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Review

Characteristics, Progress and Trends of Urban Microclimate Research: A Systematic Literature Review and Bibliometric Analysis

Yichen Zhou [1], Na An [1] and Jiawei Yao [1,2,*]

[1] College of Architecture and Urban Planning, Tongji University, Shanghai 200092, China; 1954034@tongji.edu.cn (Y.Z.); anna2010255@tongji.edu.cn (N.A.)
[2] Key Laboratory of Spatial Intelligent Planning Technology, Ministry of Natural Resources, Shanghai 200092, China
* Correspondence: jiawei.yao@tongji.edu.cn; Tel.: +86-138-1651-5004

Abstract: Climate change has been a hot topic in recent years. However, the urban microclimate is more valuable for research because it directly affects people's living environments and can be adjusted by technological means to enhance the resilience of cities in the face of climate change and disasters. This paper analyses the literature distribution characteristics, development stages, and research trends of urban microclimate research based on the literature on "urban microclimate" collected in the Web of Science core database since 1990, using CiteSpace and VOSviewer bibliometric software. It is found that the literature distribution of the urban microclimate is characterized by continuous growth, is interdisciplinary, and can be divided into four stages: nascent exploration, model quantification, diversified development and ecological synergy. Based on the knowledge mapping analysis of keyword clustering, annual overlap, and keyword highlighting, it can be predicted that the research on foreign urban land patch development has three hot trends—multi-scale modelling, multi-factor impact, and multi-policy guidance. The study's findings help recognize the literature distribution characteristics and evolutionary lineage of urban microclimate research and provide suggestions for future urban microclimate research.

Keywords: bibliometrics; citespace; development stages; distribution characteristics; research trends; urban microclimate; vosviewer

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1. Introduction

Climate risks have and will continue to affect national security, economic security, human health, infrastructure, and ecosystem stability [1]. The Global Risks Report 2022, published by the World Economic Forum, lists climate change as one of the ten most pressing global risks [2]. The United Nations Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, Climate Change 2022: Impacts, Adaptation and Vulnerability, states that humanity is pushing the limits of climate carrying capacity and points to the urgency of climate transition in the next decade [3]. Therefore, urban climate research is of great importance for healthy urban development.

The study of urban climate began in 1818 with Lake Howard's "The Climate of London", which first identified the temperature difference between urban and rural areas, i.e., the urban heat island effect, and studied the factors influencing the city's climate [4]. Most current research on urban climate change focuses on macro-scale climate change patterns such as national scales and climate zones, while climate research on the complex and variable near-surface micro spaces has a later origin and slightly less research. Compared with macro climate change, urban microclimate has a more direct impact on people's living environments. People can regulate the urban microclimate through technical means and then enhance the self-recovery ability of cities in the face of climate change and disasters, and if we enlarge the concept of resilient cities, the concept of microclimate becomes more critical [5,6].

The research plan uses WOS, the largest Database of English documents, as the raw material and combines the advantages of Citespace and VosViewer for visualization and clustering analysis. Compared with traditional bibliometric methods, the visual analysis of scientific knowledge graphs is more intuitive and readable [7]. Urban microclimate originated in 1947 [8], and 2131 articles were searched in the Web of Science database under TS = (urban microclimate) OR TS = (city microclimate). The language of the literature was limited to English, the type of literature was limited to articles, and the search date was 4 May 2022. Searched with (TS = (urban microclimate) OR TS = (city microclimate)) AND TS = (review) AND ALL = (citespace), the type of literature was Article, the language was English, the result was 0, and the search time was 9 April 2022. There are 51 reviews, and no citespace based search studies are available.

Most current microclimate studies focus on the quantification of microclimates [9], such as the calculation of thermal comfort equations [10], meteorological data monitoring [11], computer simulations [12], and subjective thermal environment questionnaires [13,14]. The concept of urban microclimate first referred to the influence of some climatic factors in the ground boundary layer by local features [10] and then also shifted to focus on urban scale differences [15], urban climate characteristics [16], and urban environmental elements [17]. Although there are some review studies on urban microclimate research, previous studies are mostly clustered analyses, and we have not yet seen time series-based development stage classification and multi-method research hotspot prediction [6].

2. Data and Methods

This paper adopts data analysis, software measurement, and scientific mapping methods to understand further the evolutionary characteristics and hot issues of urban microclimate research. It uses visual analysis of CiteSpace and VOSviewer bibliometric analysis software to conduct scientific knowledge mapping analysis of urban microclimate literature to clarify potential knowledge connections among the literature [18]. A science mapping can highlight potentially significant patterns, trends, and theories of scientific change that can guide the exploration and interpretation of visual, intellectual structures and dynamic patterns [19]. Compared to other mapping software, CiteSpace and VOSviewer have a higher frequency of use and broader dissemination as commonly used bibliometric mapping software [20]. CiteSpace can detect and visualize emerging trends and radical changes in scientific disciplines over time [21]. VOSviewer is a bibliometric analysis software jointly developed by Leiden University scholars Nees Jan van Eck and Ludo Waltman for drawing knowledge maps. It can be used for co-word, co-citation, and literature coupling analysis. It can display research results visually and has unique advantages in clustering technology and map displays [22]. Compared to Scopus, Google Scholar and PubMed, Web of Science is the world's largest and most comprehensive scholarly information resource covering a wide range of disciplines, including the most influential core academic journals in various research fields such as natural sciences, engineering and technology, and biomedicine. Therefore, this paper uses the Web of Science core collection (hereafter referred to as WOS) as the data source, and the search period was 9 April 2022, with a years limit of 1990–2022. The search mode of "subject" + "document type" was used, and the search terms were: TS = (urban microclimate) OR TS = (city microclimate), and the document language was limited to "English", the type was restricted to "articles" to ensure the scientific validity and accuracy of the research, and a total of 2070 relevant documents were obtained.

Centrality metrics provide a computational method for finding pivotal points between different specialties or tipping points in an evolving network [23]. It measures the percentage of the number of shortest paths in a network to which a given node belongs. Nodes with high-betweenness centrality tend to be found in paths connecting different clusters. This feature has been used in community-finding algorithms to identify and separate clusters [24]. Higher strength refers to a sharp increase in the number of term occurrences in this period, which is the frontier of research in this phase [23]. Kleinberg's

(2002) burst-detection algorithm can be adapted for detecting sharp increases of interest in a specialty [25]. In CiteSpace, a current research front is identified based on such burst terms extracted from keywords [23].

3. Results

3.1. Current Status of Urban Microclimate Research

3.1.1. Research Scale and Impact Analysis

The number of publications in this field has increased (Figure 1). The number of annual publications before 2005 was small (basically less than 10 publications per year), and urban microclimate research was still in the exploration stage; from 2000 to the present, the number of publications has shown an exponential increase, and urban microclimate research has received significant attention since the 21st century and has become one of the current research hot topics. As of 9 April 2022, 49 articles have been published, and the number of articles is expected to climb in 2022.

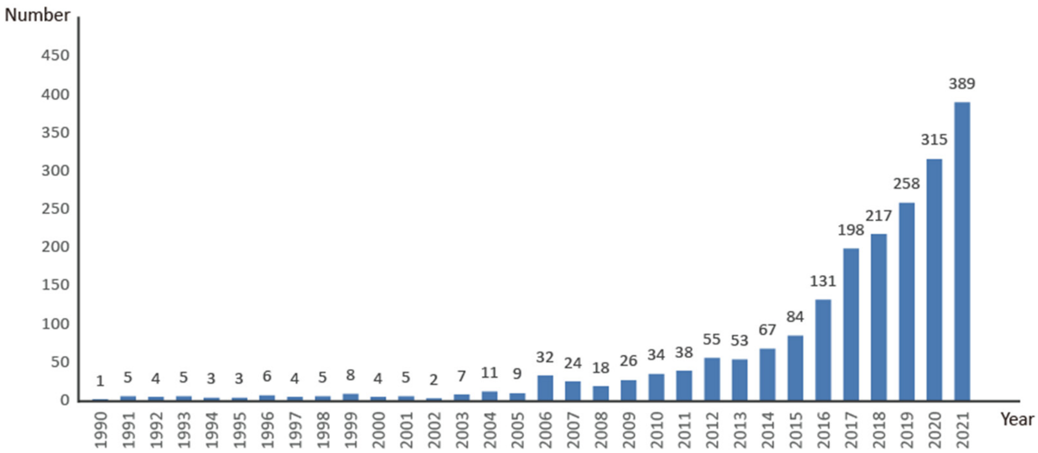

Figure 1. Number of published articles on urban microclimate.

3.1.2. Interdisciplinary and Publication Analysis

In terms of disciplinary distribution, urban microclimate research is mainly concentrated in Environmental Science (13.24%) and Construction Building Technology (11.04%), reflecting the multidisciplinary and comprehensive nature of urban microclimate research (Figure 2).

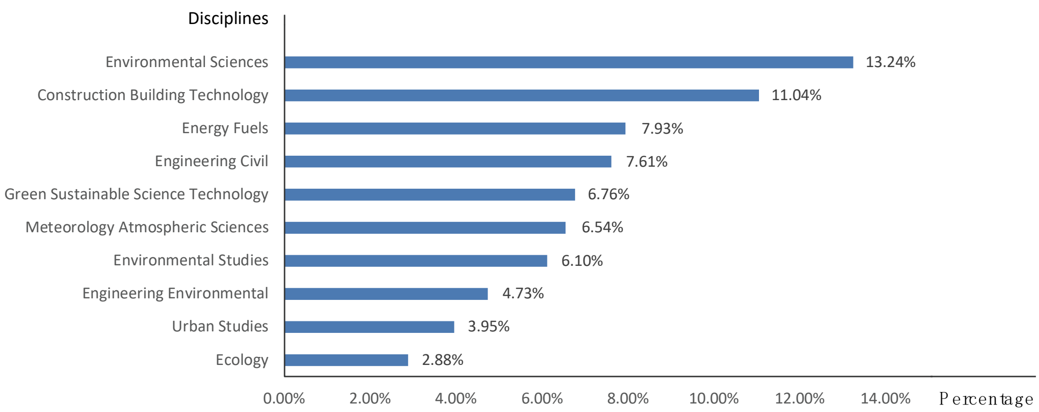

Figure 2. Percentage of urban microclimate papers by discipline (top 10).

Regarding source publications, there are 527, with *Building and Environment* and *Sustainable Cities and Society* posting the most articles, accounting for 8.72% and 6.58%, respectively. The top 10 publications focused on urban and architectural research and environmental sustainability (Figure 3).

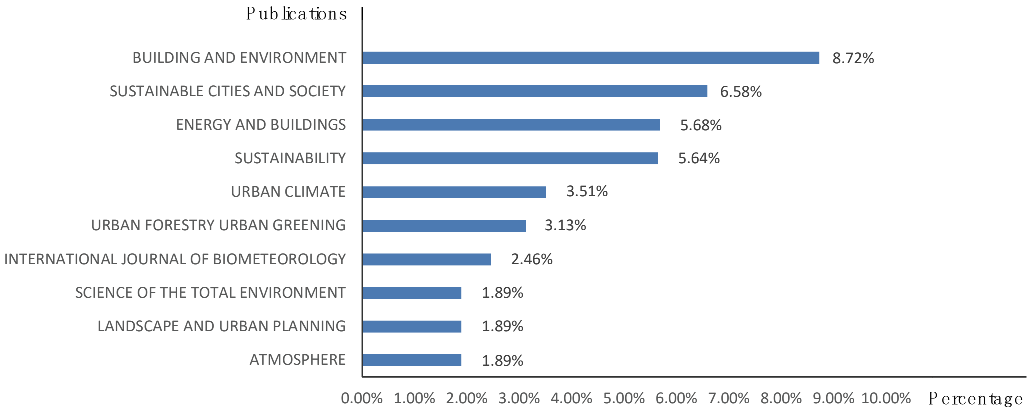

Figure 3. Percentage of urban microclimate papers published in journals (top 10).

3.1.3. Country Distribution Analysis

National time zonal mapping helps us find the most worthy references and to further select and classify the literature. In terms of the number of publications (radius size) (Figure 4), China has the highest number of articles (430) in country distribution, followed by the United States (359). The U.S. (1991) was the first to study urban microclimate, while China did not start until 2005. Centrality measures the importance of a node in the network; a more critical node means a higher centrality, indicating that the country has published more citations and is more influential in the period. In terms of centrality (more circles or colors), France (0.46) is much higher than other countries, followed by the U.S. (0.41) and Canada (0.33). Although China started later, the number of publications has shown explosive growth, probably because the urban microclimate issue has been gradually noticed due to the high-speed urban development.

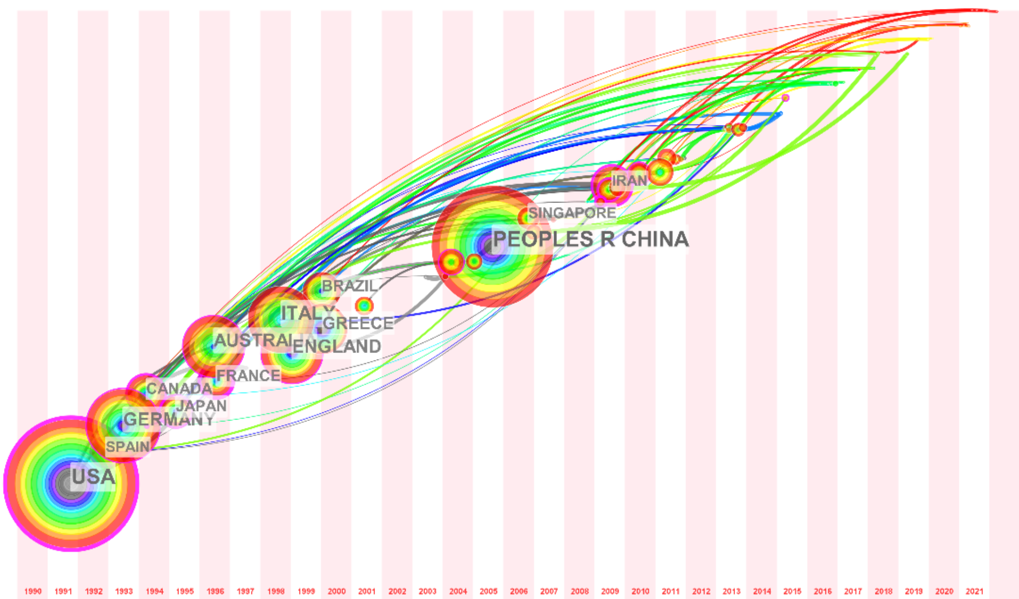

Figure 4. National time zonal mapping for urban microclimate studies.

3.2. Development Stages of Urban Microclimate Research

CiteSpace's keyword clustering analysis, centrality, and emergent detection can identify research frontiers to predict research trends. Using CiteSpace to map keyword time regions and temporal partitioning of highly cited literature can help analyze the evolutionary path of research hotspots. Combined with co-citation analysis, it can help identify turning points in research and critical literature in each period [19].

This paper uses CiteSpace to analyze the time-zoned mapping of urban microclimate research literature (Figure 5) and divides the research into four stages; the main research progress and characteristics are reviewed in stages. There are numerous urban microclimate research hotspots (Table 1), and their research hotspots have apparent characteristics of the times and are significantly influenced by the social context and policy focus. For example, the fourth Conference of the Parties to the United Nations Framework Convention on Climate Change was held in 1998, and the Paris Agreement was signed and formally implemented in 2016, which may serve as additional factors for phase division.

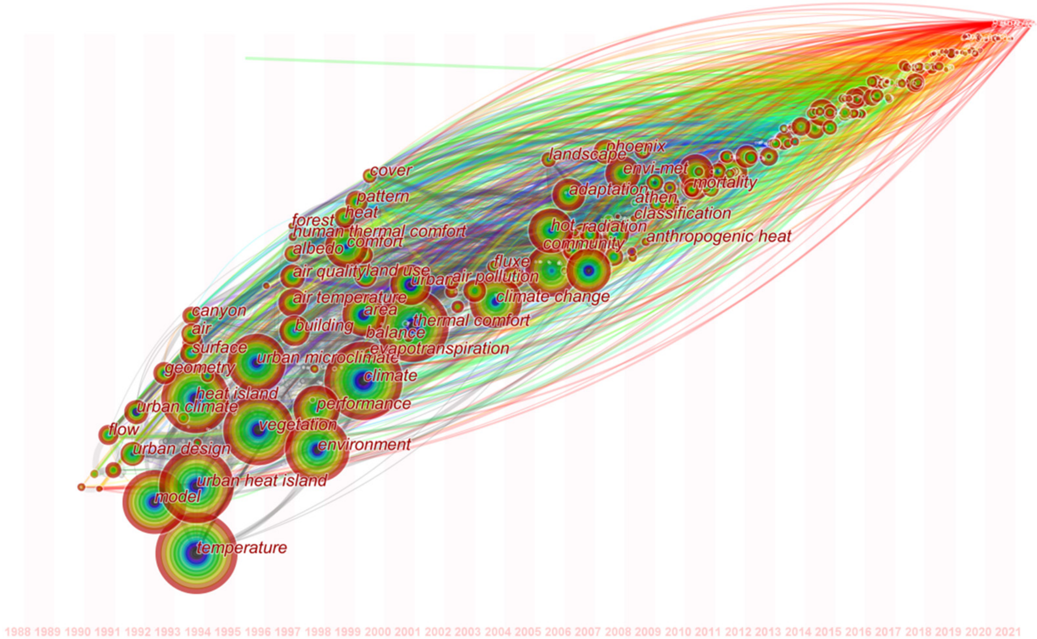

Figure 5. Temporal partition mapping of urban microclimate research keywords.

Table 1. A burst of high-frequency keywords in urban microclimate research.

Phase	Year	Frequency	Keyword	Burst
1990–1997	1993	419	Temperature	8.29
	1993	308	Heat island	
	1993	219	Model	
	1996	294	Vegetation	
	1997	46	Albedo	
1998–2005	1998	282	Environment	4.03
	1998	167	Performance	
	1999	62	Pattern	
	2000	62	Land use	7.58
	2001	331	Thermal comfort	
	2003	69	land surface temperature	
	2005	136	Hot	

Table 1. *Cont.*

Phase	Year	Frequency	Keyword	Burst
2006–2015	2006	231	Outdoor thermal comfort	
	2006	124	Urbanization	3.19
	2007	127	Energy	
	2007	126	ENVI-met	
	2009	63	Green space	
	2011	126	Mitigation	
	2011	102	Street canyon	
	2014	51	Strategy	
	2015	75	Mean radiant temperature	
	2014	87	Expansion	
	2014	58	Urban Expansion	
2016 to date	2016	55	Green infrastructure	3.50
	2016	51	Ecosystem service	
	2017	45	Ventilation	
	2018	30	Mitigation strategy	
	2019	23	Aspect ratio	4.16

Higher burst refers to a sharp increase in the number of term occurrences in this period, which is the frontier of research in this phase [21].

3.2.1. The Nascent Exploratory Phase (1990–1997): The Rise of Multidisciplinary and Urban Studies

High-frequency keywords of early studies include temperature, heat island, and vegetation (Table 1), indicating that urban microclimate studies have mainly focused on multidisciplinary integrated studies and correlation analysis of urban constituents. However, the identification of the framework and connotation of microclimate composition has not yet emerged.

Regarding multidisciplinary synthesis: Graves et al. used microclimate as one of the temperature indicator factors in the high root zone to study the effect of high-temperature zones on plant seedlings [22]. Gorbushina et al. used microclimate variability as an observable indicator of the biological activity of black fungi to study its role in morphology [26]. Regarding urban climate factors, Akbari et al. studied the feasibility of vegetation and high albedo materials in modifying the urban microclimate [27]. They found that increasing the vegetation cover by 30% with 20% albedo in dwellings in areas such as Toronto and Vancouver could reduce energy consumption by about 10% to 20%. Nichol conducted a microclimate study of the tropical city of Singapore for microclimate monitoring studies of high-rise housing and found a high correlation between satellite heat sensing data and biomass indices, with high similarity to actual temperatures [28].

In general, the literature published at this stage is small, and the attention of the academic community is low, mainly focusing on multidisciplinary microclimate auxiliary research and microclimate research in small areas within cities (e.g., indoor environments such as houses). The exploration of urban microclimate research systems has not yet emerged, which can be regarded as the nascent exploratory phase of urban microclimate research.

3.2.2. Model Quantification Phase (1998–2005): Application of Numerical Quantification and Model Evaluation

The high-frequency keywords in this phase include environment, climate, and thermal comfort (Table 1), with environmental emergence at 4.03 and land use at 7.58, which were research hotspots. This stage mainly focuses on the research of urban microclimate model quantification. A typical representative is an ENVI-met model, simulation software developed by Bruse et al. to study surface–plant–air interactions in urban environments, which has become the most widely used tool in microclimate studies [29]. The research in this phase focuses on exploring urban microclimate perturbations, their influencing effects, and model construction.

The research focuses on numerical assessment studies at the macro level on the one hand and studies the influence relationship with microclimate from different means and factors. Carlson et al. used satellite image data to obtain microclimate variables such as surface temperature, vegetation rate, ISA, and E.T, and used Chester County as an example to construct regression analysis models and predict future parameter changes [30]. Adolphe studied the relationship between urban building form and urban microclimate and used environmental form evaluation indicators to construct a simplified urban spatial model [31].

On the other hand, factors such as human perception are incorporated into microclimate model construction. Matzarakis et al. proposed the physiologically equivalent temperature (PET), considering the correlation with human thermal–physiological perception [32]. Steemers used microclimate as a research object to invert the energy consumption of buildings with different densities and analyze the urban morphology correlation, emphasizing the value of outdoor comfort research [33]. Dimoudi et al. attempted to quantify the effect of vegetation on microclimate in urban environments and found that increased vegetation had a significant effect on temperature reduction [34]. de La Flor et al. proposed an "urban canyon" computational model that considers human thermal fitness to improve the urban microclimate and save the thermal performance of buildings [35].

At this stage, the number of publications on urban microclimate started to increase, and the academic community's attention grew. The microclimate research process is complete with numerical modelling methods, but the coupling of microclimate with other factors is still unclear about the value of microclimate volume.

3.2.3. Diversified Development Phase (2006–2015): System Maturity and Expansion of Research Breadth

Urban substratum changes bring a harsh climate environment, increased anthropogenic heat emission, and the spread of pollution from urban activities [36]. This stage of urban microclimate pays attention to urban heat islands, thermal comfort and other climate change mitigation studies based on the previous stage, where the high-frequency words include outdoor thermal comfort, urbanization and energy.

From the total citations of the literature, this stage of research mainly focuses on urban planning or design, urban microclimate, and outdoor thermal comfort and gradually focuses on the actual measurement and testing of outdoor thermal comfort from the PET theory proposed in the previous stage, and combines quantitative findings to guide urban design. Subsequently, the research scope is further expanded, and the research object is no longer limited to a single model or a specific landscape, a disciplinary and social extension of the previous stage that only focused on microclimate-related factors.

In terms of macro-simulation and micro-perception, Ali-Toudert et al. studied the effect of urban street aspect ratio and orientation on urban microclimates, evaluated the effect of PET on the climate of urban streets, and found that the street with south–north orientation and aspect ratio $\geq$2 had a better thermal environment compared with other combinations [37]. Yu, C et al. explored the effect of green space on microclimate regulation, selected two parks in Singapore as examples, conducted simulation verification with TAS and ENVI-MET, and found that green space could reduce the built environment temperature by 1.3 °C and cooling load by 10% [38]. The RUROS project conducted by Nikolopoulou et al., which collected subjective human perception questionnaires from five European countries, concluded that urban microclimate is closely related to thermal comfort and that temperature and solar radiation are two essential factors influencing thermal comfort [16]. Harlan et al. used a model to estimate the summertime U.S. outdoor human thermal comfort index (HTCI) [39]. They found that community microclimate temperature has a strong negative relationship with HTCI and that lower socio-economic status and minority groups in residential areas with weak coping are more vulnerable to the adverse effects of the microclimate.

In terms of the influence of urban design elements on the thermal environment, Huang et al. took Nanjing as an example and calculated the cooling effect of four urban ground cover types, which showed a cooling effect of 0.2 ~ 2.9 °C for all urban blue-green spaces compared to bare concrete surfaces [40]. Shashua-Bar et al., also focusing on outdoor landscape cooling strategies in dry heat regions, selected six cooling combinations of trees, lawns, or shade nets and found that the cooling effect of grasses was most significant when they were in the shade of trees or shaded by shade nets [41]. Santamouris et al. analyzed the effect of reflective street pavement on microclimate and concluded that reflective pavement reduced ambient summer temperatures by up to 1.9 °C and park surface temperatures by up to 12°C [42]. Kong et al. studied the relationship between urban cold island effects (UCIs) and microclimate in Nanjing green parks, where a 10% increase in vegetation area reduced surface temperatures by approximately 0.83 °C [43].

Techniques and factors for microclimate studies have also been gradually expanded. Popular et al. used CFD simulations to predict the meteorology of the city of Rotterdam, including wind flow and heat transfer by conduction, convection and radiation and confirmed that the average deviation between simulated and experimental data was 7.9%, confirming the potential of CFD to predict urban microclimate accurately [44]. The influence of individual humans on the microclimate has also been considered. Bocker et al. were the first to systematically include behavioral activities considering thermal comfort to study the influence of climate on daily human behavior and critical activities such as walking and cycling [45]. They found that climate has a profound effect on travel.

The number of publications in this period showed rapid growth compared with the previous period (Figure 1), and the number of co-cited literature increased significantly compared with the previous period (Figure 5). Microclimate-related research and methods gradually matured and focused on the coupling research between microclimate and other objects, expanding the value volume of microclimate, providing in-depth theoretical support, mature technical methods, and high application value research directions.

3.2.4. Eco-Synergy Phase (2016 to Date): Focus on Eco-Synergy with Multiple Types of Elements

This phase focuses on urban microclimate research under interdisciplinary and multi-perspectives, and the main keywords are green infrastructure, ecosystem services, and ventilation. In addition to the wide application of new technologies and models, the relationship between urban landscape and ecology is given unprecedented attention, and the focus is on the social benefits of the urban microclimate and the innovation of research applications.

Among urban landscape benefit studies, Livesley et al. investigated the cooling benefits of urban forests on the local microclimate, including air quality, improved water quality, and biochemical cycling [46]. Wang et al. found significant effects of direct sunlight hours and mean radiation temperature on urban thermal comfort, using urban settlements in Toronto as an example [15]. Berardi simulated the impact of green roof retrofitting on an outdoor microclimate in the context of high settlement density, confirming the potential of green roofs as an urban heat island mitigation strategy [47]. Salata et al. used a university campus in Rome as an example to study different mitigation strategies for urban microclimate change. In contrast, an appropriate combination of cold roofs, urban vegetation and cold pavement can result in mean and maximum reductions of −2.5 and −3.5 in MOCI (Mediterranean Outdoor Comfort Index) [48]. Among climate adaptation benefits, Gunawardena et al. analyzed the impact of urban blue-green spaces on urban climate, and both were able to significantly mitigate the thermal effects of cities and enhance climate adaptation [49]. Among the applications, Shamshiri et al. deeply integrated microclimate with the agricultural sector to build advanced microclimate control and energy optimization models [50]. Cureau et al. focused on microclimate at the hyperlocal scale (refers to higher spatial resolution situations, usually on the meter scale) and monitored microclimate indicators from a human perspective in all aspects and multiple domains [28].

Building types are also considered in the urban content; Yang et al. investigated the thermal microclimate of two building types, residential and office, and found that office buildings are less sensitive to thermal pressure [51]. It is concluded that the spatial and temporal variability of the urban heat island effect at the local scale can have different effects on building energy efficiency.

The urban microclimate continued to develop rapidly during this period, and its research scope and methods were further expanded. Research results continued to increase, with research on elements, scale and development strategies of urban microclimate, closely following ecological issues, and more in-depth interdisciplinary directions gradually emerged, forming a diversified research direction.

4. Hot Spots and Trends in Urban Microclimate Research

4.1. Distribution of Research Hotspots Based on Keyword Clustering

Word frequency analysis of literature keywords is commonly used in bibliometrics to reveal the distribution of research hotspots [19]. The graphical analysis of VOSviewer can reflect the relationship between each important node, topic and keyword more visually [52]. First, set the statistic value of word frequency to the threshold of 30, then select the top 110 high-frequency keywords to draw the urban microclimate research keyword co-occurrence network mapping (Figure 6) and annual overlap mapping (Figure 7). Several keywords with high word frequency were temperature, climate, vegetation, outdoor thermal comfort, and urban heat island.

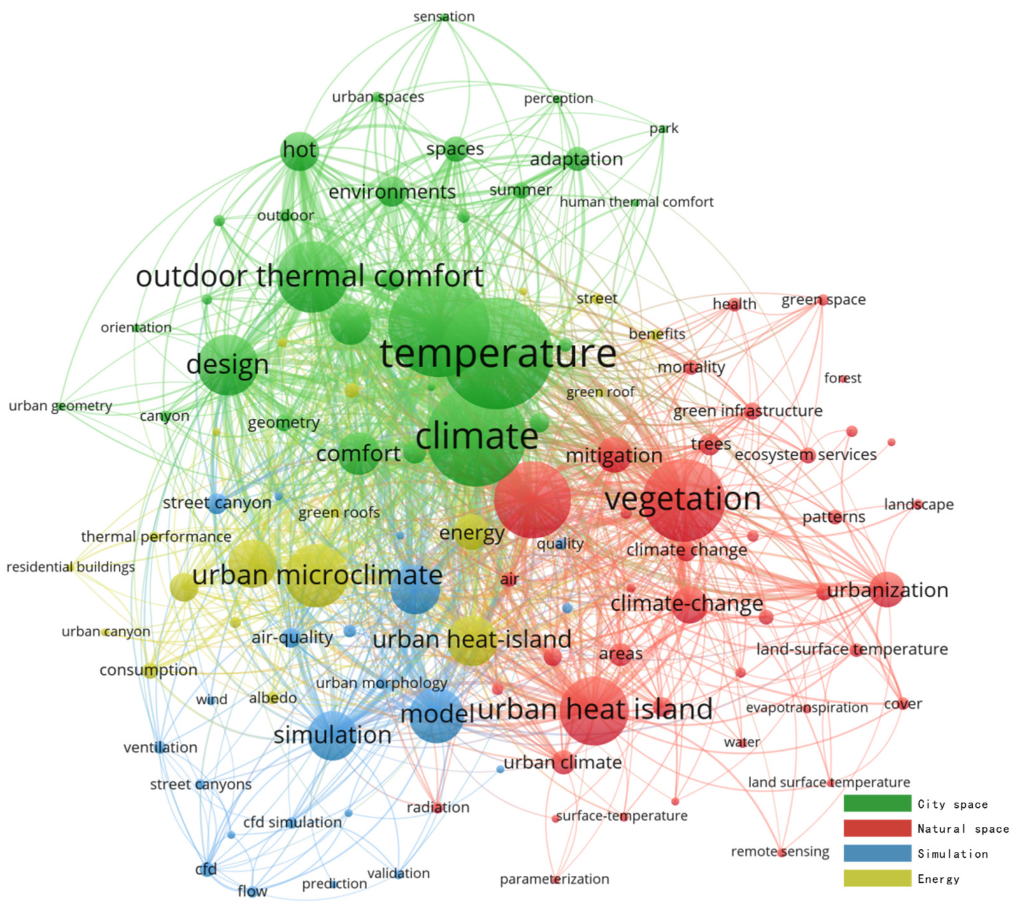

Figure 6. Keyword co-occurrence network mapping for urban microclimate research.

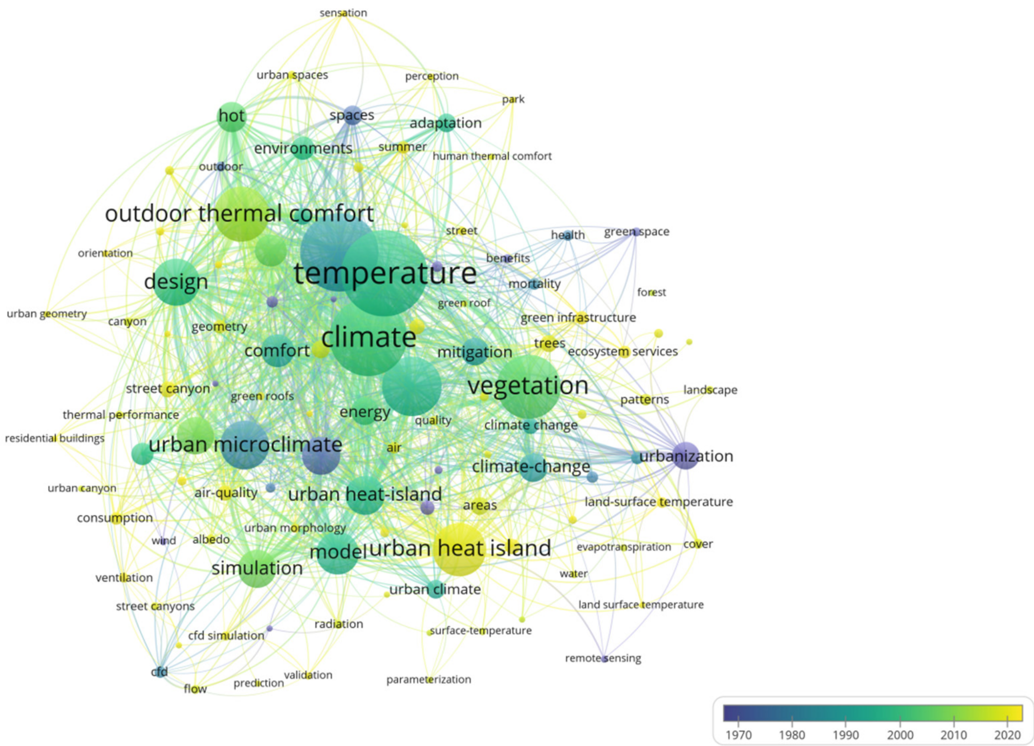

Figure 7. Annual overlap mapping of urban microclimate studies.

In the keyword co-occurrence network view (Figure 6), the four-word nodes of temperature, vegetation, model, and energy are the largest and the most frequent. Around these four core concepts, other high-frequency keywords based on co-occurrence relationships present four main research clusters: (1) Green: Focus on urban microclimate and urban environment, urban space, and other research. The high-frequency words include climate, outdoor thermal comfort, environment and adaptation. From the word frequency, the research objects focus on urban geometry, hot, environment, and summer, the purpose of the research is mainly concerned with adaptation, orientation, and perception, and the research methods involve design and ENVI-met simulation; (2) Red: Research exploring the relationship between the natural and urban environments. High-frequency words include urban heat island, climate change and urbanization. The study object is related to surface temperature, ecosystem services, and green infrastructure regarding word frequency. It focuses on health, mitigation, and land use. The research methods mainly involve covering and remote sensing; (3) Blue: The study of urban microclimate modelling. High-frequency words include simulation, street canyon, and air quality. The main objects of interest are density, pollution, and ventilation in terms of word frequency. The research methods are mainly CFD methods and prediction; (4) Yellow: In the study of urban energy consumption, its high-frequency words are consumption and albedo. The main objects of concern are the green roof and shade trees.

From the year analysis (Figure 7), the high-frequency words that appeared earlier (before 2010) include temperature, climate, vegetation and urbanization. Early urban microclimate research focused on integrated research with other disciplines such as environment, and then outdoor thermal comfort, simulation, and surface temperature were proposed, and the research objects and contents were further refined. Since 2016, the high-frequency words have been consumption, radiation, ventilation, ecosystem and CFD. Compared with the previous stages, the research perspective is more macroscopic, and new concepts and technologies are gradually applied.

4.2. Evolution of Research Hotspots Based on Annual Overlap

The Time view function in CiteSpace enables the visual analysis of evolutionary paths [23], which helps discover the turning time points of research and the critical literature of the corresponding period. The timeline view reflects the distribution of keywords with high centrality over different years. The size of the circles in Figure 8 reflects the high level of keyword centrality. Nodes with higher centrality have a more significant influence. If the keywords in a time zone are intensive, there are more research results in this period. The timeline view can also analyze the relationship among different clusters.

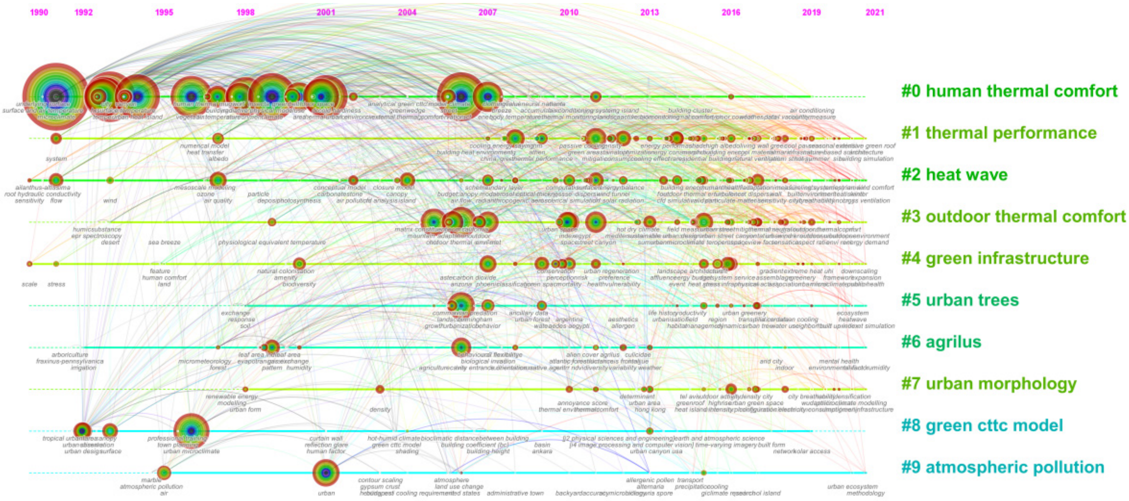

Figure 8. Time-zoned axial mapping of urban microclimate studies (top ten categories).

In this paper, we use CiteSpace's keyword analysis, set the time slice to 1 year, and plot the time-zoned axes of research in different periods (Figure 8) to analyze the relationship between each cluster and analyze the importance of different categories in different periods. Ten categories of relevant research hotspots were obtained, namely #0 human thermal comfort, #1 thermal performance, #2 heatwave, #3 outdoor thermal comfort, #4 green infrastructure, and #5 urban trees, #6 grills, #7 urban morphology, #8 green CTTC (cluster thermal time constant) model, #9 atmospheric pollution. The topics include heat, heat balance equations, environment, ecology, urban geometry, modelling, and meteorology. Human thermal comfort is the cluster with the most prolonged duration, the highest keyword centrality and the most significant influence on other clusters, which is the focus of urban microclimate research.

4.3. Research Hotspot Prediction Based on Keyword Emergence

Keyword burst detection can detect changes in the frequency of keywords over a certain period and derive promising research directions [18]. In the study from 1990 to 2021, the 24 burst keywords with the highest frequency were selected for study (Table 2). Before 2006, the main focus was on urban design and land planning. From 2006 to 2016, the research was extended towards landscape, temperature, hot, dry climate, and parameterization, and from 2016 to date, related research has focused more on morphology and materials.

This paper further analyses the keywords that appeared in the last five years (2017–2022) and the strength and timing of their appearance to mitigate the lag in the bibliometric results and more accurately analyze the research trends in urban microclimate. As shown in Table 3, coating, atmosphere boundary layer, Mediterranean climate, shading and energy efficiency are new topics in recent years.

Table 2. Top 24 most cited keywords in urban microclimate research in 1990–2021.

Keywords	Strength	Start	End	1990——2021
Urban design	5.2354	1992	2017	
Landscape	4.4904	2006	2014	
Community	4.2531	2006	2017	
Parameterization	4.093	2008	2014	
Temperature	8.2872	2008	2013	
Air pollution	4.2191	2008	2012	
Thermal performance	3.1075	2009	2011	
Urban planning	4.0628	2011	2014	
Impervious surface	3.5086	2011	2016	
Land use	7.5759	2012	2017	
Green roof	4.3646	2013	2017	
Evapotranspiration	3.8072	2013	2015	
The hot, dry climate	4.8018	2013	2016	
Urbanization	3.1877	2014	2015	
GI	3.3411	2015	2017	
Biodiversity	3.1095	2016	2017	
Cool material	4.0713	2017	2018	
Thermal sensation	3.5097	2018	2019	
Urban heat	3.5198	2019	2021	
Equivalent temperature	3.3522	2019	2019	
Energy performance	3.7053	2019	2019	
Aspect ratio	4.1644	2019	2021	
Urban park	3.9219	2020	2021	

The blue line indicates the period from 1990 to 2021, with each small segment representing one year; the red thickened line indicates the period of the sudden growth of the corresponding keyword, with the red appearing and ending positions representing its starting and ending years, and the longer the red line represents, the longer the sudden growth of the keyword is maintained.

Table 3. Keywords highlighting strength and timing of urban microclimate research in 2017–2022.

Keywords	Strength	Begin	End	2017——2022
Coating	2.0568	2017	2019	
Atmosphere boundary layer	1.9597	2017	2018	
Mediterranean climate	2.0746	2017	2018	
Shading	2.8963	2018	2019	
Energy efficiency	2.2226	2020	2022	

The blue line indicates the period from 2017 to 2022, with each small segment representing one year; the red thickened line indicates the period of the sudden growth of the corresponding keyword, with the red appearing and ending positions representing its starting and ending years, and the longer the red line represents, the longer the sudden growth of the keyword is maintained.

CiteSpace provides two metrics, module value (Q value) and average profile value (S value), based on the clarity of network structure and clustering, which can be used to judge the effectiveness of mapping. In general, Q values are generally in the interval [0, 1), Q > 0.3 means that the delineated association structure is significant, and the clustering is efficient and convincing when the S value is 0.7. The co-occurrence network relationship is simplified into clusters and labelled, and the top 10 clusters are listed with cluster module value (Q value) of 0.8013 > 0.3 and average profile value (S value) of 0.9239 > 0.7, indicating that the clusters lie in the confidence interval and the clustering quality is high. Table 4 and Figure 9 show a more in-depth analysis of the specifics contained in each cluster name.

Table 4. Keyword clustering of urban microclimate research in the last five years.

Cluster Name	Size	Profile Value	Year	Main Keywords
0. Urban ecology	35	0.913	2018	urban ecosystems; land surface temperature; air temperature; ecosystem services; indicators; physical health; global climate regulation
1. NDVI (Normalized Difference Vegetation Index)	30	0.936	2018	surface urban heat island; physical activity; citizen science; biological invasion; convective heat flux
2. Particulate matter	30	0.882	2018	agent-based model; ventilation path; twining plants; small urban planting design; geographic information system (gis); single planting
3. Thermal comfort	29	0.857	2018	cool pavement; microclimate model; thermal behavior; physiological equivalent temperature index; micrometeorological measurements; hedonic modelling; outdoor microclimate map
4. Heat mitigation	26	0.918	2018	turbulence; urban canyon; weather research and forecasting model; low-rise housing; humid tropics region; office buildings; height-to-width ratio; passive design
5. ENVI-met	25	0.953	2018	mitigation; integrated environmental assessment; residential district; direct shortwave radiation scattering; wind speed reduction; plant geometry; plant physiology
6. Urban trees	23	0.886	2018	tree species; air relative humidity; reduced soil water availability; antioxidants; surface-energy balance; light; latent heat flux; sap flow dynamics
7. EnergyPlus	23	0.879	2018	thermal adaptation; form indices; cooling energy consumption; generic residential districts; OpenFOAM
8. Thermal network model	23	0.946	2017	building energy simulation; computational fluid dynamics; vertical greenery system; CoMFA human heat balance model; lumped thermal parameter
9. Irrigation	21	0.872	2017	green walls; urban agriculture; urbanization; Teb; urban water cycle; subtropical monsoon climate; vertical farming

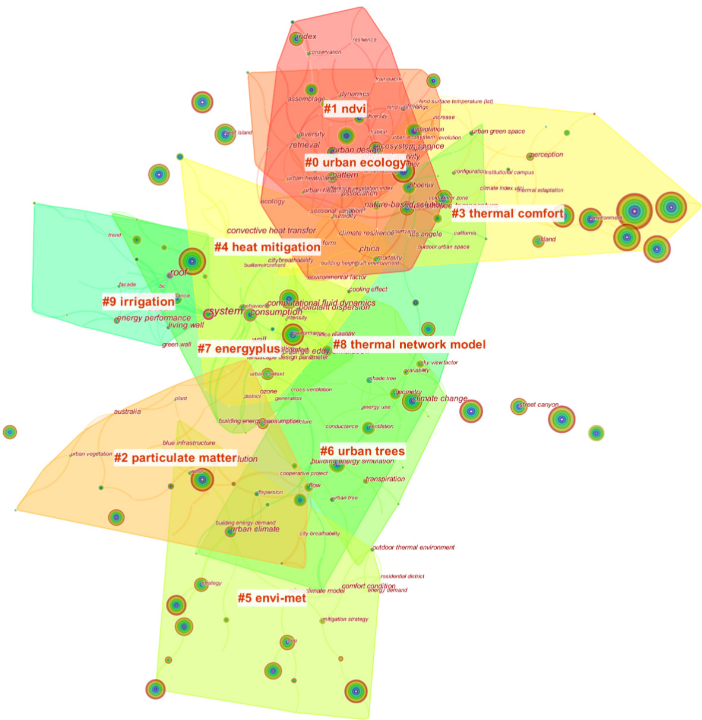

Figure 9. Cluster mapping of urban microclimate research keywords 2017–2022.

Those with greater frequency (>200 times) are temperature, urban heat island, thermal comfort, vegetation, and environment. Those with more vital centrality (greater than or equal to 0.15) are energy-saving, cooling load, biometeorological assessment, roof, cover, and heat stress.

5. General Forecast of Trends in Research Characteristics

5.1. Multi-Scale Urban Climate Simulation Study

Computer simulations can integrate the effects of different meteorological conditions on cities, buildings and humans, and play an essential role in urban microclimate assessment [53]. However, most studies have focused on micro-scale outdoor human thermal comfort using ENVI-met, and more multi-scale model coupling is needed at the urban level [54], e.g., the high-resolution urban climate model PALM-4U [55], and the urban multi-scale environmental predictor UMEP [56]. Future research could combine models at different scales with climate zones, and there are already nesting ENVI-met into local climate zones LCZ [57], WUDAPT [58], mesoscale models (e.g., WRF), or larger scale model domains [57], intending to achieve more scientific strategic plans for cities to implement climate change.

5.2. Multi-Factor Urban Microclimate Impact Study

An urban microclimate is influenced by various factors such as physical and social factors, and scholars have used methods such as fluid dynamics (CFD) [12] and weather research and forecasting (WRF) [59] to study factors such as wind speed and direction [60], building materials [61], temperature [62] and humidity [63] to determine urban microclimate parameters. Since the influencing factors of urban microclimates involve many aspects, there are still many research blind spots in the existing literature, which need to be further sorted out and comparatively studied to build a more systematic urban microclimate model, and then form a systematic scientific cycle system.

5.3. Multi-Policy Urban Microclimate Guidance Study

Compared with “smart cities” and “low-carbon cities”, there is a lack of clear policy guidance on the urban microclimate [64], and the improvement of urban environmental comfort by microclimate optimization has not been considered. In the future, the role of the urban microclimate can be highlighted in the ambient air quality standards or green building guidelines.

6. Conclusions

In this paper, we use WOS online analysis with bibliometric data analysis of CiteSpace and VOSviewer to study the literature related to the urban microclimate from 1990 to 2021, and visualize and analyze the characteristics of literature distribution, research development stages and research hotspot trends in different periods, disciplines and country situations and conclude the following:

(1) The urban microclimate research literature volume shows prominent multidisciplinary and comprehensive characteristics. The overall number of publications shows an increasing trend, and four leading research clusters are formed: theoretical research on the urban environment and urban space, research on the natural environment and urban environment, research on urban microclimate modelling, and research on urban energy consumption;

(2) Urban microclimate research can be divided into four stages: nascent exploration, model quantification, diversified development, and ecological synergy. In terms of literature and discipline distribution, research hotspots and focus, they show the “rise of multidisciplinary and urban studies”, “application of numerical quantification and model evaluation”, “maturation of system and expansion of research breadth”, and “focus on eco-synergy with multiple types of elements”;

(3) The knowledge mapping characteristics of research hotspots based on keyword clustering, annual overlap, and keyword highlighting show that urban microclimate research has three hotspot trends—multi-scale urban climate simulation research, multi-element urban microclimate impact research, and multi-policy urban microclimate guidance research.

Urban microclimate research has achieved specific results since 1990, but there are still problems such as incomplete policies and insufficient elements. The academic community needs more innovations in urban microclimate theory and practice to construct a theoretical system of the urban microclimate and solve the urban microclimate's complex and diverse practical problems.

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