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Heatwave research in India: understanding current status, trends, and future directions

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सार – मानव जीवन पर पड़ने वाले प्रभाव के कारण हाल के दशकों में हीटवेव जैसे प्राकृतिक खतरों पर शोध में वृद्धि हुई है, जिसमें 2010 के घातक हीटवेव के बाद अधिकांश प्रकाशन हुए हैं। वेब ऑफ साइंस डेटाबेस के आधार पर, हम ग्रंथसूची विश्लेषण की एक व्यवस्थित विधि का उपयोग करके अनुसंधान प्रवृत्तियों, सहयोगी देशों और संस्थानों का सांख्यिकीय विश्लेषण करते हैं। अध्ययन इस तेजी से बढ़ते क्षेत्र में अस्थायी प्रकाशन प्रवृत्तियों, सह-लेखक नेटवर्क, उद्धरण पैटर्न और कीवर्ड विकास को प्रकट करता है। परिणाम हीटवेव की वैश्विक समझ के लिए भारतीय शोधकर्ताओं और संस्थानों के महत्वपूर्ण योगदान को उजागर करते हैं, साथ ही इस शोध को बढ़ावा देने वाले मजबूत अंतरराष्ट्रीय सहयोग भी करते हैं। भारत का अन्य देशों के साथ उच्चतम स्तर का सहयोग है, जबकि संयुक्त राज्य अमेरिका दूसरे स्थान पर है। हीटवेव से संबंधित मौतों में वृद्धि के बावजूद, चिकित्सा और सार्वजनिक स्वास्थ्य संस्थान शीर्ष 10 योगदानकर्ताओं में जगह नहीं बना सके ये निष्कर्ष हीटवेव पर अंतःविषय अनुसंधान की आवश्यकता को रेखांकित करते हैं, विशेष रूप से क्षेत्र-विशिष्ट हीटवेव योजनाओं और संस्थानों के बीच सहयोग को मजबूत करने पर। हम हीटवेव अनुसंधान में प्रयुक्त कीवर्ड में अंतर और समानता को उजागर करते हुए, तीन समयावधियों में कालिक कीवर्ड प्रवृत्ति का भी विश्लेषण करते हैं। हमने पाया कि 'तापमान', 'हीटवेव', 'प्रभाव' और 'परिवर्तनशीलता' का प्रचलन सबसे अधिक है। पिछले तीन दशकों में, रुझान 'जलवायु परिवर्तन' की व्यापक अवधि से हटकर 'भूमि की सतह का तापमान', 'अंतर-वार्षिक परिवर्तनशीलता' और 'सीएमआईपी6' जैसे विशिष्ट तकनीकी कीवर्ड के उपयोग की ओर स्थानांतरित हो गए हैं। इसके अलावा, शोध पत्र प्रमुख अनुसंधान प्राथमिकताओं और ज्ञान अंतरालों की पहचान करता है, जैसे अनुकूलन रणनीतियों, सामाजिक भेद्यता और क्षेत्रीय प्रभावों पर ध्यान देने की आवश्यकता। ये भारत में सतत विकास लक्ष्य (एसडीजी) लक्ष्यों और हीटवेव लचीलेपन को प्राप्त करने हेतु प्रभावी हीटवेव प्रबंधन नीतियों को विकसित करने के लिए महत्वपूर्ण हैं।

ABSTRACT. Research on natural hazards such as heatwaves has increased in recent decades due to their impact on human life, with the majority of publications occurring after the 2010 deadly heatwave. Based on the Web of Science database, we statistically analyze the research trends, collaborating countries, and institutions using a systematic method of bibliometric analysis. The study reveals the temporal publication trends, co-authorship networks, citation patterns, and keyword evolution in this rapidly growing field. The results highlight the significant contributions of Indian researchers and institutions to the global understanding of heatwaves, as well as the strong international collaborations fostering this research. India has the highest level of cooperation with other countries, whereas the USA ranks second. Despite the rise in heatwave-related deaths, the medical and public health institutions could not make in the top 10 contributors, indicating a gap between health impact and research priority. These findings underscore the need for interdisciplinary research on heatwaves, particularly on region-specific heatwave plans and strengthening collaboration between institutions. We also analyze the temporal keyword trend in three time periods, highlighting the differences and similarities in keywords employed in heatwave research. We found that 'temperature', 'heat waves', 'impact', and 'variability' have the highest occurrence. In the last three decades, the trends have shifted from the broad term of 'climate change' to the use of specific technical keywords such as 'land surface temperature', 'interannual variability', and 'CMIP6'. Furthermore, the paper identifies key research priorities and knowledge gaps, such as the need to focus on adaptation strategies, social vulnerability, and regional impacts. These are critical for developing effective heatwave management policies in India to achieve SDG targets and heatwave resilience.

Key words – Heatwave, Temperature, Adaptation, Sustainability, SDG, Trend, Shift.

1. Introduction

A heatwave is a period of prolonged excessively hot weather, often accompanied by high humidity (World Meteorological Organization, 2024). This period is defined in relation to the region's normal weather or a long-term average of the temperature in that specific season (McGregor *et al.,* 2021). In the 21st century, climate change has been identified to increase the duration of the heatwave spell, the frequency of its occurrence in a season, and the intensity of the heatwave (Perkins-Kirkpatrick and Lewis, 2020). Temperature projections from various research groups and modeling studies also indicate that heatwaves will become more frequent and severe in the near future (Mora *et al.,* 2017). Heatwaves have the potential to impact everyone, but the most vulnerable populations, such as children, elderly, pregnant women, and people with pre-existing health conditions, are affected more (Benmarhnia *et al.,* 2015). Heatwaves can lead to increased hospital admissions and emergency visits, reduce people's productivity, and eventually result in economic losses.

Further, several studies have reported heatwaves significantly impacting human health, resulting in increased mortality and morbidity (Watts *et al.,* 2021). Heatwaves also affect the ecosystems at large by affecting the biodiversity and agricultural system, resulting in decreased yields and the potential impact on the food security of the nations (Zampieri *et al.,* 2017; Ebi *et al.,* 2021). An exponential increase in the number of publications in heatwave research since the early 2000s indicates growing interest in this field. Various studies have provided valuable insights into the characteristics of specific heatwave episodes, such as the 2003 European heatwave, the 2010 Russian heatwave, & the 2015 Indian heatwave (Robine *et al.,* 2008; Barriopedro *et al.,* 2011; Murari *et al.,* 2015). Heatwave research, which spans various disciplines not limited to climatology, public health, meteorology, social sciences, and urban planning (Haunschild *et al.,* 2016; Campbell *et al.,* 2018; Huang & Lu, 2018) accounts for an interdisciplinary approach to better understand the complex interactions between rising temperatures and its impact on human & society.

The geography of India makes the country highly vulnerable to heatwaves, which are further exacerbated due to its socioeconomic status. In sync with global trends, India has also faced increased duration, frequency, and intensity of heatwaves since the start of the 21st century (Rohini *et al.,* 2016; Mishra *et al.,* 2017). The climate projections indicate that India will experience rising heatwaves in its Northwestern and Eastern coastal regions by 2100 (Murari *et al.,* 2015; Im *et al.,* 2017; Ravindra *et al.,* 2024). Since 1992, as per the official count, more than 24,000 deaths have been attributed to extreme temperatures, whereas, during the 2015 heatwave, over 2,500 deaths were reported in India, which made it the deadliest incident in history (Sarath *et al.,* 2017). India is still a developing country where heatwaves are the single factor that can disrupt labor-intensive sectors, particularly agriculture, construction, and heavy manufacturing.

The income loss has been estimated to be 5.4% of the total Gross Domestic Product (GDP) (Romanello *et al.,* 2022). Various manmade factors, such as rapid deforestation and urbanization, have also been a cause of the urban heat island effect in cities, and this has caused major distress in the urban population, especially the people living in informal settlements, as they lack proper housing, access to cooling, and have limited green spaces. Studies have focused on the effectiveness of interventions such as cool roofs and infrastructure building using climate-compatible materials, and risk assessment tools have been a key focus (Dosio *et al.,* 2018; Khare *et al.,* 2021). There is an urgent need to assess the causes, characteristics, and potential impacts of these heatwaves to develop adaptation and mitigation plans that are both effective and sustainable in the long term. The research on heatwaves can help to strengthen early warning systems, improve remote sensing techniques, and enhance climate modeling and weather forecasting techniques to timely guide public health interventions and act as a tool for urban planners to make better decisions in addressing heatwaves (Perkins & Alexander, 2012), this is also critical to achieving the United Nations Sustainable Development Goals (SDG) Good Health And Well Being (SDG 3), Sustainable Cities And Communities (SDG 11), Climate Action (SDG 13) (United Nations Framework Convention on Climate Change, 2015).

The current study assesses the trend of heatwave research in India, implementing bibliometric analysis as a technique to provide quantitative analysis to effectively describe the trends and insights on the evolution of the field over time. In recent years, bibliometric analysis has been widely used to evaluate academic output and discuss their interrelationship. The analysis of publication trends will identify significant heatwave events, such as the 2015 heatwave, or policy interventions such as the National Heat Action Plan, and how these have influenced the research output. The temporal distribution will identify the most influential publications and institutions that built up the foundational knowledge in the field. Finally, bibliometric techniques, such as bibliographic coupling, co-authorship analysis, and co-citation analysis, provide insights into the degree of collaboration, the interconnection between crucial topics, and unique features of the Indian research landscape.

2. Data and methodology

2.1. *Data source*

Scopus and Web of Science (WoS) are two high-quality databases that are most widely used for bibliometric analysis as they provide comprehensive metadata for the bibliometric research (Mongeon and Paul-Hus, 2016; Zhu and Liu, 2020). The choice of the database depends on various characteristics such as research objectives and the discipline in focus. Whereas the Scopus database offers broader coverage of social sciences and humanities, WoS is more thorough and stricter in its indexing of journals. Therefore, WoS was chosen as the database for this analysis.

A search query plays a crucial role in retrieving the relevant literature metadata from the database (Kumar *et al.,* 2023). A comprehensive search query was used to capture variations in terminology in heatwave research, along with Boolean operators (AND, OR, NOT) and wildcard characters (*). The search was limited to the TOPIC category to reduce false-positive entries, including title, abstract, and author keywords. The search query included keywords "heatwave", “heat wave”, “hot spell”, and “extreme heat”. To refine the results, “India” was added to the search query, and articles related to “marine” were excluded to rule out marine heatwaves from the present study. The inclusion criteria based on the document type was applied to include only peer-reviewed original research articles and review articles published in English before 2024. Fig. 1 shows the systematic process of selecting articles for the bibliometric analysis. The initial database query yielded 14767 articles from the Web of Science database, with 95.9% articles being excluded due to articles of non-India context. Out of the remaining 604 articles, 88 articles were excluded as they addressed the marine heatwave phenomenon. 27 articles were excluded due to temporal criteria, 1 due to language criteria, and 26 due to document type criteria. The final article count included in the study was 462. The final search query was ((("heatwave*" OR "heat wave*" OR "extreme heat*" OR "heat spell*") AND ("India*") NOT ("marine*") (Topic) AND Article OR Review (Document Type) AND English (Language) NOT 2024 (Year Published)). The data was retrieved from the SCI-Expanded database of WoS and was manually inspected to ensure the relevance of records and precision of the search query.

2.2. *Research method*

Two bibliometric software, namely VOSviewer software (www.vosviewer.com) (Van Eck & Waltman, 2019) & the bibliometrix R - package (http://www.bibliometrix.org) (Aria and Cuccurullo, 2017), were employed to better understand the trends, key topics, and keywords in the Indian heatwave search. To the author's knowledge, this study is the first to describe the literature on heatwave research in India. Even though the search query has been designed to be thorough and data has been manually cleaned, still certain limitations must be acknowledged in the study design due to the coverage of the database and completeness of the retrieved literature, which is more often based on the metadata provided by the database and must be considered when evaluating the results.

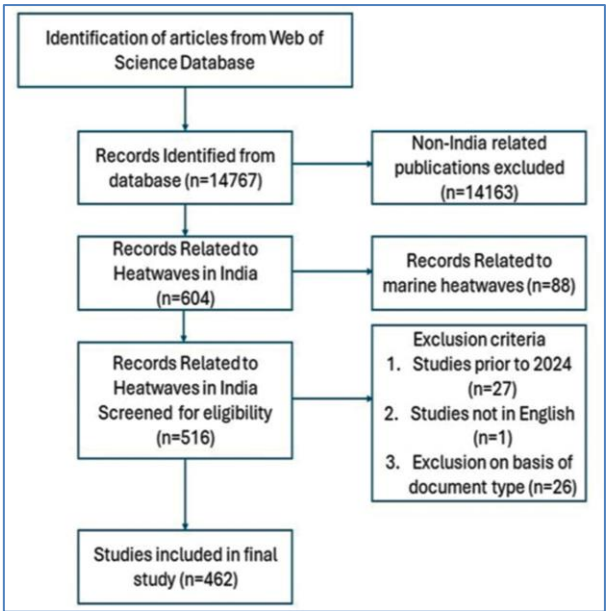


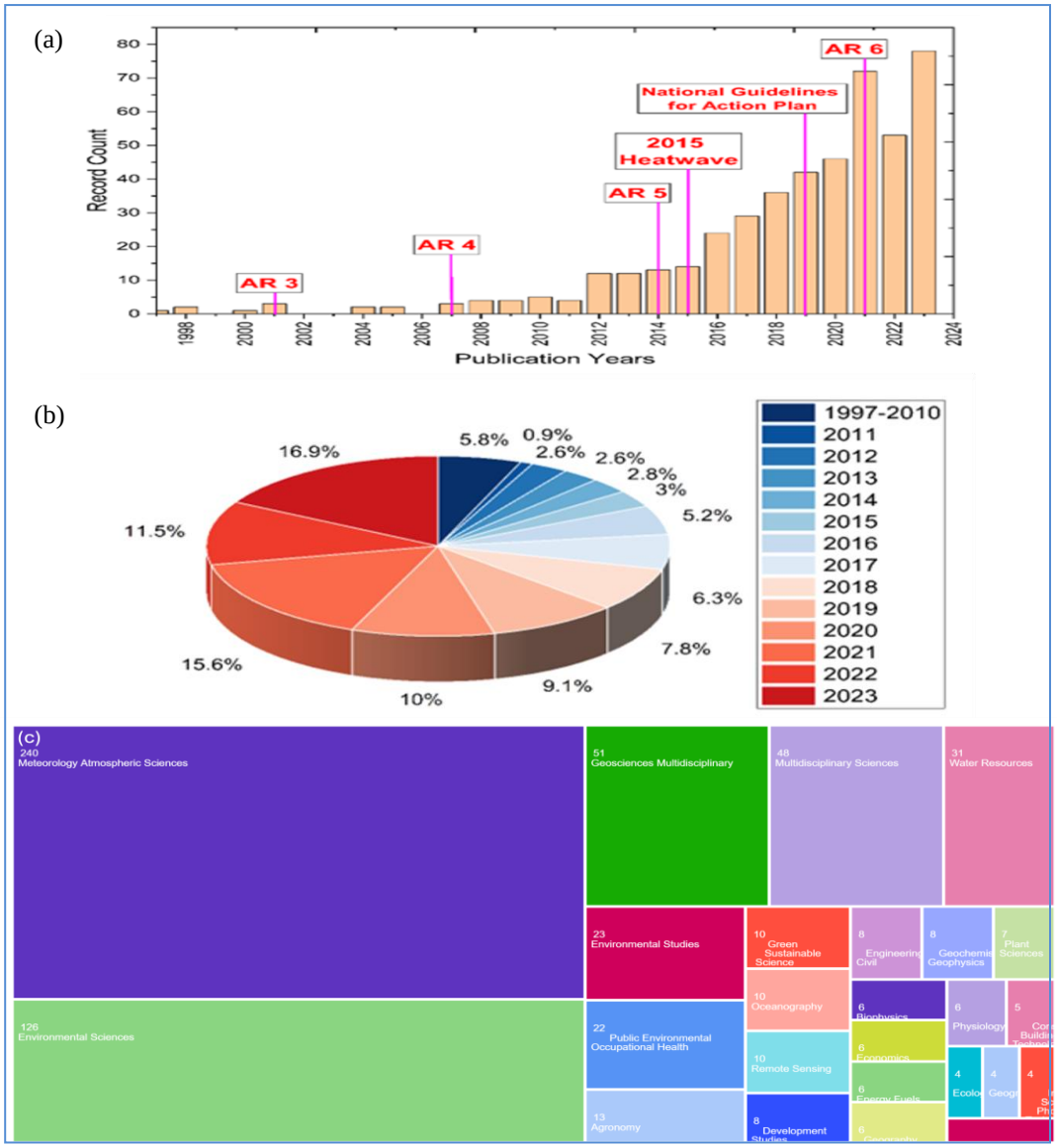
Fig. 1. Flowchart for the article selection for bibliometric analysis related to the heatwave research in India

3. Results and analysis

3.1. *Temporal publication trend*

The publication trend in the heatwave research spanning between 1997 and 2023 is depicted in Fig. 2(a) with major milestones in this field, such as United Nations Intergovernmental Panel on Climate Change (IPCC) Assessment reports and National Guidelines for developing State heat action plans. The earliest article retrieved from the database was published in 1997, indicating the niche research area is young. However, the annual publication count relative to the total number of publications has steadily increased since the 2015 Heatwave, multiplying five times from 14 in 2014 to 78 in 2023. This highlights the prominence this field has gained in recent years.

The publication output was 462 articles, with a peak in the year 2023, with an annual output of 78 articles, the



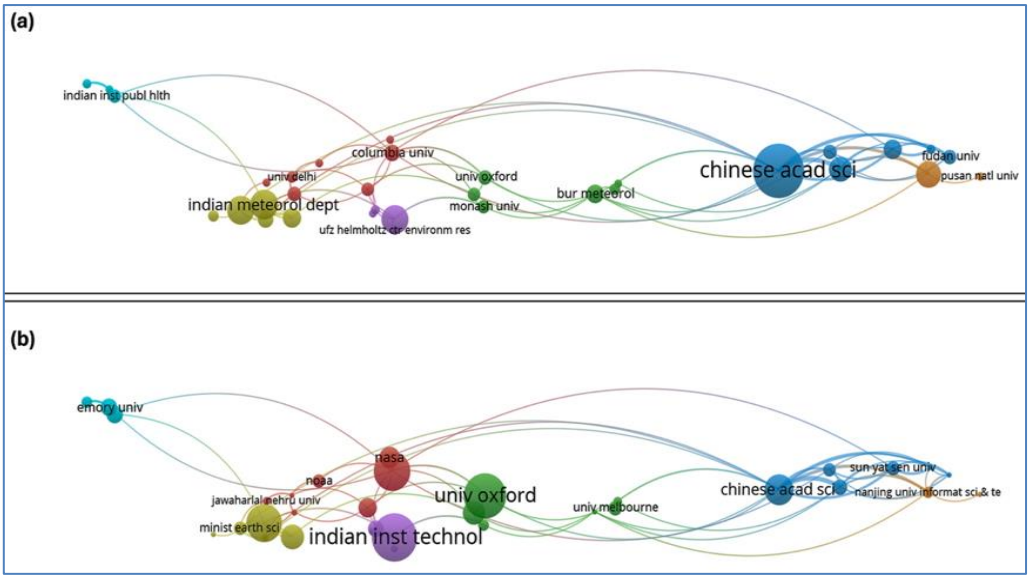
Figs. 2(a-c). (a) Temporal Trend with milestones (b) percentage-wise breakup of publications & (c) Treemap of categories of articles related to heatwave research in India

highest after the year 2021, which had 72 articles. The annual growth rate of articles was 18.63%, with an average of 5.32 articles per year. The increase in publications during 2021 likely reflects researchers having additional time to focus on manuscript preparation during COVID-19-induced lockdowns (Raynaud *et al.*, 2021). The period of 1997- 2015 can be categorized as a period of slow growth, representing only 15% of articles published, with 82 articles published in the period. The period between 2015 and 2023 has shown considerable expansion, with an average of 47 articles representing 85% of total publication output. This rise can be attributed to increasing research about the impacts of deadly heatwaves on human health and attribution to climate change.

Fig. 2(b) shows the percentage of publications annually, underlining that the maximum percentage was in 2023. Fig. 2(c) shows the treemap of the categories of the published articles related to heatwave research in India. The absolute number of articles and publication trend related to heatwave research are also recorded in Table A1, Table A2 (attached in the Appendix) shows the main publication data related to heatwave research. Table A3 (attached in the Appendix) shows the categories of articles related to heatwave research in India.

3.2. *Co-authorship analysis*

Co-author analysis aims to analyze the level of collaboration among different institutions/organizations.



Figs. 3(a&b). Co-authorship (collaboration) analysis of an organization based on (a) article count, (b) citation count related to heatwave research in India

TABLE 1

Countries with the highest number of articles based on co-authorship

Country	Documents
India	501
USA	352
People's Republic of China (PRC)	251
Australia	100
England	84
Germany	54
Netherlands	23
Canada	20
France	20
South Africa	19

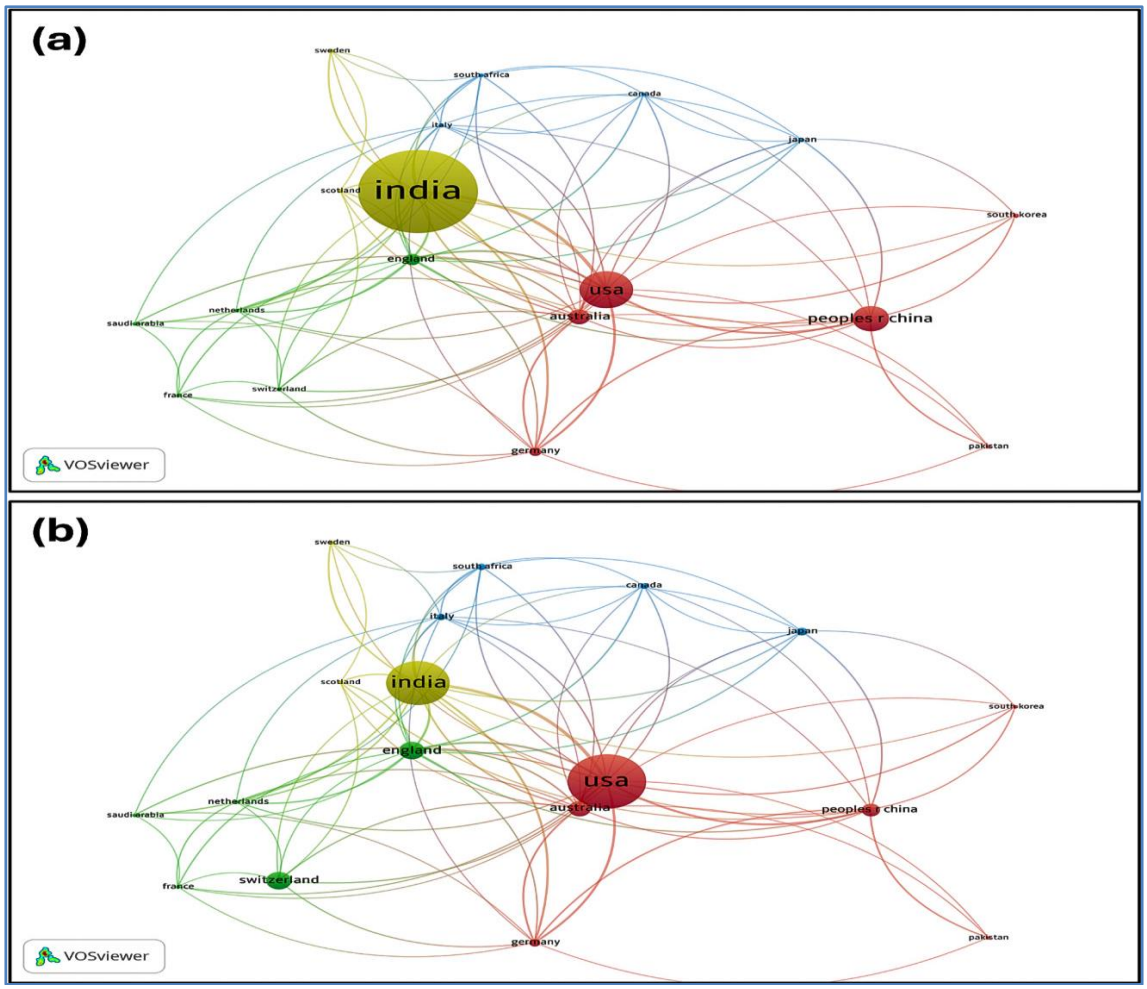
and countries in the research field of particular interest. It facilitates focused analysis to determine leading institutions. Table 1 highlights the quantum of research being done on the basis of article count and identifies countries that are leading the research in the field. India is the leading country with the highest number of articles based on co-authorship. In contrast, Europe is the leading continent with the highest publication count, as highlighted in Table A4 (attached in Appendix), highlighting the publication Trend across continents.

3.2.1. *Research institution/organizations and country network analysis*

The number of articles published by certain institutions or countries directly or indirectly reflects the level of research being conducted by their scholars based on the number of articles. Fig. 3(a) shows the analysis of co-authorship among the various organizations/ institutions. The network includes 33 nodes connected by 74 links. The organization with a minimum of 5 articles and 20 citations was selected for this study. Out of 728 organizations, only 33 met the threshold and were chosen for final analysis. There were 7 clusters, with the largest cluster of 7 organizations. The Chinese Academy of Science in Blue and the Indian Meteorology Department in Yellow had the maximum number of articles published.

Fig. 3(b) shows the organizations with the most publications based on citation count. Indian Institute of Technology, University of Oxford, and Columbia University are the top institutions. High citation counts of publications indicate high quality and influential research as per the scientific community. Also, this suggests that these institutions contribute significantly to advancing the field. Table A5 (attached in the Appendix) and Table A6 (attached in the Appendix) highlight the organization with the most publications and citations related to heatwave research, respectively. Even though the Chinese Academy of Sciences has contributed most to the field, it has fewer citations. Citations likely indicate the quality and impact of the research. Indian Institute of Technology (IIT) and Indian Meteorology Department (IMD) appear to focus on research quality rather than quantity of output. Institutions from different countries highlight the importance of geographical diversity in collaboration and knowledge sharing.

Fig. 4(a) shows the co-authorship analysis of countries, highlighting the collaboration between



Figs. 4(a&b). Co-authorship (collaboration) analysis of the countries based on, (a) article count, (b) citation count related to heatwave research in India

countries, having a minimum of 5 articles with at least 20 citations. Out of 64 countries, only 18 met the threshold and were included in the network analysis. Node size represents the number of articles from a given country. The distance between the two linked countries represents the relatedness of the countries based on their collaboration. A total of 4 interconnected clusters were formed, including the main cluster of India with 15 nodes in light green color, the USA cluster with 16 nodes in red color, the England cluster with 14 nodes in green color, and Canada cluster with 8 nodes in blue color.

Fig. 4(b) shows the co-authorship analysis of countries based on the citation count of their articles. It highlights the collaboration between countries, with a minimum of 5 articles with at least 20 citations. Table 2 shows the top 10 countries with the highest citation count. Out of 64 countries, only 18 met the threshold and were included in the network analysis. Node size represents the number of articles from a given country. The distance between the two linked countries represents the relatedness of the countries based on their collaboration. A total of 4 interconnected clusters were formed, including

TABLE 2

Citation count of articles from different countries related to heatwave research in India.

Country	Citations
USA	7478
India	6053
England	2449
Switzerland	2383
Australia	2149
People's Republic of China (PRC)	1764
Japan	1067
Germany	1048
Italy	903
South Africa	876

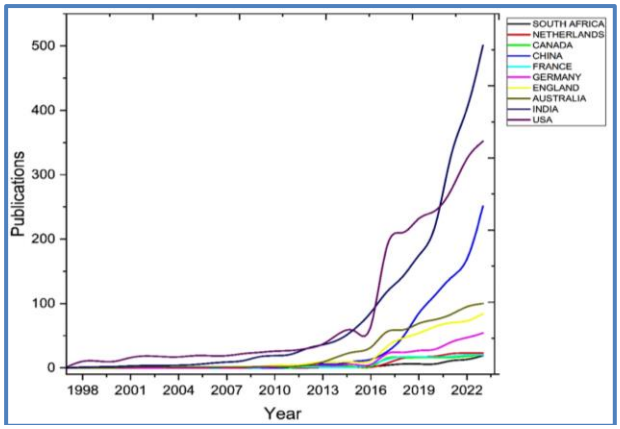


Fig. 5. Publication trend of countries (year-wise) related to the heatwave research in India

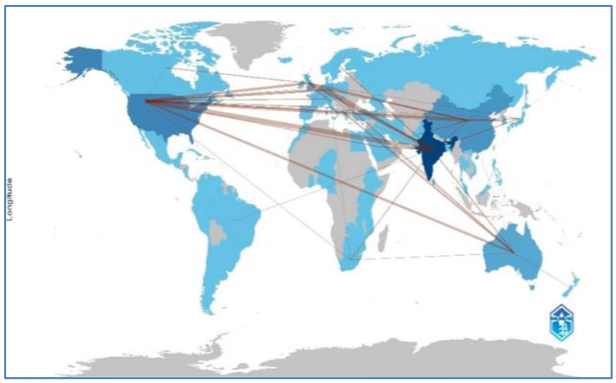


Fig. 6. World map of international research collaboration related to heatwave research in India

the main cluster of India with 15 nodes in light green color, USA cluster with 16 nodes in red color, England cluster with nodes in green color, and Canada cluster with nodes in blue color. The bigger size of the USA node in comparison to India in Fig. 4(b) shows that even though India has more articles related to heatwave research, articles from the USA are given more preference, while citing the articles.

Fig. 5 represents the publication trend of countries (year-wise) related to the heatwave research in India, where the USA led the research in previous decades, but India surpassed it in 2020.

The international research collaboration on heatwaves is shown in Fig. 6. The number of published articles is indicated by the intensity of the blue color and the thickness of the red lines, which means the strength of the collaboration based on frequency. The top 5 vital collaborations were between India and the USA (frequency = 36), the USA and China (frequency = 15), the USA and Germany (frequency = 12), India and the United Kingdom (frequency = 11), and the USA and Australia (frequency = 11).

Fig. 7 shows the strong research output from Indian institutions and their contribution to specific journals. The height of the rectangular node represents the particular institution's frequency or importance, and the width of the connecting lines indicates the strength of the collaboration between them. The diagram shows the dominance of India, China, and the USA.

3.3. Co-citation analysis

Fig. 8 shows the co-citation analysis of various articles, highlighting the most co-cited articles in heatwave research. Articles with a minimum of 20 citations were selected for the network analysis. Out of 18683 references, only 51 met the threshold and were included in the network analysis. The node size represents the number of times the article was co-cited with other connected articles. The distance between the two linked articles represents the relatedness based on their co-citation. Meehl *et al*. (2004), Rohini *et al*. (2016), and Pai *et al*. (2013) were the top three most co-cited articles provided in Table A7 (attached in Appendix), which highlights the top 10 co-cited articles related to heatwave research.

Fig. 9(a) shows the citation analysis of various articles, highlighting the most cited articles in heatwave research. Articles with a minimum of 20 citations were selected for the network analysis. Out of 462 articles, only 179 references met the threshold and were included in the network analysis. The node size represents the number of times the article was cited. The distance between the two linked articles represents the relatedness based on their co-citation. Table A8 (attached in the Appendix) represents the citation count of global articles, and Table A9 (attached in the Appendix) represents the citation count of the most cited articles by Indian authors. Patz *et al*. (2005) has 1926 citations, which is the most cited article showcasing the most influential global research addressing the broad impacts of climate change. Whereas Rohini *et al*. (2016) and Pai *et al*. (2013) are top-cited Indian author articles with 77 and 68 citations, respectively, providing an understanding of trends of heatwaves in India.

Fig. 9(b) shows the cluster of research journals, based on their citations, which are mostly cited. Journals with a minimum 5 number of articles and 20 citations of their published articles were selected for the analysis, and out of 175 cited journals, only 23 met the threshold and were selected for the network generation. Table 3 shows the top 10 cited journals, and the Articles from the Journal of Climate are the most cited articles, followed by Geophysical Research Letters and Journal of Geophysical Research: Atmospheres.

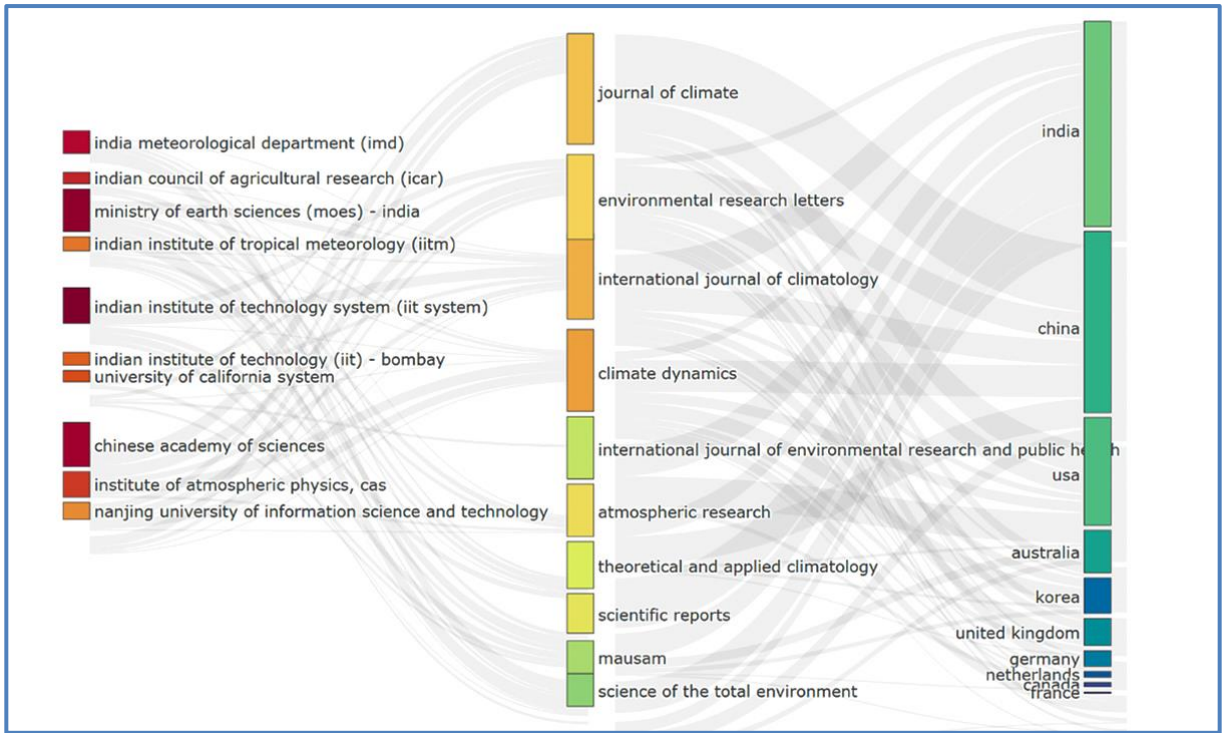


Fig. 7. Three field plots of institutions, journals, and countries related to heatwave research in India

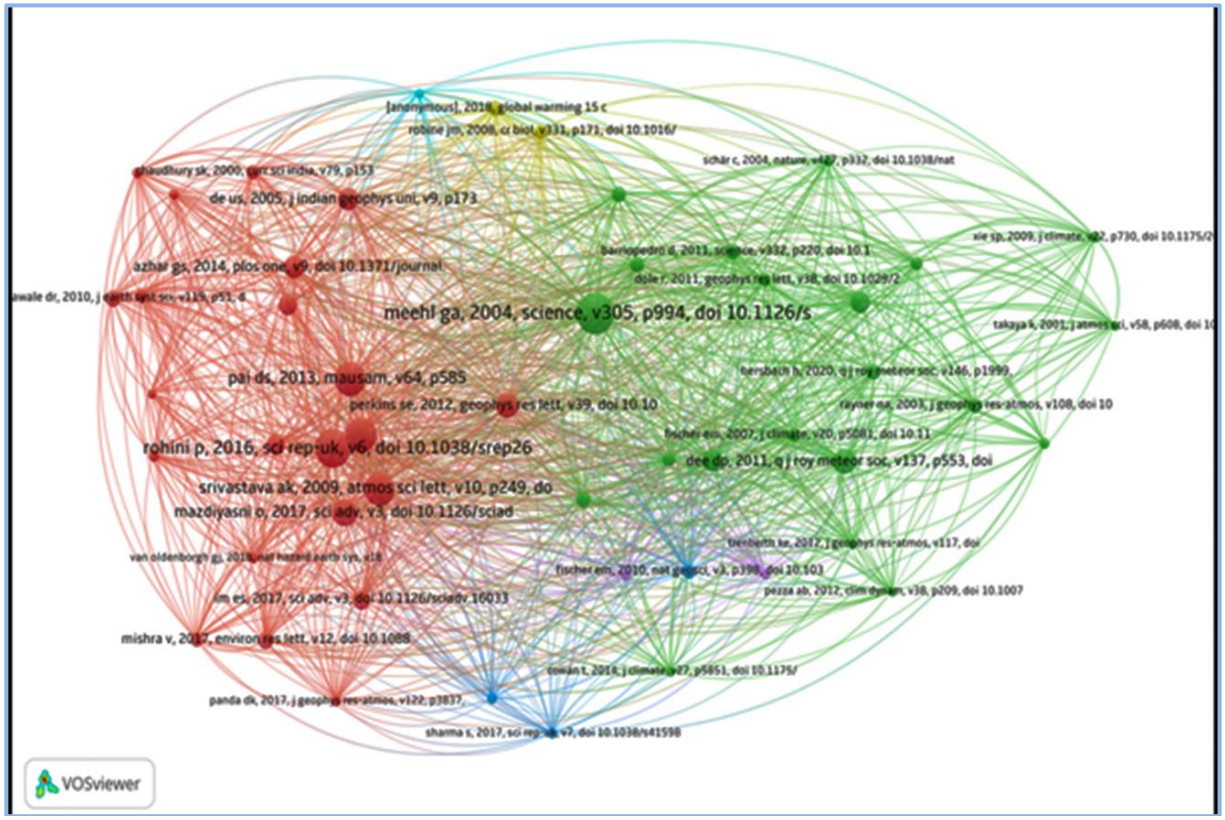
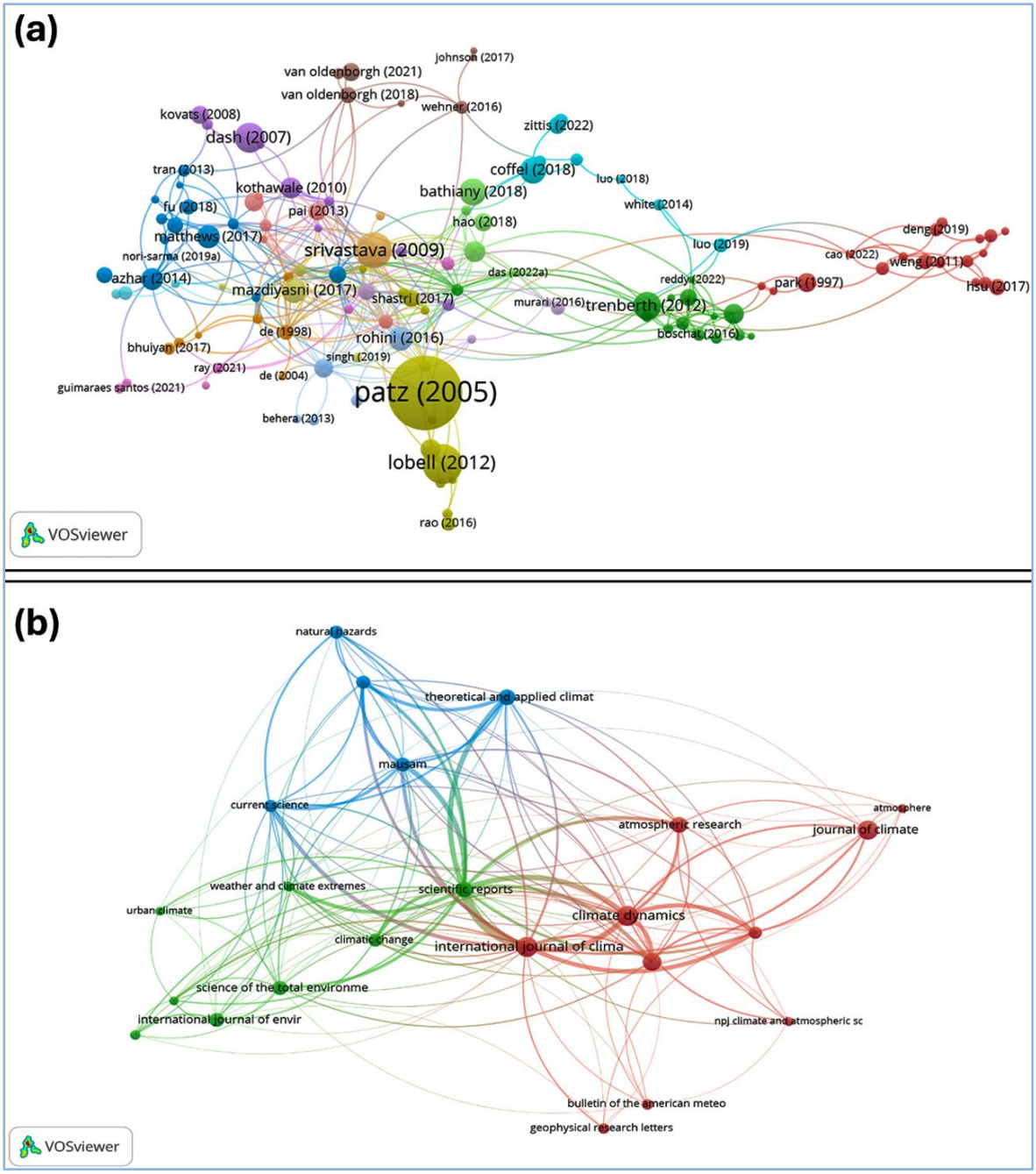


Fig. 8. Co-citation of the most cited references related to heatwave research in India



Figs. 9(a&b). Most cited (a) research articles (b) research sources/journals related to heatwave research in India

3.4. *Keyword analysis*

The co-occurrence network of "All keywords" is shown in Fig. 10. Keywords summarize the article's theme, which is the concentration and essence of any body of literature. This can be used as a proxy for the research hot spots. Frequency of the keywords and cluster analysis of keywords is an effective way to explore the trend and research hotspot in a field, and this has been widely used in bibliometrics. The figure depicts the relatedness of items based on the number of times they occur together. A total of 2,100 unique keywords were recorded in the articles. Keywords with more than 20 occurrences were included in the co-occurrence network; only 35 keywords met the threshold, and 33 were selected for the analysis. The node represents the number of times the keyword occurs (frequency), and the distance between the two linked keywords represents the relatedness based on their

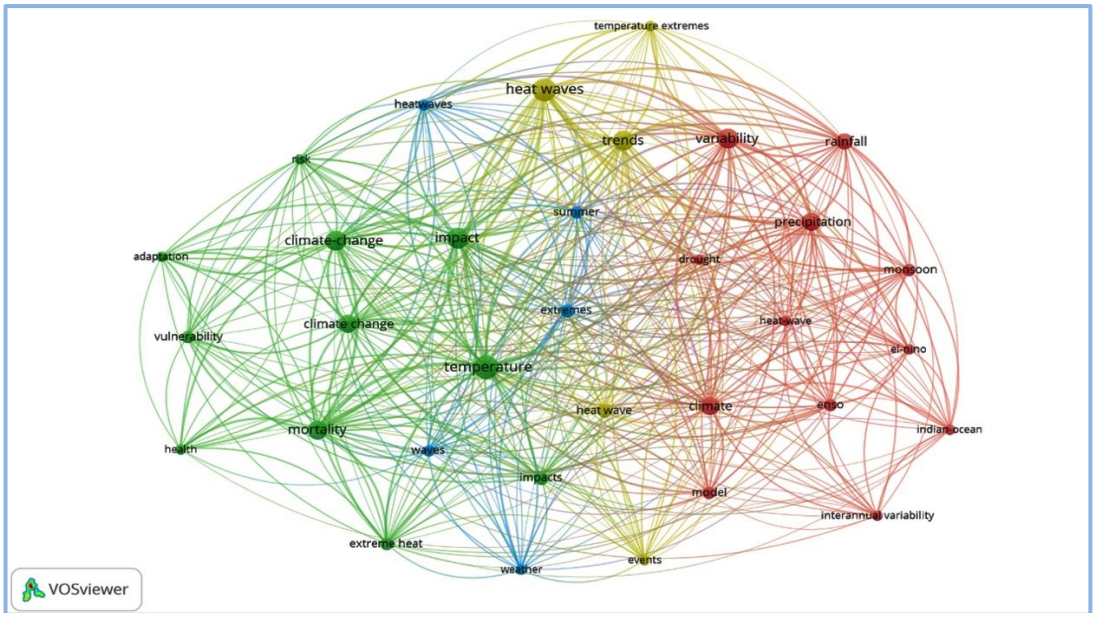


Fig. 10. Keyword co-occurrence network related to heatwave research in India

TABLE 3

Top-cited journals related to heatwave research in India

Source	Citations
Journal of Climate	1734
Geophysical Research Letters	1128
Journal of Geophysical Research: Atmospheres	862
Climate Dynamics	774
International Journal of Climatology	709
Bulletin of the American Meteorological Society	564
Environmental Research Letters	514
Scientific Reports	465
Nature Climate Change	451
Science	413

TABLE 4

Top 10 high-frequency keywords between 1997 and 2023 related to heatwave research in India

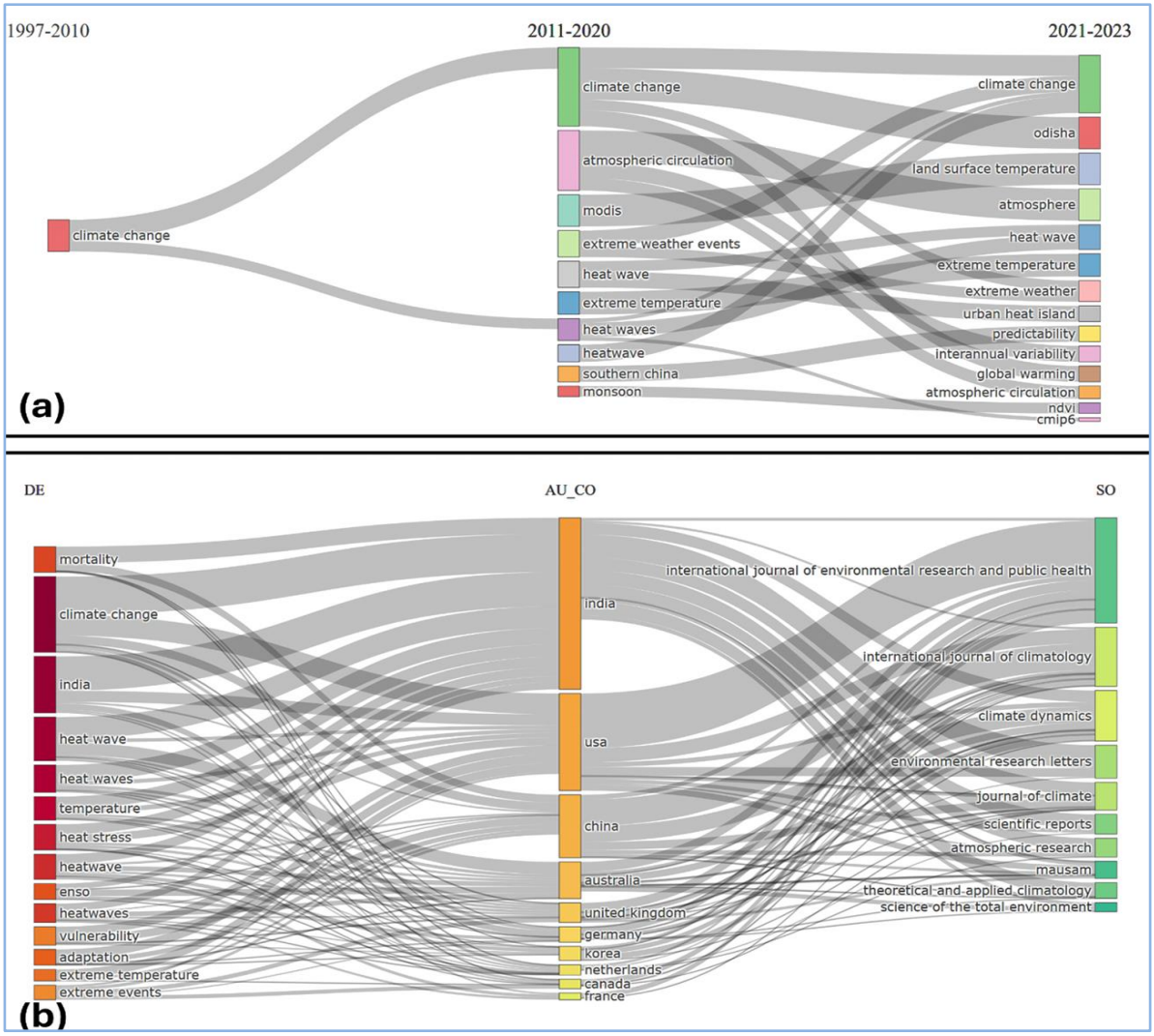
Keyword	Occurrences
Temperature	108
Heat Waves	94
Impact	80
Variability	77
Climate-Change	72
Trends	72
Mortality	67
Climate Change	63
Precipitation	61
Climate	60

number of co-occurrences. A total of 4 interconnected clusters were formed, including the main cluster of variability with 12 nodes in red color, the temperature cluster with 11 nodes in green color, the extreme cluster with 5 nodes in blue color, and the heatwave cluster with 4 nodes in yellow color.

From Fig. 10, the top 10 high-frequency keywords are extracted and shown in Table 4. The results indicate that the keywords such as 'Temperature', 'Heat waves', 'impact', and 'variability' have the highest occurrence frequencies. Figure A1 shows the tree map of the most frequently used heatwave-related keywords. 'Climate Change' was the most prominent keyword used. The size of each word is proportional to how the keyword appears in the articles on heatwave research in India.

Fig. 11(a) shows the thematic evolution of the keywords used in the heatwave research during the 3-time spans ranging from 1997 – 2010, 2011 – 2020, and 2021 – 2023. 'Climate change' was the most used word before 2010, whereas there was a shift in the keyword, accompanied by keywords such as atmospheric circulation, MODIS, and extreme weather events. During 2021 – 2023, the keywords have become more diverse, and research has also included land surface temperature, interannual variability, atmospheric circulations, and CMIP6, which shows a new direction in the field of heatwave research in India.

Sankey diagram-based three-field plot, which depicts flow from one set of values to another, as shown



Figs. 11(a&b). Three field plots of, (a) Thematic evolution of Keywords for 3-time spans (1997-2010, 2011-2020, 2021-2023), (b) keywords, countries & journals related to heatwave research in India

in Fig. 11(b), illustrates the interrelationship between 14 top keywords in the left, 10 top countries in the middle, and 9 research journals in the right. The height of the rectangular nodes is directly proportional to the frequency of occurrence of a specific country, journal, or keyword within the collaboration network. The width of the lines joining the nodes is proportional to the number of connections. The figure shows that India had the most connections, followed by the United States of America (USA) and China. USA and China are the main contributors to the International Journal of Environmental Research and Public Health. In contrast, India contributed mainly to Climate Dynamics, Environmental Research Letters, the Journal of Climate and Mausam.

In this bibliometric analysis, we analyzed 462 research documents related to heat waves in India that were available from the Web of Science database using VOSviewer and Biblioshiny. The documents were collected from the Web of Science database. The analysis provides valuable insights into the status and trends of current heatwave research in India between 1997 and 2023. The results show the temporal distribution pattern of the most impactful articles, countries, institutions, and journals that have made significant contributions to the field. There has been substantial growth in heatwave research output, which can be attributed primarily to major heatwave events like the deadly 2015 heatwave, which highlighted the need to enhance heatwave research and publication of IPCC AR6 in 2021, as the highest number of articles (78) were published in the year 2023. The temporal publication trend reveals that heatwave research is a relatively young but quickly expanding field in India, with 85% of papers published between 2015 and

2023, and can be called a period of rapid expansion. This aligns with global trends of increasing heatwave research in recent years, as these events' health impacts and socioeconomic costs are becoming more apparent (Watts *et al.,* 2021; Ebi *et al.,* 2021).

Co-authorship analysis indicates that heatwave research in India is highly collaborative both domestically and internationally. Research institutions from China and India have the highest number of publications, while the United States of America is India's top international collaborator. This finding highlights that heatwaves are a transboundary hazard, and the issue requires cooperation between various countries to advance scientific understanding and develop effective adaptation solutions that are local and can be continued in the long run (Haunschild *et al.,* 2016).

The Citation analysis reveals the most influential heatwave studies that have shaped the Indian research landscape. Highly cited global papers cover health impacts (Patz *et al.,* 2005), urban heat island effects (McCarthy *et al.,* 2010), and agricultural impacts (Lobell *et al.,* 2012), demonstrating the wide-ranging societal implications of heatwaves. Among Indian-focused studies, those characterizing heatwave trends, drivers, and mortality impacts (Rohini *et al.,* 2016; Mazdiyasni *et al.,* 2017) have received the most citations, highlighting key research priorities.

Keyword co-occurrence and thematic evolution analyses provide further insights into the intellectual structure and progression of Indian heatwave research. 'Temperature', 'impact', and 'mortality' are consistently among the most frequent keywords, reflecting a persistent focus on understanding heatwave characteristics and quantifying their health burden. However, the appearance of keywords like 'CMIP6' and 'interannual variability' in recent years points to an emerging emphasis on leveraging climate model projections and large-scale climate variability to assess future heatwave risk.

Despite the growth and evolution of Indian heatwave research, significant knowledge gaps remain that require further study. Notably, research on the effectiveness of heatwave adaptation strategies such as heat action plans is still limited. Advancing research in this domain is critical for strengthening heatwave early warning systems and protecting public health (Knowlton *et al.,* 2014). Interdisciplinary studies integrating physical sciences, epidemiology, and social vulnerability are also needed to fully capture the complex interactions between heatwaves and society (Campbell *et al.,* 2018). Finally, while the co-authorship analysis reveals strong international collaboration, heatwave research remains concentrated in only a few Indian states. Expanding studies to more regions, particularly those with lower adaptive capacity, is crucial for developing a comprehensive understanding of heatwave impacts across India's diverse climatic and socioeconomic landscape.

4. Conclusions

Heatwaves have been found to affect every country on a worldwide scale. In recent years, India has also faced this natural hazard. This has also been evident from the publications on heatwaves in India, as they have grown at an average annual rate of 18.63% since 1997. The keyword analysis identifies the most used keywords in heatwave research in India, covering topics such as the urban heat island effect, with the emerging trend of utilizing climate model projections. However, significant gaps remain, particularly in adaptation and social vulnerability. A changing trend highlights that future emphasis will be placed on climate modelling, urban heat island effect, and interannual variability. Heatwave research in India is key to strengthening the early warning systems, improving remote sensing techniques, making the climate projections more robust, and enhancing the weather forecasting capabilities. The absence of medical institutions in the list of major institutions indicates the need to focus on research on the health-related aspect of the impact of heatwaves. There is a need to percolate the research deep down to advance heatwave research, help guide public health interventions, and achieve SDGs.

Data Availability: Available on request

Author's Contributions

Sanjeev Bhardwaj: Conceptualization, Writing - review & editing, Visualization, Formal analysis
Khaiwal Ravindra: Conceptualization, Visualization, Writing - review & editing, and Formal analysis
Suman Mor: Conceptualization, Writing - review & editing, Visualization, Supervision
All authors contributed to the study's conception and design. All authors read and approved the final manuscript.

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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Appendix

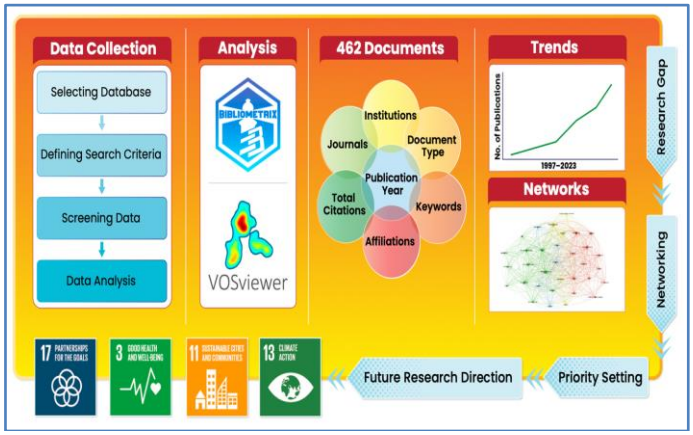


Fig. A. Graphical Abstract



Fig. A1. Word cloud of the most used heatwave-related keywords

TABLE A1

Publication Trend of heatwave-related articles

Publication Years	Record Count	% of 462
1997	1	0.216
1998	2	0.433
1999	0	-
2000	1	0.216
2001	3	0.649
2002	0	-
2003	0	-
2004	2	0.433
2005	2	0.433
2006	0	
2007	3	0.649
2008	4	0.866
2009	4	0.866
2010	5	1.082
2011	4	0.866
2012	12	2.597
2013	12	2.597
2014	13	2.814
2015	14	3.03
2016	24	5.195
2017	29	6.277
2018	36	7.792
2019	42	9.091
2020	46	9.957
2021	72	15.584
2022	53	11.472
2023	78	16.883

TABLE A2

Publication data of heatwave-related articles

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	1997:2023
Sources (Journals, Books)	175
Documents	462
Annual Growth Rate %	18.63
Document Average Age	5.32
Average citations per doc	35.46
References	18630
DOCUMENT CONTENTS	
Keywords Plus (ID)	1160
Author's Keywords (DE)	1123
AUTHORS	
Authors	2126
Authors of single-authored docs	26
AUTHORS COLLABORATION	
Co-Authors per Doc	5.55
International co-authorships %	34.2

TABLE A3

Categories of articles related to heatwave research in India

Web of Science Categories	Record Count	% of 462
Meteorology Atmospheric Sciences	240	51.948
Environmental Sciences	126	27.273
Geosciences Multidisciplinary	51	11.039
Multidisciplinary Sciences	48	10.39
Water Resources	31	6.71
Environmental Studies	23	4.978
Public Environmental Occupational Health	22	4.762
Agronomy	13	2.814
Green Sustainable Science Technology	10	2.165
Oceanography	10	2.165

TABLE A4

Heatwave-related publication trend across continents

Publication Years	Number of Publications											
	Australia	**Cumulative Count**	**Africa**	**Cumulative Count**	**Asia**	**Cumulative Count**	**Europe**	**Cumulative Count**	**North America**	**Cumulative Count**	**South America**	**Cumulative Count**
1991	1	1	-	0	-	0	-	0	-	0	-	0
1992	0	1	-	0	-	0	-	0	1	1	-	0
1993	0	1	-	0	-	0	-	0	1	2	-	0
1994	0	1	-	0	-	0	1	1	0	2	-	0
1995	1	2	-	0	-	0	0	1	1	3	-	0
1996	0	2	-	0	-	0	0	1	0	3		0
1997	2	4	1	1	1	1	3	4	0	3	-	0
1998	0	4	1	2	0	1	2	6	0	3	-	0
1999	0	4	1	3	0	1	1	7	0	3	-	0
2000	3	7	0	3	1	2	1	8	1	4	-	0
2001	4	11	3	6	3	5	2	10	2	6	1	1
2002	2	13	3	9	0	5	1	11	2	8	0	1
2003	0	13	0	9	1	6	3	14	0	8	0	1
2004	2	15	1	10	2	8	16	30	5	13	1	2
2005	1	16	5	15	1	9	23	53	3	16	0	2
2006	3	19	3	18	3	12	27	80	3	19	1	3
2007	2	21	2	20	2	14	34	114	6	25	1	4
2008	6	27	3	23	1	15	40	154	4	29	0	4
2009	7	34	3	26	6	21	38	192	2	31	0	4
2010	13	47	8	34	3	24	45	237	5	36	1	5
2011	18	65	5	39	4	28	54	291	4	40	1	6
2012	20	85	6	45	7	35	60	351	5	45	2	8
2013	35	120	10	55	11	46	67	418	12	57	3	11
2014	48	168	9	64	15	61	74	492	16	73	3	14
2015	48	216	12	76	14	75	86	578	10	83	2	16
2016	46	262	19	95	21	96	71	649	21	104	5	21
2017	57	319	22	117	23	119	78	727	18	122	4	25
2018	67	386	30	147	37	156	120	847	24	146	12	37
2019	55	441	31	178	54	210	145	992	33	179	9	46
2020	61	502	38	216	58	268	168	1160	24	203	8	54
2021	73	575	49	265	59	327	166	1326	29	232	11	65
2022	65	640	47	312	80	407	147	1473	42	274	16	81
2023	73	713	52	364	96	503	157	1630	42	316	14	95

TABLE A5

Organizations with the most publications related to heatwave research in India

Organization	Documents
Chinese Academy of Sciences	32
India Meteorological Department	18
Indian Institute of Technology	17
Ministry of Earth Sciences (India)	17
Nanjing University of Information Science & Technology	16
University of Chinese Academy of Sciences	15
Indian Institute of Tropical Meteorology	12
Sun Yat-sen University	12
Bureau of Meteorology (Australia)	11
Columbia University	10

TABLE A6

Organizations with the most citations related to heatwave research in India

Organization	Citations
Indian Institute of Technology (IIT)	1059
University of Oxford	983
Columbia University	845
India Meteorological Department (IMD)	838
Chinese Academy of Sciences (CAS)	686
Indian Institute of Tropical Meteorology (IITM)	553
National Center for Atmospheric Research (NCAR)	527
National Aeronautics and Space Administration (NASA)	470
Indian Institute of Technology Delhi (IIT Delhi)	439
Emory University	383

TABLE A7

Top 10 Co-cited heatwave related articles

Cited Reference	DOI	Citations
Meehl, G.A., Arblaster, J.M. and Tebaldi, C., 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science, 305(5686), p.994.	10.1126/science.1098704	81
Rohini, P., Rajeevan, M. and Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. Scientific Reports, 6(1), p.26153.	10.1038/srep26153	77
Pai, D.S., Nair, S.A. and Ramanathan, A.N., 2013. Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010). Mausam, 64(4), pp.585-604.	10.54302/mausam.v64i4.742	68
Ratnam, J.V., Behera, S.K., Ratna, S.B., Rajeevan, M. and Yamagata, T., 2016. Anatomy of Indian heatwaves. Scientific Reports, 6(1), p.24395.	10.1038/srep24395	68
Srivastava, A.K., Rajeevan, M. and Kshirsagar, S.R., 2009. Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmospheric Science Letters, 10(4), pp.249-254.	10.1002/asl.232	65
Mazdiyasni, O., AghaKouchak, A., Davis, S.J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C.T. and Niknejad, M., 2017. Increasing probability of mortality during Indian heat waves. Science Advances, 3(6), p.e1700066.	10.1126/sciadv.1700066	53
Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P. and Bechtold, P., 2011. The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), pp.553-597.	10.1002/qj.828	49
Perkins, S.E. and Alexander, L.V., 2012. On the measurement of heat waves. Journal of Climate, 26(13), pp.4500-4517.	10.1175/JCLI-D-12-00383.1	49
Azhar, G.S., Mavalankar, D., Nori-Sarma, A., Rajiva, A., Dutta, P., Jaiswal, A., Sheffield, P., Knowlton, K., Hess, J.J. and Ahmedabad HeatClimate Study Group, 2014. Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave. PloS One, 9(3), p.e91831.	10.1371/journal.pone.0091831	45
De, U.S., Dube, R.K. and Rao, G.P., 2005. Extreme weather events over India in the last 100 years. J. Ind. Geophys. Union, 9(3), pp.173-187.		45

TABLE A8

Top-cited global heatwave-related articles

Research Paper	DOI	Total Citations
Patz, J.A., Campbell-Lendrum, D., Holloway, T. and Foley, J.A., 2005. Impact of regional climate change on human health. Nature, 438(7066), pp.310-317.	10.1038/nature04188	1926
Wang, H., Horton, R.M., Bader, D.A., Bone, A., Chen, G., Chen, X., Guo, J., Guo, Y., Hondula, D.M., Huang, C. and Jones, B., 2022. Changing patterns of heat-related mortality in China, United Kingdom, and United States: a comparative study. The Lancet, 399(10338), pp.1807-1819.	10.1016/S0140-6736(21)02796-3	658
Lobell, D.B., Sibley, A. and Ortiz-Monasterio, J.I., 2012. Extreme heat effects on wheat senescence in India. Nature Climate Change, 2(3), pp.186-189.	10.1038/NCLIMATE1356	545
McCarthy, M.P., Best, M.J. and Betts, R.A., 2010. Climate change in cities due to global warming and urban effects. Geophysical Research Letters, 37(9).	10.1029/2010GL042845	520
Srivastava, A.K., Rajeevan, M. and Kshirsagar, S.R., 2009. Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmospheric Science Letters, 10(4), pp.249-254.	10.1002/asl.232	456
Dash, S.K. and Mamgain, A., 2011. Changes in the frequency of different categories of temperature extremes in India. Journal of Applied Meteorology and Climatology, 50(9), pp.1842-1858.	10.1007/s10584-007-9305-9	322
Trenberth, K.E., 2012. Framing the way to relate climate extremes to climate change. Climatic change, 115(2), pp.283-290.	10.1029/2012JD018020	271
Bathiany, S., Dakos, V., Scheffer, M. and Lenton, T.M., 2018. Climate models predict increasing temperature variability in poor countries. Science Advances, 4(5), p.eaar5809.	10.1126/sciadv.aar5809	251
Coffel, E.D., Horton, R.M. and de Sherbinin, A., 2018. Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century. Environmental Research Letters, 13(1), p.014001.	10.1088/1748-9326/aaa00e	243
Mazdiyasni, O., AghaKouchak, A., Davis, S.J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C.T. and Niknejad, M., 2017. Increasing probability of mortality during Indian heat waves. Science Advances, 3(6), p.e1700066.	10.1126/sciadv.1700066	225

TABLE A9

Top-cited heatwave related Indian articles

Research Paper	DOI	Year	Local Citations	Global Citations
Rohini, P., Rajeevan, M. and Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. Scientific Reports, 6(1), p.26153.	10.1038/srep26153	2016	77	200
Pai, D.S., Nair, S.A. and Ramanathan, A.N., 2013. Long term climatology and trends of heat waves over India during the recent 50 years (1961-2010). Mausam, 64(4), pp.585-604.		2013	68	118
Ratnam, J.V., Behera, S.K., Ratna, S.B., Rajeevan, M. and Yamagata, T., 2016. Anatomy of Indian heatwaves. Scientific Reports, 6(1), p.24395.	10.1038/srep24395	2016	68	131
Srivastava, A.K., Rajeevan, M. and Kshirsagar, S.R., 2009. Development of a high resolution daily gridded temperature data set (1969–2005) for the Indian region. Atmospheric Science Letters, 10(4), pp.249-254.	10.1002/asl.232	2009	65	456
Mazdiyasni, O., AghaKouchak, A., Davis, S.J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C.T. and Niknejad, M., 2017. Increasing probability of mortality during Indian heat waves. Science Advances, 3(6), p.e1700066.	10.1126/sciadv.1700066	2017	53	225
Azhar, G.S., Mavalankar, D., Nori-Sarma, A., Rajiva, A., Dutta, P., Jaiswal, A., Sheffield, P., Knowlton, K., Hess, J.J. and Ahmedabad HeatClimate Study Group, 2014. Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave. PloS One, 9(3), p.e91831.	10.1371/journal.pone.0091831	2014	45	172
Murari, K.K., Ghosh, S., Patwardhan, A., Daly, E. and Salvi, K., 2015. Intensification of future severe heat waves in India and their effect on heat stress and mortality. Regional Environmental Change, 15(4), pp.569-579.	10.1007/s10113-014-0660-6	2015	40	106
De, U.S. and Mukhopadhyay, R.K., 1998. Severe heat wave over the Indian subcontinent in 1998, in perspective of global climate. Current Science, pp.1308-1315.		1998	39	80
Mishra, V., Mukherjee, S., Kumar, R. and Stone, D.A., 2017. Heat wave exposure in India in current, 1.5 °C, and 2.0 °C worlds. Environmental Research Letters, 12(12), p.124012.	10.1088/1748-9326/aa9388	2017	34	107
Kothawale, D.R., Revadekar, J.V. and Rupa Kumar, K., 2010. Recent trends in pre-monsoon daily temperature extremes over India. Journal of Earth System Science, 119(1), pp.51-65.	10.1007/s12040-010-0008-7	2010	33	160