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Research Themes, Trends and Future Priorities in the Field of Climate Change and Health: A Review

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Abstract: Climate change is one of the biggest threats to human living and health in the 21st century. Whilst a large number of papers have been published addressing the health impact of climate change, there is a lack of comprehensive bibliometric analysis in the crosscutting field. This study evaluated the global scientific output of research in the field of climate change and health between 1990 and 2020, based on the Web of Science Core Collection database. Research themes were identified using a social network analysis technique based on author keywords. Research trends were assessed by the change in overall publication number and the percentage of publications in each research theme. Articles were further categorized by the availability of funding and author affiliation to compare the difference between developed and developing countries. Results showed that the research output in the field of climate change and health has increased dramatically in the past 30 years, mainly dominated by researchers in developed countries. The percentage of research receiving funding was found to be the lowest in those published by developing countries only and the highest in those published by the collaboration of developed and developing countries. A total of nine major research themes was identified. Research related to 'risk assessment and adaptation', 'sustainable development' and 'infectious diseases' were relatively underfunded. A significant research trend was observed between 2006 and 2020, with increased attention on research themes related to 'risk assessment and adaptation', 'sustainable development', 'extreme events' and 'air pollution', and reduced attention on research themes related to 'ocean', 'infectious disease' and 'phenology'. The shift of the research trend was mainly driven by research in developed countries. Suggestions, recommendations and future priorities identified by experts in the field of atmospheric sciences, epidemiology, public health, climate change, environmental sciences, and policy development are also provided to guide future research. It is important to shift our focus from single health aspects to an integrated system (such as One Health framework, which considers environmental health, animal health and human health as a whole), with future research focusing more on the systemic impact of climate change in order to achieve better, more effective and efficient risk governance. More funding should be mobilized to support the research capacity building in developing countries and to support climate change adaptation strategies for sustainable development.

Keywords: climate change; health; bibliometric analysis; research trends; future priorities

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1. Introduction

Climate change is considered as the top risk in the next decades [1]. On 13 December 2020, the United Nations (UN) Secretary-General Antonio Guterres called all world leaders to declare a State of Climate Emergency until carbon neutrality is reached [2]. The impact of climate change has been noted for decades. The establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, with the objective to provide governments at all

levels with scientific information for developing climate policies, marked the international consensus on the overwhelming negative impact of climate change. The adoption of the Paris Agreement, Sendai Framework for Disaster Risk Reduction 2015–2030, and the Sustainable Development Goals of Agenda 2030 in 2015 marked the international commitment to combat climate change and adapt to its effects [3–5]. Climate change affects all aspects of our lives [6], including marine, freshwater and terrestrial ecosystems [7–9] and ecosystem services [10,11], water and food security [12,13], settlements and infrastructure [14,15], health and wellbeing [16], and economies [17] and culture [18]. Reducing the complex, cascading and systemic risks induced by climate change is believed to be a key priority in the following decades, which requires strengthened disaster risk research and advanced risk-informed governance [19].

IPCC published assessment reports (AR) every 5–6 years, providing regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation [20], which have become the key documents to guide actions to combating climate change. The Lancet Countdown international project initiated in 2015, which focuses on tracking progress on health and climate change and is supported by over 120 leading experts from academic institutions and UN agencies across the globe, also published annual reports with a summary of the public health impact of climate change, the consequences of delayed action and the health benefits of a robust response [21]. While these reports provide terrific summaries of the observed risks and potential threats, they provide little information regarding the systematic data and trends of research in the field of climate change and health. The commonly used method for analyzing research outputs and trends is bibliometric analysis, which has already been applied to investigate studies related to climate change [22–26]. Currently, there is a lack of systematic investigation on research focuses on the health impacts of climate change at the global level. In this paper, we try to summarize the major research themes and identify research trends and hot topics in the field of climate change and health, through the bibliometric analysis of published scientific papers in the Web of Science Core Collection database. Considering human health is intimately related to the health of the surrounding environments, including animals and the ecosystems, the focus of this paper is not only limited to human health, but includes broader health impacts of climate change on humans, animals, and the environment. Findings from this investigation can help researchers to gain a better understanding of the landscape and breadth of research focus on climate change and health, especially the well-developed research areas and emerging and under-studied research themes. We also provide suggestions and recommendations from experts in the field of atmospheric sciences, epidemiology, public health, climate change, environmental sciences, and policy development to guide future research.

2. Materials and Methods

Research themes and trends were obtained based on the bibliometric analysis of scientific papers included in the Web of Science Core Collection (WOSCC) database (https://www.webofscience.com/wos/woscc/basic-search, accessed on 2 November 2021) with default time frame setting (1900–present), accessed through Fudan University, China on 2 November 2021.

2.1. Paper Screening

Papers related to climate change and health were screened by constraining 'Topic' and 'Year Published' in the WOSCC database with the following criteria, modified from the criteria used by the 2021 Report of the Lancet Countdown on Health and Climate Change [16]:

(Topic) "climat* chang*" or "global warming*" or "green?house effect*" or "green?house gas*" or "GHG*" or "climat* cris?s" or "climat* variability" or "climat* induced" or "climat* warming*" or "green?house emission*" or "climat* scenario*"

and

(Topic) health* or illness* or infecti*or well?being* or death* or mortality or disease*
and
(Year Published) 1900–2020

The screening rules returned a total of 35,552 records. The result was further narrowed to 27,776 records by selecting 'Article' as the 'Document Type', as original articles were believed to provide first-hand analysis of the impact of climate change.

2.2. Keywords Collection

Amongst the 27,776 papers, only 22,293 papers contained keyword information in the WOSCC record ('Author Keyword' as marked in the WOSCC record). A total of 48,230 keywords were collected. The majority of the keywords (85.3%) appeared less than 3 times, indicating that there is no consensus on the selection of keywords in the field of climate change and health. This also suggests that the research focus in the field of climate change and health varied significantly.

The 48,230 keywords were pre-treated before analysis by combining those with the same meaning but different word forms, such as singular and plural (e.g., model and models), British English and American English (e.g., urbanization and urbanisation), hyphens (e.g., heat-wave and heatwave), abbreviations (e.g., particulate matter and PM), using OpenRefine Software (https://openrefine.org, accessed on 15 November 2021). After pre-treatment, the number of keywords was reduced to 44,893. Those 14 keywords (climate change, climate change scenarios, climate scenarios, climate variability, climate warming, death, disease, global warming, greenhouse effect, greenhouse gas emissions, greenhouse gases, health, mortality, well-being), which were used for the paper screening and did not provide any information regarding research theme, were excluded in the analysis.

2.3. Keyword Clustering and Research Theme Extraction

Research themes in the field of climate change and health were derived from social network analysis of keyword co-occurrence using VOSviewer Software (version 1.6.17, developed by developed by Nees Jan van Eck and Ludo Waltman at Leiden University in the Netherlands, downloaded through https://www.vosviewer.com from Shanghai, China, accessed on 30 November 2022). In the social network analysis, each keyword represents a node in the network. The strength of the link between two nodes is calculated based on the frequency of the co-occurrence of two keywords (nodes) in the same publication. Nodes are then mapped in a two-dimensional figure using 'visualization of similarities' mapping technique, in which nodes with stronger links are located closer to each other. The nodes are grouped into different clusters using the smart local moving algorithm. Clusters identify closely related nodes, and each node will be assigned to one cluster only. For more details regarding the social network technique used by VOSviewer, please refer to [27].

A total of 1673 keywords with a frequency of at least 10 ($\geq$10), covering 19,886 papers (89.2% of the papers including keyword information) were selected in the analysis. The co-occurrence analysis divided keywords into 9 clusters, indicating the presence of 9 main research themes. Detailed information on the 9 research themes is presented in the Results section.

2.4. Country and Funding Information Extraction

Amongst the 27,776 papers, 27,564 papers contained author affiliation information in the WOSCC record ('Addresses' or 'Reprint Addresses' as marked in the WOSCC record). The country information was extracted based on all authors' affiliations. Papers were then grouped as 'by developed countries only', 'by developing countries only' or 'by mixed countries' for further analysis. The developed countries comprise a total of 36 countries, including Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Netherlands, New Zealand, Norway, Poland, Portugal,

Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom and United States [28].

Amongst the 27,776 papers, 18,337 papers contained funding information in the WOSCC record ('Funding Orgs' or 'Funding Text' as marked in the WOSCC record) and were marked as 'research receiving funding' for further analysis.

2.5. Research Trend Analysis

The research trend in the field of climate change and health was derived based on the change in the keyword frequency and the number of papers within 9 research themes in the past 30 years (1991–2020). The composition of research themes in a certain year is determined by the proportion of papers in each research theme to the total number of papers. A 2D non-metric multidimensional scaling (nMDS) plot is generated with PAST V3 software [29] to illustrate the similarity in research theme composition between each year, using a Bray–Curtis similarity index. Each point in the nMDS plot represents a year. Points with higher similarity (research theme composition) are located closer to each other. Research trend is judged by the separation of groups which contain 5 consecutive years to minimize the impact of interannual variation. Spearman's rank correlations are applied to determine the correlation between nMDS Axis values and the proportion of papers belonging to a certain research theme, to find out the research themes that contribute to the separation of groups along each Axis in the nMDS plot. The significance level is set to be 0.05.

3. Results

3.1. Research Themes in the Field of Climate Change and Health

The social network visualization based on keyword co-occurrence analysis divided the 1673 keywords into nine clusters, marked with different colors (Figure 1). Each cluster corresponded to one research theme.

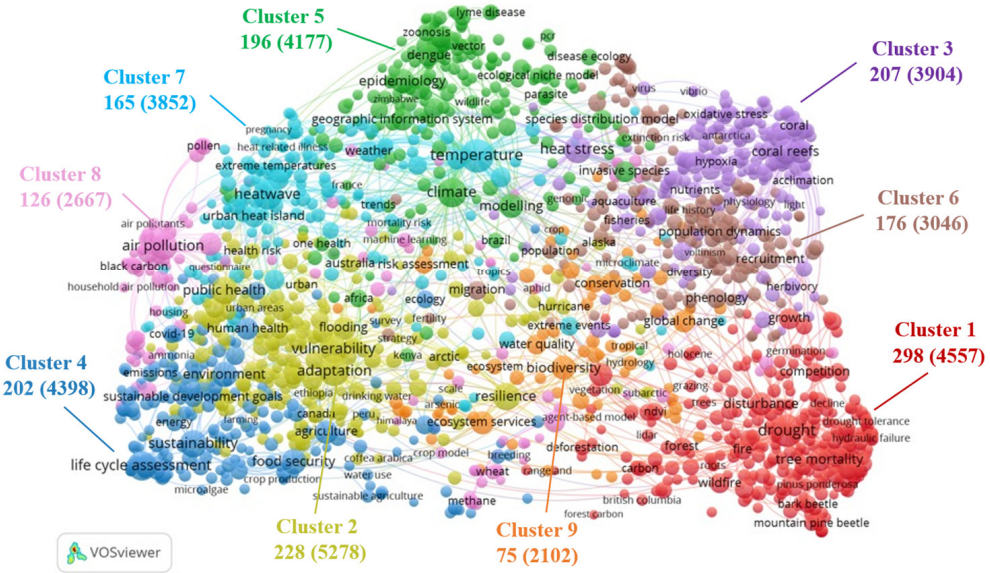

Figure 1. Social network map derived from VOSviewer Software based on the co-occurrence analysis of 1673 keywords (frequency $\geq$ 10) in the field of climate change and health. Nine clusters are differentiated by color. The numbers next to each cluster represent the number of keywords within the cluster (outside the brackets) and the number of research articles associated with these keywords (inside the brackets). The size of the nodes represents the frequency of the keyword and the line connecting two nodes represents the frequency of the co-occurrence of two keywords in the same paper.

3.1.1. Research Theme/Cluster 1 (Drought)

There is a total of 298 keywords (associated with 4557 research articles) belonging to research theme 1, marked in red color in Figure 1. This research theme mainly focuses on the impacts of drought and its derived disasters (such as fire and wildfire) on the forest and vegetation (e.g., tree mortality, growth, biomass, carbon sequestration). The representative keyword for this theme is 'drought'. The change of top 10 keywords with high frequency of occurrence at four different time intervals (1991–2005, 2006–2010, 2011–2015, 2016–2020) is illustrated in Figure 2 to show the change of hot research topics. 'Drought' was the top keyword at each time interval, suggesting it was the central focus of this research theme. The rank of 'remote sensing' increased from the fifth during the period 2006–2010 to the second during the period 2016–2020, indicating it is a frequently used method in this research theme and it is highly likely to be an important or hot method for future research. 'Wildfire' is the only new keyword that ranked top 10 during the period 2016–2020, corresponding with the significantly increased wildfire events in recent years. This suggests that the linkage between climate change, wildfire and health has received great attention. Considering wildfire events are highly likely to increase in the future [30], this topic might become an emerging research focus of this theme in the near future.

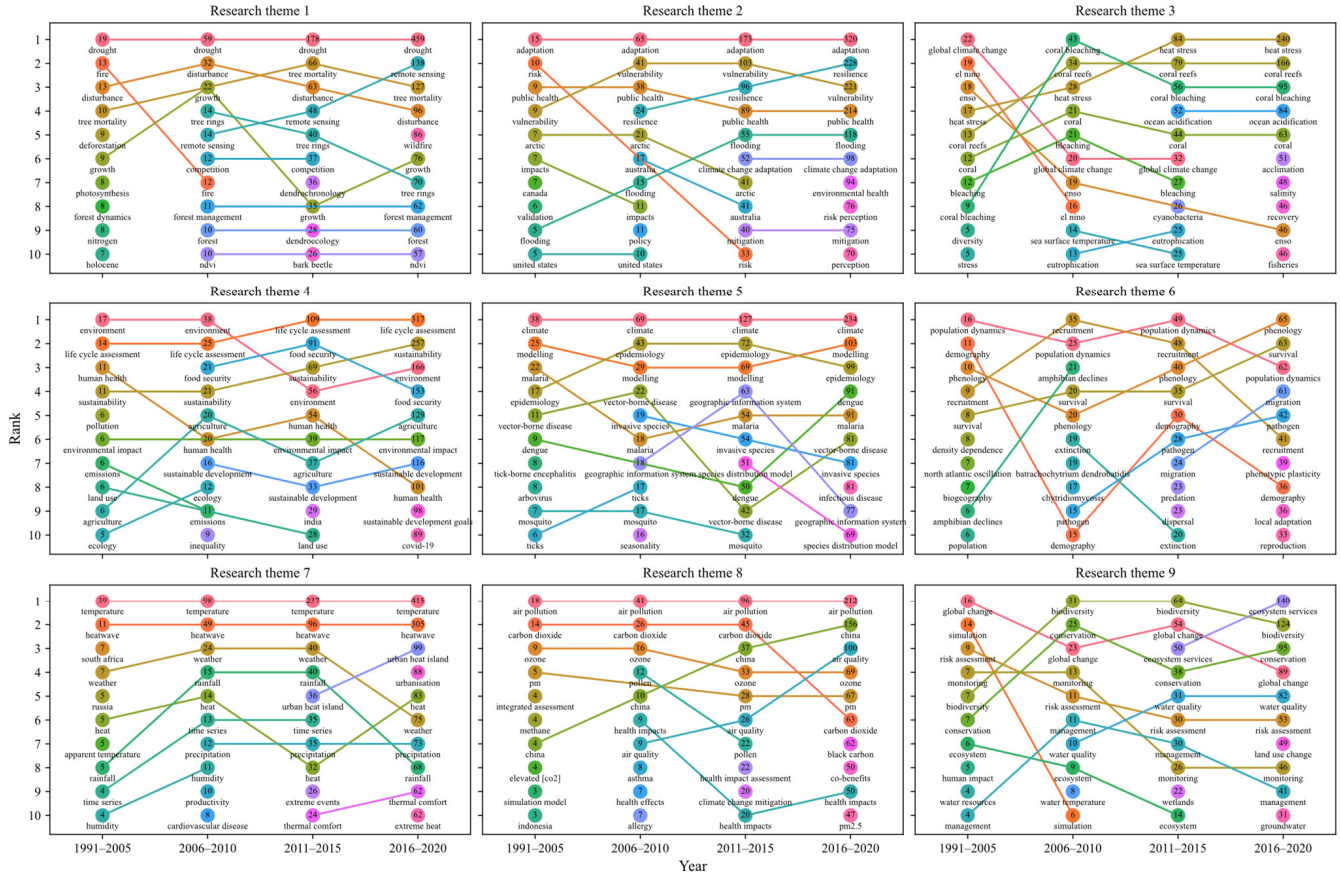

Figure 2. Change of the top 10 keywords with high frequency of occurrence in nine research themes during four time periods (1991–2005, 2006–2010, 2011–2015, 2016–2020). The number within the circle indicates the occurrence of the keyword underneath the circle.

3.1.2. Research Theme/Cluster 2 (Risk Assessment and Adaptation)

There is a total of 228 keywords (associated with 5278 research articles) belonging to research theme 2, marked in yellow color in Figure 1. This research theme is about climate change risk assessment and adaptation, with a major focus on aspects including adaptation, vulnerability and resilience. The representative keyword for this theme is 'risk assessment and adaptation'. As shown in Figure 2, 'adaptation' was the top keyword at each time interval. 'Vulnerability' and 'resilience' remained in the top 4 at all time intervals. The rank of 'resilience' increased from the fourth during the period 2006–2010 to the second during the period 2016–2020. These suggested that adaptation, vulnerability and resilience were the central focus of this research theme. 'Public health' was the other top 4 keyword during the whole time period, indicating that public health was the major concern and goal for climate change risk governance. The rank of 'flooding' increased from the ninth during the period 1991–2005 to the fifth during the period 2011–2020, implying that flooding is one of the key risks threatening public health and has attracted more and more attention in the past 30 years. 'Environment health' was a new keyword that ranked top 10 during the period 2016–2020, revealing that risk interconnectivity between climate change, environment and health has become a new focus in the past few years. 'Risk perception' and 'perception' were also new keywords that ranked top 10 during the period 2016–2020, reflecting that the public's risk perception has been noted as one of the key factors determining the effectiveness of risk governance [31,32]. Research related to these topics is anticipated to be future hotspots.

3.1.3. Research Theme/Cluster 3 (Ocean)

There is a total of 207 keywords (associated with 3904 research articles) belonging to research theme 3, marked in purple color in Figure 1. This research theme mainly focuses on the impact of global warming on marine biota (especially coral reefs) and ocean circulation. The representative keyword for this theme is 'ocean'. As shown in Figure 2, 'heat stress' due to global warming has become the major focus in recent years, of which the rank increased from the fourth during the period 1991–2005 to the first during the period 2011–2020. The impact of climate change on coral reefs has received much attention, with keywords including 'coral reefs', 'coral bleaching', 'coral', and 'bleaching' being the top 10 keywords. This suggested that coral reef is a very good indicator for monitoring the impact of climate change on marine biota. 'Acclimation' and 'recovery' were new keywords that ranked top 10 during the period 2016–2020, implying that research on acclimation and recovery of marine biota may be an emerging focus of this research theme in the future. 'Salinity' was also a new keyword that ranked top 10 during the period 2016–2020, indicating that in addition to ocean acidification, changing salinity has become a key channel through which climate change affects marine biota [33,34]. 'Fishery' was also a new keyword that ranked top 10 during the period 2016–2020, suggesting that the impact of climate change on fishery has become a new focus in recent years [35–37].

3.1.4. Research Theme/Cluster 4 (Sustainable Development)

There is a total of 202 keywords (associated with 4398 research articles) belonging to research theme 4, marked in blue color in Figure 1. This research theme mainly explores the threats and paths of sustainable development in the context of climate change, with a special focus on food, water, energy and environment. The representative keyword for this theme is 'sustainable development'. As shown in Figure 2, studies on sustainability and sustainable development increased dramatically in the past 30 years. The sustainable development goals (SDGs) adopted by the United Nations in 2015 have become the new guide for research in this research theme, marked as 'sustainable development goal' being one of the new keywords that ranked top 10 during the period 2016–2020. 'Life cycle assessment' is a key method for assessing sustainability and its rank increased from the second during the period 1991–2010 to the first during the period 2011–2020. It is believed to continue to be a key method in this research theme. Although started in 2020, 'COVID-19'

ranked the tenth during the period 2016–2020, revealing its high impact on sustainable development [38,39].

3.1.5. Research Theme/Cluster 5 (Infectious Disease)

There is a total of 196 keywords (associated with 4177 research articles) belonging to research theme 5, marked in green color in Figure 1. This research theme focuses on the impact of climate change on the distribution and transmission of infectious diseases. The representative keyword for this theme is 'infectious disease'. As shown in Figure 2, epidemiological investigation and modeling are the main methods to investigate the occurrence, development and transmission of infectious disease. The rank of 'epidemiology' and 'modelling' remained in the top 4 at all time periods. Disease 'malaria' and 'dengue' received the most concern, indicating that they were most sensitive to climate and their spread and special attention should be paid to these two diseases in the context of climate change. 'Infectious disease' is the only new keyword that ranked top 10 during the period 2016–2020, implying that the connection between infectious disease and climate change has been widely noted and received much attention in recent years [40,41].

3.1.6. Research Theme/Cluster 6 (Phenology)

There is a total of 176 keywords (associated with 3046 research articles) belonging to research theme 6, marked in brown color in Figure 1. This research theme mainly explores the impact of climate change on plants and animals at the species level (e.g., phenology, growth, reproduction) and population-level (e.g., migration, structure). The representative keyword for this theme is 'phenology'. As shown in Figure 2, the rank of 'phenology' remained at top 5 during all time periods and became the first during the period 2016–2020, revealing an increased focus on the impact of climate change on phenology. The impact of climate change on species' survival and population's migration was receiving increasing attention, with the rank of 'survival' reaching the second and the rank of 'migration' reaching the fourth during the period 2016–2020. Another significant rise in the rank was noted for the keyword 'pathogen', from the ninth during the period 2006–2010 to the fifth during the period 2016–2020, suggesting that the effect on pathogen may be an important path through which the species and the population were affected by climate change. 'Phenotypic plasticity', 'local adaptation' and 'reproduction' were new keywords that ranked top 10 during the period 2016–2020, implying that species' adaptation ability has become a crucial factor determining their reproduction and survival in the context of climate change.

3.1.7. Research Theme/Cluster 7 (Extreme Events)

There is a total of 165 keywords (associated with 3852 research articles) belonging to research theme 7, marked in sky-blue color in Figure 1. This research theme mainly focuses on the risks associated with extreme weather/climate events (especially heatwaves). The representative keyword for this theme is 'extreme events'. As shown in Figure 2, 'temperature' was the top keyword at each time interval, suggesting the change in temperature was the key cause of the health risks. Top 10 keywords such as 'heatwave', 'heat', 'extreme heat' and 'thermal comfort' indicated that risks associated with heat (high temperature) were one of the main focuses of this research theme and are likely to continue to be the main focus in future studies. 'Urbanisation' was the only new keyword that ranked top 10 during the period 2016–2020, implying the linkage of rapid urbanization and the impact of extreme events in cities were receiving more attention in recent years [42,43].

3.1.8. Research Theme/Cluster 8 (Air Pollution)

There is a total of 126 keywords (associated with 2667 research articles) belonging to research theme 8, marked in pink color in Figure 1. This research theme explores the health impacts of air pollution (especially particulate matter and ozone) and the interaction between air pollution events and local climate. The representative keyword for this theme is 'air pollution'. As shown in Figure 2, 'air pollution' was the top keyword at all time periods. The rank of 'air quality' increased from the seventh during the period 2006–2010 to the third during the period 2016–2020. These suggested that air pollution/quality was the central focus of this research theme. The rank of 'China' increased dramatically from the seventh during the period 1991–2005 to the second during the period 2016–2020, revealing that the air pollution/quality problem in China is receiving increasing attention. The top 10 keywords including particulate matter ('pm' and 'pm2.5'), ozone and black carbon indicated that these were the major pollutants inducing health concerns. 'Co-benefits' was a new keyword ranked top 10 during the period 2016–2020, showing that the coordinated action of climate mitigation and air quality control has attracted much attention in recent years [44–47].

3.1.9. Research Theme/Cluster 9 (Ecosystem Change)

There is a total of 75 keywords (associated with 2102 research articles) belonging to research theme 9, marked in orange color in Figure 1. This research theme is mainly about the impact of ecosystem function loss and biodiversity reduction caused by anthropogenetic activities (especially land use change) in the context of climate change. The representative keyword for this theme is 'ecosystem change'. As shown in Figure 2, 'ecosystem services', 'biodiversity' and 'conservation' remained in the top 4 during the period 2011–2020, highlighting the importance of maintaining ecosystem services through biodiversity conservation. 'Water quality' was another main focus of this research theme. The impact of 'land use change' and the impact on 'groundwater' became important focuses in recent years [48,49], making them the new keywords ranked top 10 during the period 2016–2020.

3.2. Research Trends in the Field of Climate Change and Health

3.2.1. Overall Trend of Publication Number and Funded Research

A total of 27,776 research articles published between 1900 and 2020 in the WOSCC belonged to the field of climate change and health. Only three papers were published before 1990 [50–52]. Since 1990, the number of papers began to increase exponentially (Figure 3A), marking the dramatic rise of studies in the field of climate change. Three distinct stages of development were noticed. In the first stage (1990–2006), the number of research articles increased slowly, with an increasing rate of approximately 16 papers each year. The increasing rate was 10 times higher in the second stage (2007–2014) compared to the first stage, with approximately 162 more papers each year. The number of research articles exceeded 1000 per year since 2011. In the third stage (2015–2020), the increasing rate became as high as 441 papers per year. In 2020, the number of research articles in the field of climate change reached 4484. To be noted, the time nodes of the three stages coincide with the release of the Intergovernmental Panel on Climate Change assessment reports (IPCC-AR, IPCC-AR1 in 1990, IPCC-AR4 in 2007, and IPCC-AR5 in 2014). This suggested that the IPCC reports significantly promoted the development of the field of climate change and health. The recent release of IPCC-AR6 is anticipated to further stimulate the increase in research in this field. The trends of publication number of all research themes are similar to that of the total number, which increased dramatically in the past 30 years (Figure 3B).

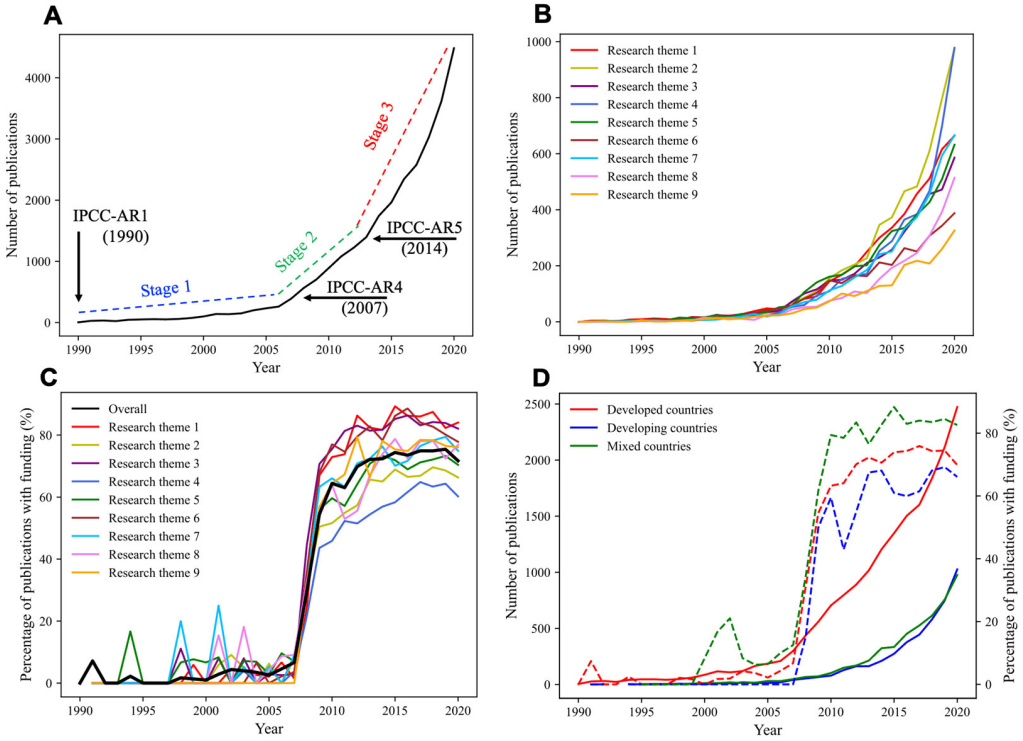

Figure 3. (**A**) Number of total research articles. (**B**) Number of publications in each research theme. (**C**) Overall level of percentage of publications with funding and its value in each research theme. (**D**) Number of publications (solid lines) and percentage of publications with funding (dashed lines) by developed countries only, developing countries only and collaboration of developed and developing countries (mixed countries), based on the affiliation of all authors. Results were extracted from research articles in the field of climate change and health in the Web of Science Core Collection database between 1990 and 2020 (data was obtained on 2 November 2021).

Amongst the 27,776 papers, a total of 18,337 papers (66%) contains funding information. When all publications were considered, the percentage of research receiving funding also showed three distinct stages of development (black line in Figure 3C). Before 2008, the percentage of research receiving funding was lower than 10%. A sharp increase was noted in the next 3 years, with the percentage of research receiving funding increasing from 6.7% in 2007 to 64.4% in 2010. Afterward, the increase became slower and reached a plateau at around 75%. Analysis of the percentage of research receiving funding in each research theme reveals that in the past 10 years, research themes 1 (drought), 3 (ocean) and 6 (phenology) received higher percentages of funding compared to the overall level. In contrast, research themes 2 (risk assessment and adaptation), 4 (sustainable development) and 5 (infectious diseases) were relatively underfunded.

The sharp increase in publication numbers in the field of climate change and health was mainly driven by developed countries (Figure 3D). In 2020, 55.2% of the output was conducted by scientists in developed countries only, which was approximately 2.5 times more than those conducted by developing countries only or by the collaboration of developed and developing countries (mixed countries). Research conducted by 'developing countries only' has found to receive the lowest percentage of funding. Interestingly, the collaborated research by mixed countries had the highest percentage of funding, indicating that funding is a key factor to promote international collaboration.

3.2.2. Trend of Keywords in Each Research Theme

The frequency-weighted mean appearance time of each cluster is calculated. The earliest and latest mean appearance time of keywords was noticed in research theme 6 (phenology, mean = 2014.2) and research theme 4 (sustainable development, mean = 2016.2), respectively. The rug plot shows that there were no new high-frequency keywords after 2018 in research themes 6 (phenology) and 9 (ecosystem change), while in research theme 4 (sustainable development), quite a few high-frequency keywords emerged in the recent 2 years (Figure 4). This suggested that during the period 2018–2020, the major research topics in research themes 6 (phenology) and 9 (ecosystem change) were all traditional, but the emergence of new topics was noted in other research themes, especially for research theme 4 (sustainable development).

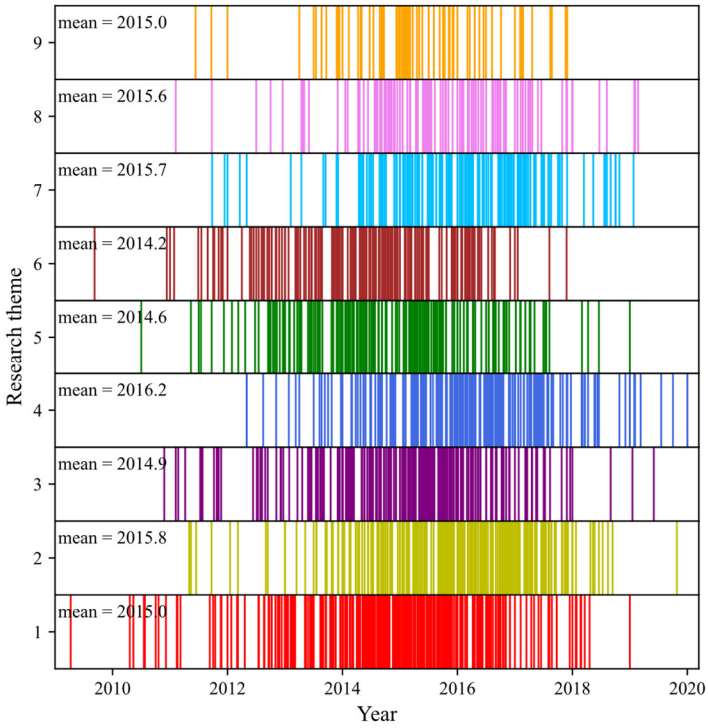

Figure 4. Rug plot showing the average appearance time of a total of 1673 keywords in nine different research themes. The mean value within each sub-figure indicates the mean appearance time of all keywords with that research theme.

3.2.3. Trend of the Research Theme

The research trend was analyzed by the changes in the composition of nine research themes (the proportion of papers in each research theme to the total number of papers) from 1991 to 2020. The nMDS plot in Figure 5 revealed that there was no clear research trend in the first 15 years (1991–2005), shown by the wide spread of points and the overlap of the color shadow. In the next 15 years (2006–2020), a clear trend was noted, shown as the separation of groups along Axis 2.

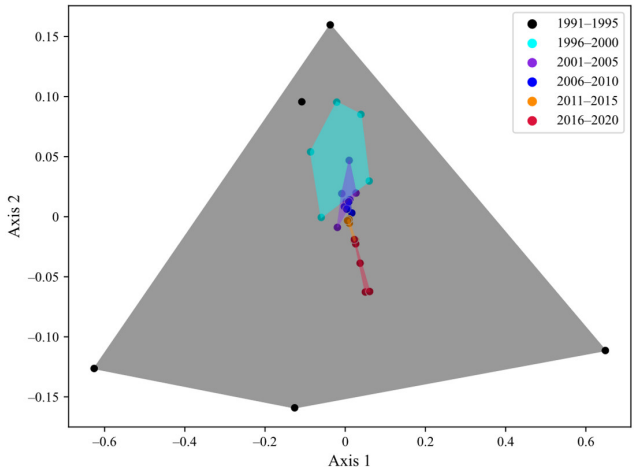

Figure 5. Non-metric multidimensional scaling (nMDS) plot based on the composition of nine research themes in a certain year, which is determined by the proportion of papers in each research theme to the total number of papers in nine research themes. Each point represents a year between 1991 and 2020 and is assigned to six groups (marked with six different colors) based on the year it represented.

Further analysis of the composition of nine research themes between 2006 and 2020 showed a significant separation of groups across Axis 1 (Figure 6). The bubble nMDS plots revealed that during the period 2006–2020, the percentage of research articles of research themes 2 (risk assessment and adaptation), 4 (sustainable development), 7 (extreme events) and 8 (air pollution) increased significantly as time increased ($p < 0.05$). In contrast, the percentage of research articles on research themes 3 (ocean), 5 (infectious disease) and 6 (phenology) decreased significantly as time increased ($p < 0.05$). The percentage of research articles of research themes 1 (drought) and 9 (ecosystem change) was not significantly changed as time increased ($p > 0.05$). This suggests that the climate change risk governance and sustainable development under climate change are becoming hotter and have attracted increasing attention. Relative to its impact on the ocean, infectious disease and phenology, more studies were conducted to investigate the health impact of climate change due to increased extreme weather events and its association with air pollution in recent years. As weather/climate extremes are becoming more frequent and have exerted severe impacts on many fields including human health, the issues of climate change adaptation have become a major task besides climate mitigation for the goals of sustainable development. It is anticipated to have more cross-cutting research prioritizing climate adaptation, such as the development and implementation of a multi-hazard early warning system.

Research trends were also investigated in three different country groups. A significant trend was noted for research conducted by authors in developed countries only during the period 2006–2020, shown as the separation of groups along Axis 1 (Figure 7). The separation was dominated by significant increases in research themes 2 (risk assessment and adaptation), 4 (sustainable development) and 7 (extreme events) and decreases in research themes 3 (ocean), 5 (infectious disease) and 6 (phenology).

There was no significant trend observed for research conducted by authors in developing countries only between 2006 and 2020, as groups were not separated either on Axis 1 or Axis 2 (Figure 8).

Regarding the collaborative publications by developed and developing countries, a distinct trend was noted from 2011 to 2020, shown as the separation of groups along Axis 1 (Figure 9). The separation was dominated by a significant increase in research theme 4 (sustainable development) and decreases in research themes 5 (infectious disease) and 6 (phenology).

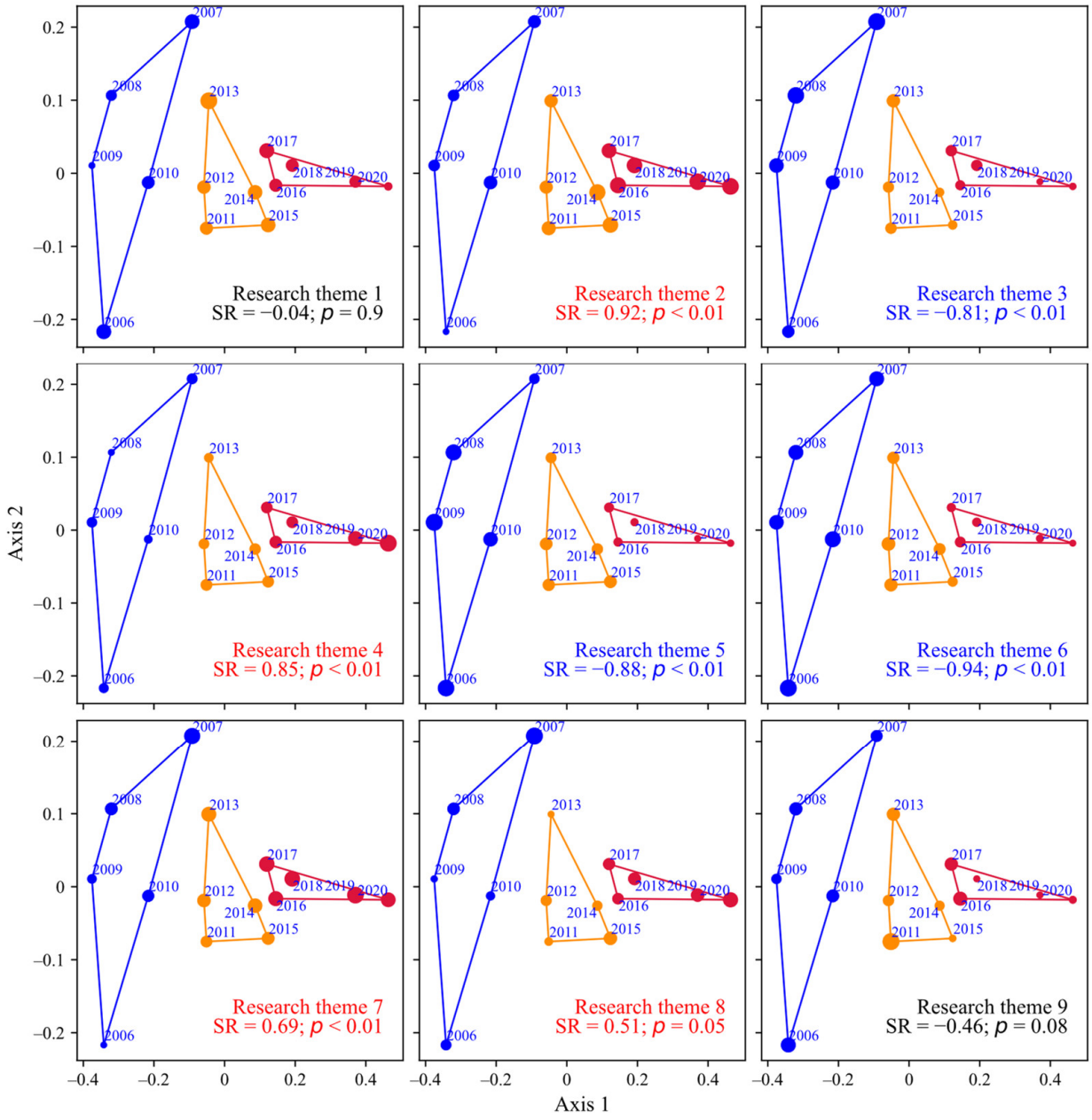

Figure 6. Bubble non-metric multidimensional scaling (nMDS) plot based on the composition of nine research themes in a certain year, which is determined by the proportion of papers in each research theme to the total number of papers in nine research themes. Each point represents a year between 2006 and 2020 and is marked with three different colors based on the year it represented. Papers published by all countries were included in the analysis. Within each subplot, larger bubbles indicate a relatively higher percentage of research articles on the research theme stated in the subplot. Bubble sizes are not comparable between subplots. The Spearman's rank correlation coefficient (SR) and *p* value between Axis 1 values and the percentage of each research theme are shown in the figure.

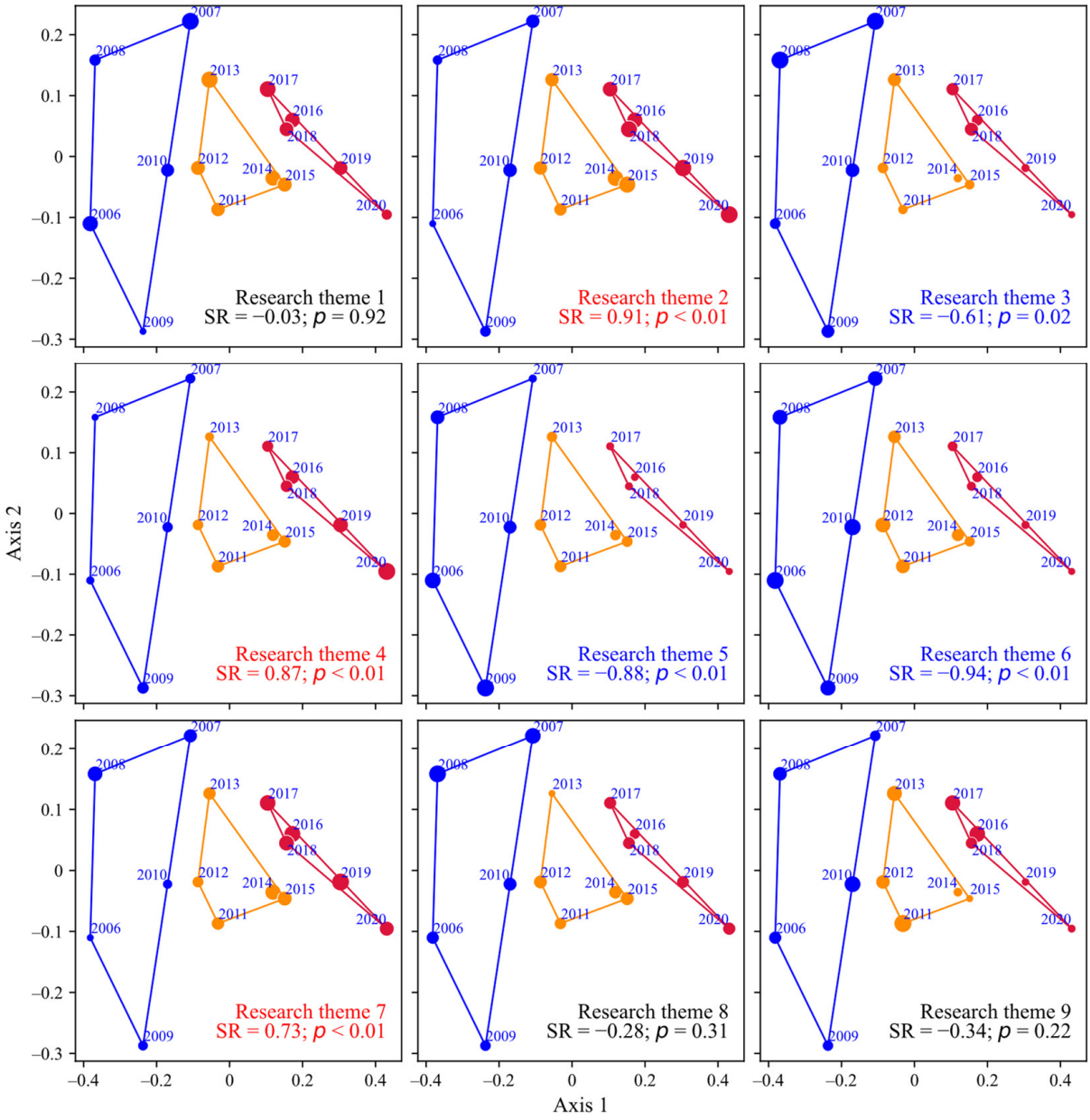

Figure 7. Bubble non-metric multidimensional scaling (nMDS) plot based on the composition of nine research themes in a certain year, which is determined by the proportion of papers in each research theme to the total number of papers in nine research themes. Each point represents a year between 2006 and 2020 and is marked with three different colors based on the year it represented. Papers published by developed countries only were included in the analysis. Within each subplot, larger bubbles indicate a relatively higher percentage of research articles of the research theme stated in the subplot. Bubble sizes are not comparable between subplots. The Spearman's rank correlation coefficient (SR) and *p* value between Axis 1 values and the percentage of each research theme are shown in the figure.

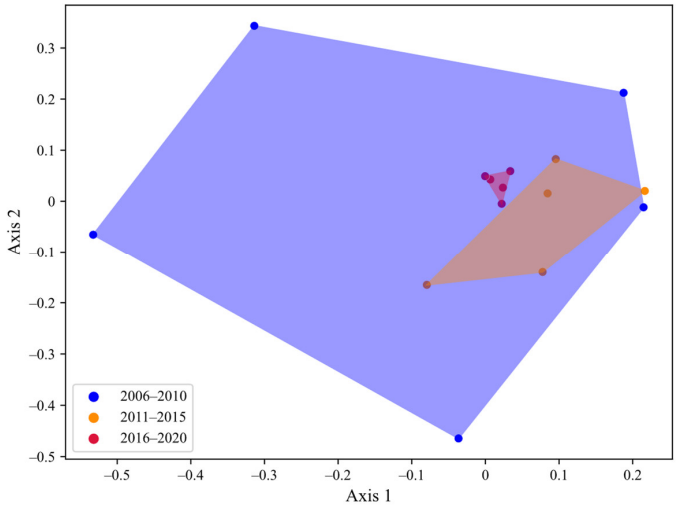

Figure 8. Non-metric multidimensional scaling (nMDS) plot based on the composition of nine research themes in a certain year, which is determined by the proportion of papers in each research theme to the total number of papers in nine research themes. Each point represents a year between 2006 and 2020 and is marked with three different colors based on the year it represented. Papers published by developing countries only were included in the analysis.

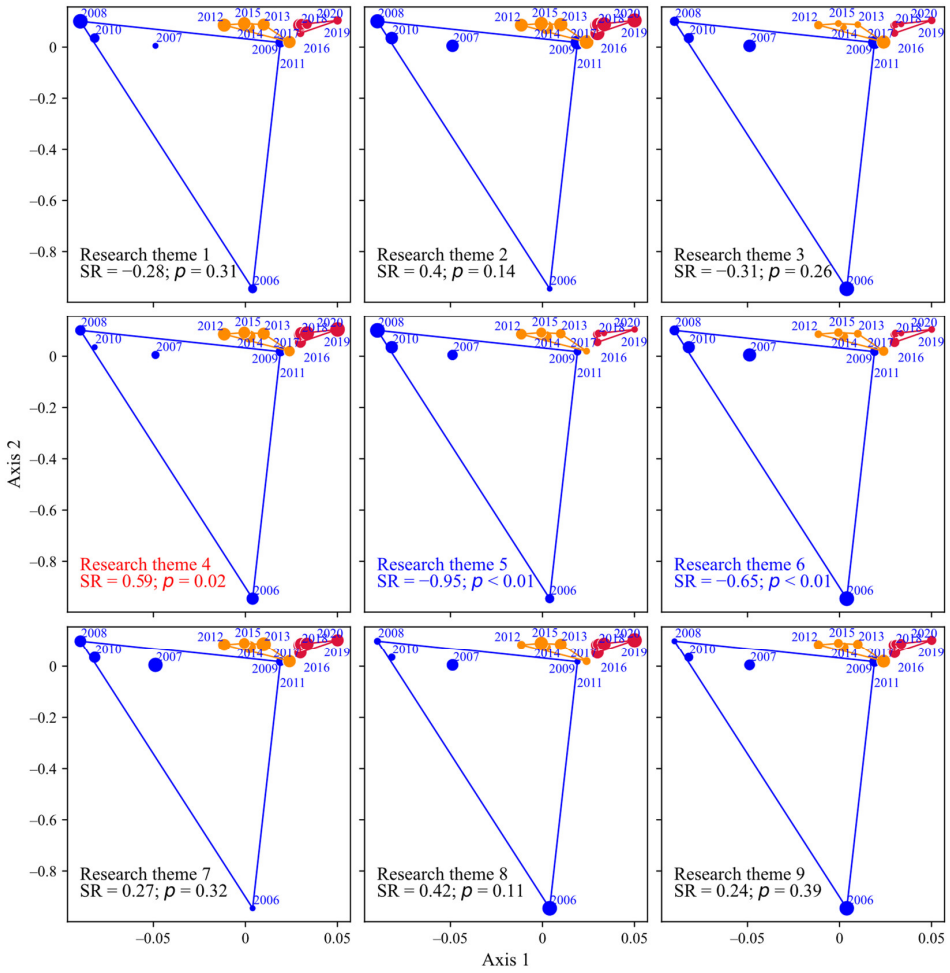

Figure 9. Bubble non-metric multidimensional scaling (nMDS) plot based on the composition of nine research themes in a certain year, which is determined by the proportion of papers in each research

theme to the total number of papers in nine research themes. Each point represents a year between 2006 and 2020 and is marked with three different colors based on the year it represented. Collaborated papers by developed and developing countries were included in the analysis. Within each subplot, larger bubbles indicate a relatively higher percentage of research articles of the research theme stated in the subplot. Bubble sizes are not comparable between subplots. The Spearman's rank correlation coefficient (SR) and *p* value between Axis 1 values and the percentage of each research theme are shown in the figure.

4. Discussion

The present study identifies nine major research themes in the field of climate change and health, which cover impacts on our lives and living environments from all aspects. This suggests that the risks of climate change could not be simply addressed, but require a systemic and holistic response and action. The One Health approach emphasizes the importance of considering the environmental health, animal health and human health as a whole as they are linked together, which is considered to be one of the best solutions for risk governance and achieving optimal health [53]. It is important to shift our focus from single health aspects to an integrated system, and future research should focus more on the systemic impact of climate change with One Health concept incorporated for better, more effective and efficient risk governance [54]. Currently, the research focus on ecosystem change (research theme 9) is relatively low, and more attention should be paid to this research theme. An alerting decreasing trend was noted in the percentage of research focus on infectious diseases (research theme 5). The COVID-19 pandemic has illustrated the huge impact that an infectious disease could cause, raising the importance of being well prepared for future emerging diseases [55,56]. In the context of climate change, the distribution and transmission of diseases may change significantly, making previously low-probability events common [54]. Thus, future investigations should pay attention to possible emerging infectious diseases and their associated risks.

Future priorities were summarized based on the expert discussion and recommendation in the three high-level forums/workshops hosted by the IRDR International Centre of Excellence on Risk Interconnectivity and Governance on Weather/Climate Extremes Impact and Public Health (ICoE-RIG-WECEIPHE) at Fudan University. The first one is the Climate Change and One Health Forum hosted on 4 June 2021, which was a session of the Pujiang Innovation Forum 2021 and a pre-session of the IRDR conference 2021. More information about this forum can be found at http://en.pujiangforum.cn/en/en_agenda_show.aspx?channel_id=21&cateid=347&id=133 (accessed on 15 May 2022) and https://www.shine.cn/news/metro/2105289737/ (accessed on 15 May 2022). The second one is the 1st Chemical Weather and Chemical Climate Youth Forum hosted on 24–26 September 2021. The third one is the Air Quality and Health Workshop hosted on 30 November 2021. More information about this workshop can be found at https://www.irdrinternational.org/news/882 (accessed on 15 May 2022). Two scientific papers led by the authors of this paper were published as the outcome of these discussions. Parts of the following statements were extracted from the published papers [54,57].

Future research priorities highlighted by experts include the following:

- Understanding the occurrence and development mechanisms of extreme weather and climate events to improve the early warning and forecasting capabilities of these events;
- Strengthening the risk interconnectivity research on extreme weather and climate events and their derived disasters for better risk governance;
- Developing a high-resolution model which couples air pollution and climate change, with a better representation of the non-linear relationship between chemical substances in the atmospheric environment;
- Developing digital tools and infrastructure for bettering monitoring of pollution and greenhouse gas emissions;

- Conducting an all-cause assessment on the health impact of climate change and environmental conditions to guide risk governance;
- Investigating the co-benefit of climate change mitigation and air quality improvement and formulating policies to maximize the co-benefits;
- Understanding the spatial difference and identifying the best adaptation strategies for local regions.

The importance of data sharing and international cooperation was also highlighted, as climate change is a global threat beyond national borders. Research trends revealed that there is a large disparity between developed countries and developing countries in terms of research output. Funding is a key factor that limits research capacity and output. Although the percentage of funded research increased significantly in the past 30 years, around 25% of the research in the field of climate change and health was conducted without funding. The percentage of underfunded research was even greater in developing countries. Experts called for more investments to support the interdisciplinary and innovative research in the field of climate change and health, to enhance the risk governance capacities through early detection, early identification, early warning and early response. More funding should be mobilized to developing countries to support research capacity building. Strengthened international cooperation with supports from developed countries to developing countries are of great importance to create a more equal, fair and healthier world. It is also noted that combating climate change is not only a scientific issue but also requires multi-stakeholder participation. Raising the public's risk awareness and perception of climate change and promoting green and low-carbon behaviors are of great importance [58,59] and are considered to be one of the key priorities of all governments. Adaptation directly contributes to reducing disaster risks and is crucial to reduce the health impact of climate change [60]. Currently, research themes 2 (risk assessment and adaptation) and 4 (sustainable development) were relatively underfunded compared with other research themes. Increased endeavors including funding should be made to increase the adaptive capacity of our society to climate change.

The risk of climate change is a combination of hazard, vulnerability and exposure. Cities, which are more concentrated on population, infrastructure and wealth, are subject to higher risks of climate change. Within the top 10 keywords shown in Figure 2, city-related keywords were only noted in research theme 7. The rank of the keyword 'urban heat island' increased from the fifth during the period 2011–2015 to the third during the period 2016–2020 and the keyword 'urbanisation' appeared as the emerging keyword within 2016–2020. This suggests that the impact of extreme heat on urban inhabitants received the most attention among all the risk factors. It has been noted that cities intensified human-induced warming in the local region and further urbanization together with more frequent hot extremes due to climate change will increase the severity of heatwaves [61]. Cities currently host approximately 4.2 billion people, which is about 55% of the global population, and this number is anticipated to increase to 68% by 2050 due to continued urbanization, especially in the Asia region [62]. Estimations showed that by the 2050s, over 1.6 billion people in more than 970 cities may experience heat exposure annually for at least 3 months with a temperature higher than 35 °C [63]. In addition to stronger heatwaves, urbanization would also increase precipitation in cities, and it is highly likely to increase flooding events for coastal cities with the combination of more frequent extreme rainfall events [61]. The emergence of 'urbanisation' as one of the top 10 keywords in research theme 7 during the period 2016–2020 confirmed that the impact of urbanization on public health on top of climate change has drawn much attention in the past few years. Considering these, enhanced climate change adaptation strategies are urgently needed for cities to reduce the associated health burden. As the center for most research institutes and universities and the key contributor to human-caused emissions [60], cities have crucial roles in tackling climate change by promoting deeper research in the field of climate change and health, increasing the adaptive capacity of billions of urban inhabitants and reducing their health burden, and implementing measurable mitigation actions. Under

these circumstances, cities are called to behave as early responders in ways that contribute to climate resilience and sustainable development.

Some limitations of the present study should be noted, due to the selection of the WOSCC database. First, most papers in the WOSCC database are in English and, thus, papers in other languages are not included in the analysis. Second, the WOSSC database mainly focuses on science and technology related research, with limited inclusion of research related to social science and medical science. Future investigations could expand article searching in other databases, for a better overview of the research in this field.

5. Conclusions

The present research investigated the research themes, hot topics and trends in the field of climate change and health, through bibliometric analysis of papers in the WOSCC database. The number of research articles increased dramatically in the past 30 years and the majority of studies were conducted by authors in developed countries. The percentage of research receiving funding was extremely low before 2008, with a sharp increase in the following few years until reaching a plateau of around 75%. Research conducted by developing countries only received the lowest percentage of funding. Nine research themes were identified by social network analysis of author keywords, as follows: (1) impacts of drought and its derived disasters on the forest and vegetation; (2) climate change risk assessment and adaptation, with a major focus on aspects including adaptation, vulnerability and resilience; (3) the impact of global warming on marine biota (especially coral reefs) and ocean circulation; (4) the threats and paths of sustainable development in the context of climate change, with special focus on food, water, energy and environment; (5) the impact of climate change on the distribution and transmission of infectious diseases; (6) the impact of climate change on plants and animals at species level and population level; (7) the risks associated with the extreme weather/climate events; (8) the health impacts of air pollution and the interaction between air pollution events and local climate; (9) the impact of ecosystem function loss and biodiversity reduction. Research related to risk assessment and adaptation (theme 2), sustainable development (theme 4) and infectious diseases (theme 5) were relatively underfunded. Meanwhile, research related to drought (theme 1), ocean (theme 3) and phenology (theme 6) receiver higher percentages of funding compared to the average level. The number of published articles increased in the past 30 years on all nine research themes. However, varied trends were observed for different research themes. Research themes related to risk assessment and adaptation (theme 2), sustainable development (theme 4), extreme events (theme 7) and air pollution (theme 8) were becoming more popular with faster increasing speed in publication numbers during the past 15 years, while a relatively slower increasing speed was noted in research related to the ocean (theme 3), infectious disease (theme 5) and phenology (theme 6). The trend was mainly driven by the shift of research focus in developed countries.

As climate change could affect our lives and living environments from all aspects, it is important to shift our focus from single health aspects to an integrated system (such as One Health framework, which considers environmental health, animal health and human health as a whole), in order to achieve better, more effective and efficient risk governance. Promoting the investigation of climate change impacts on One Health should be prioritized by academia, policy-making and funding agencies. More funding should be mobilized to developing countries to support research capacity building. Other priorities include strengthening the identification of interconnectivity of multi-risks and the capacity building to support early detection, early identification, early warning and early response. Furthermore, international cooperation and multi-stakeholder participation should be enhanced. Adaptation is of great importance to reduce the health impact of climate change, yet research related to risk assessment and adaptation (theme 2) and sustainable development (theme 4) were relatively underfunded. Increased endeavors should be made to support these research themes, to increase the adaptive capacity of our society to climate change for the goals of sustainable development.

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