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ORIGINAL PAPER

Urban heat island research from 1991 to 2015: a bibliometric analysis

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Abstract A bibliometric analysis based on the Science Citation Index-Expanded (SCI-Expanded) database from the Web of Science was performed to review urban heat island (UHI) research from 1991 to 2015 and statistically assess its developments, trends, and directions. In total, 1822 papers published in 352 journals over the past 25 years were analyzed for scientific output; citations; subject categories; major journals; outstanding keywords; and leading countries, institutions, authors, and research collaborations. The number of UHI-related publications has continuously increased since 1991. Meteorology atmospheric sciences, environmental sciences, and construction building technology were the three most frequent subject categories. Building and Environment, International Journal of Climatology, and Theoretical and Applied Climatology were the three most popular publishing journals. The USA and China were the two leading countries in UHI research, contributing 49.56% of the total articles. Chinese Academy of Science, Arizona State University, and China Meteorological Administration published the most UHI articles. Weng QH and Santamouris M were the two most prolific authors. Author keywords were classified into four major groups: (1) research methods and indicators, e.g., remote sensing, field measurement, and models; (2) generation factors, e.g., impervious urban surfaces, urban geometry, waste heat, vegetation, and pollutants; (3) environmental effects, e.g., urban climate, heat wave, ecology, and pollution; and (4) mitigation and adaption strategies, e.g., roof technology cooling, reflective cooling, vegetation cooling, and urban geometry cooling. A comparative analysis of popular issues revealed that UHI determination (intensity, heat source, supporting techniques) remains the central topic, whereas UHI impacts and mitigation strategies are becoming the popular issues that will receive increasing scientific attention in the future. Modeling will continue to be the leading research method, and remote sensing will be used more widely. Additionally, a combination of remote sensing and field measurements with models is expected.

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1 Introduction

The urban heat island (UHI) is a phenomenon in which an urban area is warmer than its surrounding suburban and rural areas (Sundborg 1951). It is caused by the special urban underlying surface (fabric, topography) and anthropogenic heat release from urban activities. Since Howard's first observation in London in 1818 (Howard 1818), UHI has been widely observed and documented in many major cities around the world, both in developed and in developing countries. Although the warming effect of UHI on global climate is controversial (Emmanuel and Krüger 2012; Hoornweg and Symposium 2011; Parker 2004; Peterson 2003), it is widely agreed that UHI can impact local and regional climates (Kalnay and Cai 2003; Zhang et al. 2011), with the warming contribution from UHI accounting for 10–40% (Gaffin et al. 2008; Jin et al. 2015) and even up to 80% (Ren et al. 2007) in rapid urbanization areas.

As a striking form of anthropogenic climate modification induced by urbanization and industrialization, UHI exerts great impacts on urban physical and social systems. The negative effects include increases in energy consumption and carbon emissions (Hirano and Fujita 2015; Santamouris 2014), the aggravation of air pollution (Gerasopoulos et al. 2006; Šimac et al. 2011), increased likelihood of an epidemic (Kovats et al. 2004; Patz et al. 2005), the deterioration of living environments, and increased mortality rates (Baccini et al. 2008; Kim et al. 2006; Wong et al. 2013). Therefore, UHI is considered as one of the major problems of the twenty-first century (Rizwan et al. 2008). For the sustainable development of urban society, determining the factors that contribute to UHI and how to address, mitigate, and adapt to this urban climate have earned special attention from the perspective of climatology, environmental sciences, material design, building design, energy fuels, medicine, urban planning, and urban design. Many studies have been published on various aspects of UHI, including the spatiotemporal patterns of UHI (Jin et al. 2015; Miao et al. 2009; Ren et al. 2007); the causes of UHI (Ryu and Baik 2012; Schwarz and Manceur 2014); the methods and technologies for UHI research (Adachi et al. 2012; Lauwaet et al. 2015; Mirzaei and Haghighat 2010); impacts on precipitation (Dixon 2003), pollution (Liao et al. 2015), health (Tan et al. 2009), boundary layer structure (Pal et al. 2012), energy use (Santamouris 2014), and phenology (Jochner et al. 2013); and mitigation strategies (Krüger and Pearlmutter 2008; Saneinejad et al. 2014; Takebayashi and Moriyama 2012).

In addition, UHI research has been reviewed from different perspectives. Rizwan et al. (2008) summarized the generation, determination, and mitigation of UHI. Mirzaei and Haghighat (2010) reviewed the techniques (observational approaches, thermal remote sensing, small-scale modeling, simulation approaches) used to study UHI and presented the abilities and limitations of each approach for the investigation of UHI mitigation and prediction. Stewart (2011) assessed the UHI empirical literatures' methodological quality based on 190 articles that target canopy-layer, ground-based nocturnal UHI on local-meso time and space scales during 1950–2007 and then made suggestions for improving methodological quality in UHI studies. Gago et al. (2013) summarized strategies that mitigated the effects of UHI. Santamouris (2013) introduced the development of the main technologies associated with cool pavements. However, a comprehensive quantitative analysis of global development and future trends of UHI has not been addressed.

Bibliometrics is an effective method for evaluating the scientific production and research trends in a certain field and has been widely used in many disciplines (Peng et al. 2015; Wang et al. 2012; Zhang et al. 2016; Zhi et al. 2015). Bibliometrics focuses on citation and research content analysis, which can elucidate the global trends or future projections for a specific research area. To explore international exchange and cooperation, bibliometric website analyses on co-authorship and co-publication analysis have been performed, and various visual software programs, such as CiteSpace, UNINET, and ArcGIS, are utilized for intuitive results. To evaluate the academic influence in a specific scientific field, three assessment indicators have been adopted, including an h-index (Hirsch 2005), average citation, and impact factor (IF). For the source database, the Science Citation Index-Expanded (SCI-Expanded) database in the Web of Science is the most frequently used from an international perspective.

Therefore, in this study, we used bibliometrics to comprehensively and systematically assess the scientific progress of UHI-related research during the period of 1991–2015. The main objectives of this study were (1) to identify the publication pattern of UHI-related research; (2) to evaluate the UHI outputs by nation, institution, and author and to investigate international collaboration and author distribution in the field of UHI research; and (3) to reveal popular issues and future trends in this research area. Findings from this analysis will help relevant research to provide an integrated understanding of global UHI research progress and to target future research directions and content.

2 Data and methods

2.1 Data

We gathered all of the data from the SCI-Expanded database of the Web of Science (Thompson Reuters Corporation, USA) on March 2, 2016, such that the publications from 2015 were completely included. In 1991, abstracts were added to the Web of Science topic searching system; under a certain search keyword, all of the publications that contain the search topic in the title, abstract, and keywords became available beginning from 1991. Thus, five keywords—"urban heat island," "urban heat islands," "city heat island," "city heat islands," and "UHI"—were used to compile a bibliography of all UHI-related researches during the period of 1991–2015. Subsequently, a preliminary checklist of the records was created, and duplicate records were deleted.

The previous procedure yielded a total of 1910 publications. All of the information, including the title, author, source journal, language, keywords, affiliation, cited reference list, cited times, publisher information, pages, ISSN and subject category of these records, was downloaded and organized into Microsoft Excel 2010 for further analysis. The data were then analyzed based on the following: publication characteristics (including the outputs by year, subject category, country, institution, author), collaboration analysis, and research hotspots. CiteSpace was utilized to visually demonstrate the geographic distribution of the authors, institutions, country, and territories in this scientific area together with the collaboration quantity and intensity. To evaluate the academic influence, indicators of total citations (TC)/total publications (TP) (average number of citations per paper), total local citations (TLC)/TP (average number of local citations cited by the UHI-related articles per paper), the IF, and h-index were calculated and compared. For the collaboration analysis, publications originating from England, Scotland, Northern Ireland, and Wales were grouped under the heading of the UK, while publications from Hong Kong, Macau, and Taiwan were separated from China. The collaboration type was determined using the author addresses; those whose authors were from the same country were designated as a "single-country publication," whereas those whose authors came from different countries were designated as an "internationally collaborative publication." In terms of institutional affiliation, the term "single-institution publication" was assigned to those whose authors were from the same institution; in contrast, the term "inter-institutionally collaborative publication" represented those whose authors came from different institutions. The collaboration rate was measured as the rate of internationally (inter-institutionally) collaborative publications to total publications.

2.2 Analysis method

Statistical analyses, co-occurrence analysis, and spatial mapping were conducted in this study. Statistical analyses, including calculations of the average, maximum, and minimum values, were performed using the Statistical Program for Social Sciences (SPSS) 17.0 software. Co-occurrence analysis was conducted using the Thomson Data Analyzer (TDA). Spatial mapping was performed by CiteSpace and ArcGIS 10.3.

3 Results and discussion

3.1 Characteristics of academic output

According to the aforementioned search strategies, 1910 outputs were identified as UHI-related publications during the period of 1991–2015. To provide a summary review of the output history, the annual output of this research area from 1900 to 2015 is displayed in Fig. 1. UHI research experienced a few quiet years and a period of stagnation after 1818, when the phenomenon of UHI was first observed by Howard (1818). Later, this area of research entered a developing period in 1991, when the annual output first reached double digits. Therefore, the period from 1991 to 2015 was suitable for an academic analysis of UHI research. Beginning in 2005 and continuing into the subsequent years, UHI publications grew rapidly, from 62 in 2005 to 313 in 2015, which reveals an increasing interest in this research area. This result can be attributed to the total growth in SCI publications; however, it may have been inspired by the publication of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report in 2001 and the effectiveness of the Kyoto agreement in 2005. The increase in UHI-related publications was also a result of concern about the pattern of world urbanization.

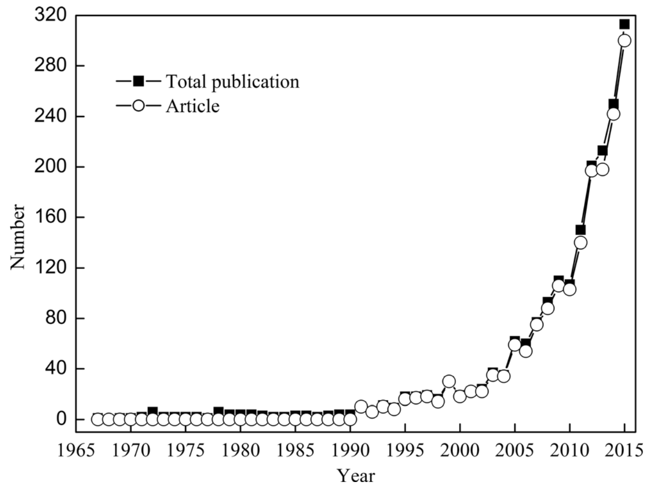


Fig. 1 Characteristics by year of UHI-related articles

Ten document types were associated with the 1910 publications. Articles (1822) were the most common, representing 95.39% of the total publications. Proceeding papers (82; 4.29%) and reviews (60; 3.14%) also accounted for an important percentage of the outputs. However, only original and peer-reviewed articles were accepted for further analysis. English (98.52%) dominated the academic output of UHI research, and the other eight languages also found included Chinese (13), German (5), Spanish (3), Portuguese (2), Turkish (1), Russian (1), Korean (1), and French (1).

Based on the classification of subject categories in the 2015 Journal Citation Reports (JCR), UHI research covered 110 subject categories. The top 10 subject categories included meteorology atmospheric sciences (711; 39.02%), environmental sciences (460; 25.25%), construction building technology (248; 13.61%), engineering civil (213; 11.69%), energy fuels (187; 10.26%), remote sensing (187; 10.26%), geosciences multidisciplinary (145; 7.96%), engineering environmental (135; 7.41%), imaging science photographic technology (135; 7.41%), and geography physical (111; 6.09%). The annual output of the top 6 subject categories is listed in Fig. 2. During the period of 1991–2015, meteorology atmospheric sciences dominated the research until a downturn in 2014. Environmental sciences ranked second and grew rapidly, especially after 2010, indicating a close relationship between UHI and environmental issues and underscoring the recent emphasis on the effects of UHIs on the environment. These top subject categories also signified high correlations of building, civil engineering, and energy fuels with UHI and the methods of mitigation. It was also observed that remote sensing was an important and widely used research method.

UHI-related research was highly concentrated in a limited variety of journals. A total of 12, or 3.41%, of 352 journals published 663, or 36.39%, of the total 1822 articles during the period 1991–2015, whereas 178 journals published only one

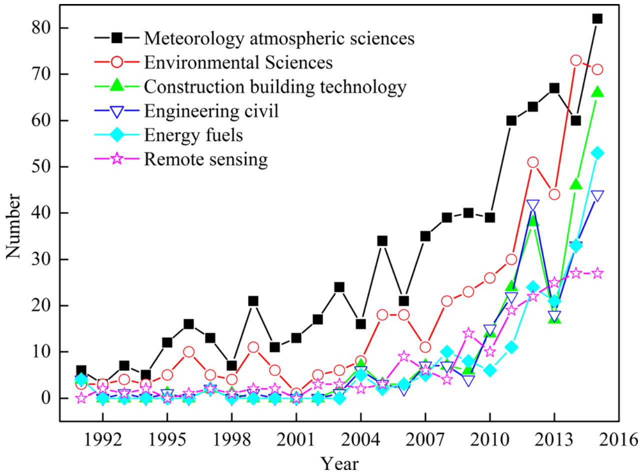


Fig. 2 Topics by year in the top 6 subject categories

UHI article, 48 journals published two, and 270 journals (76.70%) published fewer than five. The top 12 most productive journals are summarized in Table 1. Building and Environment published the largest number of UHI-related articles (90; 4.90%), followed by International Journal of Climatology (84; 4.60%) and Theoretical and Applied Climatology (74; 4.1%). Remote Sensing of Environment attracted wide attention in UHI research using remote sensing and earned its considerable influence in this area with a consistently high ranking in TC/TP (first), TLC (first), TLC/TP (first), IF (first), and TC (second), even though it published fewer papers (41; 2.25%). Atmospheric Environment and International Journal of Climatology were two other journals with leading authority with respect to overall general coverage. Furthermore, the titles and themes of these top journals highlighted the central position of meteorology atmospheric sciences, environmental sciences, construction building technology, energy fuels, remote sensing, and urban studies in UHI research.

3.2 Cooperation

Of the 1822 articles, 1427 (78.32%) were single-country articles, and 395 (21.68%) were internationally collaborative articles. Based on the author addresses, the geographical distribution of UHI research is plotted in Fig. 3 using CiteSpace. North America, Western Europe, Southern Europe, and East Asia were the major spatial clusters; several other minor clusters, such as South Asia, West Asia, Brazil, and Australia, were also found, and the clusters were mainly located within coastal areas. As shown in Fig. 4, although both the single-country articles and internationally collaborative articles increased over the 25 years, the percentage of internationally collaborative articles increased from 10% in 1991 to 27.33% in 2015. The change in the proportion of internationally collaborative articles revealed an increasingly international tendency in UHI research.

A total of 80 countries/territories participated in UHI research during this time period. The top 21 most productive countries/territories are summarized in Table 2 based on the following nine indicators: total publications, single-country articles, internationally collaborative articles, first-author articles, corresponding author articles, citation rate per paper, local citation rate per paper, percentage of internationally collaborative articles for each country (*C%*), and h-index. The local citation rate per paper counted the average number of citations cited in the 1822 UHI articles, which measured the academic influence of a country in UHI research. Among these 21 countries, 11 were from Europe, 6 from Asia, 2 from North America, 1 from Oceania, and 1 from South America. The USA was a leader in UHI research, contributing the most publications (499), single-country articles (331), and internationally collaborative articles (168). Furthermore, the USA

Table 1 Top 12 active journals in UHI research

Journals	TP	(%)	TC (R)	TC/TP (R)	TLC (R)	TLC/TP (R)	IF (R)	h-index (R)
Building and Environment	90	4.9	1628 (4)	18.09 (9)	495 (5)	5.50 (10)	3.598 (6)	24 (3)
International Journal of Climatology	84	4.6	2395 (1)	28.51 (3)	744 (2)	8.86 (5)	3.659 (3)	29 (1)
Theoretical and Applied Climatology	74	4.1	1358 (5)	18.35 (6)	695 (4)	9.39 (4)	2.287 (9)	22 (4)
Energy and Buildings	68	3.7	1233 (6)	18.13 (8)	434 (6)	6.38 (8)	3.617 (5)	17 (6)
Journal of Applied and Meteorology Climatology	61	3.3	911 (9)	14.93 (11)	350 (9)	5.74 (9)	2.697 (7)	17 (6)
Atmospheric Environment	58	3.2	2016 (3)	34.76 (2)	728 (3)	12.55 (2)	3.780 (2)	26 (2)
International Journal of Remote Sensing	43	2.4	947 (7)	22.02 (5)	368 (8)	8.56 (6)	1.859 (10)	14 (9)
Remote Sensing of Environment	41	2.3	2156 (2)	52.59 (1)	884 (1)	21.56 (1)	7.769 (1)	21 (5)
Landscape and Urban Planning	38	2.1	692 (10)	18.21 (7)	277 (10)	7.29 (7)	3.659 (3)	13 (11)
Boundary Layer Meteorology	37	2.0	927 (8)	25.05 (4)	376 (7)	10.16 (3)	2.47 (8)	16 (8)
Journal of Geophysical Research[a] Atmospheres	37	2.0	604 (11)	16.32 (10)	27 (12)	0.73 (12)		14 (9)
Sustainable Cities and Society[a]	32	1.8	75 (12)	2.34 (12)	52 (11)	1.63 (11)		5 (12)

TP total publications, % percentage share of publications, *TC* total citation counts, *TC/TP* average number of citations per paper, *TLC* total local citations cited by the 1822 articles, *TLC/TP* average number of local citations per paper, *IF* journal impact factor from the 2015 JCR, *R* rank

[a] Without impact factor

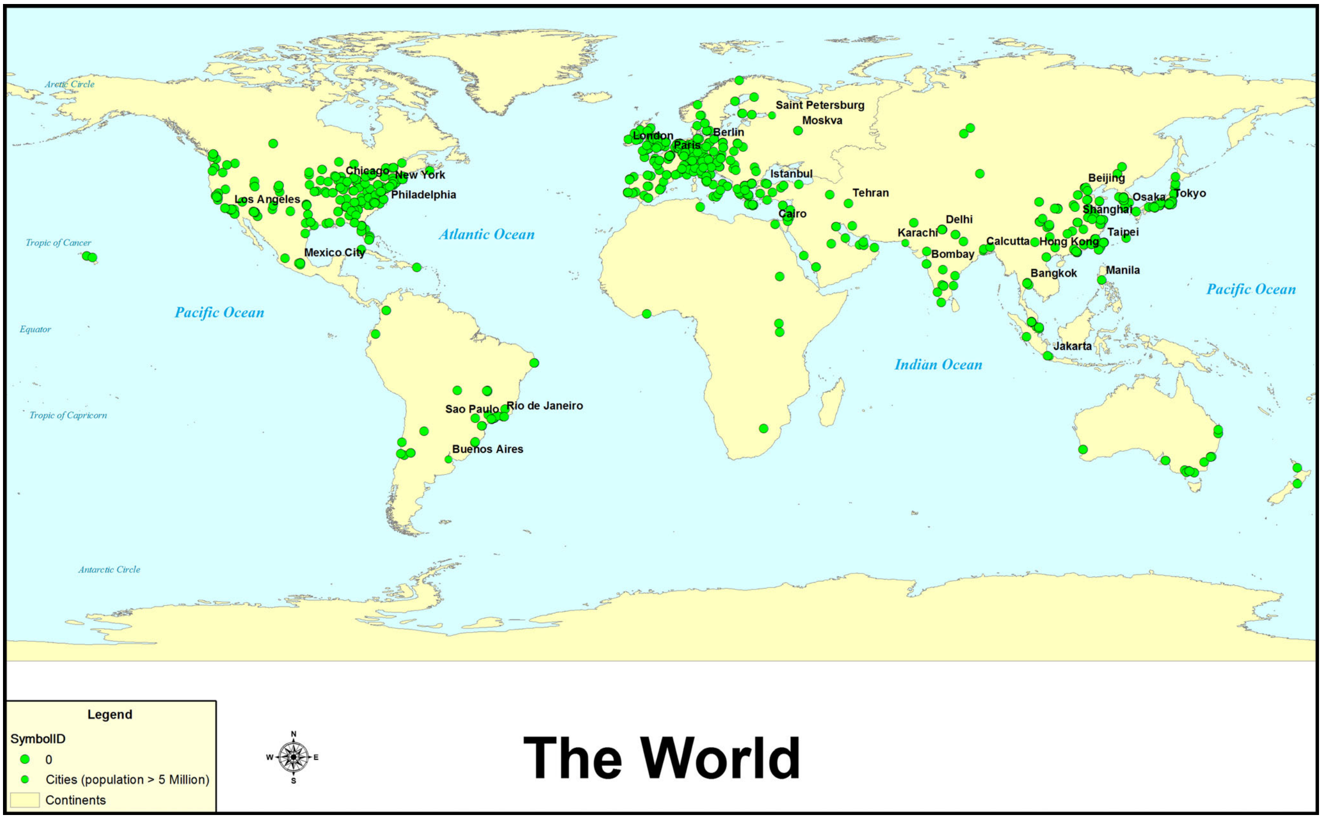


Fig. 3 Global geographic distribution of authors

had the highest h-index of 61. China ranked second, with 404 TP, 271 SP, and a 35 h-index, followed by the UK, Japan, Italy, and Germany. However, China ranked 15th in percentage of international collaboration, whereas Switzerland ranked 21st in total publications but exhibited the highest proportion of collaborative papers. Singapore, the USA, and Australia ranked high in both TC/TP and TLC/TP, indicating their great academic influence in UHI research. Simultaneously, the seven major industrialized countries (G7: Canada, France, Germany, Italy, Japan, the UK, and the USA) were all among the top 10 countries responsible for 61.25% of all articles during the period of 1991–2015. This finding is to be expected, as UHI is associated with urbanization, while urbanization is a preferred means of social and economic development and general social progress. The more developed an area, the higher the urbanization rate and, thus, the more significant the UHI effect; consequently, more attention has been attracted to more developed areas. Four major developing countries (Brazil, Russia, India, and China (BRIC)) published 27.11% of the total articles.

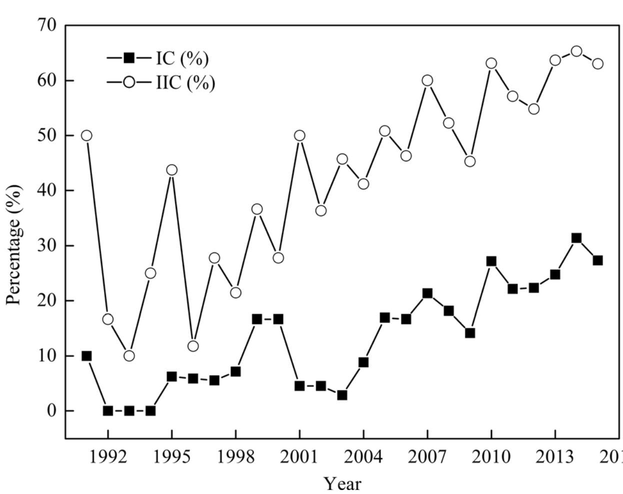


Fig. 4 Trends in the percentage of international collaboration articles (IC) (%) and inter-institutional collaboration articles (IIC) (%)

The time-change trend of UHI publications among the top 5 most productive countries is displayed in Fig. 5. The results indicated an overall increase in publications, referring to UHI in the five countries during the research period, especially from the USA and China. The USA had an early start and stayed ahead from 1994 to 2015, whereas the other four countries basically began their UHI research after 1997, when the "Kyoto Protocol" was formed. China did not exhibit stable and rapid growth until 2003, but it quickly caught up with other countries and soon surpassed the USA in 2010, 2011, 2013, and 2015. This trend was greatly guided and encouraged by government investment in climate research, such as the "863" and "973" projects. Rapid urbanization and industrialization, ever-increasing consciousness of local climates, and highly accelerated academic development in China also

Table 2 Top 21 major countries/territories in UHI research

Country	TP	SP	IP	FP	CP	C% (R)	TC/TP (R)	TLC/TP (R)	h-index (R)
USA	499	331	168	398	390	33.7 (14)	25.48 (2)	7.81 (4)	61 (1)
China	404	271	133	365	352	32.9 (15)	12.16 (16)	4.44 (14)	35 (2)
UK	164	93	71	123	111	43.3 (5)	16.20 (10)	4.85 (11)	28 (3)
Japan	128	89	39	108	105	30.5 (16)	16.78 (9)	5.82 (10)	25 (4)
Italy	94	60	34	79	75	36.2 (10)	10.80 (18)	3.24 (15)	18 (8)
Germany	90	56	34	75	72	37.8 (9)	11.26 (17)	3.19 (16)	18 (8)
Canada	76	40	36	48	51	47.4 (4)	22.24 (4)	5.84 (9)	20 (5)
Greece	73	57	16	65	66	21.9 (17)	16.93 (7)	7.35 (6)	20 (5)
France	64	37	27	51	47	42.2 (7)	14.56 (13)	4.65 (12)	18 (8)
Australia	53	31	22	42	43	41.5 (8)	21.50 (5)	8.12 (3)	18 (8)
Spain	51	19	32	34	33	62.7 (2)	15.06 (12)	6.59 (8)	16 (12)
South Korea	46	36	10	39	41	21.7 (18)	15.58 (11)	7.36 (5)	14 (13)
India	45	29	16	38	37	35.6 (11)	5.11 (21)	1.47 (21)	8 (20)
Netherlands	41	20	21	30	32	51.2 (3)	10.80 (19)	1.90 (19)	11 (17)
Brazil	34	22	12	29	29	35.3 (12)	8.44 (20)	1.53 (20)	9 (19)
Taiwan	33	19	14	30	29	42.4 (6)	12.33 (14)	4.52 (13)	12 (16)
Turkey	29	24	5	29	29	17.2 (20)	12.24 (15)	2.79 (17)	8 (20)
Singapore	29	19	10	24	22	34.5 (13)	23.50 (3)	8.79 (2)	13 (14)
Hungary	29	24	5	28	28	17.2 (20)	17.82 (6)	8.89 (1)	11 (17)
Sweden	28	23	5	24	24	17.9 (19)	38.92 (1)	6.92 (7)	19 (7)
Switzerland	27	9	18	14	15	66.7 (1)	16.81 (8)	2.44 (18)	13 (14)

TP total publications; *SP* single-country papers; *IP* internationally collaborative papers; *FP* first-author papers; *CP* corresponding author papers; *C%* the ratio of internationally collaborative papers to total papers; *TC/TP* average number of citations per paper; *TLC/TP* average number of local citations per paper; *h-index* h papers of an author, journal, institution, or country/territory having at least h citations each and the other papers having ≤h citations each; *R* rank

contributed to the high growth rate and enabled China to take a leading position in publishing UHI research papers. In total, the top 5 countries contributed 70.75% of the 1822 articles during the past 25 years.

Altogether, 1451 institutes engaged in UHI research. Among the top 21 institutes shown in Table 3, 9 were from

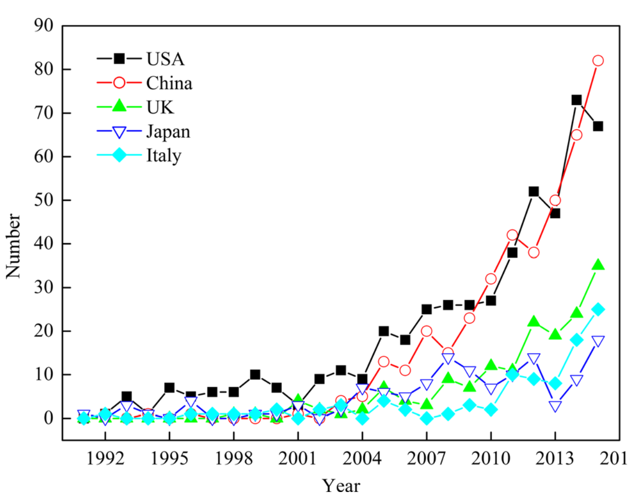


Fig. 5 The growth trends of the top 5 most productive countries

the USA, 7 from China, and 1 each from Hong Kong, Greece, South Korea, Singapore, and the UK. Thus, the USA and China also exhibited a leading position at the institutional level. Chinese Academy of Science headed the institutional production list with 111 articles, followed by Arizona State University with 71, China Meteorological Administration with 48, the National Center for Atmospheric Research with 40, and the University of California System with 40. Of these 21 most fruitful institutes, the University of California System led the academic influence with the highest TC/TP and had the second highest h-index, followed by the National Center for Atmospheric Research and the US Department of Energy. The percentage of inter-institutional articles was higher than that of internationally collaborative articles (Fig. 4), indicating more active cooperation and exchange among institutions than between countries. However, it is important to note that some bias exists in the results because institutes, such as Chinese Academy of Science and Arizona State University, have many branches or departments. Subdividing such institutions in the analysis might result in different rankings.

The Web of Science dataset recorded 4442 authors involved in UHI research. As in other areas (Liu et al. 2011), a large amount of the research was distributed among a handful

Table 3 Top 21 major research institutes in UHI research

Institution	TP	%	TC/TP	R	h-index
Chinese Academy of Science	111	6.09	10.62	17	20
Arizona State University	71	3.90	23.01	11	23
China Meteorological Administration	48	2.63	26.31	9	18
National Center for Atmospheric Research (NCAR)	40	2.20	43.15	2	22
University of California System	40	2.20	45.38	1	19
Nanjing University	37	2.03	7.49	20	10
University of Athens	36	1.98	27.28	8	19
Centre National De La Recherche Scientifique (CNRS)	36	1.98	14.92	16	13
Beijing Normal University	35	1.92	9.09	19	9
National Aeronautics Space Administration (NASA)	33	1.81	34.24	6	14
University System of Georgia	30	1.65	36.80	5	15
National Oceanic Atmospheric Administration (NOAA)	30	1.65	32.97	7	15
University of Hong Kong	27	1.48	17.52	15	12
Indiana State University	27	1.48	40.04	4	16
United States Department of Energy (DOE)	25	1.37	43.12	3	14
Peking University	25	1.37	24.68	10	9
University of London	23	1.26	21.78	12	11
University of Chinese Academy of Sciences	22	1.21	4.5	21	6
Seoul National University	21	1.15	18.71	14	11
National University of Singapore	21	1.15	19.90	13	10
Nanjing University of Information Science & Technology	21	1.15	9.19	18	7

TP total publications; *%* percentage share of publications; *TC/TP* average number of citations per paper; *R* rank; *h-index* h papers of an author, journal, institution, or country/territory having at least h citations each and the other papers having ≤h citations each

of researchers. Of the 4442 authors, 3392 published only one paper, whereas the top 20 most prolific authors produced 14.54% of all articles. The most productive authors included Weng QH with 24 articles, Santamouris M with 24, and Baik JJ with 20. Weng QH (Indiana State University, USA) produced the most publications, the most first-author articles, and the second highest number of corresponding author articles (Fig. 6). Unger J (University of Szeged, Hungary) also published the most first-author articles (Fig. 6). Baik JJ (Seoul National University, South Korea) contributed the most corresponding author articles (Fig. 6). In terms of academic influence according to TC, TC/TP, and h-index, Taha H (Altostratus Inc., USA) and Weng QH ranked high in all three indexes, indicating that they had more high-quality articles. Gallo KP (NOAA, USA) is an important research pioneer as he was one of the earliest authors to engage in UHI research, and six of his eight articles were published before 2000, with the other two in 2002, for an h-index of 7. Conversely, Bechtel B (University of Hamburg, Germany) is a newer name, and all seven of his articles were published after 2010.

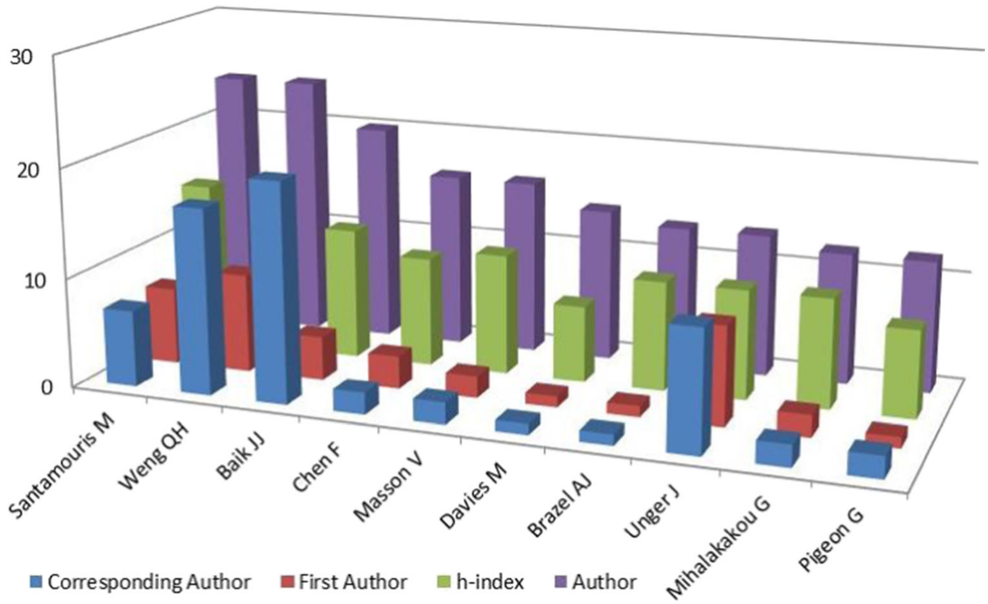
3.3 Keyword analysis and popular issues

Author keywords provide core information about the paper; thus, keyword analysis is often performed to review the history and development of science and to identify "hotspots" and future trends. To better detect dynamic changes in the UHI field, both a keyword frequency analysis and a co-word analysis were employed.

After merging and categorizing the keywords, we obtained 3382 author keywords in the 1822 articles. Among them, 2667 appeared only once, and 94.94% of the author keywords were used fewer than five times. The magnitude of the low-frequency keywords suggested a discontinuity in research and a wide disparity in research focus (Chuang et al. 2007), or it indicated the use of non-standard terminology (Ugolini et al. 2001), such as city heat island instead of UHI. The top 25 author keywords in five 5-year periods are listed in Table 4, and a co-occurrence relationship among the top 50 keywords is provided in Fig. 7 using CiteSpace. The size of the nodes is proportional to the occurrence frequency of each keyword, and the lines portray the connection between two words, the intensity of which is depicted in their connection strength. The colors illustrate the k value, which represents the number of connections with other keywords: red = $30 < k < 50$, green = $20 < k < 29$, blue = $10 < k < 19$, yellow = $5 < k < 9$, and black = $1 < k < 4$.

Similar to searching keywords, urban heat island constituted the largest proportion of the total scientific outputs during each period, with frequencies of 14.85, 10.95, 9.88, 10.09, and 9.54% for the 5-year periods. The remaining keywords with

Fig. 6 The top 10 most productive authors during the period of 1991–2015



high frequency could be categorized into four research topics: research methods and indicators, generation factors, environmental effects, and mitigating strategies. As shown in Fig. 7, UHI had the largest cooperation frequency with land surface temperature; cooperation between UHI and urbanization, climate change, remote sensing, land use, urban climate, cool roof, green roof, thermal comfort, and heat wave also exhibited high frequencies, emphasizing the four most interesting research topics in UHI noted earlier. To gain a comprehensive understanding of the research trends, a comparative analysis was also performed.

3.3.1 Research methods and indicators

UHI and UHI intensity are measured by the temperature difference between urban and rural areas, and the research indicators include temperature, surface temperature, land surface temperature, and air temperature. Figure 8 shows that land surface temperature was the most frequently used thermal indicator, ranking second among the total keywords, and it presented a vigorous increasing trend after its first appearance in 2003 and soon surpassed temperature in the past decade. Air temperature fluctuated during the research period but maintained a stable position. These two indicators represent two types of UHI: UHI and land surface urban heat island (LUHI). The former (usually 2 m) is either identified from field observations or from mobile traverse detection across an urban area, whereas the latter is derived directly from satellite data based on the thermal radiation of land surface. With the wide application of remote sensing in UHI research, the remotely sensed satellite land surface temperatures are anticipated to have a continuously growing popularity for UHI research. However, as a well-known and basic indicator, ground-observed air temperature may continue to fluctuate or remain relatively stable or may even start decreasing and be replaced by more important keywords, although increasing interest will be given to this type of UHI. Temperature experienced a drastic change in interest, moving from the least interest before 2000 to a peak interest from 2001 to 2005 and then steadily decreasing. Although surface temperature exhibited a difference from temperature, it also displayed a downward trend in usage in the past decade. Because UHI-related temperature includes air temperature, land surface temperature, and soil temperature and because surface temperature includes land surface temperature and sea surface temperature, these two terms will be less frequently used for the accuracy and normalization of scientific research.

Various methods have been used in UHI studies: field measurement, remote sensing, small-scale physical models, GPS, GIS, and mathematical models. The former three are observational methods, whereas the last is the simulation and predication method. Figure 9 displays the changes in the three main UHI monitoring methods: remote sensing, modeling, and field measurement. Although they started from the same premise, these three methods exhibited different tendencies in use. Due to its advantage of having a wider source, broader coverage, and steady period (Hu and Brunsell 2013), remote sensing prevailed over the five periods and exhibited an upward trend. As shown in Fig. 7, "Moderate Resolution Imaging Spectroradiometer (MODIS)" and "Landsat" had the largest cooperation frequency with remote sensing, indicating the importance of these sensors in UHI analysis. MODIS is the most used data source in UHI research. Both the Terra and Aqua satellites can provide images twice per day at 1000-m resolution. The Landsat sensors can acquire images once per day at building-

Table 4 The temporal evolution of the most frequently used author keywords

Keywords	Total	TP (R)				
		1991–1995	1996–2000	2000–2001	2006–2010	2011–2015
Urban heat island	670	15 (1)	31 (1)	49 (1)	152 (1)	423 (1)
Land surface temperature ↑	104	0 (11)	0 (14)	4 (6)	22 (2)	78 (2)
Climate change	87	1 (4)	5 (2)	5 (5)	17 (4)	59 (3)
Urbanization	80	0 (11)	0 (14)	6 (4)	22 (2)	52 (4)
Urban climate ↓	70	6 (2)	5 (2)	8 (3)	16 (6)	35 (7)
Remote sensing	69	1 (4)	2 (4)	4 (6)	17 (4)	45 (5)
Land use ↑	54	0 (11)	0 (14)	1 (16)	16 (6)	37 (6)
Temperature ↓	46	0 (11)	1 (6)	9 (2)	12 (8)	24 (12)
Heat island effect	41	0 (11)	1 (6)	2 (9)	12 (8)	26 (10)
Cool roof ↑	36	1 (4)	0 (14)	0 (20)	0 (25)	35 (7)
Green roof ↑	33	0 (11)	0 (14)	0 (20)	4 (20)	29 (9)
Air temperature ↓	33	1 (4)	2 (4)	2 (9)	10 (10)	18 (18)
Surface temperature ↓	30	1 (4)	0 (14)	2 (9)	10 (10)	17 (20)
Thermal comfort ↑	30	0 (11)	0 (14)	0 (20)	5 (15)	25 (11)
MODIS	27	0 (11)	0 (14)	2 (9)	5 (15)	20 (14)
Urban	26	0 (11)	0 (14)	0 (20)	8 (12)	18 (18)
Heat wave	25	0 (11)	0 (14)	1 (16)	4 (20)	20 (14)
NDVI	25	0 (11)	1 (6)	0 (20)	5 (15)	19 (16)
Global warming ↓	24	1 (4)	0 (14)	2 (9)	7 (13)	14 (22)
Solar reflectance ↑	24	0 (11)	1 (6)	0 (20)	1 (24)	22 (13)
Vegetation ↓	24	0 (11)	1 (6)	2 (9)	5 (15)	16 (21)
Mesoscale model ↓	23	1 (4)	1 (6)	4 (6)	5 (15)	12 (24)
Microclimate	22	0 (11)	0 (14)	1 (16)	2 (23)	19 (16)
Pollution ↓	22	2 (3)	1 (6)	1 (16)	7 (13)	11 (25)
Albedo	21	0 (11)	1 (6)	2 (9)	4 (20)	14 (22)

TP total publications; *R* rank; ↑ the upward trends in rank (e.g., "land surface temperature" did not appear before 2000, but soon its occurrence frequency went up to 22 during 2006–2010 and 78 during 2011–2015, with its rank growing from the bottom during 1991–2000 to 2nd among the total keywords during 2006–2015); ↓ the downward trends in rank (e.g., "air temperature" descended from 4th in 1991–2000 to 18th in 2010–2015); *MODIS* Moderate Resolution Imaging Spectroradiometer; *NDVI* normalized difference vegetation index

scale resolution. Therefore, applications of these two instruments have increased in UHI research. Using remote sensing, the traditional point-scale measurement is extended to a continental and even global-scale analysis and comparison. However, an instrument with a better combination of time and spatial resolution and excellent cloud screen algorithm and filtration model are expected.

Traditional field measurements have long time series but poor spatial resolution from heterogeneously distributed stations and inefficient data (Sismanidis et al. 2015). In addition, considering the relocation of many stations and the deficiency of proper pairs of urban and rural stations, the use of this method has been declining.

As Fig. 9 indicates, attraction has always been and will be further drawn into mathematical modeling, as models play a key role in urban climate simulation and prediction. Among the models, the microclimate urban canopy model (UCM) simulates the impacts of building within the urban canopy layer on urban meteorology by setting up a homogeneous urban neighborhood (Bonacquisti et al. 2006). The microclimate computational fluid dynamic (CFD) model analyzes the airflow disturbance and diffusion (Mirzaei and Haghighat 2010), whereas the mesoscale weather research and forecasting (WRF) model simulates and predicts city-scale atmospheric phenomena, considering the incidence rate, thermal conductivity, and roughness length of cities, but not considering the effects of building canyons, especially its multi-reflection. To better depict the atmospheric system at various spatial scales, the microscale and mesoscale models are presently coupled together (Chen et al. 2011; Kwak et al. 2015), and this cross-scale simulation shows great promise for future UHI research. Therefore, the closer integration of modeling with remote sensing and field measurements is anticipated, as models are greatly supported by observational data.

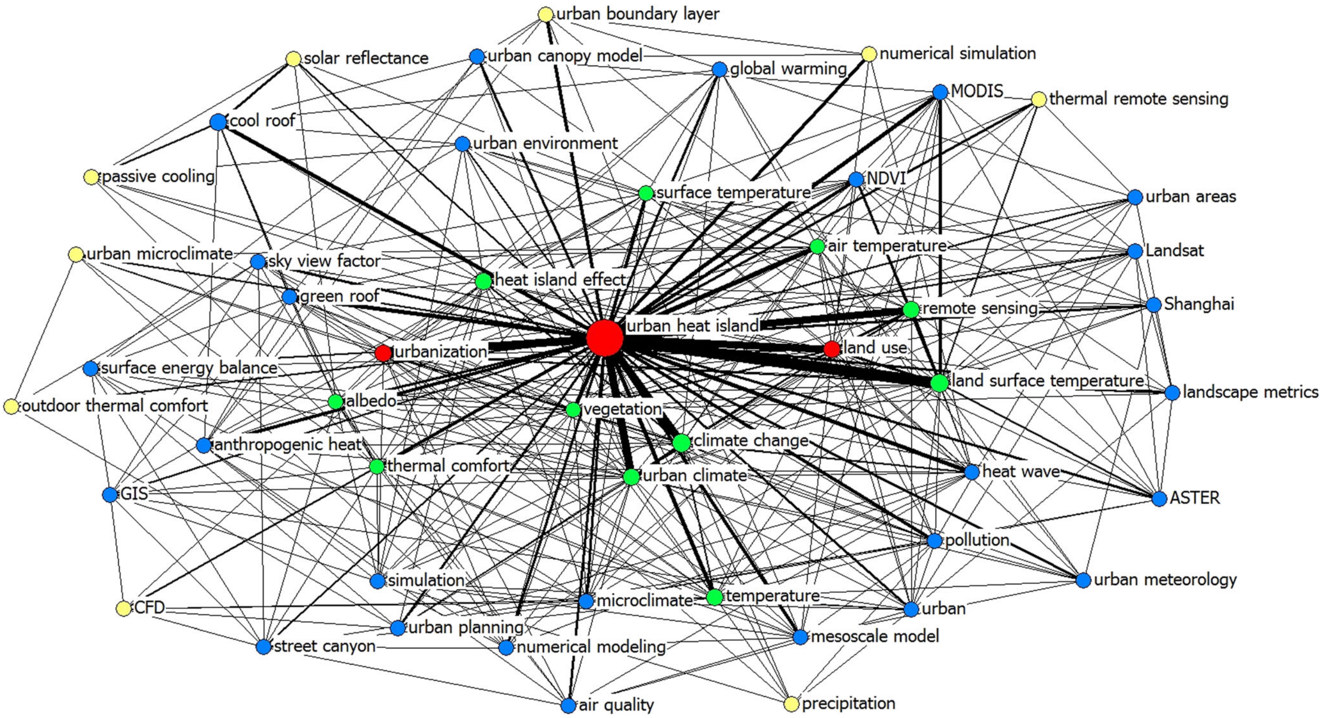


Fig. 7 Co-word network of high-frequency keywords in UHI research

3.3.2 Generation factors

Urbanization, urban, land use, solar reflectance, vegetation, albedo, pollution, anthropogenic heat, sky view factor, and street canyon are generation-related keywords with high frequency. Furthermore, according to the k-core analysis, urbanization and vegetation were core themes during the period of 1991–2015. In fact, urban, urbanization, and the resulting land use change are the ultimate causes of UHI. These results present five causation categories. First, impervious urban surfaces (such as asphalt, concrete, brick, and metal) have lower albedo and higher thermal conductivity and heat storage capacity than rural pervious surfaces (Rizwan et al. 2008), which causes urban areas to absorb and store more solar radiation during the daytime than rural areas; therefore, albedo is considered as one of the main reasons of UHI. Second, the small tall pencil buildings or the decreased sky view factor (street canyon geometry) reduces outgoing longwave radiation loss and turbulent heat transfer, being another major cause of UHI (Gago et al. 2013; Unger 2004). Third, decreased vegetation and increased impervious surface in urban areas reduce evapotranspiration latent heat loss (Kondoh and Nishiyama 2000) and direct solar energy as a result of shading. Fourth, fuel combustion, on the one hand, discharges greenhouse gases, contributing to more longwave absorption; on the other hand, the utilization of fuels releases a large quantity of waste heat from

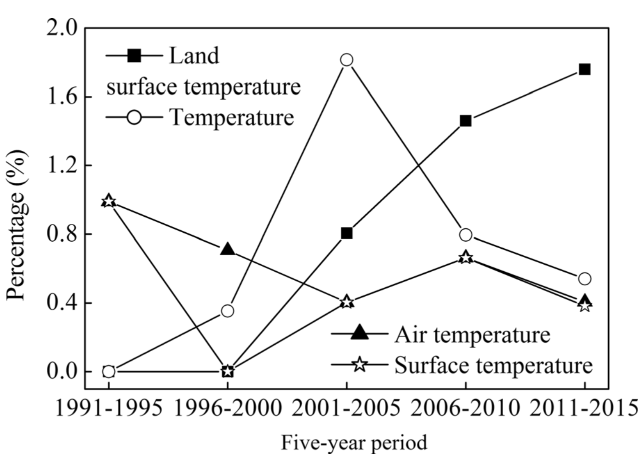


Fig. 8 Keywords associated with UHI indicators

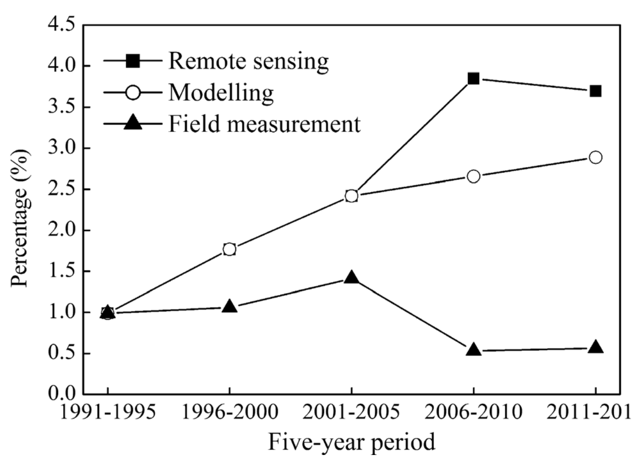


Fig. 9 Keywords associated with UHI research methods

factories, automobiles, air conditioners, and other sources. Fifth, pollutants, especially aerosols, can induce a pseudo-greenhouse effect. In addition, meteorological conditions, such as wind speed and cloud cover, also play a role in UHI (Kim and Baik 2005).

3.3.3 Environmental effects

The meteorological influences remained dominant in the ranking, proportion, and total outputs (Fig. 10), although they exhibited a clear decreasing trend. Early research concentrated on the topic of whether UHI exacerbated global warming; then, attention was given to urban climate analysis, such as thunderstorms (Bornstein and Lin 2000), precipitation (Dixon 2003), lightning (Farias et al. 2009), wind (Zhang et al. 2010), and the boundary layer (Pal et al. 2012). Heat waves and heat-related mortality associated with UHI attracted increasing attention during the period of 1996–2015. On the background of global warming, UHI may strengthen the intensity and duration of heat waves, leading to higher mortality risk from heat waves (Tan et al. 2009). When considering the large urban population influenced by UHI, this issue will receive increasing attention. Pollution is another topic concerning urban inhabitants' health, which has maintained steady interest. Furthermore, research on the effect of UHI on pollution concentrations and dispersion will continue.

UHI-induced summer cooling energy consumption increase, which conversely aggravates UHI, became another concern of increased importance. Investigating the effect of UHI on ecosystems, with an emphasis on phenological observation, and investigations into the phenology of animals, the influence of UHI on biological behavior, floristic composition, population structure, distribution, reproduction, and ecosystem services would also be desirable.

3.3.4 Mitigation strategies

Mitigation and adaptation strategies include the use of high albedo materials (Saneinejad et al. 2014), increasing evaporation from urban watersheds (Krüger and Pearlmutter 2008) and evapotranspiration from vegetation (Kondoh and Nishiyama 2000), roof technologies (Zinzi 2010), and building structure and distribution adjustment (Takebayashi and Moriyama 2012), which can be categorized into four major classes of mitigation measures: roof technology cooling, reflective cooling, vegetation cooling, and urban geometry cooling. As shown in Fig. 11, increasing attention has been paid to mitigation and adaption measures. This finding is not surprising considering the speed of global urbanization, the size of urban populations, and the consequences of UHIs. Predictably, mitigation and adaption strategies will become a priority in future UHI research.

Because pavement covers a high percentage of urban surfaces, reflective cooling contributes greatly to UHI mitigation and thus occupies an important position in all mitigation strategies. High-albedo pavements or cool pavements use reflective, permeable, and water-retentive material, which has high reflectivity in both solar radiation and thermal emittance, thus increasing the sensible heat flux to the atmosphere, yet also increases the latent heat flux from water evaporation (Santamouris 2013). Vegetation cooling is the most widely used and constantly increasing measurement, which comes from latent heat loss from evapotranspiration and the shading of direct solar radiation. Roof technology cooling includes cool roofs using light-colored surfaces and green roofs using vegetation covering. Due to the large fraction of roofs in urban areas and the excellent operability, this type of cooling could achieve major UHI mitigation. Furthermore, urban design factors, such as building geometry, built forms, orientation, and density, could also be best designed to counteract UHIs by influencing solar radiation and air flows; thus, there will be stable interest in this area.

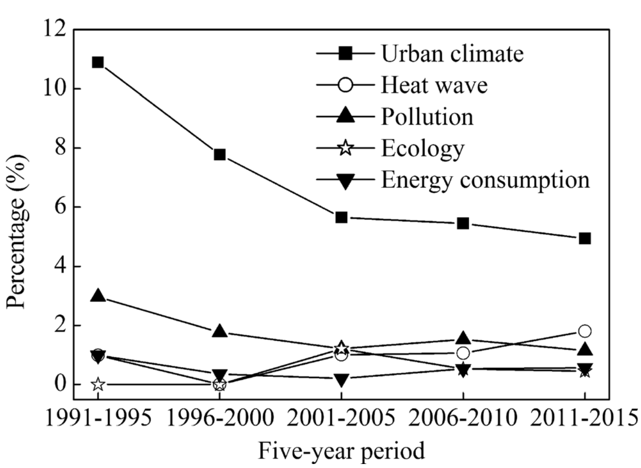


Fig. 10 Keywords belonging to UHI impacts

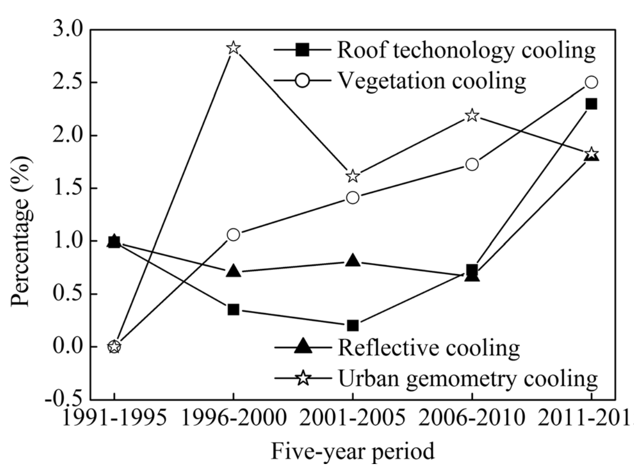


Fig. 11 Keywords associated with UHI mitigation strategies

4 Conclusion

We obtained an overall understanding of the development of UHI research during the period of 1991–2015 by employing bibliometric analysis. UHI research has experienced steady growth in outputs, academic influence, geographic distribution, and collaboration. In total, 1822 articles in 110 subject categories were published in 352 journals by 4442 authors. Meteorology atmospheric sciences, environmental sciences, construction building technology, engineering civil, and energy fuels were the most popular categories. Building and Environment, International Journal of Climatology, Theoretical and Applied Climatology, Energy and Buildings, and Journal of Applied and Meteorology Climatology were the five most productive journals, and Chinese Academy of Science, Arizona State University, and China Meteorological Administration were the three most productive institutes.

A popular topic analysis indicated that determination is still the central topic in UHI research. For regularity and prediction, modeling will continue to be the leading research method, and microscale and mesoscale models are expected to be more effectively combined. Remote sensing spreads traditional "point" measurements to "surface" investigation and achieves data acquisition more efficiently and comprehensively with higher quality; therefore, this remarkable technique will be used more widely. Furthermore, a closer combination of remote sensing and field measurements combined with models is expected. This study also suggests that UHI impacts, especially heat wave-related mortality, pollution, and ecological changes that are induced or exacerbated by UHI, will be important issues that receive increasing scientific attention in the future. In particular, UHI mitigation and adaption strategies will receive special attention. Vegetation arrangements, pavement and building material research, roof cooling design, and urban planning are actively being studied.

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