2008). In the past, many cities did not face the challenges caused by climate change, thus the earlier

studies focused on a narrower range of latitudes and altitudes. However, with the current increasing UHI trend being associated with rapid climate change and urbanization, scientists have begun to conduct relevant studies in cities where these challenges had not been previously considered.

3.3. The spatial locations (hotspots) across the globe where UHI-related research is concentrated in multiple cities

All city data in the 1901-2022 time period were combined and the Shannon evenness index was calculated in grid units and displayed on a map (Fig. 8). The grids were divided into four quartile classes: 1st quartile 0-0.59; 2nd quartile 0.6-0.83; 3rd quartile 0.84-0.96; and 4th quartile 0.97-1.00, representing high-to-low evenness, while an additional gray grid represents ‘no city studied’. The three continents – North America, Europe and Asia – containing the greatest number of hotspots (i.e., locations with an evenness index ≥ 0.59) were zoomed in to visualize the details.

The Shannon evenness index was used to measure the extent to which the number of cities in a region where UHI-related research was conducted was evenly distributed among those affected by UHI (cities subjected to at least one UHI study). The value of the index ranges from 0 to 1, with 0 indicating minimal diversity and 1 indicating maximal diversity. When UHI-related research in a region is concentrated in a single city, the value is 0, and when UHI-related research is conducted in all cities of our database and the number of studies is evenly distributed among them, the value is 1. Therefore, the hotspot locations are those having a higher concentration of UHI-

related research focusing on multiple cities rather than a single city. In other words, hotspot areas are likely to reflect the UHI characteristics of the entire region to a larger extent and the cities of the region studied are more evenly distributed.

As shown in Figure 8, most of the hotspots are concentrated in all three continents. Furthermore, the hotspots in North America are almost entirely in the United States. In Europe, most of the hotspots are concentrated in Western Europe, such as the United Kingdom, Spain and the Netherlands, while in Asia they are located in China, Japan, Indonesia and India.

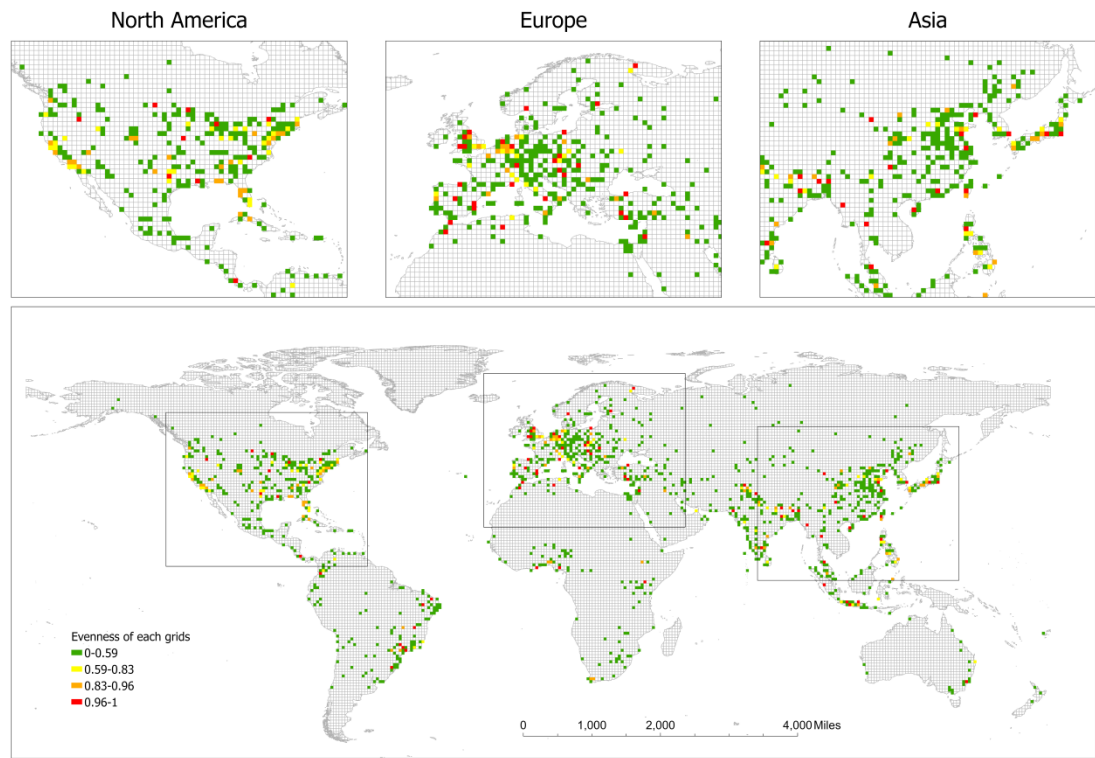


Figure 8. Evenness of cities worldwide where UHI-related research was conducted from 1901 to 2022.

3.4. Economic, demographic and environmental drivers underlying hotspot/non-hotspot distribution in the European continent

A dynamic analysis of economic, demographic and environmental drivers underlying

hotspot/non-hotspot distribution was conducted using GDP, population density, and minimum and maximum summer temperatures as (surrogate) proxies. The analysis was conducted with a focus on the European continent beginning in 2001 (for GDP, population density and summer temperature) and ending in 2018 (for summer temperatures only) and in 2021 (for GDP and population density). Grids with an evenness index ≤ 0.59 (Fig. 8) were considered as non-hotspots and are represented by green lines (Fig. 9), while hotspots are represented by red lines (Fig. 9).

The results show a clear upward trend in GDP and population density for both hotspots and non-hotspots, with two exceptions. The negative growth in GDP and population in 2011 could relate to the impact of the European sovereign debt crisis, while that of 2021 might be due to the COVID-19 pandemic. However, hotspots demonstrated a consistently higher growth rate in comparison to non-hotspots. This trend may be attributed to the rapid economic expansion of hotspots, which tends to attract more population and resources, thereby exacerbating the UHI effect.

The analysis of summer temperature trends between hotspots and non-hotspots showed a surprisingly consistent pattern, with only minor differences observed. This finding suggests that the impact of changes in summer temperature on the extent of concentration of UHI-related research may not be relevant. However, even in 2004, the year with the highest rate of change, the summer temperature only changed by 2.1° ; therefore, the temperature change over a 20-year period was not considered significant. When comparing GDP and population density with summer temperature, the latter can be regarded as an insignificant driver.

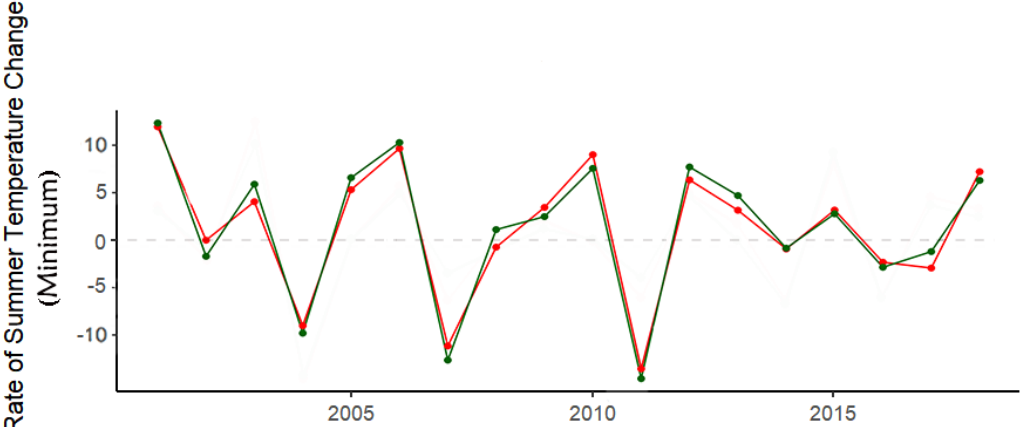
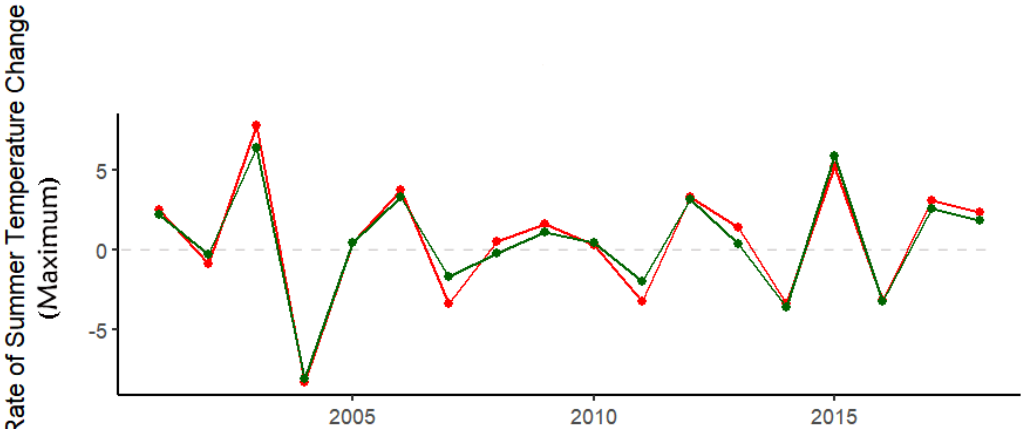
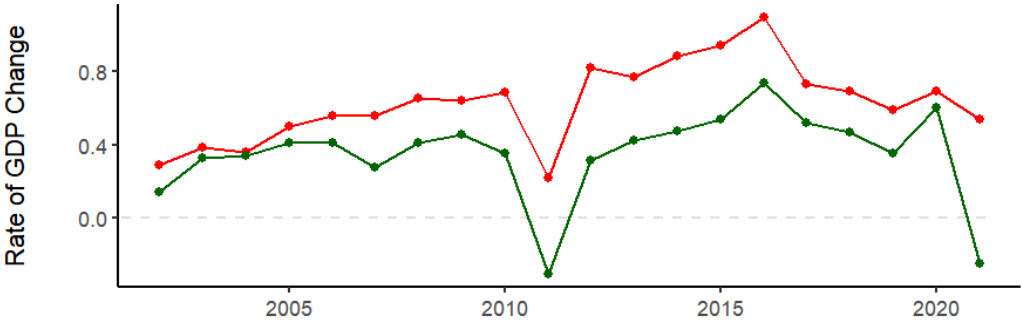
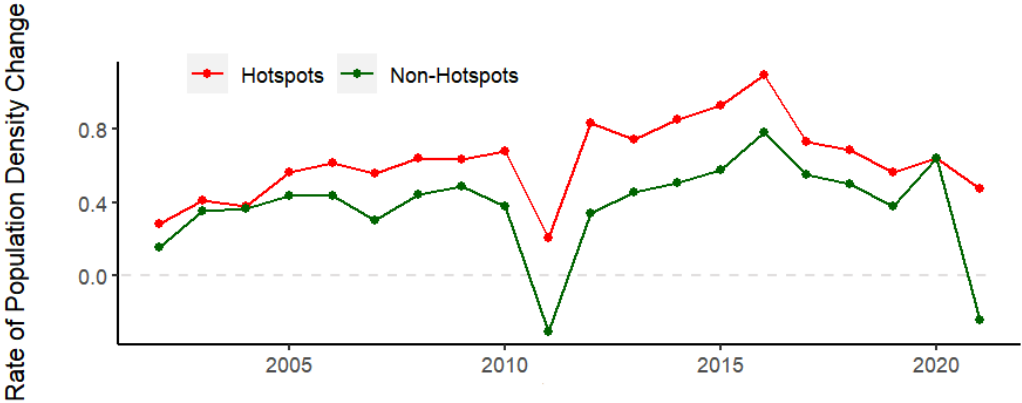


Figure 9. Changes in gross domestic product (GDP), population density, and summer temperatures (minimum and maximum) in hotspots and non-hotspots over the last two decades beginning in 2001 (for GDP, population density and summer temperature) and ending in 2018 (for summer temperature) and in 2021 (for GDP and population density).

4. Discussion and conclusions

Previous studies on the UHI in relation to climate change, shedding light on its global phenomenology by analyzing thermal behavior aggregated at city scale or over seasonal or annual time periods (Mentaschi et al., 2022). For example, Zhang et al. (2010) assessed SUHI globally, while Clinton and Gong (2013) investigated urban areas with latitudes between 71° and -55° to characterize urban surface heat differences and identify urban environmental variables that are globally significant for diagnosing and predicting SUHI, but limited to one year: 2010. New research based on a global long-term dataset of daytime UHI delves into the space–time variability of urban–rural temperature differences, which is unprecedented at global scale (Mentaschi et al., 2022). Further study, proceeding from a literature review using data from 16 countries worldwide, analyzed UHI’s global trend and provides insight on how it is linked with pollution (Ulpiani, 2021). The research we propose herein is rather based on an extensive and highly comprehensive global literature review and presents a unique aspect of the global UHI trend by focusing on its occurrences at different latitudes and altitudes over time. Our study results are solid and impressive. They not only confirm the rapid growth of global research related to UHI over the last century and beyond, as represented by much of the collected literature

(Aleksandrowicz et al., 2017; Deilami et al., 2018; Mohajerani et al., 2017), but also and perhaps more importantly demonstrate the unrelenting expansion of the UHI phenomenon to different geographical regions. Specifically, we have pioneered an analysis on the number of cities related to UHI research rather than concentrate on the number of publications as has been done in other review articles (Balany et al., 2020; Santamouris, 2013; Ward et al., 2016) to gain a more intuitive understanding of the worldwide expansion of UHI. Furthermore, the latitude and altitude of these cities were investigated to track the dynamic trend of UHI expansion, with most of the research at the beginning of the 20th century focusing on a latitude range from 25° to 50° and then expanding to lower and higher latitudes, as mentioned in other literature (Arnfield, 2003; Stewart, 2019). In this manner, our work has demonstrated how the UHI has affected an increasing number of cities across the globe during the course of 120 years.

In the time period (1901-2022) selected for our study, the results showed an increasing number of cities where UHI research was conducted (Figs. 3 and 4). While earlier studies were more often conducted for air temperature data collection, the later satellite era gave rise to more SUHI studies (Fig. 4). However, some geographical areas still exist where UHI has not been investigated (Fig. 3), perhaps because they are not affected by this phenomenon or as a result of lack of funding to conduct related research. Nevertheless, in recent decades the number of cities experiencing UHI has continued to increase, suggesting that its expansion will not come to a halt, at least in the short term.

To explore the spatial locations that have attracted widespread scientific interest in UHI during the last century, we identified hotspots and non-hotspots at global scale based on a widely used diversity index – Shannon evenness. The focus on Europe served as an example to explore the economic, demographic, and environmental drivers underlying the distribution of hotspots and non-hotspots. Our analysis reveals that the growth of GDP and population density is positively associated with scientists' interest in the UHI phenomenon. However, we also found that the increase in summer temperature (both minimum and maximum) did not correspond to the expansion of the UHI effect, which is inconsistent with the results of other studies, such as that of Zhou (2014), who argued that climate has an overwhelming control on the spatial variability of UHI. One potential reason for this divergence of trends stems from the public perception that apparent temperature is influenced by humidity, wind, and radiation in addition to land surface temperature (Steadman, 1979). Another reason could be the limited resolution of the temperature data obtained from satellite images. In particular, the monthly temperature data from Worldclim have a resolution of only 21 km², and many of the urban biophysical elements that contribute to temperature variability are smaller than 60 m (Small, 2009). We intend to further investigate this aspect of the analysis, which is currently limited by lack of available data, by introducing other variables in order to acquire an in-depth understanding thereof. This research will likely point to important health and well-being implications of the UHI effect for urban residents.

Although the concept of UHI was first introduced in 1958 (see Manley), the increase of higher temperatures in urban centers compared to suburban areas has been documented as early as 1833 (see Howard). For this reason, all relevant literature has been included and analyzed to the greatest extent possible to afford this study the most comprehensive perspective. Moreover, it is highly improbable for any database to contain all the early research because of the limits of technology. Some literature was not included in the Scopus database we employed, or if it was, no mention was found of cities being investigated for UHI, whether in the abstracts, keywords and titles, or references made to provinces and regions; therefore, this literature was not added to our study. Evidently, this could represent a study limitation, but we believe that for our intents and purposes the final database of 6,078 publications is highly satisfactory.

Our study points out that research gaps exist in some geographic regions, especially in the concentrated latitudinal and altitudinal range of UHI-related studies, and that further in-depth studies are warranted. Meanwhile, research on the UHI effect has become increasingly important and urgent due to the rapid advance in climate change and urbanization (Chapman et al., 2017; Grimmond, 2007; Ren, 2015), which necessitated an understanding of its history and trends. Hence, this work provides a broader perspective in time of UHI as a global phenomenon, which may enable scientists dedicated to urban forestry research and climate change to be more intuitive about UHI's impacts on current society and the environment as well as its expanding trend. From their own perspective, policy makers and practitioners will be encouraged

to become more vigilant in formulating appropriate mitigation and adaptation strategies. In point of fact, this study underscores the urgency of developing targeted mitigation and adaptation strategies to address the challenges posed by UHI and highlights the need for collaborative efforts among various stakeholders to achieve this goal.

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References

- Akbari, H., M. Pomerantz, and H. Taha. 2001. “Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas.” *Solar Energy* 70(3):295–310. doi: 10.1016/S0038-092X(00)00089-X.
- Aleksandrowicz, O., M. Vuckovic, K. Kiesel, and A. Mahdavi. 2017. “Current Trends in Urban Heat Island Mitigation Research: Observations Based on a Comprehensive Research Repository.” *Urban Climate* 21:1–26. doi: 10.1016/j.uclim.2017.04.002.
- Anon. n.d. “OECD Regional Statistics.” Retrieved March 12, 2023 (<https://www.oecd->

538 ilibrary.org/urban-rural-and-regional-development/data/oecd-regional-
 539 statistics_region-data-en).
 540 Arnfield, A. J. 2003. “Two Decades of Urban Climate Research: A Review of
 541 Turbulence, Exchanges of Energy and Water, and the Urban Heat Island.” *International*
 542 *Journal of Climatology* 23(1):1–26. doi: 10.1002/joc.859.
 543 Balany, F., A. W. M. Ng, N. Muttill, S. Muthukumaran, and M. S. Wong. 2020. “Green
 544 Infrastructure as an Urban Heat Island Mitigation Strategy—a Review.” *Water*
 545 *(Switzerland)* 12(12). doi: 10.3390/w12123577.
 546 Balchin, W. G. V., and Norman Pye. 1947. “A Micro-Climatological Investigation of
 547 Bath and the Surrounding District.” *Quarterly Journal of the Royal Meteorological*
 548 *Society* 73(317–318):297–323. doi: 10.1002/qj.49707331706.
 549 Barbierato, Elena, Iacopo Bernetti, Irene Capecchi, and Claudio Saragosa. 2019.
 550 “Quantifying the Impact of Trees on Land Surface Temperature: A Downscaling
 551 Algorithm at City-Scale.” *European Journal of Remote Sensing* 52:74–83. doi:
 552 10.1080/22797254.2019.1646104.
 553 Besson, L. 1931. “L’altération du climat d’une grande ville [Change of climate of a
 554 large town].” *Annales d’Hygiene Publique, Industrielle et Sociale* 9:405–38.
 555 Bowler, Diana E., Lisette Buyung-Ali, Teri M. Knight, and Andrew S. Pullin. 2010.
 556 “Urban Greening to Cool Towns and Cities: A Systematic Review of the Empirical
 557 Evidence.” *Landscape and Urban Planning* 97(3):147–55. doi:
 558 10.1016/j.landurbplan.2010.05.006.
 559 Broadbent, Ashley M., Andrew M. Coutts, Nigel J. Tapper, and Matthias Demuzere.

2018. “The Cooling Effect of Irrigation on Urban Microclimate during Heatwave
 Conditions.” *Urban Climate* 23:309–29. doi: 10.1016/j.uclim.2017.05.002.

Brondizio, Eduardo S., Maria Carmen Lemos, Dabo Guan, Neil Jennings, Cheikh
 Mbow, Harini Nagendra, and Petra Tschakert. 2021. “Global Environmental Change:
 30 Years of Interdisciplinary Research on the Human and Policy Dimensions of
 Environmental Change.” *Global Environmental Change* 71:102416. doi:
 10.1016/j.gloenvcha.2021.102416.

Budel, A., and J. Wolf. 1933. “Münchener Stadtklimatische Studien [Munich Town
 Climatic Studies].” *Zeitschrift Für Angewandte Meteorologie* 4–10.

Chapman, Sarah, James E. M. Watson, Alvaro Salazar, Marcus Thatcher, and Clive A.
 McAlpine. 2017. “The Impact of Urbanization and Climate Change on Urban
 Temperatures: A Systematic Review.” *Landscape Ecology* 32(10):1921–35. doi:
 10.1007/s10980-017-0561-4.

Chen, Yanhua, Wendy Y. Chen, Vincenzo Giannico, and Raffaele Laforzezza. 2022.
 “Modelling Inter-Pixel Spatial Variation of Surface Urban Heat Island Intensity.”
Landscape Ecology 37(8):2179–94. doi: 10.1007/s10980-022-01464-2.

Clinton, Nicholas, and Peng Gong. 2013. “MODIS Detected Surface Urban Heat
 Islands and Sinks: Global Locations and Controls.” *Remote Sensing of Environment*
 134:294–304. doi: 10.1016/j.rse.2013.03.008.

Cohen, Joel E., and Christopher Small. 1998. “Hypsographic Demography: The
 Distribution of Human Population by Altitude.” *Proceedings of the National Academy
 of Sciences of the United States of America* 95(24):14009–14.

582 Deilami, Kaveh, Md Kamruzzaman, and Yan Liu. 2018. "Urban Heat Island Effect: A
 583 Systematic Review of Spatio-Temporal Factors, Data, Methods, and Mitigation
 584 Measures." *International Journal of Applied Earth Observation and Geoinformation*
 585 67:30–42. doi: 10.1016/j.jag.2017.12.009.

586 Donovan, Geoffrey H., and David T. Butry. 2009. "The Value of Shade: Estimating the
 587 Effect of Urban Trees on Summertime Electricity Use." *Energy and Buildings*
 588 41(6):662–68. doi: 10.1016/j.enbuild.2009.01.002.

589 Doulos, L., M. Santamouris, and I. Livada. 2004. "Passive Cooling of Outdoor Urban
 590 Spaces. The Role of Materials." *Solar Energy* 77(2):231–49. doi:
 591 10.1016/j.solener.2004.04.005.

592 Fukui, Eiichirô. 1941. "Horizontal Distribution of the Air Temperature in Greater Cities
 593 of Japan." *Geographical Review of Japan* 17(5):354–72. doi: 10.4157/grj.17.354.

594 GeoNames. 2009. "GeoNames."

595 Gill, S. E., J. F. Handley, A. R. Ennos, and S. Pauleit. n.d. "Adapting Cities for Climate
 596 Change: The Role of the Green Infrastructure." *CLIMATE CHANGE AND CITIES*
 597 33(1):19.

598 Givoni, B. 1991. "Impact of Planted Areas on Urban Environmental Quality: A Review."
 599 *Atmospheric Environment. Part B. Urban Atmosphere* 25(3):289–99. doi:
 600 10.1016/0957-1272(91)90001-U.

601 Grimmond, Sue. 2007. "Urbanization and Global Environmental Change: Local Effects
 602 of Urban Warming." *Geographical Journal* 173:83–88. doi: 10.1111/j.1475-
 603 4959.2007.232_3.x.

604 Guo-Yu, Ren. 2015. "Urbanization as a Major Driver of Urban Climate Change."
605 *Advances in Climate Change Research* 6(1):1–6. doi: 10.1016/j.accre.2015.08.003.

606 Hirano, Y., and T. Fujita. 2012. "Evaluation of the Impact of the Urban Heat Island on
607 Residential and Commercial Energy Consumption in Tokyo." *Energy* 37(1):371–83.
608 doi: 10.1016/j.energy.2011.11.018.

609 Howard, Luke. 1833. *The Climate of London: Deduced from Meteorological*
610 *Observations Made in the Metropolis and at Various Places Around It*. Harvey and
611 Darton, J. and A. Arch, Longman, Hatchard, S. Highley [and] R. Hunter.

612 Huang, Chudong, and Xinyue Ye. 2015. "Spatial Modeling of Urban Vegetation and
613 Land Surface Temperature: A Case Study of Beijing." *Sustainability* 7(7):9478–9504.
614 doi: 10.3390/su7079478.

615 Huang, Qunfang, and Yuqi Lu. 2018. "Urban Heat Island Research from 1991 to 2015:
616 A Bibliometric Analysis." *Theoretical and Applied Climatology* 131(3):1055–67. doi:
617 10.1007/s00704-016-2025-1.

618 IPCC. 2013. *Climate Change 2013: The Physical Science Basis*.

619 Jin, Kai, Fei Wang, Deliang Chen, Qiao Jiao, Lei Xia, Luuk Fleskens, and Xingmin Mu.
620 2015. "Assessment of Urban Effect on Observed Warming Trends during 1955–2012
621 over China: A Case of 45 Cities." *Climatic Change* 132(4):631–43.

622 KC, B., and M. Ruth. 2015. "Modeling of Urban Heat Island at Global Scale."
623 2015:B32D-03.

624 Kong, F., H. Yin, P. James, L. R. Hutyra, and H. S. He. 2014. "Effects of Spatial Pattern
625 of Greenspace on Urban Cooling in a Large Metropolitan Area of Eastern China."

626 *Landscape and Urban Planning* 128:35–47. doi: 10.1016/j.landurbplan.2014.04.018.

627 Lemos, Maria Carmen, Hallie Eakin, Lisa Dilling, and Jessica Worl. 2019. “Social
628 Sciences, Weather, and Climate Change.” *Meteorological Monographs* 59(1):26.1-
629 26.25. doi: 10.1175/AMSMONOGRAPHS-D-18-0011.1.

630 Li, Ying, Yanwei Sun, Jialin Li, and Chao Gao. 2020. “Socioeconomic Drivers of Urban
631 Heat Island Effect: Empirical Evidence from Major Chinese Cities.” *Sustainable Cities
632 and Society* 63:102425. doi: 10.1016/j.scs.2020.102425.

633 Lowry, William P. 1977. “Empirical Estimation of Urban Effects on Climate: A Problem
634 Analysis.” *Journal of Applied Meteorology (1962-1982)* 16(2):129–35.

635 Manley, G. 1958. “On the Frequency of Snowfall in Metropolitan England.” *Quarterly
636 Journal of the Royal Meteorological Society* 84(359):70–72. doi:
637 10.1002/qj.49708435910.

638 Marcotullio, Peter J., Carsten Keßler, and Balázs M. Fekete. 2021. “The Future Urban
639 Heat-Wave Challenge in Africa: Exploratory Analysis.” *Global Environmental Change*
640 66:102190. doi: 10.1016/j.gloenvcha.2020.102190.

641 Mentaschi, Lorenzo, Grégory Duveiller, Grazia Zulian, Christina Corbane, Martino
642 Pesaresi, Joachim Maes, Alessandro Stocchino, and Luc Feyen. 2022. “Global Long-
643 Term Mapping of Surface Temperature Shows Intensified Intra-City Urban Heat Island
644 Extremes.” *Global Environmental Change* 72:102441. doi:
645 10.1016/j.gloenvcha.2021.102441.

646 Mohajerani, Abbas, Jason Bakaric, and Tristan Jeffrey-Bailey. 2017. “The Urban Heat
647 Island Effect, Its Causes, and Mitigation, with Reference to the Thermal Properties of

648 Asphalt Concrete.” *Journal of Environmental Management* 197:522–38. doi:
649 10.1016/j.jenvman.2017.03.095.

650 Neinavaz, E., M. Schlerf, R. Darvishzadeh, M. Gerhards, and A. K. Skidmore. 2021.
651 “Thermal Infrared Remote Sensing of Vegetation: Current Status and Perspectives.”
652 *International Journal of Applied Earth Observation and Geoinformation* 102. doi:
653 10.1016/j.jag.2021.102415.

654 Norton, Briony A., Andrew M. Coutts, Stephen J. Livesley, Richard J. Harris, Annie M.
655 Hunter, and Nicholas S. G. Williams. 2015. “Planning for Cooler Cities: A Framework
656 to Prioritise Green Infrastructure to Mitigate High Temperatures in Urban Landscapes.”
657 *Landscape and Urban Planning* 134:127–38. doi: 10.1016/j.landurbplan.2014.10.018.

658 Oke, T. R. 1976. “The Distinction between Canopy and Boundary-Layer Urban Heat
659 Islands.” *Atmosphere* 14(4):268–77. doi: 10.1080/00046973.1976.9648422.

660 Oke, T. R. 1982. “The Energetic Basis of the Urban Heat Island.” *Quarterly Journal of*
661 *the Royal Meteorological Society* 108(455):1–24. doi: 10.1002/qj.49710845502.

662 Oke, T. R. 1995. “Classics in Physical Geography Revisited: Sundborg, Å. 1951:
663 Climatological Studies in Uppsala with Special Regard to the Temperature Conditions
664 in the Urban Area. *Geographica* 22.” *Progress in Physical Geography: Earth and*
665 *Environment* 19(1):107–13. doi: 10.1177/030913339501900105.

666 Oliveira, Sandra. 2011. “The Cooling Effect of Green Spaces as a Contribution to the
667 Mitigation of Urban Heat: A Case Study in Lisbon.” *Building and Environment* 9.

668 Peng, Shushi, Shilong Piao, Philippe Ciais, Pierre Friedlingstein, Catherine Ottle,
669 Francois-Marie Breon, Huijuan Nan, Liming Zhou, and Ranga B. Myneni. 2012.

670 “Surface Urban Heat Island Across 419 Global Big Cities.” *Environmental Science &*
671 *Technology* 46(2):696–703. doi: 10.1021/es2030438.

672 Qi, J. D., B. J. He, M. Wang, J. Zhu, and W. C. Fu. 2019. “Do Grey Infrastructures
673 Always Elevate Urban Temperature? No, Utilizing Grey Infrastructures to Mitigate
674 Urban Heat Island Effects.” *Sustainable Cities and Society* 46. doi:
675 10.1016/j.scs.2018.12.020.

676 Radhi, Hassan, Fayze Fikry, and Stephen Sharples. 2013. “Impacts of Urbanisation on
677 the Thermal Behaviour of New Built up Environments: A Scoping Study of the Urban
678 Heat Island in Bahrain.” *Landscape and Urban Planning* 113:47–61. doi:
679 10.1016/j.landurbplan.2013.01.013.

680 Ren, G. Y., Z. Y. Chu, Z. H. Chen, and Y. Y. Ren. 2007. “Implications of Temporal
681 Change in Urban Heat Island Intensity Observed at Beijing and Wuhan Stations.”
682 *Geophysical Research Letters* 34(5). doi: 10.1029/2006GL027927.

683 Ren, Zhibin, Xingyuan He, Haifeng Zheng, Dan Zhang, Xingyang Yu, Guoqiang Shen,
684 and Ruichao Guo. 2013. “Estimation of the Relationship between Urban Park
685 Characteristics and Park Cool Island Intensity by Remote Sensing Data and Field
686 Measurement.” *Forests* 4(4):868–86. doi: 10.3390/f4040868.

687 Rossi, F., A. L. Pisello, A. Nicolini, M. Filippini, and M. Palombo. 2014. “Analysis of
688 Retro-Reflective Surfaces for Urban Heat Island Mitigation: A New Analytical Model.”
689 *Applied Energy* 114:621–31. doi: 10.1016/j.apenergy.2013.10.038.

690 Santamouris, M. 2013. “Using Cool Pavements as a Mitigation Strategy to Fight Urban
691 Heat Island-A Review of the Actual Developments.” *Renewable & Sustainable Energy*

692 *Reviews* 26:224–40. doi: 10.1016/j.rser.2013.05.047.

693 Schmidt, W. 1927. “Die Verteilung der Minimumtemperaturen in der Frostnacht des
694 12.5.1927 im Gemeindegebiet von Wien.” *Fortschr. Landwirtsch.* 2(21):681–86.

695 Schwarz, Nina, Uwe Schlink, Ulrich Franck, and Katrin Großmann. 2012.
696 “Relationship of Land Surface and Air Temperatures and Its Implications for
697 Quantifying Urban Heat Island Indicators—An Application for the City of Leipzig
698 (Germany).” *Ecological Indicators* 18:693–704. doi: 10.1016/j.ecolind.2012.01.001.

699 Shannon, C. E. 1948. “A Mathematical Theory of Communication.” *The Bell System*
700 *Technical Journal* 27(3):379–423. doi: 10.1002/j.1538-7305.1948.tb01338.x.

701 Shi, Yi, Shuguang Liu, Wende Yan, Shuqing Zhao, Ying Ning, Xi Peng, Wei Chen,
702 Liding Chen, Xijun Hu, Bojie Fu, Robert Kennedy, Yihe Lv, Juyang Liao, Chunliang
703 Peng, Isabel M. D. Rosa, David Roy, Shouyun Shen, Andy Smith, Cheng Wang, Zhao
704 Wang, Li Xiao, Jingfeng Xiao, Lu Yang, Wenping Yuan, Min Yi, Hankui Zhang,
705 Meifang Zhao, and Yu Zhu. 2021. “Influence of Landscape Features on Urban Land
706 Surface Temperature: Scale and Neighborhood Effects.” *Science of The Total*
707 *Environment* 771:145381. doi: 10.1016/j.scitotenv.2021.145381.

708 Small, An Overview of Urban Spectral Diversity Christopher. 2009. “The Color of
709 Cities.” in *Global Mapping of Human Settlement*. CRC Press.

710 Steadman, R. G. 1979. “The Assessment of Sultriness. Part II: Effects of Wind, Extra
711 Radiation and Barometric Pressure on Apparent Temperature.” *Journal of Applied*
712 *Meteorology* 18:874–85. doi: 10.1175/1520-0450(1979)018<0874:TAOSPI>2.0.CO;2.

713 Stewart, I. D. 2011. “A Systematic Review and Scientific Critique of Methodology in

714 Modern Urban Heat Island Literature.” *International Journal of Climatology*
715 31(2):200–217. doi: 10.1002/joc.2141.

716 Stewart, Iain D. 2019. “Why Should Urban Heat Island Researchers Study History?”
717 *Urban Climate* 30:100484. doi: 10.1016/j.uclim.2019.100484.

718 Tan, Jianguo, Youfei Zheng, Xu Tang, Changyi Guo, Liping Li, Guixiang Song,
719 Xinrong Zhen, Dong Yuan, Adam J. Kalkstein, Furong Li, and Heng Chen. 2010. “The
720 Urban Heat Island and Its Impact on Heat Waves and Human Health in Shanghai.”
721 *International Journal of Biometeorology* 54(1):75–84. doi: 10.1007/s00484-009-0256-
722 x.

723 Ulpiani, Giulia. 2021. “On the Linkage between Urban Heat Island and Urban Pollution
724 Island: Three-Decade Literature Review towards a Conceptual Framework.” *Science of*
725 *The Total Environment* 751:141727. doi: 10.1016/j.scitotenv.2020.141727.

726 United Nations. 2018. *The World’s Cities in 2018*. UN.

727 Ward, Kathrin, Steffen Lauf, Birgit Kleinschmit, and Wilfried Endlicher. 2016. “Heat
728 Waves and Urban Heat Islands in Europe: A Review of Relevant Drivers.” *Science of*
729 *the Total Environment* 569:527–39. doi: 10.1016/j.scitotenv.2016.06.119.

730 Wickham, Hadley. 2016. *Ggplot2: Elegant Graphics for Data Analysis*. 2nd ed. 2016.
731 Cham: Springer International Publishing : Imprint: Springer.

732 Yang, Chen, and Shuqing Zhao. 2022. “A Building Height Dataset across China in 2017
733 Estimated by the Spatially-Informed Approach.” *Scientific Data* 9(1):76.

734 Zhou, D., S. Zhao, S. Liu, L. Zhang, and C. Zhu. 2014. “Surface Urban Heat Island in
735 China’s 32 Major Cities: Spatial Patterns and Drivers.” *Remote Sensing of Environment*

736 152:51–61. doi: 10.1016/j.rse.2014.05.017.

737 Zhou, Decheng, Jingfeng Xiao, Stefania Bonafoni, Christian Berger, Kaveh Deilami,

738 Yuyu Zhou, Steve Frolking, Rui Yao, Zhi Qiao, and Jose A. Sobrino. 2019. “Satellite

739 Remote Sensing of Surface Urban Heat Islands: Progress, Challenges, and

740 Perspectives.” *Remote Sensing* 11(1):48. doi: 10.3390/rs11010048.

741 Zhou, Y., H. Zhao, S. Mao, G. Zhang, Y. Jin, Y. Luo, W. Huo, Z. Pan, P. An, and F. Lun.

742 2022. “Exploring Surface Urban Heat Island (SUHI) Intensity and Its Implications

743 Based on Urban 3D Neighborhood Metrics: An Investigation of 57 Chinese Cities.”

744 *Science of the Total Environment* 847. doi: 10.1016/j.scitotenv.2022.157662.

745