Received: 28 June 2023 | Revised: 19 February 2024 | Accepted: 29 February 2024

DOI: 10.1002/wcc.884

SYSTEMATIC REVIEW

WIREs CLIMATE CHANGE WILEY

Climate change science is evolving toward adaptation and mitigation solutions

Danial Khojasteh[1,2] | **Milad Haghani**[3] | **Abbas Shamsipour**[4] | **Clara C. Zwack**[5] | **William Glamore**[1] | **Robert J. Nicholls**[6] | **Matthew H. England**[7,8]

[1]Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Sydney, Sydney, New South Wales, Australia

[2]Water, Wetlands and Coastal Science, NSW Department of Climate Change, Energy the Environment and Water, Sydney, New South Wales, Australia

[3]School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia

[4]School of Mechanical Engineering, Shiraz University, Shiraz, Iran

[5]Department of Nursing and Allied Health, School of Health Sciences, Swinburne University of Technology, Victoria, Australia

[6]Tyndall Centre for Climate Change Research, University of East Anglia (UEA), Norwich, UK

[7]Centre for Marine Science and Innovation, University of New South Wales, Sydney, New South Wales, Australia

[8]ARC Australian Centre for Excellence in Antarctic Science, University of New South Wales, Sydney, New South Wales, Australia

Correspondence
Danial Khojasteh, Water Research Laboratory, School of Civil and Environmental Engineering, UNSW Sydney, Sydney, NSW, Australia.
Email: danial.khojasteh@unsw.edu.au, danial.khojasteh@environment.nsw.gov.au

Matthew H. England, Centre for Marine Science and Innovation, University of New South Wales, Sydney, NSW, Australia.
Email: m.england@unsw.edu.au

Edited by: Matthias Heymann, Domain Editor and Maria Carmen Lemos, Editor-in-Chief

Abstract

Synthesizing the extensive and ever-growing climate change literature is becoming increasingly challenging using conventional review processes, yet is crucial to understand key trends, including knowledge and policy related gaps, managing widespread impacts, and prioritizing future efforts. Here, we employ a systematic approach to interrogate ∼130,000 international peer-reviewed climate change articles published between 1990 and 2021. We examine the time–space evolution of research topics and international collaborations, providing insights into broad scale climate change research themes, how they are developed and/or are interconnected. Our analyses indicate that significant thematic adjustments have occurred over the past three decades. Whilst all major areas of climate research have grown in output metrics, there has been a relative shift from understanding the physical science basis toward evaluating climate change impacts, adaptation, and mitigation. There has also been a significant internationalization of climate research with the ratio of international over domestic research increasing from 0.05 in 1990 to nearly 0.60 in 2021. These findings reveal a growing need for collective and coupled adaptation-mitigation actions to address climate change. The repeatable method and overall results presented herein can help to complement existing large-scale literature assessments, such as future IPCC reports.

This article is categorized under:
Climate, History, Society, Culture > Disciplinary Perspectives
Integrated Assessment of Climate Change > Methods of Integrated Assessment of Climate Change

KEYWORDS
biodiversity, climate change impacts, climate risks, ecosystem services, global change, integrative assessment, sustainability

1 | INTRODUCTION

Global climate change impacts are widespread, threatening the lives of billions of people worldwide, and disrupting nature (Masson-Delmotte et al., 2021; Pörtner et al., 2022). These impacts are often concurrent and interconnected (Lawrence et al., 2020) and cause species losses and mass mortality events (McKechnie & Wolf, 2010; Sippo et al., 2018), deterioration in ecosystem services (Cheung et al., 2021; Xi et al., 2021), more frequent extreme events (Arnell & Gosling, 2016; Davis et al., 2019; Laufkötter et al., 2020), food (Ortiz-Bobea et al., 2021; Wheeler & Braun, 2013), water (Gosling & Arnell, 2016; Schewe et al., 2014), and energy (van Ruijven et al., 2019) insecurity, air and/or water borne diseases (Funari et al., 2012; Silva et al., 2017), human physical and mental health problems (Doherty & Clayton, 2011; Palinkas & Wong, 2020), undesired redistribution (Pecl et al., 2017), and migration (Hauer et al., 2020), social inequalities (Carleton & Hsiang, 2016; Islam & Winkel, 2017), and undermined economic livelihoods (Olsson et al., 2014; Smith et al., 2021). To help inform responses on these far-reaching effects, identify knowledge and policy related gaps, promote international collaborative research, and prioritize future efforts, this study illustrates how climate change research has evolved in the scholarly literature over the past three decades in a way that has seen a relative increase in research on both *adapting* to and *mitigating* future climate change, and a relative decline in work aimed at *understanding* the physical basis of climate change.

A pivotal moment in building scientific knowledge on climate change was the establishment of the Intergovernmental Panel on Climate Change (IPCC) by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. The IPCC was commissioned to provide governments with the necessary scientific and socio-economic knowledge required to assess climate change and its implications and to design effective climate policies worldwide. This includes the preparation of reports assessing the state of knowledge of climate via three working groups (WGs), each analyzing a different aspect, which since 2001 have comprised WGI "The Physical Science Basis"; WGII "Impacts, Adaptation, and Vulnerability"; and WGIII "Mitigation of Climate Change." According to the IPCC, a key part of the First Assessment Report (FAR—1990) emphasized the consequences of global warming and the significance of international cooperation; the Second Assessment Report (SAR—1995) highlighted a discernible human influence on the Earth's climate which set the foundation for the Kyoto Protocol; part of the Third Assessment Report (TAR—2001) underlined complex climate change impacts and an urgency for adaptation and sustainable development; the Fourth Assessment Report (AR4–2007), among other findings, concluded that warming of the climate system is unequivocal encouraging limiting warming to 2°C due to the recognition of tipping points; the Fifth Assessment Report (AR5—2013–2014) evidenced an unprecedented acceleration of climate change impacts requiring substantial reduction in emissions together with effective adaptation measures and laid the groundwork for the Paris Agreement; and part of the Sixth Assessment Report (AR6—2021) outlined that climate changes are increasing in all regions of the globe bringing about increasingly irreversible losses in ecosystems with a need to limit global warming to 1.5°C.

These IPCC activities (e.g., review assessments, special reports), together with increasing research on climate change since 1990s, have created a large body of academic scholarship. In this context, the existing research could be synthesized via nontraditional machine learning techniques (Cheng et al., 2018), or bibliometric/scientometric approaches (Fang et al., 2018; Z. Wang et al., 2018), as they allow a rapid, reliable assessment and classification of thousands of publications that is impractical using conventional methods (Berrang-Ford et al., 2021; Haunschild et al., 2016). The resultant synthesis can provide an integrated and comprehensive understanding of diverse disciplines and how they respond to progressing climatic issues, enhancing climate knowledge to better inform relevant policies and practices (Lesnikowski et al., 2015; Tai & Robinson, 2018).

To date, most efforts to map the climatic scientific literature have focused on a specific aspect of climate change. For instance, large-scale analyses of adaptation and mitigation research have indicated that documented adaptation is scarce though growing rapidly, and studies do not tend to be interdisciplinary and do not lead to a coherent solution (Berrang-Ford et al., 2021; Einecker & Kirby, 2020; Nalau & Verrall, 2021; Z. Wang et al., 2018). Research on climate change vulnerability was observed to grow exponentially, with the relevant research topics predominantly focusing on health issues, food/water security, and socioeconomic processes (Di Matteo et al., 2018; Wang et al., 2014). Using a bibliometric approach, climate change induced food insecurity was identified as an emerging global challenge, encouraging innovative and mitigative solutions at a global scale (Sweileh, 2020). Systematic studies on extreme heat events suggested that heat adaptation solutions largely depend on geographic region and national income, with further international collaborative solutions required moving forward (Hintz et al., 2018; Turek-Hankins et al., 2021). A bibliometric examination of sea-level rise science underlined that new research is geared toward more solution-focused topics associated with risks of rising sea levels and should be more responsive to ongoing research topics related to societal and policy challenges (Khojasteh, Haghani, et al., 2023).

In broader assessments of climate change topics, often the climate solutions, common threads and terms, and key contributing journals or countries were analyzed (Fu & Waltman, 2022; Haunschild et al., 2016). Although comparative research on climate change vulnerability, adaptation, and mitigation formed a small portion of the existing climate literature, it possesses the largest proportion of influential publications with highest citation impacts (Haunschild et al., 2016). A high-level analysis of climate science revealed a recent move toward new technologies and policies with national demands/strategies identified as key drivers influencing research priorities in different geographic regions (Fu & Waltman, 2022). A recent study presented a topical map of climate change science highlighting that, in recent IPCC assessments, social sciences are overrepresented whereas technical and engineering knowledge is underrepresented, recommending future large-scale review assessments to identify interdisciplinarity features (e.g., collaboration networks) (Callaghan et al., 2020).

In this study, we develop a new sophisticated search strategy (using term-based and journal-based schemes) and adopt a big data bibliometric approach to expand upon previous studies and explore the full set of climate change articles (∼130,000) published between 1990 and 2021, spanning the period from the first to the most recent IPCC reports. This article, for the first time, scrutinizes research divisions of climate science at a detailed level of aggregation and how they have been fashioned from broader themes or evolved over time or through national and international research initiatives as well as across the IPCC WGs. This enables an in-depth and objective overview derived from scholarly sources, while generating multiple lines of evidence and highlighting trends in research disciplines. In summary, the present study addresses the following three overarching questions:

1. What are the broad themes of climate change research and how are they comparable against the typical structure of the IPCC WGs?
2. What are the growing, declining, and emerging (relative to total work produced) research topics and how have research activities and interdependencies changed over time and across different subjects assessed by the IPCC WGs?
3. How internationally collaborative is the current global climate change research effort?

The answers to these questions are presented and discussed in Sections 3, 4, and 5, respectively. The findings from this article can assist in understanding the recent history of climate change research and identifying future priorities while discussing the opportunities offered by such a large-scale and integrative literature assessment.

2 | MATERIALS AND METHODS

2.1 | Data acquisition

The dataset of climate change articles from January 1st 1990 to December 31st 2021 was sourced from the Web of Science (WoS) Core Collection using the extensive search query presented in Table S1. Bibliometric data extracted from WoS has be shown to provide an acceptable coverage of scholarly literature (Callaghan et al., 2020; Haghani et al., 2022). As the climate change literature is extensive and unique, a mix of term-based and journal-based schemes were adopted to capture the bibliographic details of articles with adequate coverage and specificity.

Three main layers are embedded in the search query (see Table S1). The first layer is a pure term-based query, retrieving climate change articles from anywhere in the WoS based on the mention of distinct climate change terminologies in the title of articles indexed by the WoS. The second layer captures the full content of all specialty climate journals indiscriminately and irrespective of the language/terminologies that they have used in their titles. The third layer is a combination of term-based and journal-based queries. This limits the search to a subset of semi-specialty climate journals (i.e., those that often publish research on climate change but not exclusively), while also searching their titles for a less restrictive set of terms than that of the first layer. All three layers are combined using the Boolean Operator "OR" and work as a conjoint query string. Therefore, duplicates are automatically avoided if an article is captured by more than one layer of the query string. This yielded $n = 129{,}494$ unique articles ($n = 33{,}186$ during 1990–2009, $n = 38{,}957$ during 2010–2015, $n = 57{,}351$ during 2016–2021), where the data of titles, authors, affiliations, publication year, journals, conferences, citations, document type, abstract, keywords, fundings, and cited references of each article were retrieved and analyzed (for details, see Khojasteh, Haghani, et al., 2023). The adopted search query is presented in Table S1.

2.2 | Title and abstract analysis

The broad academic structure of climate change research was determined using the occurrence and co-occurrence of terms in the titles and abstracts of extracted articles. The visualization of similarities (VOS) between terms was identified and presented via VOSviewer software (Van Eck & Waltman, 2007; Van Eck & Waltman, 2010). In this method, a pair of terms are positioned such that the distance between them exhibits their similarities and frequency of co-mention. When this approach was applied to climate change research, four distinct clusters were identified (Figure 1a). In this analysis, a node represents an item of interest (term) and its size is proportional to the frequency of the term occurrence. For details, see Van Eck and Waltman (2007) and Van Eck and Waltman (2010).

2.3 | Bibliographical coupling analysis at the level of individual articles

This analysis is similar to title and abstract analysis, although it maintains the individuality of articles. As such, it presents a more detailed level of research streams in climate change science. Four major clusters of bibliographically coupled articles (i.e., articles with a high degree of similarity between their list of references) were identified and illustrated in Figure S1. In this figure, the colors of clusters are associated with those used in title and abstract analysis (Figure 1a). For details of this analysis, see Kessler (1963) and Weinberg (1974).

2.4 | Keyword analysis

All keywords of documents published in three different periods of 1990–2009, 2010–2015, and 2016–2021 were extracted and analyzed. The top 30 keywords with most occurrences in each period were presented (Figure 1b) to highlight the shifts in the direction of climate change research topics from 1990 to 2021.

2.5 | Document co-citation analysis

This analysis presents the sub-clusters of references that have been co-cited by articles from the climate change literature. The underlying concept is that references of climate change articles that are frequently co-cited by climate change documents are likely representative of the knowledge foundation of thematically similar climate change articles (Chen, 2004; Haghani et al., 2021). As such, their citing articles represent a particular sub-cluster (i.e., sub-theme/stream) of climate change research, with the sub-cluster of co-cited references forming the knowledge foundation of their respective research stream. In other words, the produced network of thematically identical sub-clusters can characterize distinct streams of research activities in climate change science (Figures 2 and 3). CiteSpace (Chen, 2006) has been employed to sub-cluster climate change references, classify spatial and temporal trends during various stages of its development, and determine influential references/articles within each research stream. The analysis timestep was set

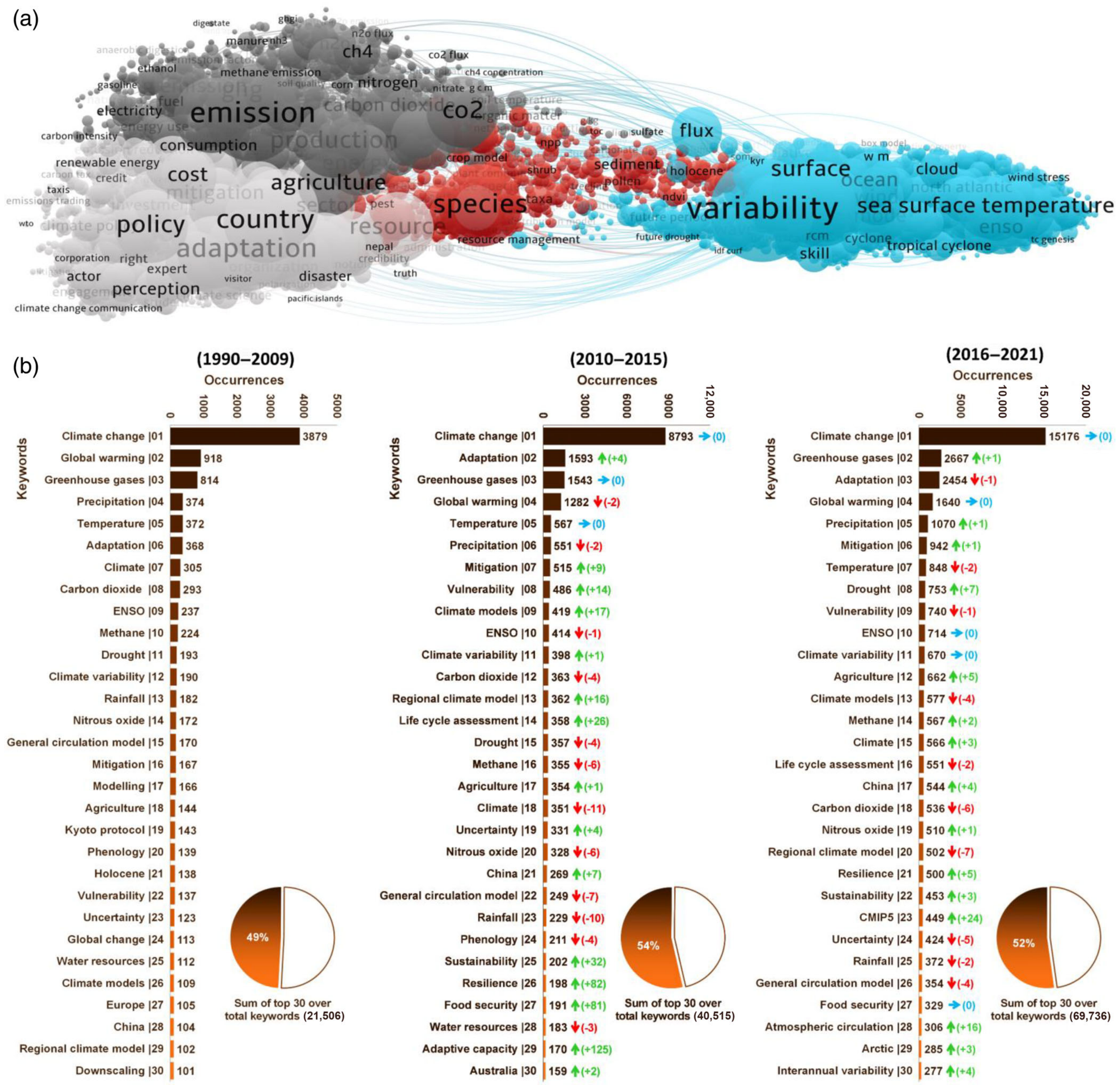

FIGURE 1 (a) Four major research clusters (divisions) of climate change research including climate variability, ocean/air/land temperature, and climatic and hydrological cycles and models (blue division), paleoclimatology, geology, habitat distribution, and biodiversity (red division), greenhouse gases, environmental impacts, and supply/demand of food, water, and energy (dark gray division), and climate policy, adaptation, mitigation, public perception/engagement, and sustainability (light gray division). (b) Top 30 keywords in climate change articles during 1990–2009 (bottom left panel), 2010–2015 (bottom canter panel), and 2016–2021 (bottom right panel). In (b), Green, blue, and red arrows and numbers in brackets indicate positive, zero, and negative displacement of keywords between two consecutive time periods highlighting potential shifts in climate change research topics.

to 1 year, and the look-back parameter was specified as 50 years (i.e., for an article, references up to 50 years older than publication time of that article were considered).

In visualizing the results of this analysis, each node represents a unique reference and its size depicts the local citation counts (i.e., the frequency of being referenced by climate change articles exclusively) (Khojasteh, Shamsipour, et al., 2023; Tavakoli et al., 2023). Sub-clusters were ranked based on the number of cited references and influential citing articles embodied within them with larger sub-clusters presented with smaller numbers (Khojasteh, Haghani,

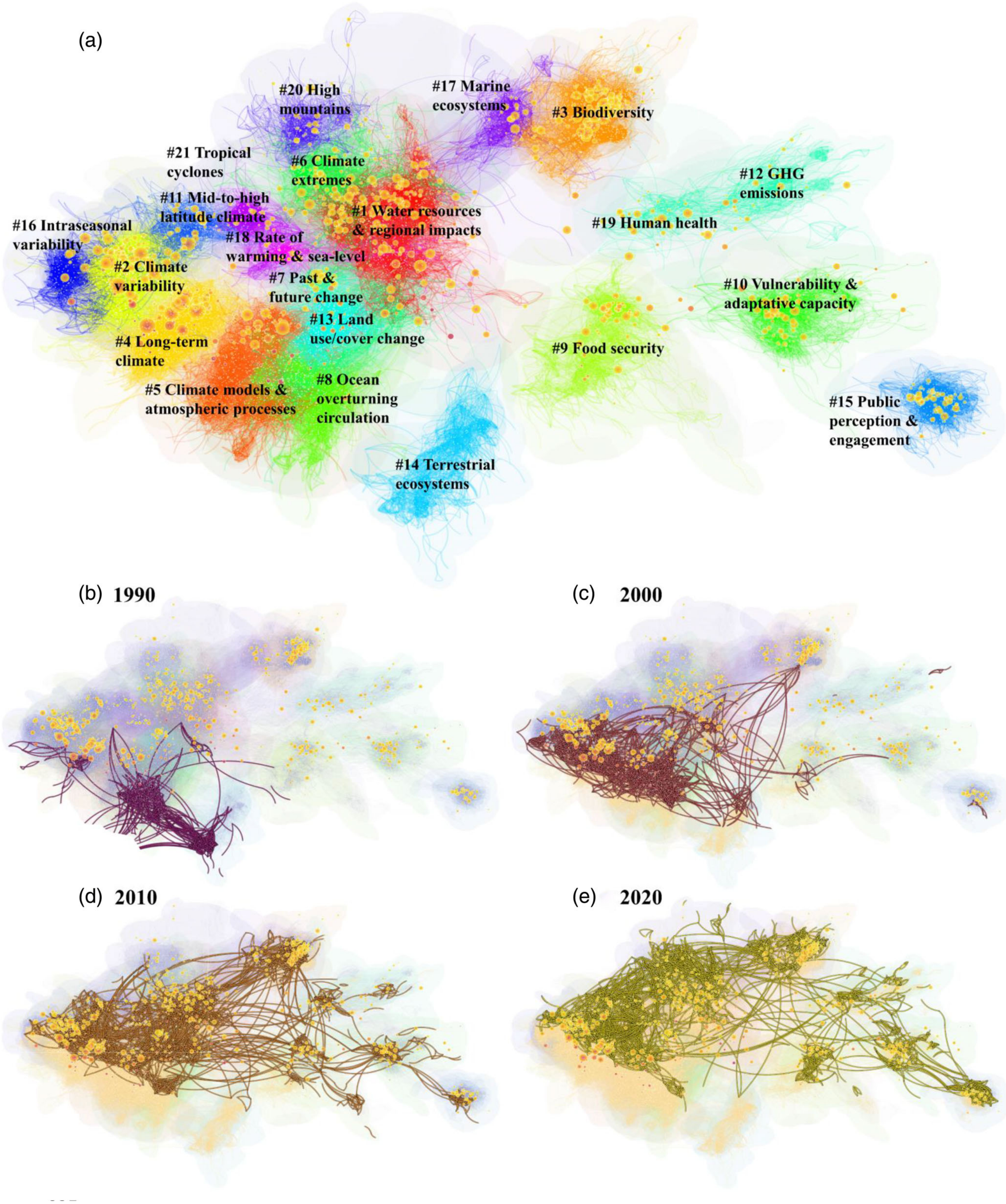

FIGURE 2 Legend on next page.

et al., 2023). The extent of activities within sub-clusters and during each year was determined by analyzing the counts of local citations to the set of cited references of that cluster as well as the number of such citing articles (Haghani et al., 2021). Note that sub-clusters were labeled to best represent their contents (i.e., contents of citing articles within them), and were only given indicative labels based on the main themes of the citing articles. Additionally, sub-clusters with less than 100 cited references within them were not labeled nor presented in Figures 2 and 3. Table S2 presents further information regarding all 21 sub-clusters illustrated in Figures 2 and 3.

2.6 | Growth rate and doubling time

In this study, the average annual growth rate was assessed, which is a useful metric in assessing long-term trends in science (Ma et al., 2016). To evaluate the average growth rate (g), the yearly growth rate was first calculated as follows:

$$g = ((VF - VP)/VP) \times 100\% \tag{1}$$

where VF and VP are the future value (here articles) and the present value, respectively. To calculate the growth rate for a certain period, g was evaluated between two consecutive years. Values of g for different periods were then averaged, providing the average growth rate of the entire period (1990–2021). The doubling time d (the period of time over which the number of articles doubled) can be then obtained (Bornmann et al., 2021):

$$d = \frac{\ln(2)}{\ln(1+g)} \tag{2}$$

3 | BROAD THEMATIC FOCUS IN CLIMATE CHANGE RESEARCH

Four key clusters (divisions) for climate change research were identified using an analysis on frequency of co-occurred terms (Figure 1a and Section 2). These major clusters include (i) the blue division dominated by climate variability, ocean/air/land temperature, and climatic/hydrological cycles and models; (ii) the red division comprising paleoclimatology, geology, habitat distribution, biodiversity, and ecosystems; (iii) the dark gray division encompassing emissions, environmental impacts, and food-water-energy nexus; and (iv) the light gray division including climate policy, public perception, adaptation, mitigation, and sustainability (Figure 1a). This is an interesting observation as these divisions do not map seamlessly onto the typical structure of the IPCC WGs, but rather are fashioned from a combination of subjects. Generally, scientific topics of (i) blue division focused on physical science (WGI); (ii) red and (iii) dark gray divisions covered physical basis and impacts (WGI and WGII); and (iv) light gray division examined adaptation and mitigation strategies (WGII and WGIII). This finding reflects a relative domination of research aligned with WGI and WGII over the last 30+ years. However, the average publication year of the papers within the dataset reveals a trend that progresses from division (i) toward division (iv) (Figure S2). This highlights a recent shift, primarily from 2016 onward, where scholars/researchers have applied the lessons from observations, models, and past/present/future

FIGURE 2 (a) A network-view of the 21 sub-clusters of thematically connected research streams in climate change literature identified through patterns of document co-citation (i.e., documents that are frequently co-cited). In (a), larger sub-clusters contain higher numbers of cited references and influential articles and are presented with smaller cluster IDs. The extent of activities across diverse climate science disciplines in (b) 1990, (c) 2000, (d) 2010, and (e) 2020 highlights research sub-clusters that were most active during each cross-section of time. In (a–e), each node depicts an individual reference, node size is proportional to the number of local citations (i.e., exclusive citations within the field of climate science) to the cited references, and links (i.e., connecting lines) indicate instances of co-citation. In (a), each sub-cluster is represented with a unique color theme whereas in (b–e), sub-clusters are only visualized as a background map to better highlight when and how each sub-cluster was active/inactive and/or had interactions with neighboring sub-clusters over time. In (a–e), nodes which are overlaid by a red ring (circle) mark those cited references that their local citation burst (i.e., duration and strength) is recorded. In (a–e), additional sub-clusters with less than 100 cited references within them were eliminated from visualizations (see Section 2).

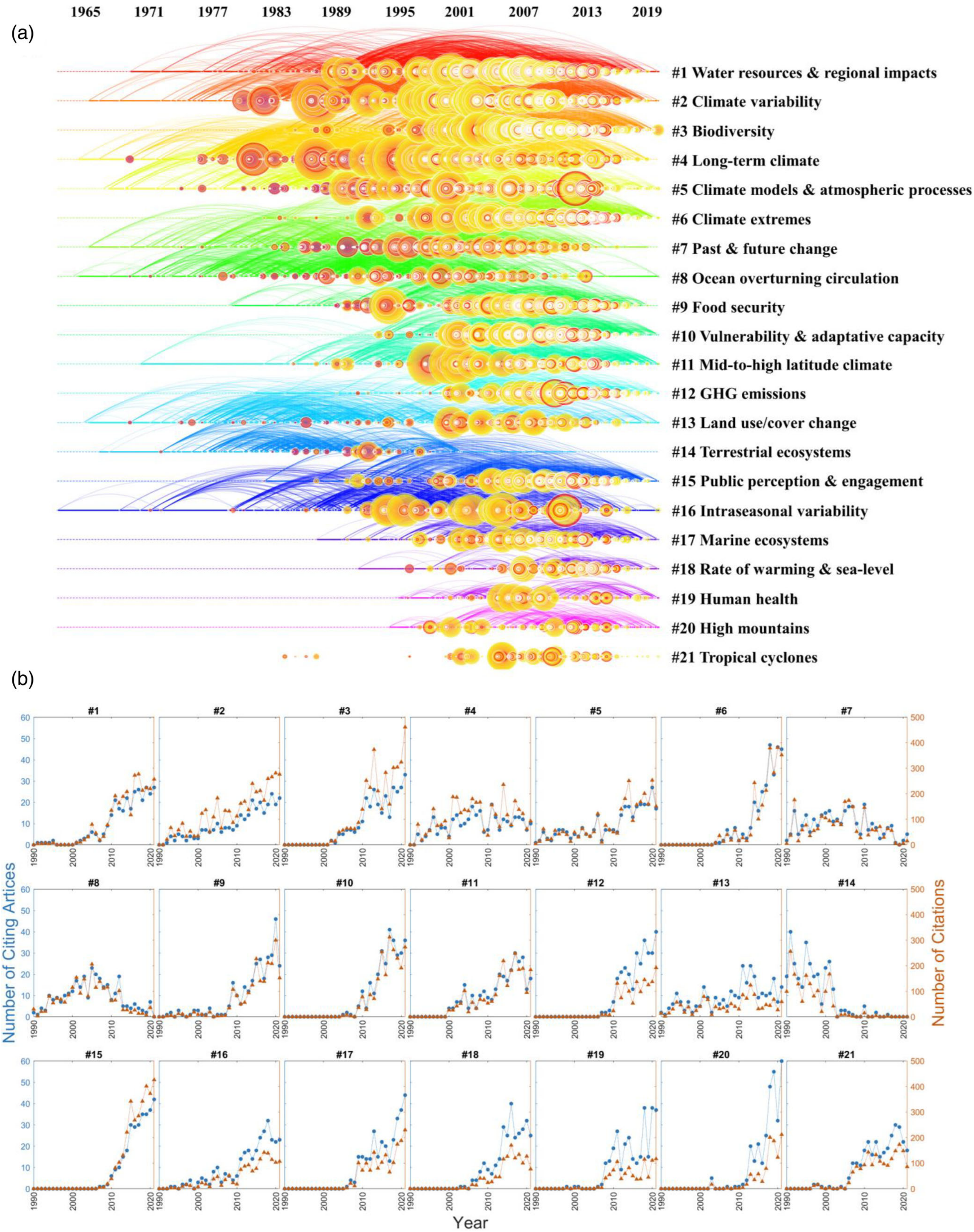

FIGURE 3 Legend on next page.

climate variability (WGI) to produce new work focused on understanding impacts, vulnerability, and adaptation (of both human and natural systems), including mitigation. This new research includes food/water/energy security (WGII), and stabilizing greenhouse gas levels and achieving high-level mitigation targets (WGIII).

Further, as highlighted in Figure 1a, terms that cross two or more different divisions are often multidisciplinary or transboundary in nature. For instance, the term "ecosystem services" is positioned along the boundary of divisions (ii), (iii), and (iv). This indicates its usage across different disciplines as climate change affects ecosystems (e.g., via changing temperature, precipitation, and carbon dioxide concentration) and threatens biodiversity and food security (Malhi et al., 2020; Mooney et al., 2009). Moreover, ecosystem services can also mitigate climate change effects by removing carbon from the atmosphere, regulate floods, and naturally purify water (Locatelli, 2016; Munang et al., 2013; Nedkov & Burkhard, 2012). A few other noticeable terms that border multiple research divisions (clusters) include "hydrological modeling", "resource management", "restoration", and "agriculture" (Figure 1a). Hydrological models, for instance, are frequently used to estimate climate change impacts to food/water resources by simulating the dynamic transformation of precipitation into runoff via complex processes (e.g., infiltration, transpiration, and evaporation; Ghonchepour et al., 2021; Haddeland et al., 2014; Hagemann et al., 2013). As a potential response to these impacts, ecological restoration (e.g., rehabilitating lands, forests, and coastal vegetated communities) provides promising opportunities to reduce emissions, and contribute to diverse policy objectives related to food and water security, improved resilience, sustainable development, biodiversity conservation, and environmental justice (Bustamante et al., 2019; Constenla-Villoslada et al., 2022; Erbaugh et al., 2020; Glamore et al., 2021; Harris et al., 2006; Koch & Kaplan, 2022; Sadat-Noori et al., 2021; Serrano et al., 2019; Su et al., 2021; Woolf et al., 2018). This is reflected in observations from a detailed bibliographically coupled analysis of individual articles during 2010–2015 and 2016–2021 (Section 2 and Figure S1), where in the latter period, climate change impacts on food/water/energy sector are blended with climate policy and management themes within an integrative, interdisciplinary topic that crosses the boundary of divisions (iii) and (iv) (Figure 1a).

Temporal trends in climate change research topics are observable via the evolution of the top 30 keywords across different time periods (Figure 1b and Section 2). Not surprisingly, "Climate change", "Global warming", and "Greenhouse gases" are always ranked in the top four key research areas. The sum of the top 30 keywords forms 52% of the sum of all keywords used during 1990–2021, with the total number of keywords increasing by 88% from 1990–2009 (left panel of Figure 1b) to 2010–2015 (mid panel of Figure 1b), and by 72% from 2010–2015 to 2016–2021 (right panel of Figure 1b). When 2010–2015 keywords are compared to 1990–2009, or when 2016–2021 keywords are compared to 2010–2015, emerging, declining, and the evolution of integrated research topics can be assessed. During 2010–2015, for example, "Adaptation", "Mitigation", "Vulnerability", "Climate models", "Life cycle assessment", "Sustainability", "Resilience", "Food security", and "Adaptive capacity" were on the rise, constituting the key research foci attributable to predicted or observed wide-ranging impacts of climate change in the earlier period. These research themes were nearly unchanged during 2016–2021, but "Agriculture", "Resilience", "CMIP5", and "Atmospheric circulation" increased in prominence because of a growing focus on better understanding the historic and future climatic changes using coordinated experiments (Knutti & Sedláček, 2013; B. Wang et al., 2018), enhancing food security and climate-smart agriculture (Arora, 2019), and improving societal and environmental resilience (Nelson et al., 2007). In contrast, since 1990, related (and often isolated) research on "Carbon dioxide", "Methane", and "Nitrous oxide" has been decreasing relative to other topics or occurs in other contexts rather than being the key focus. This aligns with progress in current understanding of the sources and sinks of greenhouse gases over the past 30 years. As an example, four keywords of "Adaptation", "Carbon dioxide", "Mitigation", and "Climate models" are further tracked in Figure S3, highlighting potential shifts (i.e., positive or negative displacements with different degrees of strength) in the direction of research topics during 1990–2021.

FIGURE 3 (a) A temporal map of co-cited references of the 21 research sub-clusters of climate change science indicating times and rates at which individual references have received citations as well as the duration and age of knowledge foundation for each sub-cluster. In (a), each reference is indicated by a node and connecting lines represent instances of co-citation. The size of each node shows the number of local citations to a cited reference and red rings marked references that a burst in their local citations was recorded. (b) Citing articles and their corresponding citation counts in climate change research sub-clusters highlighting their extent of temporal evolutions as well as younger/older and most/least active topics during 1990–2021. In (b), research activity of each sub-cluster can be quantified over time according to its number of citing articles during each year as well as the total number of citation counts recorded from citing articles to the cited references of each sub-cluster.

4 | TRENDS IN CLIMATE CHANGE RESEARCH

Figure 2 is generated using document co-citation analysis (see Section 2), providing fine resolution insights into evolution of climate change science sub-clusters. Figure 2a depicts the spatial distribution of thematically coupled sub-clusters in climate science formed during 1990–2021. The key logic behind this clustering is that the references, which are frequently co-cited by climate change related articles, are grouped together and form a thematically similar cluster (for details, see Khojasteh, Haghani, et al. (2023)). Overall, 21 research sub-clusters emerged in the climate change science domain. Larger sub-clusters contain higher numbers of cited references and influential articles and are presented with smaller sub-cluster IDs (see Table S2). The sub-clusters were labeled based on the contents of citing articles within them (e.g., see "highest coverage citing articles" column in Table S2). Note that our shorthand labelling of sub-clusters here at times is not inclusive of all articles in any given sub-cluster and only aims to represent the contents of the majority of articles within that sub-cluster. For instance, "#1 Water resources and regional impacts", "#2 Climatic variability", and "#3 Biodiversity" are the three largest sub-clusters with the greatest number of cited references and influential citing articles. Larger sub-clusters often contain general climate terms and diverse references from across different disciplines, including topics from outside the core climate change domain (e.g., water policy and legislation), whereas smaller sub-clusters typically use specific terms and exclusive citations (Table S2). Research areas positioned in the center of Figure 2a (i.e., sub-clusters 1, 7, 9, 13, and 18) often have a multidisciplinary role in climate change science, suggesting that they are explored both individually and interconnectedly with other peripheral sub-clusters.

A temporal analysis of the climate change literature highlights which parts of the network have been most active in 1990, 2000, 2010, and 2020 by visualizing the corresponding links between active research topics (Figure 2b–e). In 1990, climate variability, long-term climate, ocean overturning circulation, land use/cover change, and terrestrial ecosystems were the most active research sub-clusters. In 2000, the water resources, biodiversity, mid-to-high latitude climate, and climate models emerged as major research sub-clusters. In 2010 and 2020, further interdisciplinary research was observed among all sub-clusters, with particular attention to looming research topics related to the rate of warming and sea-level, human/ecosystem health, agriculture and food security, adaptive management, public perception, tropical cyclones, and mountains including their rapidly disappearing glaciers. This evolutionary trend matches with the identified research topics assessed by the IPCC WGI and WGII and the recent research shifts from primarily exploring the physical science basis of climate change (WGI) to understanding impacts on humans/ecosystems and options for adaptations (WGII) and to reducing global emissions by integrating interdisciplinary adaptive and mitigative measures (WGIII).

Many of the temporal variations seen in the analyses presented can be understood in terms of variations in the demands for certain areas of climate change research. For example, there is a growing awareness that sea-level rise has major ramifications, potentially threatening more than 600 million people worldwide as soon as 2100 (Kulp & Strauss, 2019), and resulting in loss/degradation of biodiversity and highly valued ecosystem services (Khojasteh et al., 2021; Schuerch et al., 2018; Spencer et al., 2016). This is exacerbated by higher extreme sea levels during tropical and extratropical storm surges, with surges likely to alter under climate change, affecting populated coastal/deltaic cities (Walsh et al., 2016). Following an IPCC expert panel meeting in Ireland in 2015, the implications of climate change for agriculture sector and food security received urgent attention (Hertel, 2016), with significant impacts observed and anticipated on crop, livestock, and fisheries production (Campbell et al., 2016). Climate change also impacts glacial melting and precipitation patterns in mountain ranges, and hence, river flows, water security, and agriculture in downstream areas (Immerzeel et al., 2010). Understanding public perception in a changing climate is necessary to ensure effective risk communication, implement adaptive-mitigative management strategies, and take decisive actions at local or global scales (Fuentes et al., 2016; Kunreuther et al., 2014; Shi et al., 2015). Further, an expanding body of literature has emerged across multiple disciplines investigating the interactions between climate change and other global challenges (e.g., water/food crisis, pandemics) and actions required on multiple fronts to ensuring human-nature health (Hanjra & Qureshi, 2010; Khojasteh et al., 2022).

To further highlight the temporal evolution of climate science at different timeframes, cited references of research sub-clusters are presented along a shared timeline based on their publication year (Figure 3a), while the magnitude of their activities, as reflected in the citation counts and number of citing articles to the cited references of each sub-cluster, have also been quantified (Figure 3b). The former represents the age of knowledge foundation for different climate change research sub-clusters while the latter represents periods of emergence, peak, and activity (Section 2 and Table S2). Fundamental sub-clusters, often with citation occurrences and new references/articles that continue from early years to the present time, are becoming increasingly important in climate science (Figure 3a,b). For instance, research sub-clusters water resources, climatic variability, and climate models exhibit an established knowledge foundation with influential references present from the 1960s to 2021 (Figure 3a), and the number of articles/citations related to these topics grow constantly over time (Figure 3b). A few climate sub-clusters periodically plateau or fluctuate, such as past and future change, ocean overturning circulation, and terrestrial ecosystems. Other research sub-clusters grow in prominence, such as biodiversity, climate extremes, food security, vulnerability and adaptation, greenhouse gases, public health/engagement, sea-level change, high mountains, and tropical cyclones. The increasing prominence of these sub-clusters is apparent from the recent rise in the number of articles and their corresponding citation counts from 1990 to 2021 (Figure 3b).

As an example, and in order to further spotlight the recent significance of a few emerging research topics, the sub-clusters high mountains, climate extremes, and biodiversity are briefly discussed here as they have attracted significant attention lately (Figure 3b). High mountains (sometimes introduced as global water towers), as primary providers of anthropogenic and natural water demand, are found to be among the most vulnerable environments. Climatic changes, together with future socio-economic challenges, may threaten 1.9 billion people who live near mountainous areas (Immerzeel et al., 2020). If emissions are ambitiously reduced by 2100, global populations will be exposed to one extreme event (e.g., droughts, wildfires, sea-level rise, floods), otherwise they will face 3–6 concurrent events (Mora et al., 2018). During 2000–2019, over 5 million cases of death globally were associated with nonoptimal temperatures per year (Zhao et al., 2021), and nearly 700 million people will experience extreme heatwaves once every 20 years in a 1.5°C world (Dosio et al., 2018), rising to 2 billion people for a 2°C world. The warming associated with continued business-as-usual emissions may lead to further losses in biodiversity, habitat, and primary productivity, requiring proactive, integrated adaptation-mitigation strategies (Bruno et al., 2018; Mori et al., 2021; Weiskopf et al., 2020).

5 | DISCUSSION

Climate change research is ongoing and expanding, with an overall growth rate of 10.3% and a doubling time of 7.1 years during 1990–2021 (Figure S4). Growth rates and doubling times vary between the IPCC reports, amounting to 15.7% and 4.7 years (FAR-SAR, 1990–1995), 6.0% and 12.0 years (SAR-TAR, 1995–2001), 7.9% and 9.1 years (TAR-AR4, 2001–2007), 15.0% and 4.9 years (AR4-AR5, 2007–2014), and 7.3% and 9.8 years (AR5-AR6, 2014–2021) (Section 2 and Figure S4). The observed doubling time is nearly consistent with previous climate studies reported as 11 years (1951–1997) (Stanhill, 2001), 7 years (1997–2004) (Grieneisen & Zhang, 2011), and 5–6 years (1980–2014) (Haunschild et al., 2016). The overall increase in the entire modern science literature (i.e., not solely climate science) demonstrates a growth rate of 4.1% and a doubling time of 17.3 years (Bornmann et al., 2021), highlighting the exceptionally rapid expansion in climate research. A total of 153 countries contributed to climate research during 1990–2009, which increased to 197 countries during 2010–2015, and to 203 countries during 2016–2021 (Table S3). Among all nations, USA, UK, China, Germany, and Australia had the largest cumulative number of publications during 1990–2021 (Figure 4a).

Of all publications produced during 1990–2021, 40% were from Europe, 28% from North America, 19% from Asia, 6% from Oceania, 4% from Africa, and 3% from South America (Figure 4b). Europe consistently remained the top continent in producing climate change research, whereas contributions from North America declined over time to the extent that Asia, for the first time, secured the second place among all continents when measuring total publications during 2016–2021 (Figure 4b). The most joint publications were produced by scholars from USA, China, UK, Germany, Canada, and Australia (Figure S5).

Domination of domestic research performed by more affluent nations is despite the fact that globally, all populations are exposed to the threat of climate change, regardless of location, sex, age, and socio-economic classes (Zhao et al., 2021). Further, climate change is unfortunately intertwined with inequality, with low-income countries (typically with lower emissions) being more impacted than high-income countries (often with higher emissions) (Levy & Patz, 2015). This inequality aligns with the observed trend in the increase in focus on adaptation research that often involves locally or nationally based measures, as opposed to mitigation research/action that generally requires shared and collective efforts across nations to be effective. For instance, a recent study highlighted that USA dominates the focus of research on adaptation responses to compound climate events (e.g., drought, heatwave, flooding), whereas adaptation studies on South and Central America, Middle East, Russia, and North Africa are underrepresented, and hence, an equal global distribution of research is not being achieved thus far (Simpson et al., 2023). Although our study suggests that EU, USA, China, and India generate the most recent research on climate change, Small Island Developing

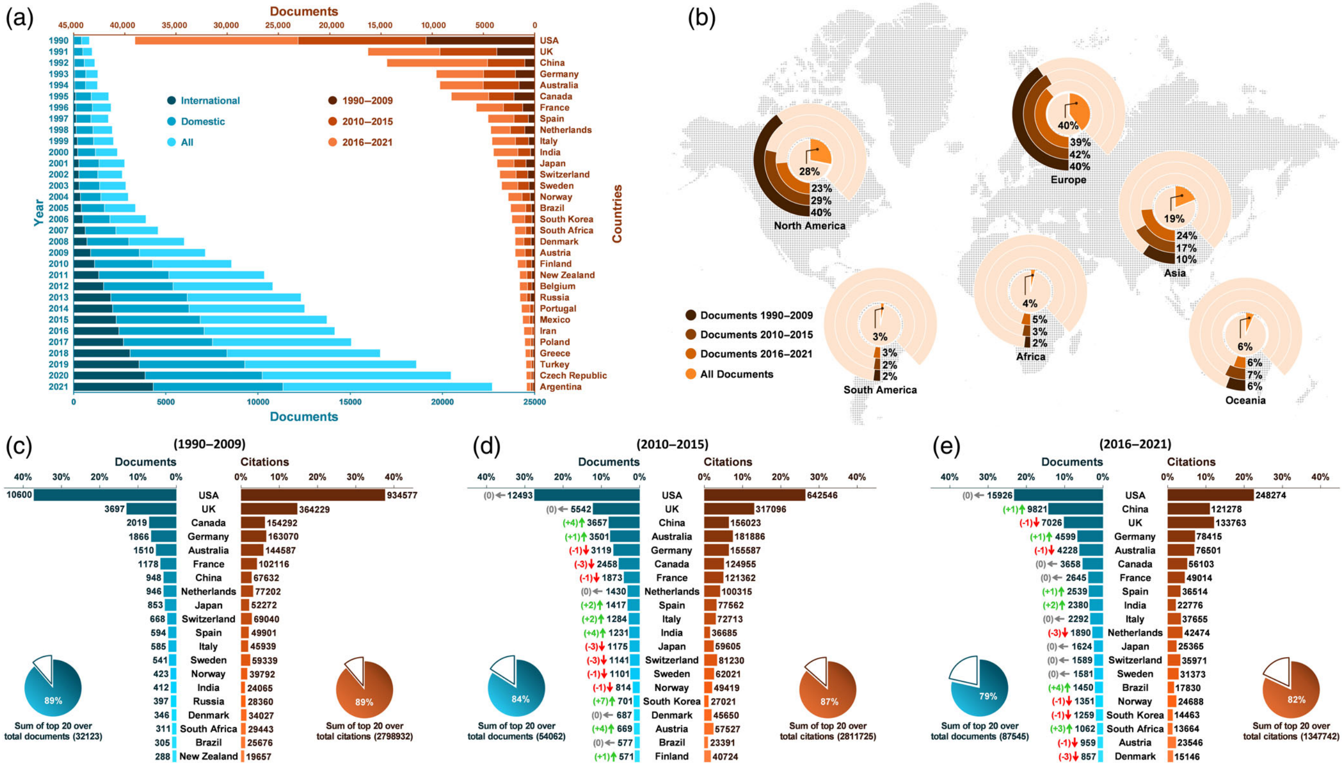

FIGURE 4 (a) Temporal patterns of international, domestic, and all (domestic plus international) climate change publications for the top 32 countries with cumulative documents (articles) during 1990–2021. (b) Continental contribution to climate change science during 1990–2009, 2010–2015, 2016–2021, and 1990–2021. Percentage and number of documents (articles) and citation counts within the top 20 countries, with most climate change related publications during (c) 1990–2009, (d) 2010–2015, and (e) 2016–2021 periods. In (c-e), pie charts indicate the proportion of the top 20 countries producing global articles (blue pies) and receiving citations (red pies). In (d-e), green, gray, and red arrows and numbers in brackets indicate positive, zero, and negative displacement of countries between two consecutive time periods. In (a–e), all documents (articles) from all contributing nations are considered, and some documents maybe counted multiple times.

States, Africa, and large (often termed Mega) deltas (particularly in Asia) are widely recognized as the most vulnerable regions to climate change and yet are ill-prepared to deal with its impacts while producing minimal emissions compared to major emitting countries (Huq & Ayers, 2007). On the other hand, relatively limited research identified herein on climate change mitigation could be attributed to the absence of major investment and adequate fiscal capacity required to meet the ambitious low carbon targets at a global scale. While our research indicated that the physical understanding of climate systems appears to be well-established, and there is a general international consensus on the science behind climate change, investigations on climate change mitigation are relatively limited, though growing. Overall, the literature to date reflects that there is no "one-size-fits-all" solution for curbing emissions, and that mitigation efforts are thus far relatively ad hoc and specific to nations and/or economic blocks. There is also little consensus on how to support the most affected nations.

A promising observation that may result in a greater focus on mitigation is the substantial increase and the upward trajectory in international collaborative research (Figure S6). The number of countries contributing to climate change research increased steadily over time, such that the domination of the top 20 countries in terms of publishing documents and receiving citations reduced from nearly 90% during 1990–2009 to nearly 85% during 2010–2015, and to nearly 80% during 2016–2021 (Figure 4c–e and Table S3). Interestingly, the ratio of international (i.e., documents with multinational authors) to domestic (i.e., documents with single nation authors) publications has markedly increased from 0.05 in 1990 to nearly 0.60 in 2021 (Figure S6).

Recent research acknowledges that global mitigation actions are equally as important as global adaptation actions. To further stimulate this shift in research focus nationally and internationally, future research topics should strive to design a global framework for implementation of adaptation and mitigation strategies by presenting more explicit, quantitative, and trackable targets/metrics, breaking down political barriers, and advancing climate solutions (Magnan & Ribera, 2016; Meckling & Karplus, 2023).

It is worth noting that the method used herein, analogous to other large-scale approaches, contains certain limitations. This approach does not capture gray/indigenous knowledge and can often provide insights on broad topics and general trends of climate science whereas higher resolution studies are required to address specific climatic questions (Khojasteh, Haghani, et al., 2023; Sietsma et al., 2021). Although emerging research disciplines were presented and discussed, communities of climate experts, such as those assembled by the IPCC and other initiatives, are better positioned to guide future priorities (Callaghan et al., 2020). Overall, the big data bibliometric analysis presented here can complement existing literature assessments by elaborating on the spatial and temporal evolution of climate science, highlighting interconnections and activities across topics and within the IPCC WGs, and describing domestic and international contributions and collaborations. This study, although not comprehensive, allows a fast and transparent consolidation and mapping of scholarly climate research. Further, our method can be repeated and improved, and used in future assessments of large-scale literature, such as within future IPCC reports.

6 | CONCLUSIONS

As research on climate science contains multidisciplinary subjects and continues to expand exponentially, the application of traditional procedures and review assessments to synthesize the large scientific literature becomes increasingly challenging. In this study, we presented a big data, bibliometric analysis of nearly 130,000 climate change articles published between 1990 and 2021. Following 30+ years of literature, four major research themes across different IPCC WGs were identified. Studies were shown to move from focusing on the past/present/future state of climate at a domestic scale toward more international research focused on realizing climate impacts and exploring adaptation-mitigation options. Emergent research topics included (but are not limited to) biodiversity, climate extremes, food security, vulnerability and adaptation, public health and perception, sea-level change, and high mountains. Future research also appears to support the establishment of a more clear, coupled, and global adaptation-mitigation framework. Overall, our analyses and results, on a macro-level basis, may help guide scholars and policymakers in identifying broad knowledge gaps, recognizing declining, understudied or emerging climate topics, reinforcing global collaborative research initiatives, and helping to provide big picture insights into future IPCC reports or other global assessments.

AUTHOR CONTRIBUTIONS

Danial Khojasteh: Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (lead); methodology (supporting); project administration (lead); software (equal); visualization (equal); writing – original draft (lead); writing – review and editing (equal). **Milad Haghani:** Conceptualization (equal); data curation (equal); formal analysis (equal); investigation (supporting); methodology (lead); resources (equal); software (lead); visualization (equal); writing – review and editing (equal). **Abbas Shamsipour:** Data curation (equal); formal analysis (equal); investigation (supporting); software (supporting); visualization (equal). **Clara C. Zwack:** Conceptualization (supporting); data curation (equal); formal analysis (supporting); investigation (supporting); writing – original draft (supporting). **William Glamore:** Funding acquisition (equal); resources (equal); supervision (equal); writing – review and editing (equal). **Robert J. Nicholls:** Investigation (supporting); writing – review and editing (equal). **Matthew England:** Conceptualization (supporting); formal analysis (supporting); investigation (equal); supervision (equal); visualization (supporting); writing – original draft (supporting); writing – review and editing (equal).

ACKNOWLEDGMENTS

The first author was a research associate at UNSW Sydney when this work was conceptualized and partly undertaken. The authors would like to acknowledge the constructive feedback received from the editors and the reviewers as well as from David Hanslow, Kym Bilham, and Tracey MacDonald that enhanced the quality of this article. Open access publishing facilitated by University of New South Wales, as part of the Wiley - University of New South Wales agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study is available in the manuscript and Supporting Information and also on reasonable request from the corresponding authors.

RELATED WIREs ARTICLES

A bibliometric analysis of climate engineering research
Overcoming early career barriers to interdisciplinary climate change research
Adaptive capacity to climate change: A synthesis of concepts, methods, and findings in a fragmented field
Transformations for climate change mitigation: A systematic review of terminology, concepts, and characteristics

ORCID

Danial Khojasteh https://orcid.org/0000-0002-6095-2885

REFERENCES

Arnell, N. W., & Gosling, S. N. (2016). The impacts of climate change on river flood risk at the global scale. *Climatic Change*, *134*(3), 387–401. https://doi.org/10.1007/s10584-014-1084-5

Arora, N. K. (2019). Impact of climate change on agriculture production and its sustainable solutions. *Environmental Sustainability*, *2*(2), 95–96.

Berrang-Ford, L., Siders, A. R., Lesnikowski, A., Fischer, A. P., Callaghan, M. W., Haddaway, N. R., Araos, M., Mach, K. J., Shah, M. A. R., Wannewitz, M., Doshi, D., Leiter, T., Matavel, C., Musah-Surugu, J. I., Wong-Parodi, G., Antwi-Agyei, P., Ajibade, I., Chauhan, N., Kakenmaster, W., … Abu, T. Z. (2021). A systematic global stocktake of evidence on human adaptation to climate change. *Nature Climate Change*, *11*(11), 989–1000. https://doi.org/10.1038/s41558-021-01170-y

Bornmann, L., Haunschild, R., & Mutz, R. (2021). Growth rates of modern science: A latent piecewise growth curve approach to model publication numbers from established and new literature databases. *Humanities and Social Sciences Communications*, *8*(1), 224. https://doi.org/10.1057/s41599-021-00903-w

Bruno, J. F., Bates, A. E., Cacciapaglia, C., Pike, E. P., Amstrup, S. C., van Hooidonk, R., Aronson, R. B., & Henson, S. A. (2018). Climate change threatens the world's marine protected areas. *Nature Climate Change*, *8*(6), 499–503. https://doi.org/10.1038/s41558-018-0149-2

Bustamante, M. M. C., Silva, J. S., Scariot, A., Sampaio, A. B., Mascia, D. L., Garcia, E., Fernandes, G. W., Sano, E., Durigan, G., Roitman, I., Figueiredo, I., Rodrigues, R. R., Pillar, V. D., de Oliveira, A. O., Malhado, A. C., Alencar, A., Vendramini, A., Padovezi, A., Carrascosa, H., … Nobre, C. (2019). Ecological restoration as a strategy for mitigating and adapting to climate change: Lessons and challenges from Brazil. *Mitigation and Adaptation Strategies for Global Change*, *24*(7), 1249–1270. https://doi.org/10.1007/s11027-018-9837-5

Callaghan, M. W., Minx, J. C., & Forster, P. M. (2020). A topography of climate change research. *Nature Climate Change*, *10*(2), 118–123. https://doi.org/10.1038/s41558-019-0684-5

Campbell, B. M., Vermeulen, S. J., Aggarwal, P. K., Corner-Dolloff, C., Girvetz, E., Loboguerrero, A. M., Rosenstock, T., Ramirez-Villegas, J., Sebastian, L., Thornton, P. K., & Wollenberg, E. (2016). Reducing risks to food security from climate change. *Global Food Security*, *11*, 34–43. https://doi.org/10.1016/j.gfs.2016.06.002

Carleton, T. A., & Hsiang, S. M. (2016). Social and economic impacts of climate. *Science*, *353*(6304), aad9837. https://doi.org/10.1126/science.aad9837

Chen, C. (2004). Searching for intellectual turning points: Progressive knowledge domain visualization. *Proceedings of the National Academy of Sciences*, *101*(suppl 1), 5303–5310.

Chen, C. (2006). CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *Journal of the American Society for Information Science and Technology*, *57*(3), 359–377.

Cheng, S. H., Augustin, C., Bethel, A., Gill, D., Anzaroot, S., Brun, J., Minnich, R. C., DeWilde, B., Garside, R., Masuda, Y. J., Miller, D. C., Wilkie, D., Wongbusarakum, S., & McKinnon, M. C. (2018). Using machine learning to advance synthesis and use of conservation and environmental evidence. *Conservation Biology*, *32*(4), 762–764. https://doi.org/10.1111/cobi.13117

Cheung, W. W. L., Frölicher, T. L., Lam, V. W. Y., Oyinlola, M. A., Reygondeau, G., Sumaila, U. R., Teh, L. C. L., Tai, T. C., & Wabnitz, C. C. C. (2021). Marine high temperature extremes amplify the impacts of climate change on fish and fisheries. *Science Advances*, *7*(40), eabh0895. https://doi.org/10.1126/sciadv.abh0895

Constenla-Villoslada, S., Liu, Y., Wen, J., Sun, Y., & Chonabayashi, S. (2022). Large-scale land restoration improved drought resilience in Ethiopia's degraded watersheds. *Nature Sustainability*, *5*, 488–497. https://doi.org/10.1038/s41893-022-00861-4

Davis, K. T., Dobrowski, S. Z., Higuera, P. E., Holden, Z. A., Veblen, T. T., Rother, M. T., Sala, A., Parks, S. A., & Maneta, M. P. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. *Proceedings of the National Academy of Sciences*, *116*(13), 6193–6198. https://doi.org/10.1073/pnas.1815107116

Di Matteo, G., Nardi, P., Grego, S., & Guidi, C. (2018). Bibliometric analysis of climate change vulnerability assessment research. *Environment Systems and Decisions*, *38*(4), 508–516. https://doi.org/10.1007/s10669-018-9687-4

Doherty, T. J., & Clayton, S. (2011). The psychological impacts of global climate change. *American Psychologist*, *66*(4), 265–276.

Dosio, A., Mentaschi, L., Fischer, E. M., & Wyser, K. (2018). Extreme heat waves under 1.5°C and 2°C global warming. *Environmental Research Letters*, *13*(5), 054006. https://doi.org/10.1088/1748-9326/aab827

Einecker, R., & Kirby, A. (2020). Climate change: A bibliometric study of adaptation, mitigation and resilience. *Sustainability*, *12*(17), 6935 https://www.mdpi.com/2071-1050/12/17/6935

Erbaugh, J. T., Pradhan, N., Adams, J., Oldekop, J. A., Agrawal, A., Brockington, D., Chhatre, A., & Pritchard, R. (2020). Global forest restoration and the importance of prioritizing local communities. *Nature Ecology & Evolution*, *4*(11), 1472–1476. https://doi.org/10.1038/s41559-020-01282-2

Fang, Y., Yin, J., & Wu, B. (2018). Climate change and tourism: A scientometric analysis using CiteSpace. *Journal of Sustainable Tourism*, *26*(1), 108–126. https://doi.org/10.1080/09669582.2017.1329310

Fu, H.-Z., & Waltman, L. (2022). A large-scale bibliometric analysis of global climate change research between 2001 and 2018. *Climatic Change*, *170*(3), 1–21.

Fuentes, M. M. P. B., Chambers, L., Chin, A., Dann, P., Dobbs, K., Marsh, H., Maison, K., Poloczanska, E. S., Turner, M., & Pressey, R. L. (2016). Adaptive management of marine mega-fauna in a changing climate. *Mitigation and Adaptation Strategies for Global Change*, *21*(2), 209–224. https://doi.org/10.1007/s11027-014-9590-3

Funari, E., Manganelli, M., & Sinisi, L. (2012). Impact of climate change on waterborne diseases. *Annali dell'Istituto Superiore di Sanità*, *48*, 473–487.

Ghonchepour, D., Sadoddin, A., Bahremand, A., Croke, B., Jakeman, A., & Salmanmahiny, A. (2021). A methodological framework for the hydrological model selection process in water resource management projects. *Natural Resource Modeling*, *34*(3), e12326. https://doi.org/10.1111/nrm.12326

Glamore, W., Rayner, D., Ruprecht, J., Sadat-Noori, M., & Khojasteh, D. (2021). Eco-hydrology as a driver for tidal restoration: Observations from a Ramsar wetland in eastern Australia. *PLoS One*, *16*(8), e0254701.

Gosling, S. N., & Arnell, N. W. (2016). A global assessment of the impact of climate change on water scarcity. *Climatic Change*, *134*(3), 371–385. https://doi.org/10.1007/s10584-013-0853-x

Grieneisen, M. L., & Zhang, M. (2011). The current status of climate change research. *Nature Climate Change*, *1*(2), 72–73. https://doi.org/10.1038/nclimate1093

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Ludwig, F., Konzmann, M., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z. D., Wada, Y., & Wisser, D. (2014). Global water resources affected by human interventions and climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3251–3256. https://doi.org/10.1073/pnas.1222475110

Hagemann, S., Chen, C., Clark, D. B., Folwell, S., Gosling, S. N., Haddeland, I., Heinke, J., Hanasaki, N., Ludwig, F., Voss, F., & Wiltshire, A. J. (2013). Climate change impact on available water resources obtained using multiple global climate and hydrology models. *Earth System Dynamics*, *4*(1), 129–144. https://doi.org/10.5194/esd-4-129-2013

Haghani, M., Bliemer, M. C. J., & Hensher, D. A. (2021). The landscape of econometric discrete choice modelling research. *Journal of Choice Modelling*, *40*, 100303. https://doi.org/10.1016/j.jocm.2021.100303

Haghani, M., Kuligowski, E., Rajabifard, A., & Lentini, P. (2022). Fifty years of scholarly research on terrorism: Intellectual progression, structural composition, trends and knowledge gaps of the field. *International Journal of Disaster Risk Reduction*, *68*, 102714. https://doi.org/10.1016/j.ijdrr.2021.102714

Hanjra, M. A., & Qureshi, M. E. (2010). Global water crisis and future food security in an era of climate change. *Food Policy*, *35*(5), 365–377. https://doi.org/10.1016/j.foodpol.2010.05.006

Harris, J. A., Hobbs, R. J., Higgs, E., & Aronson, J. (2006). Ecological restoration and global climate change. *Restoration Ecology*, *14*(2), 170–176. https://doi.org/10.1111/j.1526-100X.2006.00136.x

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., McLeman, R., & Wrathall, D. (2020). Sea-level rise and human migration. *Nature Reviews Earth & Environment*, *1*(1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

Haunschild, R., Bornmann, L., & Marx, W. (2016). Climate change research in view of bibliometrics. *PLoS One*, *11*(7), e0160393.

Hertel, T. W. (2016). Food security under climate change. *Nature Climate Change*, *6*(1), 10–13. https://doi.org/10.1038/nclimate2834

Hintz, M. J., Luederitz, C., Lang, D. J., & von Wehrden, H. (2018). Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. *Urban Climate*, *24*, 714–727. https://doi.org/10.1016/j.uclim.2017.08.011

Huq, S., & Ayers, J. (2007). *Critical list: The 100 nations most vulnerable to climate change* (IIED sustainable development opinion, Issue).

Immerzeel, W. W., Beek, L. P. H. v., & Bierkens, M. F. P. (2010). Climate change will affect the Asian water towers. *Science*, *328*(5984), 1382–1385. https://doi.org/10.1126/science.1183188

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., … Baillie, J. E. M. (2020). Importance and vulnerability of the world's water towers. *Nature*, *577*(7790), 364–369. https://doi.org/10.1038/s41586-019-1822-y

Islam, N., & Winkel, J. (2017). Climate change and social inequality. United Nations, Department of Economic and Social Affairs.

Kessler, M. M. (1963). Bibliographic coupling between scientific papers. *American Documentation*, *14*(1), 10–25.

Khojasteh, D., Davani, E., Shamsipour, A., Haghani, M., & Glamore, W. (2022). Climate change and COVID-19: Interdisciplinary perspectives from two global crises. *Science of the Total Environment*, *844*, 157142. https://doi.org/10.1016/j.scitotenv.2022.157142

Khojasteh, D., Glamore, W., Heimhuber, V., & Felder, S. (2021). Sea level rise impacts on estuarine dynamics: A review. *Science of the Total Environment*, *780*, 146470.

Khojasteh, D., Haghani, M., Nicholls, R. J., Moftakhari, H., Sadat-Noori, M., Mach, K. J., Fagherazzi, S., Vafeidis, A. T., Barbier, E., Shamsipour, A., & Glamore, W. (2023). The evolving landscape of sea-level rise science from 1990 to 2021. *Communications Earth & Environment*, *4*(1), 257. https://doi.org/10.1038/s43247-023-00920-4

Khojasteh, D., Shamsipour, A., Huang, L., Tavakoli, S., Haghani, M., Flocard, F., Farzadkhoo, M., Iglesias, G., Hemer, M., Lewis, M., Neill, S., Bernitsas, M. M., & Glamore, W. (2023). A large-scale review of wave and tidal energy research over the last 20 years. *Ocean Engineering*, *282*, 114995. https://doi.org/10.1016/j.oceaneng.2023.114995

Knutti, R., & Sedláček, J. (2013). Robustness and uncertainties in the new CMIP5 climate model projections. *Nature Climate Change*, *3*(4), 369–373.

Koch, A., & Kaplan, J. O. (2022). Tropical forest restoration under future climate change. *Nature Climate Change*, *12*(3), 279–283. https://doi.org/10.1038/s41558-022-01289-6

Kulp, S. A., & Strauss, B. H. (2019). New elevation data triple estimates of global vulnerability to sea-level rise and coastal flooding. *Nature Communications*, *10*(1), 4844. https://doi.org/10.1038/s41467-019-12808-z

Kunreuther, H., Gupta, S., Bosetti, V., Cooke, R., Dutt, V., Ha-Duong, M., Held, H., Llanes-Regueiro, J., Patt, A., & Shittu, E. (2014). Integrated risk and uncertainty assessment of climate change response policies. In Climate change 2014: Mitigation of climate change: Working group III contribution to the fifth assessment report of the intergovernmental panel on climate change (pp. 151–206). Cambridge University Press.

Laufkötter, C., Zscheischler, J., & Frölicher, T. L. (2020). High-impact marine heatwaves attributable to human-induced global warming. *Science*, *369*(6511), 1621–1625. https://doi.org/10.1126/science.aba0690

Lawrence, J., Blackett, P., & Cradock-Henry, N. A. (2020). Cascading climate change impacts and implications. *Climate Risk Management*, *29*, 100234. https://doi.org/10.1016/j.crm.2020.100234

Lesnikowski, A. C., Ford, J. D., Berrang-Ford, L., Barrera, M., & Heymann, J. (2015). How are we adapting to climate change? A global assessment. *Mitigation and Adaptation Strategies for Global Change*, *20*(2), 277–293. https://doi.org/10.1007/s11027-013-9491-x

Levy, B. S., & Patz, J. A. (2015). Climate change, human rights, and social justice. *Annals of Global Health*, *81*(3), 310–322. https://doi.org/10.1016/j.aogh.2015.08.008

Locatelli, B. (2016). Ecosystem services and climate change. In *Handbook of ecosystem services*. Routledge.

Ma, Y., Dong, M., Zhou, K., Mita, C., Liu, J., & Wayne, P. M. (2016). Publication trends in acupuncture research: A 20-year bibliometric analysis based on PubMed. *PLoS One*, *11*(12), e0168123. https://doi.org/10.1371/journal.pone.0168123

Magnan, A. K., & Ribera, T. (2016). Global adaptation after Paris. *Science*, *352*(6291), 1280–1282.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M. G., Field, C. B., & Knowlton, N. (2020). Climate change and ecosystems: Threats, opportunities and solutions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *375*, 20190104.

Masson-Delmotte, V., Zhai, P., Priani, A., Connors, S. L., Pean, C., Berger, S., Huang, M., Yelekçi, O., Yu, R., Zhou, B., Lonnoy, E., Maycock, T. K., Waterfield, T., Leitzell, K., Caud, N., & Zhou, B. (2021). IPCC, 2021: Summary for policymakers. In: Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change.

McKechnie, A. E., & Wolf, B. O. (2010). Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biology Letters*, *6*(2), 253–256. https://doi.org/10.1098/rsbl.2009.0702

Meckling, J., & Karplus, V. J. (2023). Political strategies for climate and environmental solutions. *Nature Sustainability*, *6*(7), 742–751. https://doi.org/10.1038/s41893-023-01109-5

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G. M., Palmer, M., Scholes, R., & Yahara, T. (2009). Biodiversity, climate change, and ecosystem services. *Current Opinion in Environmental Sustainability*, *1*(1), 46–54. https://doi.org/10.1016/j.cosust.2009.07.006

Mora, C., Spirandelli, D., Franklin, E. C., Lynham, J., Kantar, M. B., Miles, W., Smith, C. Z., Freel, K., Moy, J., Louis, L. V., Barba, E. W., Bettinger, K., Frazier, A. G., Colburn IX, J. F., Hanasaki, N., Hawkins, E., Hirabayashi, Y., Knorr, W., Little, C. M., … Hunter, C. L. (2018). Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nature Climate Change*, *8*(12), 1062–1071. https://doi.org/10.1038/s41558-018-0315-6

Mori, A. S., Dee, L. E., Gonzalez, A., Ohashi, H., Cowles, J., Wright, A. J., Loreau, M., Hautier, Y., Newbold, T., Reich, P. B., Matsui, T., Takeuchi, W., Okada, K. I., Seidl, R., & Isbell, F. (2021). Biodiversity–productivity relationships are key to nature-based climate solutions. *Nature Climate Change*, *11*(6), 543–550. https://doi.org/10.1038/s41558-021-01062-1

Munang, R., Thiaw, I., Alverson, K., Liu, J., & Han, Z. (2013). The role of ecosystem services in climate change adaptation and disaster risk reduction. *Current Opinion in Environmental Sustainability*, *5*(1), 47–52. https://doi.org/10.1016/j.cosust.2013.02.002

Nalau, J., & Verrall, B. (2021). Mapping the evolution and current trends in climate change adaptation science. *Climate Risk Management*, *32*, 100290. https://doi.org/10.1016/j.crm.2021.100290

Nedkov, S., & Burkhard, B. (2012). Flood regulating ecosystem services—Mapping supply and demand, in the Etropole municipality, Bulgaria. *Ecological Indicators*, *21*, 67–79. https://doi.org/10.1016/j.ecolind.2011.06.022

Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: Contributions of a resilience framework. *Annual Review of Environment and Resources*, *32*, 395–419.

Olsson, L., Opondo, M., Tschakert, P., Agrawal, A., Eriksen, S. E., Ma, S., Perc, L. N., & Zakieldeen, S. (2014). Livelihoods and poverty. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

Ortiz-Bobea, A., Ault, T. R., Carrillo, C. M., Chambers, R. G., & Lobell, D. B. (2021). Anthropogenic climate change has slowed global agricultural productivity growth. *Nature Climate Change*, *11*(4), 306–312. https://doi.org/10.1038/s41558-021-01000-1

Palinkas, L. A., & Wong, M. (2020). Global climate change and mental health. *Current Opinion in Psychology*, *32*, 12–16. https://doi.org/10.1016/j.copsyc.2019.06.023

Pecl, G. T., Araújo, M. B., Bell, J. D., Blanchard, J., Bonebrake, T. C., Chen, I.-C., Clark, T. D., Colwell, R. K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R. A., Griffis, R. B., Hobday, A. J., Janion-Scheepers, C., Jarzyna, M. A., Jennings, S., … Williams, S. E. (2017). Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science*, *355*(6332), eaai9214. https://doi.org/10.1126/science.aai9214

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., Begum, R. A., Betts, R., Kerr, R. B., & Biesbroek, R. (2022). Climate change 2022: Impacts, adaptation, and vulnerability. In *Contribution of working group II to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Sadat-Noori, M., Rankin, C., Rayner, D., Heimhuber, V., Gaston, T., Drummond, C., Chalmers, A., Khojasteh, D., & Glamore, W. (2021). Coastal wetlands can be saved from sea level rise by recreating past tidal regimes. *Scientific Reports*, *11*(1), 1196.

Schewe, J., Heinke, J., Gerten, D., Haddeland, I., Arnell, N. W., Clark, D. B., Dankers, R., Eisner, S., Fekete, B. M., Colón-González, F. J., Gosling, S. N., Kim, H., Liu, X., Masaki, Y., Portmann, F. T., Satoh, Y., Stacke, T., Tang, Q., Wada, Y., … Kabat, P. (2014). Multimodel assessment of water scarcity under climate change. *Proceedings of the National Academy of Sciences*, *111*(9), 3245–3250. https://doi.org/10.1073/pnas.1222460110

Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., McOwen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., Hinkel, J., Nicholls, R. J., & Brown, S. (2018). Future response of global coastal wetlands to sea-level rise. *Nature*, *561*(7722), 231–234. https://doi.org/10.1038/s41586-018-0476-5

Serrano, O., Lovelock, C. E., B. Atwood, T., Macreadie, P. I., Canto, R., Phinn, S., Arias-Ortiz, A., Bai, L., Baldock, J., Bedulli, C., Carnell, P., Connolly, R. M., Donaldson, P., Esteban, A., Ewers Lewis, C. J., Eyre, B. D., Hayes, M. A., Horwitz, P., Hutley, L. B., … Duarte, C. M. (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. *Nature Communications*, *10*(1), 4313. https://doi.org/10.1038/s41467-019-12176-8

Shi, J., Visschers, V. H. M., & Siegrist, M. (2015). Public perception of climate change: The importance of knowledge and cultural worldviews. *Risk Analysis*, *35*(12), 2183–2201. https://doi.org/10.1111/risa.12406

Sietsma, A. J., Ford, J. D., Callaghan, M. W., & Minx, J. C. (2021). Progress in climate change adaptation research. *Environmental Research Letters*, *16*(5), 054038.

Silva, R. A., West, J. J., Lamarque, J.-F., Shindell, D. T., Collins, W. J., Faluvegi, G., Folberth, G. A., Horowitz, L. W., Nagashima, T., Naik, V., Rumbold, S. T., Sudo, K., Takemura, T., Bergmann, D., Cameron-Smith, P., Doherty, R. M., Josse, B., MacKenzie, I. A., Stevenson, D. S., & Zeng, G. (2017). Future global mortality from changes in air pollution attributable to climate change. *Nature Climate Change*, *7*(9), 647–651. https://doi.org/10.1038/nclimate3354

Simpson, N. P., Williams, P. A., Mach, K. J., Berrang-Ford, L., Biesbroek, R., Haasnoot, M., Segnon, A. C., Campbell, D., Musah-Surugu, J. I., Joe, E. T., Nunbogu, A. M., Sabour, S., Meyer, A. L. S., Andrews, T. M., Singh, C., Siders, A. R., Lawrence, J., van Aalst, M., Trisos, C. H., & Global Adaptation Mapping Initiative Team. (2023). Adaptation to compound climate risks: A systematic global stocktake. *Iscience*, *26*(2), 105926.

Sippo, J. Z., Lovelock, C. E., Santos, I. R., Sanders, C. J., & Maher, D. T. (2018). Mangrove mortality in a changing climate: An overview. *Estuarine, Coastal and Shelf Science*, *215*, 241–249. https://doi.org/10.1016/j.ecss.2018.10.011

Smith, K. E., Burrows, M. T., Hobday, A. J., Sen Gupta, A., Moore, P. J., Thomsen, M., Wernberg, T., & Smale, D. A. (2021). Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, *374*(6566), eabj3593. https://doi.org/10.1126/science.abj3593

Spencer, T., Schuerch, M., Nicholls, R. J., Hinkel, J., Lincke, D., Vafeidis, A. T., Reef, R., McFadden, L., & Brown, S. (2016). Global coastal wetland change under sea-level rise and related stresses: The DIVA wetland change model. *Global and Planetary Change*, *139*, 15–30. https://doi.org/10.1016/j.gloplacha.2015.12.018

Stanhill, G. (2001). The growth of climate change science: A scientometric study. *Climatic Change*, *48*(2), 515–524.

Su, J., Friess, D. A., & Gasparatos, A. (2021). A meta-analysis of the ecological and economic outcomes of mangrove restoration. *Nature Communications*, *12*(1), 5050. https://doi.org/10.1038/s41467-021-25349-1

Sweileh, W. M. (2020). Bibliometric analysis of peer-reviewed literature on food security in the context of climate change from 1980 to 2019. *Agriculture & Food Security*, *9*(1), 11. https://doi.org/10.1186/s40066-020-00266-6

Tai, T. C., & Robinson, J. P. W. (2018). Enhancing climate change research with Open Science. *Frontiers in Environmental Science*, *6*. https://doi.org/10.3389/fenvs.2018.00115

Tavakoli, S., Khojasteh, D., Haghani, M., & Hirdaris, S. (2023). A review on the progress and research directions of ocean engineering. *Ocean Engineering*, *272*, 113617. https://doi.org/10.1016/j.oceaneng.2023.113617

Turek-Hankins, L. L., Coughlan de Perez, E., Scarpa, G., Ruiz-Diaz, R., Schwerdtle, P. N., Joe, E. T., Galappaththi, E. K., French, E. M., Austin, S. E., Singh, C., Siña, M., Siders, A. R., van Aalst, M. K., Templeman, S., Nunbogu, A. M., Berrang-Ford, L., Agrawal, T., The Global Adaptation Mapping Initiative Team, & Mach, K. J. (2021). Climate change adaptation to extreme heat: A global systematic review of implemented action. *Oxford Open Climate Change*, *1*(1), kgab005. https://doi.org/10.1093/oxfclm/kgab005

Van Eck, N., & Waltman, L. (2007). VOS: A new method for visualizing similarities between objects. In *Advances in data analysis* (pp. 299–306). Springer.

Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538.

van Ruijven, B. J., De Cian, E., & Sue Wing, I. (2019). Amplification of future energy demand growth due to climate change. *Nature Communications*, *10*(1), 2762. https://doi.org/10.1038/s41467-019-10399-3

Walsh, K. J., McBride, J. L., Klotzbach, P. J., Balachandran, S., Camargo, S. J., Holland, G., Knutson, T. R., Kossin, J. P., Lee, T.-c., Sobel, A., & Sobel, A. (2016). Tropical cyclones and climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(1), 65–89.

Wang, B., Pan, S.-Y., Ke, R.-Y., Wang, K., & Wei, Y.-M. (2014). An overview of climate change vulnerability: A bibliometric analysis based on web of science database. *Natural Hazards*, *74*(3), 1649–1666. https://doi.org/10.1007/s11069-014-1260-y

Wang, B., Zheng, L., Liu, D. L., Ji, F., Clark, A., & Yu, Q. (2018). Using multi-model ensembles of CMIP5 global climate models to reproduce observed monthly rainfall and temperature with machine learning methods in Australia. *International Journal of Climatology*, *38*(13), 4891–4902.

Wang, Z., Zhao, Y., & Wang, B. (2018). A bibliometric analysis of climate change adaptation based on massive research literature data. *Journal of Cleaner Production*, *199*, 1072–1082.

Weinberg, B. H. (1974). Bibliographic coupling: A review. *Information Storage and Retrieval*, *10*(5–6), 189–196.

Weiskopf, S. R., Rubenstein, M. A., Crozier, L. G., Gaichas, S., Griffis, R., Halofsky, J. E., Hyde, K. J. W., Morelli, T. L., Morisette, J. T., Muñoz, R. C., Pershing, A. J., Peterson, D. L., Poudel, R., Staudinger, M. D., Sutton-Grier, A. E., Thompson, L., Vose, J., Weltzin, J. F., & Whyte, K. P. (2020). Climate change effects on biodiversity, ecosystems, ecosystem services, and natural resource management in the United States. *Science of the Total Environment*, *733*, 137782. https://doi.org/10.1016/j.scitotenv.2020.137782

Wheeler, T., & Braun, J. V. (2013). Climate change impacts on global food security. *Science*, *341*(6145), 508–513. https://doi.org/10.1126/science.1239402

Woolf, D., Solomon, D., & Lehmann, J. (2018). Land restoration in food security programmes: Synergies with climate change mitigation. *Climate Policy*, *18*(10), 1260–1270. https://doi.org/10.1080/14693062.2018.1427537

Xi, Y., Peng, S., Ciais, P., & Chen, Y. (2021). Future impacts of climate change on inland Ramsar wetlands. *Nature Climate Change*, *11*(1), 45–51. https://doi.org/10.1038/s41558-020-00942-2

Zhao, Q., Guo, Y., Ye, T., Gasparrini, A., Tong, S., Overcenco, A., Urban, A., Schneider, A., Entezari, A., Vicedo-Cabrera, A. M., Zanobetti, A., Analitis, A., Zeka, A., Tobias, A., Nunes, B., Alahmad, B., Armstrong, B., Forsberg, B., Pan, S. C., … Li, S. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: A three-stage modelling study. *The Lancet Planetary Health*, *5*(7), e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Khojasteh, D., Haghani, M., Shamsipour, A., Zwack, C. C., Glamore, W., Nicholls, R. J., & England, M. H. (2024). Climate change science is evolving toward adaptation and mitigation solutions. *WIREs Climate Change*, *15*(4), e884. https://doi.org/10.1002/wcc.884