

# A Review of Remotely Sensed Surface Urban Heat Islands from the Fresh Perspective of Comparisons among Different Regions

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*(Invited Review)*

**Abstract**—Urban heat islands (UHIs) threaten the ecological environment and human health. A large number of studies have focused on surface UHIs (SUHIs) across different spatial and temporal scales around the world with the development of satellite remote sensing technology. However, the influences of heterogeneous urbanization processes and background climates on SUHIs are still unclear and are important for targeted mitigation policies. A systematic review of the current status of SUHI studies, particularly from the perspective of comparisons among different regions, is urgently needed. We first introduce the commonly used satellite-retrieved data products and quantification methods used in SUHI studies. Subsequently, we summarize the potential driving factors of SUHI and compare the specific findings for different regions. Finally, we point out the deficiencies in the existing research and propose several prospects for the consideration of future SUHI studies. Additional global-scale research should be conducted using more advanced spatial statistical models. This can help better explore the spatially heterogeneous relationship between the SUHI and its associated driving factors. The effects of urbanization and climate from different regions should be further explored. Moreover, the problems of imperfections in the satellite data and from dynamic land use should not be ignored.

## 1. INTRODUCTION

Urbanization has become a worldwide historical process since the 20th century because of the rapid development of global economic integration. According to the latest revision of the World Urbanization Prospect (2018) by the Population Division of the United Nations Department of Economic and Social Affairs, approximately 55% of the population dwells in the urban environment, and this number is expected to increase to 70% by 2050 [1]. Urban growth has been transforming the original natural surfaces of vegetation, water, soil, and so forth into impervious urban areas that are mainly composed of built-up areas and infrastructure accompanied by a large number of human activities [2]. This changes the local meteorology, regional climate condition, and the energy exchanged at the interface of the surface and the atmosphere between the urban area and the surrounding suburban or rural areas [3]. Consequently, the urban area or metropolitan area becomes hotter than the surrounding rural area, leading to the urban heat island (UHI) phenomenon [4].

The UHI effect occurs in almost all urban areas and has been observed in more than 1,000 cities of different sizes worldwide [5–7]. In developing countries such as China, India, and Nigeria, whose urban populations accounts for almost 34% of the global urban population [1], UHIs have received increasing attention from academia, climate organizations, and other social sectors. UHIs are caused by a series

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of environmental alterations, such as regional climate change [8, 9], impaired vegetation growth [10, 11], and water and air quality deterioration [3]. Considering that urban areas account for approximately 55% of the world's population, these changes will probably cause serious damage to human health, such as increasing morbidity and mortality [12], and even causing potential threats of violence [13]. Meanwhile, excess energy consumption from refrigeration systems further increases the emissions of greenhouse gases and damages the ozone layer [14]. This further threatens human survival and development [15]. The UHI is a typical phenomenon of change in the natural environment caused by human activities. Therefore, it is of practical significance to study the temporal and spatial distribution of global UHIs and their influencing factors. Such efforts can surely be beneficial for mitigating the UHI phenomenon and promoting sustainable urban development.

The UHI is typically characterized by the urban-rural temperature difference. The quantification of UHI via the land surface temperature (LST) is called the surface UHI (SUHI). Recently, a series of reviews on SUHIs have been reported that have focused on the data sources, methodologies, spatiotemporal factors, and mitigation strategies based on satellite remote sensing technology. Huang & Lu (2017), for example, conducted a bibliometric analysis of over one thousand publications, and their results indicated that SUHI research had continuously increased since 1991 [16]. By reviewing the current quantification methods on SUHIs and the surface urban cold islands (SUCIs), Rasul et al. (2017) pointed out the insufficient development of the SUHI/SUCI simulation model and suggested that more attention should be paid to arid and semiarid areas [17]. Chapman et al. (2017) filtered the literature from 2000 to 2016 and conducted a systematic review on the studies involving the effects of climate change or urban growth on urban temperature and thereby on SUHI. They stressed the necessity of focusing on the impacts of urban growth on the SUHI in climate change studies [18]. Deilami et al. (2018) selected 75 representative articles that either used remote sensing to detect SUHIs or to explore the underlying spatiotemporal driving factors to summarize and analyze the data sources, analytical methods and driving mechanism of SUHI intensity. Their findings provided a useful policy guide for mitigating the UHI effect [19]. Zhou et al. (2019) screened the satellite-based SUHI bibliographies that had been published since 1972 and presented a historical review of the research foci and identified the used sensors and methods and the challenges therein [20]. In addition, some other regional reviews emerged recently that covered South Asia [21], tropical areas [22], and smaller areas such as greater Kuala Lumpur, Malaysia [23]. Most of the existing reviews were more concerned with the general characteristics of SUHI studies based on the literature involved. Nevertheless, to further explore the status of SUHI studies and uncover the driving mechanisms of SUHI, a comprehensive analysis of the study methodologies and the characteristics and mechanisms of SUHI, particularly the progress and findings for different climate zones and cities in different development phases worldwide, is still needed.

Hence, by extending the latest progress, we elaborated the data sources, quantification methods, driving factors, and specific findings of SUHI concerning the comparisons among the different regions. In the end, we proposed several future prospects of satellite based SUHI research. The criteria used to select the relevant literature were as follows: (1) several keywords were combined as 'urban heat island' OR 'urban thermal environment' AND 'satellite remote sensing' OR 'remote sensing' to filter articles from Science Direct, Web of Science, the Wiley online library, and the Google Scholar database; (2) by scanning the titles and abstracts, some irrelevant articles were removed, whereas the literature concerning the subject of urbanization, urban growth, global warming, or climate change was marked as object of special concern; and (3) the references of selected papers were rechecked to pick up some uncovered literature in the above search results. After full-text screening, over 100 published journal articles were selected for further analysis.

## 2. PRIMARY SATELLITE MISSIONS FOR SUHI STUDIES

Since satellite remote sensing can provide LST data with sufficient large-scale and long-term sequence coverage, it has been widely used for monitoring SUHIs [24, 25]. Rao (1972) was the first to observe the SUHI phenomenon using remote sensing image data [26]. Since then, the application of satellite remote sensing data to SUHI research has shown an exponential increase year by year [27–29]. Currently, the widely used thermal infrared remote sensing data products include those from the Landsat series, Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Spaceborne Thermal Emission

and Reflection Radiometer (ASTER), and Advanced Very High Resolution Radiometer (AVHRR), with Landsat and MODIS being the most frequently used products. The AVHRR data from the National Oceanic and Atmospheric Administration (NOAA) were applied to SUHI research in the early days of the discipline [30]. Later, the Landsat Thematic Mapper (TM) and enhanced Thematic Mapper Plus (ETM+) gained more attention for retrieving LST. A large number of studies on LST/SUHI and land use/land cover (LULC) using Landsat satellite observation data have been carried out [31]. Despite a high spatial resolution (30 m) and a revisit period of 16 days providing global-scale surface monitoring data, the insufficiency in the Landsat data due to its relatively long revisit period of approximately 16 days cannot be easily overcome. Fortunately, the NASA Earth Observation System (EOS) launched the Terra and Aqua satellites in 1999 and 2002, respectively. The MODIS, which is onboard the Terra and Aqua satellites, can scan the entire Earth every 1 to 2 days, providing continuous global day/night surface temperature data products with a spatial resolution of 1 km [32]. In addition, MODIS also provides a series of atmospheric and surface products that span nearly 20 years, which makes large-scale research on SUHI and its driving factors possible.

### 3. QUANTIFICATION METHODS

#### 3.1. SUHI Intensity

SUHI intensity (SUHII) is one of the indices that can be calculated using satellite remote sensing data to depict the spatiotemporal pattern of SUHI. Currently, the prevailing method for quantifying the SUHII is to calculate the difference between the urban and rural LSTs. After identifying the urban areas, the equal buffer area surrounding the urban built-up area is selected as the suburbs, wherein the average LST is usually regarded as a reference background [6, 33, 34]. To improve the validity of the SUHII, the urban fringe areas can be excluded, and the outer layer is used as rural areas to better represent the rural background temperatures [35]. While the LST difference method is intuitive and convenient, inconsistent identification of rural areas are likely to cause different or even opposite quantifications of SUHII for the same research objects [7, 36]. For example, in arid or semiarid regions, using the vegetation areas surrounding built-up areas as backgrounds can allow the detection of SUHI at night, which is undetectable when using the whole rural area as the background [37]. In this sense, it becomes difficult to compare the results of different studies.

#### 3.2. SUHI Footprint

The negative effects of urbanization and UHI often extend beyond the physical boundary of the city itself [38]. Compared with the spatiotemporal pattern of SUHI, its distribution pattern (i.e., footprint (FP)) can better reflect its status [39]. The commonly used UHI-FP method mainly consists of the “urban-rural temperature difference model” and “Gaussian volume model”. The fundamental “urban-rural temperature difference model” for determining the UHI-FP comprises two basic steps. The first is to obtain the background temperature considered to be unaffected by urban activities. This value can then be used as a criterion for calculating the SUHII that spreads from the urban center to the second step [36, 40]. Although brief and simple, it is difficult to identify purely rural areas that are not affected by the city, so uncertainties still exist in this method [41]. The Gaussian volume model measures the intensity and area of the SUHI with Gaussian ellipsoid parameters [27]. In addition to the need of detection of the rural area, the Gaussian model also requires a smooth SUHI, thus making it more complex in actual applications. Even so, the spatial pattern of SUHI could be better depicted via the Gaussian model [42, 43]. Therefore, the UHI-FP represented by the Gaussian volume model is precise and suitable for comparative study among different cities.

#### 3.3. Other Methods

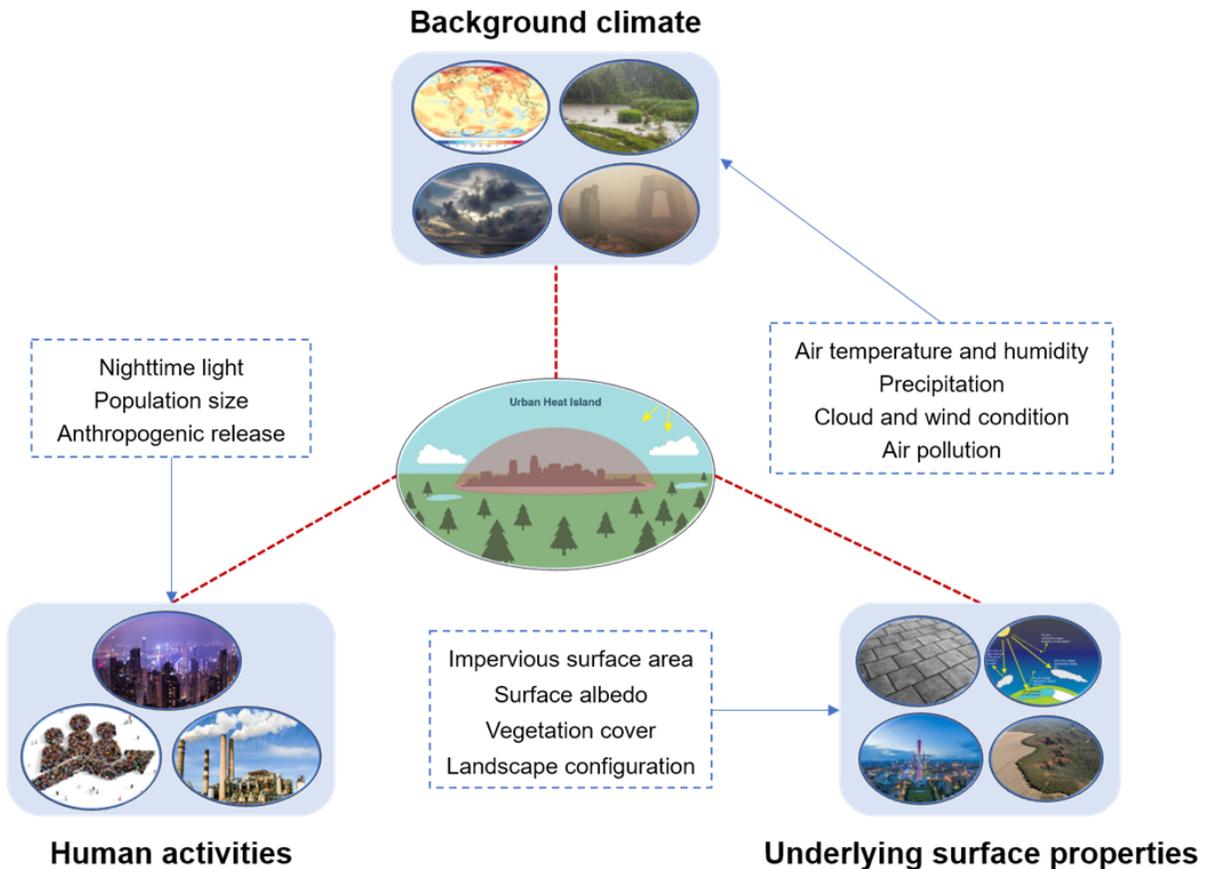
In fact, the urban areas and their surrounding suburbs are interconnected ecosystems. To fully account for the influence of urban expansion within urban agglomerations and avoid the subjective definition of rural areas, the concept of “relative LST” was proposed, in which the average temperature of the

entire region is used as the background temperature [44]. However, the threshold at which the SUHI phenomenon exists is difficult to determine.

In addition to the aforementioned methods, the traditional quantification of SUHI based on local zone LST would be more typical. The meteorological observations show superiority of measuring surface temperature data at local-scale, thus reports the LST difference between certain points of interest [8]. However, for studies at larger scale, the LST products from satellite missions brings out wide spatial and temporal coverage [45, 46]. Since we concern on the satellite based SUHI study, we mainly introduced the quantification methods based on regional LST in previous paragraphs.

#### 4. DRIVING FACTORS

With the rapid development of global urbanization, modifications in the LULC and surface structure constantly alter the surface temperature, which further determines the spatiotemporal pattern of SUHI [47, 48]. Human activities have dramatically increased energy consumption and generated a large amount of waste heat, leading to additional surface heat flux, which affects the urban climate and the near-surface temperature [49]. In summary, the LULC change, human activities, and global climate change caused by the urbanization process are the main driving factors of the globally ubiquitous SUHI phenomenon. The distribution pattern of SUHIs is determined by a combination of multiple factors, and summarizing the driving factors is necessary and beneficial for future research. A diagram in Fig. 1 illustrates the potential driving factors contributing to the UHI phenomenon.



**Figure 1.** Potential driving factors contributing to Urban Heat Island.

#### 4.1. Underlying Surface Properties

The modification of surface properties due to LULC change is the direct cause of the SUHI phenomenon. A city with woodland as the background usually has a stronger SUHI than that with grass or bush [50]. Different LULCs can lead to different diurnal variations in the SUHI [51]. Gallo et al. (1993) first explored the relationship between the urban thermal environment and vegetation by calculating the correlations between the SUHI and NDVI [52]. Since then, the NDVI has been used as the main indicator for exploring the relationship between the urban thermal environment and vegetation. Weng et al. (2004) introduced the vegetation fraction index instead of the NDVI and found that its correlation with LST was stronger than that of NDVI-LST, which may have implications for SUHI studies [30]. The impervious surface changes the attributes of the surface and thereby affects the surface thermal environment. Lu and Weng were the first to explore the impact of impervious surfaces on the SUHI pattern [53]; since then, it has become one of the most widely used surface attributes in SUHI research. In recent years, SUHI research has also employed landscape ecology methods. Factors such as landscape patterns have also become the focus of research for SUHI [54–56].

#### 4.2. Urbanization Process

The urbanization process is the primary cause of surface attribute alteration. City size, urban structure, population, human activity, and the socioeconomic development level under urban expansion are potential drivers of the SUHI. In general, there is a positive correlation between anthropogenic heat flux and the SUHI [39]. It is necessary and meaningful to explore the contributions of anthropogenic heat sources to the SUHI effect. Current anthropogenic thermal emissions data are mostly from emission inventories collected in different administrative units. These data are relatively difficult to collect and contain high levels of uncertainty. Therefore, nighttime light intensity data from DMSP-OLS and VIIRS are used as proxies for the contribution of human activities [34, 35, 40]. In addition to nighttime light intensity, other factors, such as the proportions of urban surface types, can also be used to characterize the intensity of urban development [57]. Studies have also confirmed that the SUHI is affected by city size and urban form [58–62]. Moreover, increased air pollution [63] and population density [64] also lead to an increase in the SUHI.

#### 4.3. Background Climate

The background climate also has a strong impact on the SUHI. The difference in surface turbulence over the urban and suburban areas often vary across different background climate zones. Cities in warm and humid regions usually have stronger SUHIs than those in cold and dry regions [65, 66]. A recent global study found that the SUHI in summer showed a nonlinear increasing trend with precipitation. This indicates that water and energy constraints can regulate regional SUHIs by controlling evapotranspiration [67]. In general, precipitation and temperature are positively correlated with SUHI. Warm and humid climates enhance the SUHI, while wind can weaken the SUHI [68]. Other weather conditions, such as cloud cover, are also driving forces of SUHI [69, 70]. The impact of urbanization can also indirectly affect the SUHI through its impact on climate, including extreme weather, wind, and precipitation [71]. In contrast, the SUHI effect in turn affects the urban climate, thereby further exacerbating the negative impact of the UHI [72].

#### 4.4. Assessment of the Relationship between SUHI and Multi-Factors

SUHI is the result of the combined effects of human activities, surface properties, and the background climate. In general, the current research has fully explored the driving factors described above for the characteristics of SUHIs. The analysis of the underlying mechanisms of the combination of multiple factors is a research trend [73]. A series of analysis tools have been adopted, such as correlation analysis [57, 74, 75], comparative analysis [76–78], linear regression models [79], spatial association analysis [80], and geographically weighted regressions [81, 82]. To further account for the pattern and influencing factors of SUHI, multifactor models are encouraged to be employed so that the contributions of multi-impact factors can be unveiled [83].

## 5. PROGRESS AND FINDINGS IN DIFFERENT REGIONS

The following section mainly describes the SUHI studies regarding different geographical regions, urban development phases and climate zones to which their study areas belong. Finally, relevant SUHI mitigation strategies are also described.

### 5.1. Different Geographical Regions

The SUHI and corresponding driving factors have been studied in most regions of the world using satellite retrieved LST at multiple scales [84–87]. Globally, the spatial and temporal characteristics and driving mechanisms of the SUHI in most large cities worldwide have been explored for certain periods [6, 7, 67]. At the continental and regional scales, the SUHIs in Europe, Asia, and North America have been studied more frequently [21, 65, 75, 88, 89]. Nationally, various SUHI studies in populous countries such as China and India have been reported [33, 35, 64, 90–92]. The representative studies of SUHIs at multiple scales around the world are summarized in Table 1.

**Table 1.** A summary of SUHI studies over different regions worldwide.

Study scale	Research region	Time period	Study foci	Reference study
Global	419 cities	2003–2008	Spatiotemporal patterns and driving factors	Peng et al. [6]
	Cities between 55°S–71°N	2010	Spatiotemporal patterns and driving factors	Clinton and Gong [7]
	Global cities	2013	Driving factor	Manoli et al. [67]
Regional	All cities in Europe	2006–2011	Spatiotemporal patterns and driving factors	Zhou et al. [88]
	Asia Mega cities	2001–2003	Spatiotemporal patterns and driving factors	Hung et al. [75]
National	285 Chinese cities	2001–2010	Spatiotemporal patterns and driving factors	Peng et al. [35]
	332 Chinese cities/city agglomeration	2014–2016	Spatiotemporal patterns and driving factors at different climate zones	Yang et al. [55]
	84 Indian cities	2003–2013	Spatiotemporal patterns	Shastri et al. [93]
Local	Metropolitan region in South China	1995–2015	Spatiotemporal patterns	Yu et al. [44]
	Beijing (China)	2000–2012	Trajectory of SUHI centroids	Quan et al. [41]
	Mashhad (Iran)	2014.06.27	Driving factors	Soltanifard and Aliabadi [94]
	Four African cities	2015–2017 (single day)	Spatial patterns	Simwanda et al. [95]
	Mexico City	2006	Spatiotemporal patterns	Cui and Benjamin [96]

### 5.2. Different Development Phases

Urbanization is the main influencing factor in forming urban climates and thereby SUHI. Studies at the global scale indicate that the intensity of the summer SUHI varies with population size and annual average precipitation, disclosing the contribution of climate and population to the summer SUHI [67]. Concerning regional or local cases, the driving mechanisms may differ with different urbanization patterns. In the US, SUHI shows a nonlinear growth trend, with the expansion of city size and urbanization contributing to 87% of the change in SUHI [97]. In China, a study in its Yangtze River Basin also found that the increase rate of SUHI differs as the development phase changes [98].

**Table 2.** A brief introduction of comparative SUHI studies under different development phases.

Research region	Time period	Main SUHI findings	Reference study
Continental United States (CONUS)	2010	SUHI grow nonlinearly with city size expansion	Li et al. [97]
10 big cities in Yangtze River Basin, China	2001–2016	Increase rate of SUHI differs with urbanization development	Yao et al. [98]
China vs. CONUS	2001–2012	Warming trend irrespective of the national development phase	Cai et al. [100]
China vs. CONUS (cities between 30–45°N)	2003	Population size dominant at early urbanization stage, while GDP afterwards	Cui et al. [76]
Two cities in Myanmar	2000–2013	Urban expansion type contributes to urban warmer differently	Wang et al. [101]

The SUHI effect expands with the boundaries of urbanization [99]. A comparative study of China and the United States showed that there is a trend of urban area warming caused by urbanization irrespective of the national development phase [100]. Another study explored the differences in the impact of urbanization levels on SUHI among several representative cities in China and the United States that were located between 30–45°N. The results show that urbanization factors such as gross domestic product (GDP), population size, and urban spatial extent spatially differently impact SUHI. In the early stage of urbanization, the impact of population size is more significant, while the GDP becomes a major factor only when the city approaches a certain phase [76]. Another comparative study in two capital cities (former and new) in Myanmar indicated that Government-induced municipal infrastructure development pattern could potentially increase the daytime LST greater than that of population induced urban expansion [101]. A brief introduction of the comparative SUHI studies under different development phases are presented in Table 2. In summary, the impact of urbanization on SUHI may present spatiotemporal heterogeneity. However, the current findings have mainly been concluded from studies in limited regions, which necessitates a comparative analysis of the SUHI effects of cities at different development stages or different urbanization pattern on a global scale.

### 5.3. Different Climatic Zones

The SUHI phenomenon is a result of the combination of urban expansion and climate change. Current research on SUHI focuses more on tropical, Mediterranean, and cold climate zones. In tropical climate zones, the topography, forest coverage, and land development patterns have the dominant effects on the

**Table 3.** A brief introduction of comparative SUHI studies in different climatic zones.

Research region	Time period	Main SUHI findings	Reference study
Tropical SUHI	1997–2016	Topography, forest coverage, and land development patterns dominant tropical SUHI	Giridharan et al. [22]
US cities	2000–2009	Land cover change (urban expansion) has different local climate impacts on urban temperature	Krayenhoff et al. [102]
31 China cities	2001–2015	Different climate driving factors for SUHI at Northern cities	Yao et al. [103]
332 China cities/city agglomerations in different climatic zones	2004–2016	Correlation between SUHI and landscape metrics influenced by climatic factors	Yang et al. [55]

SUHI. The impacts of urban density, energy consumption, and the role of related governance policies on SUHI have been fully investigated [22]. Using the Weather Research and Forecasting (WRF) model, a study showed that land use change had different mechanisms for affecting SUHI in different climate backgrounds [102]. By dividing the study region into different typical climatic zones, studies also found that the relationship between the SUHI and its driving factors not only changed with seasonal and diurnal variations but were also affected by climatic factors [55]. In China, a study for 31 cities across different climate zones found that in Northern part, the total precipitation particularly had a positive correlation with daytime SUHI [103]. A brief introduction of the comparative SUHI studies in different climatic zones are presented in Table 3. In summary, the SUHI performs differently in different climate zones. Nevertheless, the mechanisms of all climate zones have not been deeply investigated. Therefore, a global-scale comparative analysis of the heat island effect in different geographical regions is urgently needed.

#### 5.4. Mitigation Strategies

It is widely known that UHIs negatively impact energy use, urban population health, and air quality. Currently, the effect has attracted considerable attention from scientific research teams, urban planners, and government departments. Methods for effectively and efficiently mitigating the UHI effect have also received increasing attention [104]. The currently proposed measures are mostly small-scale methods. These measures include changes in the building materials and increases in surface vegetation. They are mostly suitable for subtropical areas and more developed regions, such as East Asia, North America and the Mediterranean region of Europe [105, 106]. Meteorological factors, such as wind, precipitation, cloud cover, and fog, may have greater impacts on UHIs. The question of how to use these meteorological parameters to regulate the UHI effect is also the focus of current research [107]. To this end, it is also necessary to enhance the theoretical research on UHI. As described above, many inconsistencies exist in the current investigations due to different time ranges, regional scopes, and analysis methods. For example, global-scale studies have shown that city size has an impact on the SUHI [7, 58], while studies on 32 cities in China have shown no significant correlation between these factors [33]. Although several previous studies have investigated this issue [6, 108], the response mechanisms of SUHI over different regions still need to be further investigated.

## 6. DISCUSSIONS AND FUTURE PROSPECTS

### 6.1. Lack of Systematic Research on a Global Scale

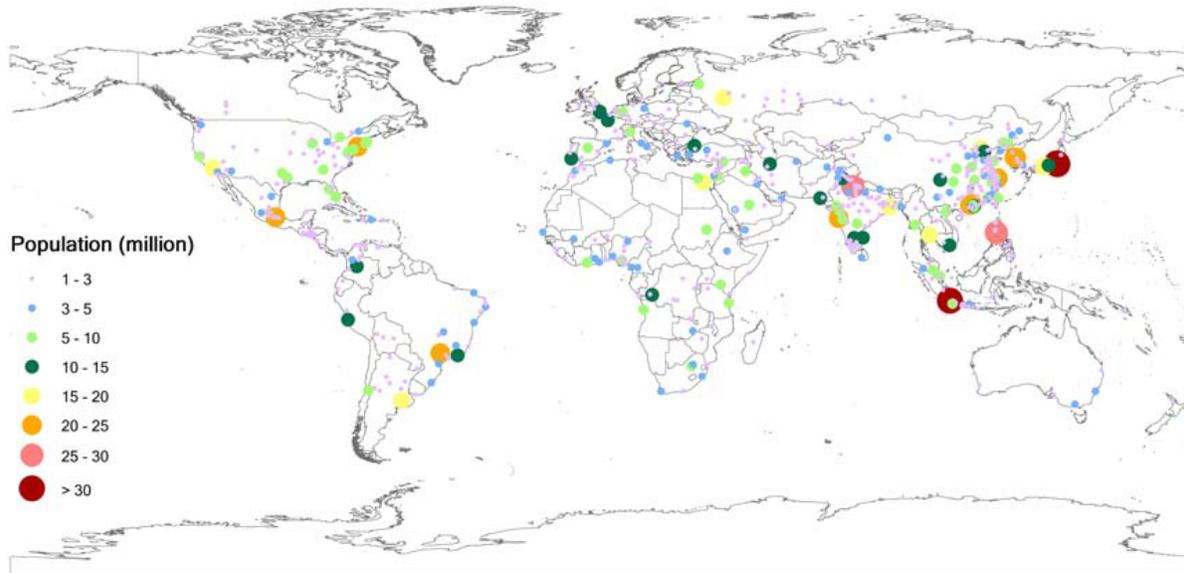
While the application of satellite remote sensing to SUHI research has experienced great development for nearly half a century, a large proportion of the existing studies focus on the city, regional, and national scales. According to the summary of worldwide SUHI studies in Table 1, only a few studies concentrated on the spatial and temporal patterns and influencing factors of SUHI on a global scale. In addition, the current research mainly involves developing or developed countries, such as those in Asia, North America, and Europe, while the least developed countries, such as those in Africa, are rarely individually explored [20]. Demographic data provided by the United Nations show that the most populous cities are mainly distributed in Asia, especially in China and India (Fig. 2), which have frequently been the focus of previous research. Additionally, the population sizes in Africa and South America are also large. SUHI studies in these regions are urgently needed.

Furthermore, a systematic comparison of the SUHI driving mechanisms across different regions is still lacking. The spatial and temporal characteristics of SUHI in different regions across the world have such considerable differences that the influencing factors and mechanisms many have inconsistent or even conflicting laws. Therefore, it is urgent to establish a large-scale and long-term comprehensive research system around the world.

### 6.2. Improvement of the Model to Assess the Driving Mechanisms of SUHI

The SUHI, which is typically calculated with the LST, is a spatial variable. Hence, its measurements are probably spatially dependent. Traditional statistical regression models such as Pearson correlation

### Continuous Urban Areas with Population over One Million



**Figure 2.** Global distribution of continuous urban areas with populations of over one million by 2019. The demographic data were provided by the United Nations, Department of Economic Social Affairs Population Division (adapted from [1]).

analysis and linear regression may not be able to address this type of spatial dependency well. Spatial heterogeneities might also exist among SUHIs and their associated driving factors. Traditional statistical regression models are also not capable of addressing such heterogeneity. More advanced spatial statistical models are encouraged to be employed to better explore the driving mechanisms of the SUHI. In addition, the anthropogenic heat (AH) emissions would also be used to quantify the effect of human activity on SUHI in future studies, since the long-term gridded AH at global scale has been investigated in early investigations [49, 109].

### 6.3. Indeterminate Influence of Urbanization

Deeper exploration of the response mechanism of urbanization to SUHIs will help to inform the proposal of more effective mitigation policies. Current research typically employs the city size, city structure, and urban population to indicate the level of urbanization. In fact, the urbanization level indicates the economic, cultural, political, and other prosperities of a country. The driving mechanism of urbanization on SUHI may change with the development phase. The aspects mentioned above cannot be well characterized by simple indices. With respect to the human influence in the process of urbanization, heat emissions are the main factor that disturbs the energy balance on the surface and thereby impacts the SUHI. Due to the lack of global gridded anthropogenic thermal emission data, some studies have explored the fusion of energy emission inventory data and multisource remote sensing data to reproduce it [49, 109]. In addition, some studies have used land-based models to quantify and analyze the impact of anthropogenic heat emissions on temperature [39]. However, due to the large number of input parameters required by the models, they are difficult to apply on a global scale. There is plenty of room for improvement through the exploration of new indices to better reflect the urbanization level and quantify the anthropogenic heat emissions on a global scale. In this sense, the impact of the urbanization level and associated human activities on the SUHI can be better investigated.

#### **6.4. Uncertainty of the Effects of Heterogeneity of the Background Climate in Different Regions**

The SUHI reflects the impact of human activities on the urban climate. It not only is affected by surface properties and human activities but also is characterized by spatially and temporally different driving mechanisms under different climate backgrounds. Studies have explored the effects of background climate factors, such as temperature and precipitation, on the SUHI and found that the driving mechanisms of the SUHI present different characteristics under different climate backgrounds. Nevertheless, the conclusions were established at relatively small scales. Global comparative studies among different climate zones are still limited.

Simultaneously, the current research on SUHIs pays more attention to biophysical (e.g., vegetation activity and albedo), climate (e.g., temperature, precipitation, and wind), and human (e.g., land use change, anthropogenic heat emissions, urban structure, and building ventilation) factors that are brought about by the urbanization process. Other factors, such as urban climate change in the global climate-driven context, such as increased greenhouse gases, changes in pollutants and aerosol concentrations, are also potential influencing factors of the temperature change and should be further considered in SUHI studies [110]. Additionally, the quantification of the relative contributions of these factors to the total SUHI is still lacking. It is significant to compare the similarities and differences of the driving mechanisms in the different climate zones.

#### **6.5. Dynamic Land Use Change**

Limited by data availability, most studies use Landsat products from discontinuous years for land use classification and even assume that the types of land cover are relatively static [35, 57]. However, the urbanization process can cause drastic changes in land use. Using static land use maps may not be able to accurately identify the urban and rural areas in consecutive years, particularly for those areas with rapid urbanization processes [40]. Therefore, it is of great significance to use global-scale dynamic land-use monitoring data to accurately explore the spatiotemporal patterns and driving mechanisms of SUHIs in the context of urbanization [111].

#### **6.6. Effects of the Imperfection of Satellite Remote Sensing Data**

During the application of satellite remote sensing data in studying SUHIs, missing data due to cloud cover is a common problem. Clouds form more easily in urban areas than in rural areas due to the effects of sensible heat flux, atmospheric turbulence, and urban aggregation, especially during the daytime [112]. The polar orbit satellite overpass time is usually not synchronous with the time of the day of the maximum or minimum LST. Therefore, in practical applications, methods for using the instantaneous LST monitored by satellite remote sensing to accurately quantify the SUHI intensity at multiple time scales also need to be further investigated. The spatial resolution of related remote sensing data ranges from tens of meters to kilometers. The multiscale problem of SUHI research and the discrepant methods used at different scales also lack a systematic theoretical basis [113].

### **7. CONCLUSIONS**

This article reviewed studies that applied satellite remote sensing to the SUHI field. The quantification methods and driving factors of the spatial and temporal characteristics of SUHIs at multiple scales were fully discussed. We found that the quantification methods for SUHI varied in different studies and thus might lead to inconsistent conclusions. Relatively speaking, the SUHI footprint measured by the Gaussian model was more suitable for indicating the impact scope of the SUHI. The progress and findings in different regions distinguished by urban development phases and background climate zones were summarized and compared. The correlation between urbanization and the SUHI still needs to be further explored by introducing more representative factors to specify the urbanization level. In terms of the background climate factors, new factors such as urban climate and pollution should be considered, and global-scale comparative analysis of different geographical regions is urgently needed. Finally, yet importantly, we pointed out several new prospects in the SUHI field. Systematic research

at the global scale is relatively lacking. More advanced spatial statistical models are encouraged to be employed to construct a comprehensive SUHI research system. The influence of urbanization remains unclear. The heterogeneities of climate factors should be taken into full consideration to better reveal the driving mechanism of the SUHI. The lack of dynamic land use data and the problem of missing data in satellite remote sensing products should also not be ignored in future research.

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