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# The evolving landscape of sea-level rise science from 1990 to 2021

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As sea-level rise (SLR) accelerates due to climate change, its multidisciplinary field of science has similarly expanded, from 41 articles published in 1990 to 1475 articles published in 2021, and nearly 15,000 articles published in the Web of Science over this 32-year period. Here, big-data bibliometric techniques are adopted to systematically analyse this large literature set. Four main research clusters (themes) emerge: (I) geological dimensions and sea-level indicators, (II) impacts, risks, and adaptation, (III) physical components of sea-level change, and (IV) coastal ecosystems and habitats, with 16 associated sub-themes. This analysis provides insights into the evolution of research agendas, the challenges and opportunities for future assessments (e.g. next IPCC reports), and growing focus on adaptation. For example, the relative importance of sub-themes evolves consistently with a relative decline in pure science analysis towards solution-focused topics associated with SLR risks such as high-end rises, declining ecosystem services, flood hazards, and coastal erosion/squeeze.

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As a consequence of rising temperatures leading to thermal expansion of oceans, loss of ice sheets and glaciers, and variations in land water storage[1], global mean sea-level (GMSL) has risen by 20 cm from 1901 to 2018[2]. GMSL is projected to increase faster in the future[3], possibly exceeding a 2 m rise in 2100[4]. A growing body of literature indicates that sea-level rise (SLR) threatens low-lying coastal and estuarine zones worldwide[5], which may have nearly 1 billion inhabitants by 2030[6], through a range of hazards and impacts including more frequent and/or intense coastal flooding[7–10], degradation/loss of habitats/ecosystems[11,12] including islands[13,14] and coral reefs[15], coastal erosion and shoreline changes[16,17], and salinisation of surface water and groundwater[18–20]. These hazards and impacts, in turn, can damage economic assets, urban and coastal infrastructure, and coastal tourism[21–25], influence and induce human migration[26,27], impact the livelihoods and safety of vulnerable coastal populations[28,29], threaten heritage sites[30,31], and even jeopardise renewable energy plans[32,33].

To adapt to these growing risks, governments, industries, and communities are increasingly working collaboratively through integrated, multidimensional management schemes that cross the boundaries of natural sciences, social sciences, and engineering[34]. Research on SLR science has increased exponentially, as reflected by the number of publications reviewed and cited in the periodic Intergovernmental Panel on Climate Change (IPCC) reviews. For example, the first IPCC report published in 1990[35] reviewed fewer than 50 SLR documents, whereas the 2019 IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)[5] cited and reviewed nearly 950 SLR documents. Given the fast-growing and evolving literature of SLR science, it has become difficult to synthesise its vast scope using conventional and manual methods. In this context, the application of big-data and bibliometric analysis techniques seems essential as they can rapidly classify thousands of articles, complement human observation and judgement, and reliably track and present the evolution of a field of research under examination[36,37].

These approaches have been recently employed to synthesise important research areas such as the science of sciences (i.e. physical, technical, life, and health sciences)[38], climate change[39–41], coastal flooding[42], seawater intrusion[43], and adaptation and vulnerability plans[37,44–46]. However, a comprehensive analysis of the totality of SLR science in academic scholarship is absent. Such an analysis will promote a deeper understanding of the spatial and temporal trends in SLR research, its broad and specific research streams, the extent of research activities employed by different disciplines, and research and management requirements. The results can help identify the evolution of scientific themes over time and the recognition of understudied SLR impacts and issues. This information could inform both research and policy, such as designing effective risk management efforts in coastal areas, developing long-term adaptation and mitigation opportunities, protecting and restoring valuable ecosystems, implementing collective environmental strategies, ranking global fund-based climate change initiatives, and identifying knowledge and administration requirements for the way forward.

The aim of this study is to attempt such an analysis of SLR science. The evolving landscape of SLR literature is assessed through a term-based search strategy and a bibliometric approach that scrutinises titles, abstracts, keywords, and references of nearly 15,000 SLR-related articles in the Web of Science, published between 1990 and 2021 (Methods). All these articles included "sea-level rise" or "sea level rise" in either their titles, abstracts, or keywords (Methods).

This broad perspective provides illuminating insights into (i) the development of SLR science since 1990, (ii) the relative contribution of scholars by country, (iii) the major research clusters (themes) and sub-themes, (iv) the relationship between these research themes and their geographic and temporal evolution, (v) the multidisciplinary and influential references most widely used by SLR researchers, (vi) research, funding, policy, and equity agendas required for the way forward, and (vii) plausible projections of the number of SLR-related articles likely to be available for the next IPCC assessment (expected 2026–2030). The comprehensive and large-scale overview approach developed herein can serve as a framework for scholars and policymakers to utilise similar techniques when evaluating other integrative, multidisciplinary, and expanding research fields.

## Results

**Distribution of sea-level rise articles**. During 1990–2021, $N = 14,951$ unique SLR articles were identified in the Web of Science (Methods). The contributing nations were determined based on all authors' affiliations (Methods, Supplementary Table S1, and Supplementary Fig. S1). Overall, 169 nations contributing to at least one; 63 nations contributing to at least 20; and 36 nations contributing to at least 100 SLR articles (Supplementary Table S1), respectively. Production of all articles was distributed as follows: Europe 42.2%, North and Central America 29.6%, Asia 15.7%, Oceania 7.8%, Africa 2.4%, and South America 2.3% (Methods and Supplementary Fig. S1). Developed nations are dominant with 9 out of the 10 top nations being developed: USA ($N = 5909$), England ($N = 1875$), Australia ($N = 1388$), Germany ($N = 1334$), China ($N = 1160$), Netherlands ($N = 1035$), France ($N = 1030$), Canada ($N = 806$), Italy ($N = 748$), and Spain ($N = 558$) (Fig. 1a and Supplementary Table S1).

A keyword analysis was performed for six continents (based on all authors' affiliation data) to highlight the developmental trends and shifts in SLR research by timeframes and regions (Fig. 1b and Methods). During 1990–2021, the top 10 most frequently used keywords included "sea-level rise", "climate change", "sea-level", "Holocene", "adaptation", storm surge", "saltmarsh", "sea-level change", "coastal erosion", and "sequence stratigraphy". During 2010–2021, "sea-level rise" and "climate change" remained the top two keywords. However, the research focus shifted from geology-ecology-oriented and pure science research topics (e.g. "sequence stratigraphy", "subsidence") and localised studies (e.g. "Nile delta", "New Zealand") during 1990–2009, to more multidisciplinary and diverse subjects such as environmental sciences, oceanography, water resources (management), bio-geomorphology, economics, political science, and cross-border studies. The research topics also broadened to include the major SLR hazards and their risks (e.g. "coastal erosion", "coastal flooding"), the ability to understand, prepare for, and respond to induced threats (e.g. "adaptation", "vulnerability", "resilience", "coastal management"), importance and susceptibility of coastal estuaries and wetlands (e.g. "mangroves", "ecosystem services"), relevant processes (e.g. "storm surge"), and the application of new approaches in assessing the impacts of climate change (e.g. "remote sensing") (Fig. 1b). From these patterns, it can be concluded that SLR science has evolved from problem recognition to solution identification over the last 30 years.

**Major research clusters (themes) of sea-level rise science**. Based on the frequency of occurrence of terms in the titles and abstracts of the SLR articles analysed, four major themes were evident: (I) geological dimensions and sea-level indicators, (II) impacts, risks, and adaptation, (III) physical components of sea-level change, and (IV) coastal ecosystems and habitats (Fig. 2a). Terms that mutually appear in multiple articles are visualised adjacently and create a theme (cluster) of research at an aggregate level. Nodes represent terms, with their size being proportional to the number of occurrences within each research theme. The top 5

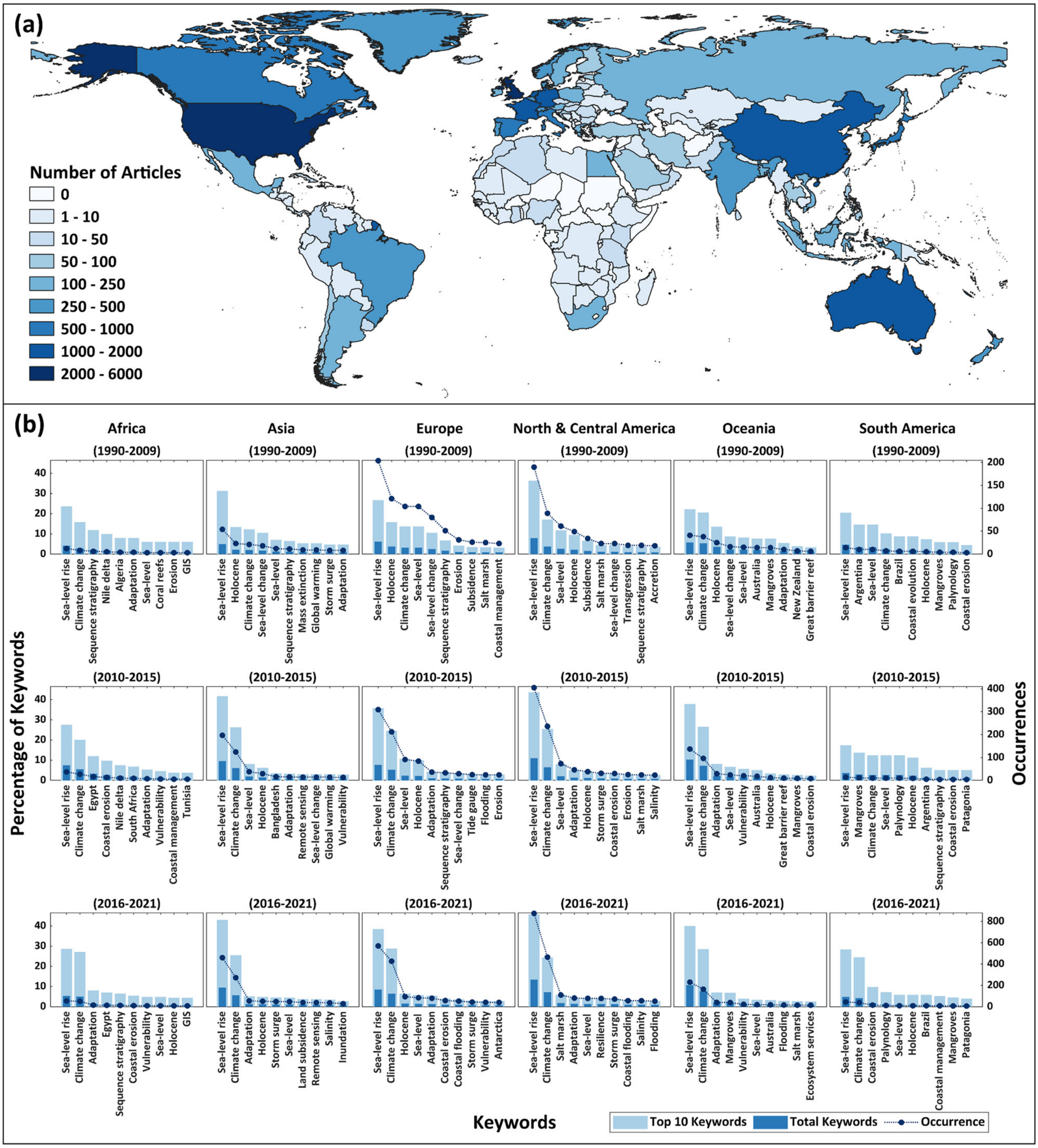


**Fig. 1 Global distribution of SLR articles and keywords. a** Geographical distribution of SLR articles included in the analysis based on the region where research was conducted (i.e. articles are assigned to countries as per all authors' affiliation data in any given article). In (**a**), articles from all contributing regions were considered and therefore, some articles may have been counted multiple times. **b** An analysis on the top 10 keywords during 1990–2009, 2010–2015, and 2016–2021 periods performed for different continents (i.e. Africa, Asia, Europe, North and Central America, Oceania, and South America), indicating temporal and geographic shifts in SLR research focus across different time spans and global regions. In (**b**), left *y*-axis represents the share (percentage) of a keyword amongst all (dark blue) or the top 10 (light blue) keywords used, and right *y*-axis indicates the number of occurrences for each keyword.

most frequently used terms, namely "sediment", "record", "basin", "formation", and "deposition" characterise Cluster (I); "climate change", "risk", "assessment", "SLR", and "vulnerability" characterise Cluster (II); "contribution", "level change", "warming", "uncertainty", and "projection" characterise Cluster (III); and "marsh", "saltmarsh", "plant", "soil", and "coastal wetland" characterise Cluster (IV).

In general, articles in Cluster (I) focus on the mechanisms of sea-level fluctuation[47,48] and the application of sea-level records preserved in geological or sedimentary data to identify how much and how fast GMSL may change over time and space[49,50]. Cluster (II) articles consider the risks that low-lying areas and coastal ecosystems face due to SLR-related hazards (e.g. flooding, salinisation, coastal squeeze) and exposure/vulnerability

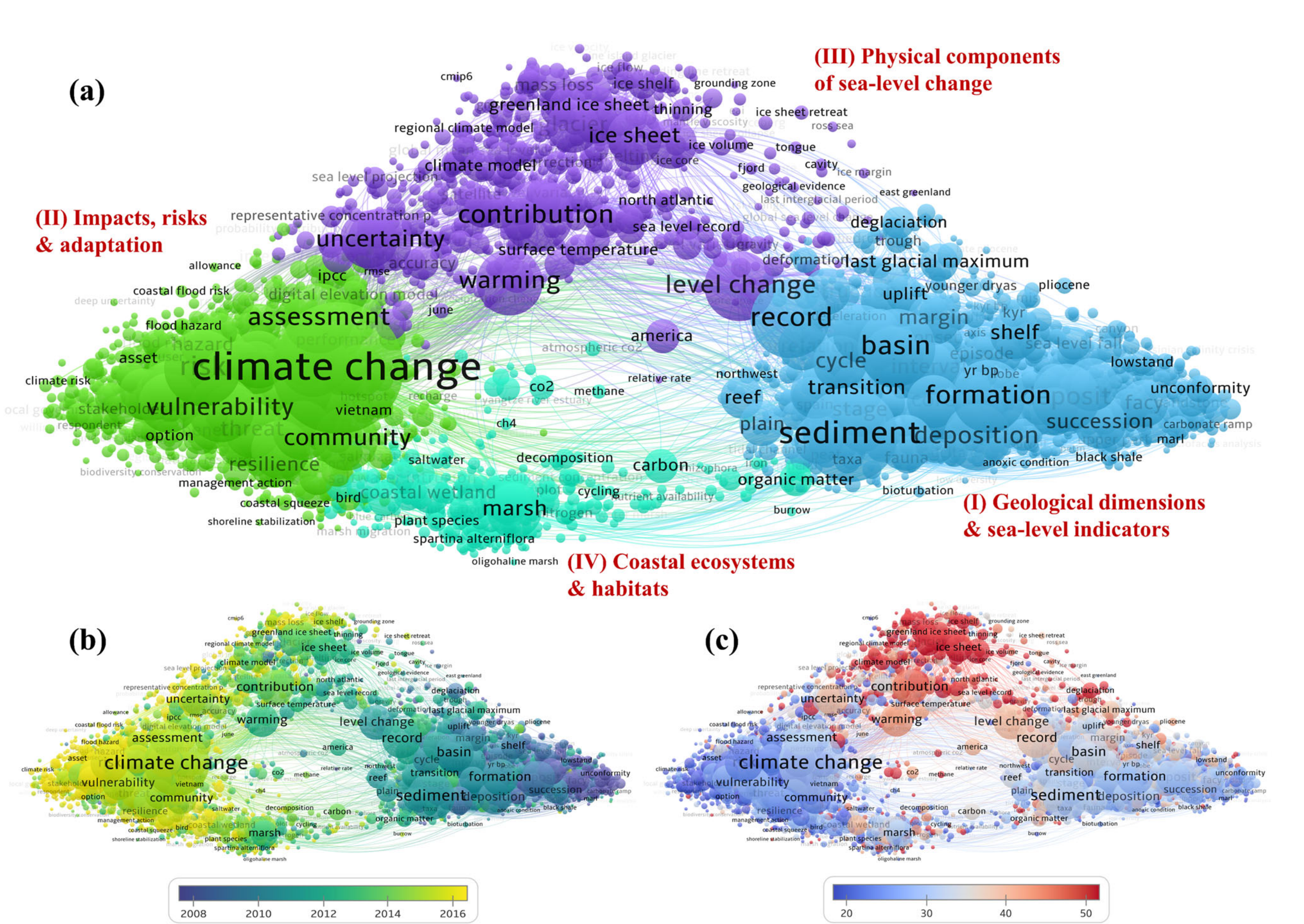


**Fig. 2 Major themes of SLR science. a** Clusters of frequently co-occurred terms illustrating major themes of SLR science including (I) geological dimensions and sea-level indicators, (II) impacts, risks, and adaptation, (III) physical components of sea-level change, and (IV) coastal ecosystems and habitats. **b**, **c** Indicate the colour coded maps of average publication year and the average number of citations for different terms used in titles and abstracts of SLR articles, respectively. An interactive map is accessible for (**a**–**c**) at https://app.vosviewer.com/?json=https://drive.google.com/uc?id=1JACE3aVunhFJpayVygnCoUN7Ty-dmylx.

(linked to socio-economic factors)[5], assessment methods[51], and adaptive responses to manage these risks for people, assets, biodiversity, and ecosystem services[52,53]. These articles also present collective environmental risk management schemes via public engagement, effective national and international governance activities, and technological advancements[2].

Cluster (III) articles consider the physical basis for sea-level change including gain or loss of ice sheets and glaciers[54,55], thermal expansion and variations in global water storage[1], significance of atmosphere-ocean models and data requirements (e.g. from tidal gauges and altimetry satellites)[56], and studies about sea-level trajectories[57,58]. Cluster (IV) articles reflect on the value of coastal ecosystems (e.g. saltmarshes, mangroves, seagrasses), their exposure to SLR[59–61], ability to respond to SLR (e.g. via sediment accretion and organic matter accumulation)[62,63], and wide-ranging services such as bio-sequestration of blue carbon[64,65], as well as efforts, initiatives, and options for preserving and/or restoring these ecosystems worldwide[66,67]. It is worth noting that Clusters (I) and (II) are positioned furthermost from each other, indicating significant thematic differences between their studies (Fig. 2a). This reflects a distinct geologic and humancentric perspective in these two themes, respectively, as they are often drawing on fundamentally distinct literature.

A map of the average publication year (i.e. the average publication year of the articles within the dataset that have mentioned that term in their titles or abstracts) indicates that earlier research focused on Cluster (I), whereas recent research focused on Clusters (III) and (IV), and predominantly on Cluster (II) (Fig. 2b). This is consistent with the identified trend of moving from problem identification to solutions. It suggests a shift in the direction of SLR science from understanding the factors that govern sea-level change in the long-term (e.g. variations in the shape of ocean basins and land-sea distribution) towards reliable SLR projections (in the short-term), far-reaching impacts, conservation and restoration of ecosystems, prevention of saltwater intrusion, raising public awareness, and implementing climate mitigation. Overall, the articles within Clusters (III) and (IV) received the largest average number of citations (i.e. citation counts recorded by the Web of Science divided by articles that mentioned those terms) (Fig. 2c), highlighting their broad research significance.

**Research sub-themes of sea-level rise science**. Overall, 16 sub-themes for SLR science were identified in the same literature using document co-citation analysis (Fig. 3a and Methods). This analysis is based on the observation that articles (also called *citing articles*) of a research field often cite references (from inside and outside of that domain—and hereafter called *cited references*) that are thematically similar and thereby represent a distinct research sub-theme[68] (Methods). Sub-themes are then ranked based on the number of cited and influential references within them and are labelled based on the contents of citing articles associated with the sub-themes (Methods).

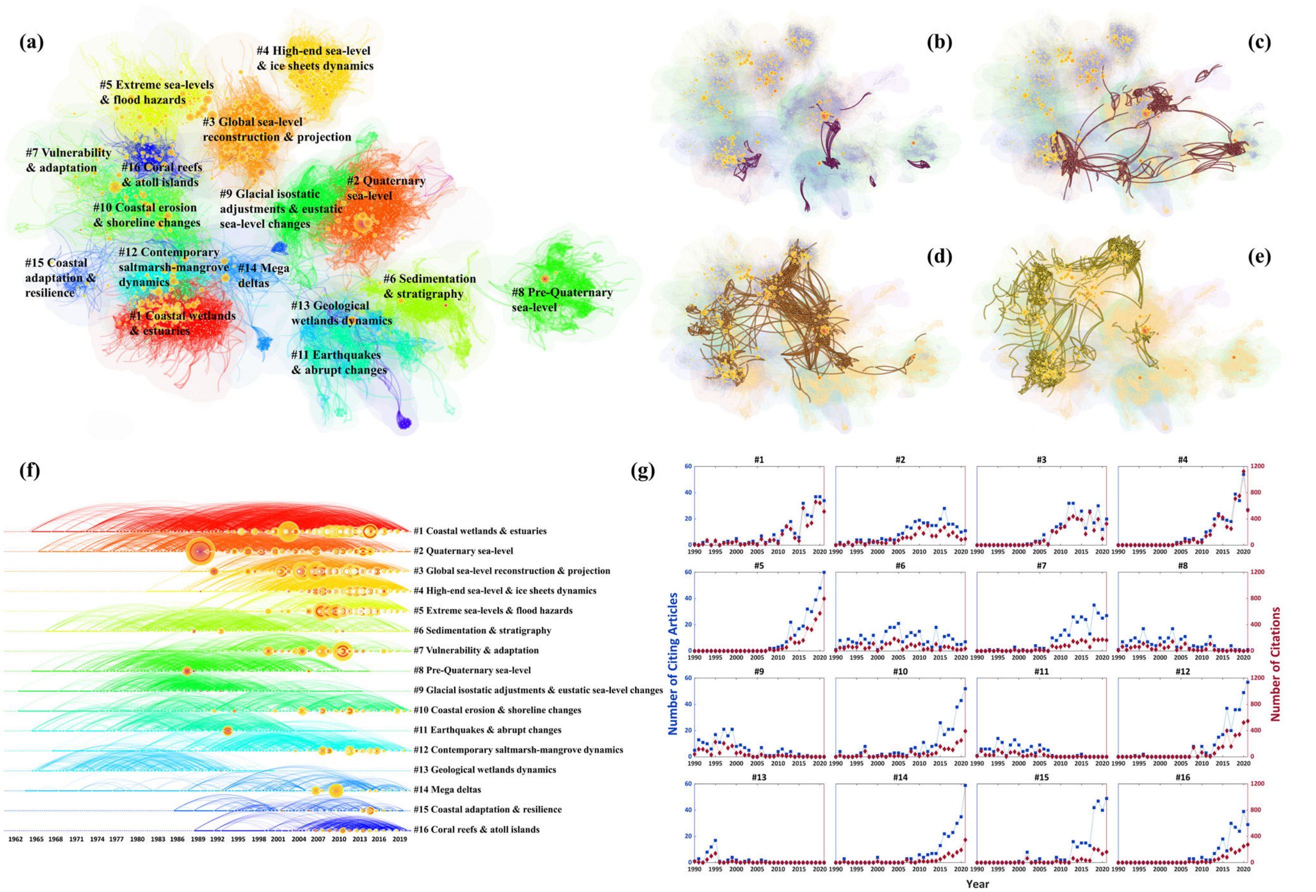


**Fig. 3 SLR research sub-themes and their temporal activities. a** A spatially distributed network of 16 research sub-themes in SLR science resulted from a co-citation analysis performed on the patterns of references that are frequently cited. The extent of spatial research activities within these sub-themes in (**b**) 1990, (**c**) 2000, (**d**) 2010, and (**e**) 2020 illustrates the most and the least active research sub-themes during different time spans. **f** A temporal network of mutually cited references for SLR research sub-themes highlighting the age and duration of the knowledge foundation for each sub-theme. **g** Plots of SLR citing articles and their associated citation counts during 1990–2021, underpinning persistent, emerging, declining, and fluctuating research sub-themes. In (**a**, **f**, **g**), smaller cluster IDs represent larger sub-themes populated with larger number of cited references. In (**a**–**e**), the sizes of the nodes are proportional to the number of local citations (i.e. citations within the field of SLR science solely) to the cited references, and additional clusters with fewer than 50 references within them were discarded and not presented.

The sub-themes of SLR science are ranked from 1 to 16 (sub-theme 1 has the highest whereas sub-theme 16 has the lowest number of cited and influential references) comprising (1) coastal wetlands and estuaries, (2) Quaternary sea-level, (3) global sea-level reconstruction and projection, (4) high-end sea-level and ice sheets dynamics, (5) extreme sea-levels and flood hazards, (6) sedimentation and stratigraphy, (7) vulnerability and adaptation, (8) pre-Quaternary sea-level, (9) glacial isostatic adjustments and eustatic sea-level changes, (10) coastal erosion and shoreline changes, (11) earthquakes and abrupt changes, (12) contemporary saltmarsh-mangrove dynamics, (13) geological wetlands dynamics, (14) mega deltas, (15) coastal adaptation and resilience, and (16) coral reefs and atoll islands (Fig. 3a and Supplementary Table S2). Some central sub-themes (e.g. #3, #10) have a multidisciplinary role as they have been studied exclusively or jointly with several surrounding research sub-themes. In contrast, peripheral sub-themes (e.g. #8, #11) are typically explored in isolation or in conjunction with a limited number of research sub-themes. To illustrate this point, research sub-theme "pre-Quaternary sea-level" is only strongly interconnected to one other sub-theme of "sedimentation and stratigraphy", whereas "coastal erosion and shoreline changes" interacts with several sub-themes comprising "global sea-level reconstruction and projection", "extreme sea-levels and flood hazards", "coral reefs and atoll islands", "vulnerability and adaptation", "coastal adaptation and resilience", "coastal wetlands and estuaries", "contemporary saltmarsh-mangrove dynamics", and "mega deltas" (Fig. 3a), highlighting this sub-theme's strong linkages across SLR science.

Understanding the absence or presence of citations to a set of cited references of a specific sub-theme can provide insights into its level of activity over time[69] (Fig. 3b–e). The links between sub-themes demonstrate how and when a research sub-theme has been inactive/active or had interactions with other sub-themes, emphasising the evolving network and temporal trends in SLR science. As detailed in Fig. 3b–e, the 10-year snapshots of SLR research activities indicate that some sub-themes persistently grew during the entire period, whereas other sub-themes declined or emerged. For instance, in 1990, "coastal wetlands and estuaries" and "Quaternary sea-level" were the most active research disciplines followed by "pre-Quaternary sea-level", "earthquakes and abrupt changes", and "sedimentation and stratigraphy" (Fig. 3b). In 2000, interdisciplinary research formed between the sub-themes "Quaternary sea-level", "glacial isostatic adjustments and eustatic sea-level changes", "contemporary saltmarsh-mangrove dynamics", "coastal wetlands and estuaries", "geological wetlands dynamics", and "sedimentation and stratigraphy" (Fig. 3c). In 2010, alternative research sub-themes emerged including "high-end sea-level and ice sheets dynamics", "coral reefs and atoll islands", and "vulnerability and adaptation", whereas direct research activities in "pre-Quaternary sea-level", "earthquakes and abrupt changes", and "geological wetlands dynamics" declined (Fig. 3d). In 2020, new research sub-themes emerged as "extreme sea-levels and flood hazards", "mega deltas", and "coastal adaptation and resilience", with the least active research sub-themes remaining similar to 2010 (Fig. 3e). This trend again highlights the emergence and recognition of solution-focused topics associated with SLR risks over time.

The temporal trends of SLR science are further highlighted by analysing the maturity of the knowledge foundation (i.e. age and frequency of the cited, fundamental references within each research sub-theme) (Methods and Fig. 3f) and the degree of persistence, growth, emergence, and disappearance of SLR citing articles within each sub-theme (Fig. 3g). Cited references of all sub-themes are plotted against a timeline based on their publication year, and the 'concentration of references' indicates the age and duration of the knowledge basis for each sub-theme (Fig. 3f). Red circles represent cited references for which citation bursts (i.e. the temporal increase in the citation counts of an article) have been recorded, with circle size indicating burst duration (i.e. a period of time over which an article received citations) (Fig. 3f). Across all sub-themes, knowledge of "coastal wetlands and estuaries", "Quaternary sea-level", "sedimentation and stratigraphy", "coastal erosion and shoreline changes", and "contemporary saltmarsh-mangrove dynamics" has been established since the 1960s with influential references distributed throughout the entire period to date. In contrast, knowledge of "pre-Quaternary sea-level", "glacial isostatic adjustments and eustatic sea-level changes", "earthquakes and abrupt changes", and "geological wetlands dynamics" was primarily founded during the 1960s–1990s with limited influential references recognised after the 2000s. Finally, knowledge of "global sea-level reconstruction and projection", "high-end sea-level and ice sheets dynamics", "extreme sea-levels and flood hazards", "vulnerability and adaptation", "mega deltas", "coastal adaptation and resilience", and "coral reefs and atoll islands" was established during the 1980s and has been growing ever since (Fig. 3f).

Based on the number of citing articles (SLR articles themselves) and their corresponding citations from 1990 to 2021, the research sub-themes "coastal wetlands and estuaries", "Quaternary sea-level", and "coastal erosion and shoreline changes" were generally, consistently active and rising; "pre-Quaternary sea-level", "glacial isostatic adjustments and eustatic sea-level changes", "earthquakes and abrupt changes", and "geological wetlands dynamics" were declining; "sedimentation and stratigraphy" was fluctuating; and "global sea-level reconstruction and projection", "high-end sea-level and ice sheets dynamics", "extreme sea-levels and flood hazards", "vulnerability and adaptation", "contemporary saltmarsh-mangrove dynamics", "mega deltas", "coastal adaptation and resilience", and "coral reefs and atoll islands" were emerging and attracting growing attention in recent years (Fig. 3g). Further details regarding each research sub-theme are presented in the Supplementary Table S2 and Supplementary Fig. S2. It should be noted that the observed trends reported herein are in the context of SLR science and different trajectories and level of activities may be observed for these sub-themes in other fields of science.

The temporal trends discussed above highlight the evolution of SLR scientific research from a predominately pure academic discipline towards a more applied research field due to the widespread, well-documented, and observed short-term and long-term compounding and cumulative impacts of SLR[34]. The emerging disciplines often focus on applying the knowledge gained at designing effective climate responses and policies. These policies typically integrate climate change adaptation strategies into broader coastal management plans. It is also apparent that SLR science is getting more specific with interest in distinct coastal environments (e.g. "mega deltas" or "coastal reefs and atoll islands") and detailed processes and hazards (e.g. "coastal erosion and shoreline change" and "extreme sea-levels and flood hazards") continuing to emerge.

## Discussion

SLR science is a multidisciplinary field of research. This study identified geological dimensions and sea-level indicators, impacts, risks, and adaptation, physical components of sea-level change, and coastal ecosystems and habitats as major SLR research clusters (themes), and 16 detailed research streams as its key sub-themes (Fig. 4a). Analysis of 30+ years of SLR literature indicates that these prevalent research topics have evolved over time. Understanding this scientific evolution (Fig. 4b, c) provides insights into the funding and prioritisation of research agendas, the challenges and opportunities of periodic integrative assessment of the literature, and how science is informing societal adaptation responses and policies[39]. Below, a brief discussion on some examples of areas that could benefit from the findings of this study is presented, highlighting the importance, distribution, and development of SLR science in recent decades.

**Research agendas**. Research agendas continue to evolve as SLR impacts emerge and gaps are addressed through ongoing research and the prioritisation in research funding. For instance, the rapid loss of estuarine and coastal ecosystems in recent years has raised concerns over declining critical ecosystem services[59] (valued at up to US$194,000 per hectare, per year[70]) including flood, storm, and erosion protection[53,71–73], carbon sequestration[65,74], and water quality improvement[75,76], including the potential intensification of hazards through feedback loops[77]. In recent times, these studies have increased substantially (Fig. 4b, c), including a wide variety of ecosystems. However, a recent review found that worldwide geographical coverage remains limited, with most valuation studies considering United States and tropical Asian coastal ecosystems[78]. Further, these studies have largely focused on saltmarsh, mangroves, and near-shore reefs and do not consider sea grass meadows, dunes, and barrier islands[78].

**Equity**. The recent literature on SLR highlights the growing imbalance in both geographical and distributional impacts[6,9,22,27,28]. Almost all of the world's 85 million poor people living in rural low-elevation coastal zones reside in 20 developing countries, including Cambodia, Pakistan, Indonesia, Mozambique, Senegal, and the Philippines[79]. On the other hand, the overall contribution of these exemplified countries to SLR research conducted during 1990–2021 is <1% (see Supplementary Table S1). The same concern exists for people inhabiting Small Island Developing States (SIDS)[29] and deltaic areas[80,81]. As such, this analysis highlights vulnerable coastal locations and populations where research needs to engage local experts to study the local coastal systems in detail and develop appropriate strategies and plans to adapt to damaging SLR impacts.

**Assessing the growing literature**. SLR science must be responsive to areas of ongoing research, geared towards societal and policy relevance. Advances in assessment have thereby prioritised combinations of multi-model comparisons, meta-analysis, systematic review, and multi-criteria methods of determining the strengths and limitations of current understanding[82,83]. These challenges are particularly relevant to SLR science given its growing, multidisciplinary topics and methods. A large and growing body of academic literature has been developed to address these expanding topics. In 1990, only 41 SLR-related articles were recorded in the Web of Science, and the cumulative

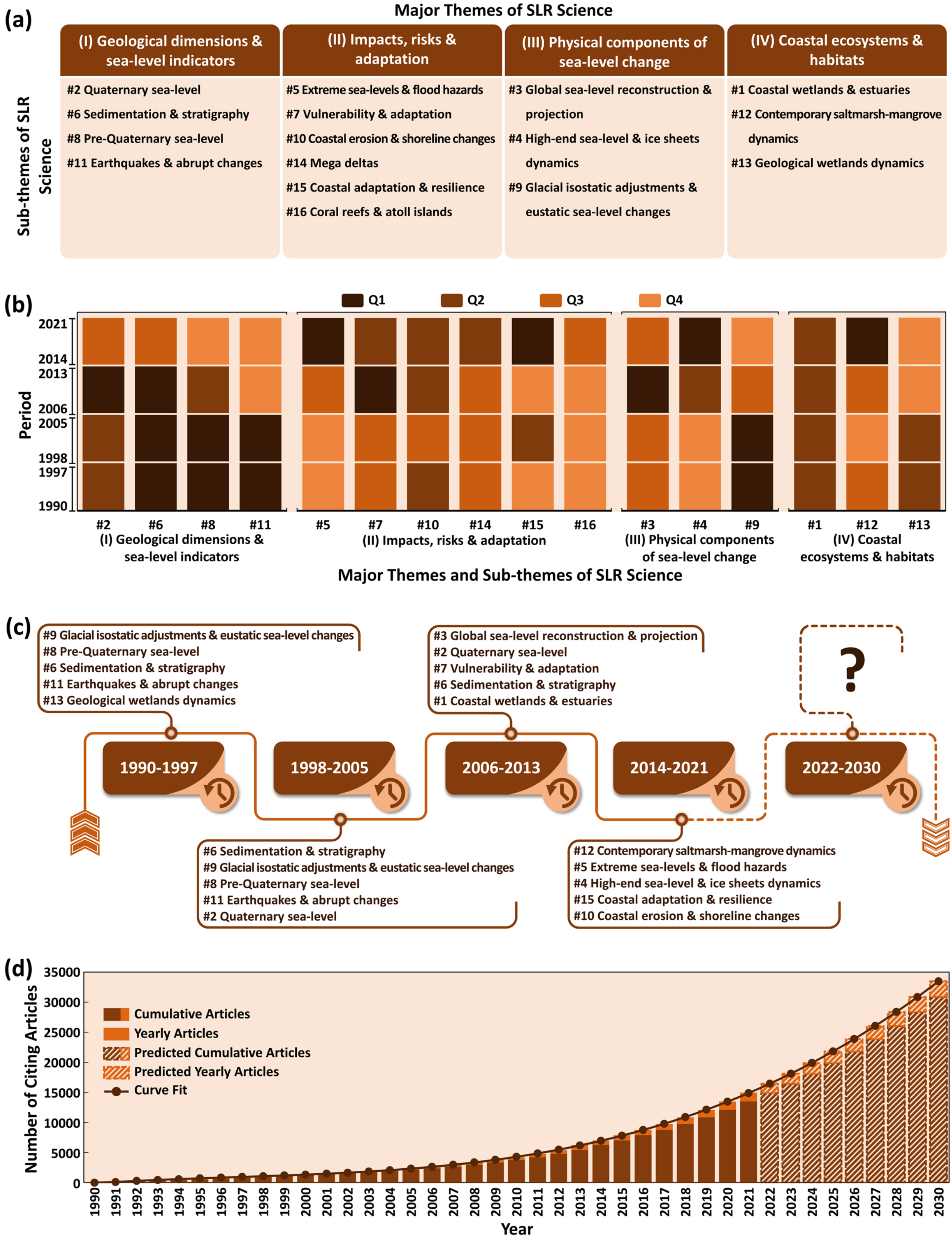


**Fig. 4 Evolutionary trends in SLR research. a** The 4 major themes and 16 associated sub-themes of SLR science identified from 1990 to 2021, highlighting its wide-ranging and multidisciplinary nature. **b** A colour coded map of 4 major themes and 16 associated sub-themes of SLR science, highlighting when SLR research sub-themes shifted between the first 25% (Q1), second 25% (Q2), third 25% (Q3), and last 25% (Q4) quartiles based on their cumulative number of articles during each period. **c** An infographic timeline indicating the top 5 research sub-themes with largest number of (citing) articles during different periods. **d** Temporal trends of cumulative and annual number of SLR articles as well as their predicted values for the period 2022–2030 using a third-degree polynomial curve fit equation derived from the existing data.

number increased to 1369 by 2000, 4195 by 2010, and 13,476 by 2020 (Fig. 4d). From 1990 to 2021, the growth and doubling rates of SLR science were 15.4% and 4.8 years (Methods), respectively, which are higher compared to other fields of science (e.g. a doubling time of over 17 years for the entire literature of modern science[38]). If these trends continue, the next IPCC assessment report (expected from 2026 to 2030), will face the daunting challenge of exploring nearly 9000–18,500 additional SLR-related articles (Fig. 4d).

**Policy**. SLR literature has increasingly focused on challenges associated with adaptation responses, as reflected in the growing and emerging sub-themes within Cluster (II) (Fig. 4b). In this context, new research could explore the appropriate ‘mix’ of protection from SLR and climate change from both grey infrastructure, such as seawalls, dikes, barrages, and diversions, as well as raising the elevation of buildings and flood-proofing structures, and green infrastructure, such as saltmarshes, oyster and coral reefs, mangroves, seagrass beds, barrier islands, and beaches[53,84]. The main adaptive response to SLR in coastal areas is to either protect, manage, accommodate, or retreat[9,85]. In many coastal areas, managed retreat and associated migration may be unavoidable, which could encompass a variety of strategies, including the controlled flooding of low-lying coastal areas or the abandonment/relocation of assets and people allowing the shoreline to move inland[86]. To this end, the literature has increasingly focused not only on adaptation options, but also on the adaptation process, including evaluation, implementation, monitoring, side-effects, and co-benefits.

After 30+ years of increasing SLR knowledge, this analysis, as a first attempt, allows a new conceptual and practical perspective on how SLR research themes and sub-themes have developed and evolved, which is not possible using conventional methods. The paper informs what research is being conducted or used, and thereby presents a systematic analysis of the research needs, connections, and agendas in SLR science. Given the explosion in published literature, this study provides a repeatable method that can support and complement large-scale assessment processes such as future IPCC reports, and hence, guide and inform the global community in their responses to rising sea-levels and related issues. While we are still learning about the best use of these methods, further innovation is encouraged. For example, as SLR science is moving towards practise (i.e. vulnerability and adaptation), the grey literature, local knowledge, and Indigenous knowledge covering these areas may also need to be assessed in the future. Overall, this research can assist global scale assessments by identifying emerging or trending research topics and highlighting geographic discrepancies. The findings could also serve as a guideline for designing evidence-based management strategies and directing future research funding.

## Methods

**Data acquisition strategy**. Synthesising the growing volume of sea-level rise (SLR) science in 2022–2023 using manual assessment and review methods is nearly impossible. Hence, the bibliometric approach is becoming a popular technique to overcome such literature assessment challenges[40,87]. This method allows for a rapid classification of thousands of articles and reliably and consistently captures the breadth of literature related to a specific field[41,45]. Adopting a bibliometric technique enables identifying term co-occurrence patterns, similarity of references between articles, and patterns of co-referencing, providing a comprehensive understanding of the evolution of a field under investigation[69].

In this study, the global SLR literature was systematically assessed utilising a term-based search strategy in the Web of Science (Supplementary Fig. S3). This search extracted academic literature (and not reports such as IPCC assessments—see below for details), such as research articles, review papers, data papers, letters, and proceeding papers. Grey literature and Indigenous knowledge, although valuable, were not considered in the search. A suitable search strategy was implemented to ensure the majority of key and relevant SLR articles are captured, while minimising false positives. Here, false positives are defined as studies that are not directly related to SLR, although they have used the term “SLR” or similar close terms.

The following methodological approach was applied while constructing the term-based element of the search strategy. Individual terms relevant to SLR (e.g. search units) were used to create a query string. Further, to make the search term more specific and relevant, terms were combined using Boolean operators (e.g. OR) to form search units or a combination of terms. A search unit is a component of the query string that can generate search results on its own. For example, in the queries used, a search unit is “sea level rise” or “sea-level rise”. Each search unit was then assessed separately in the Web of Science using the titles (TI), abstracts (AB), and authors’ keywords (AK) as the search domain. A sanity check was carried out on the first and the last fifteen pages of results in the Web of Science (nearly 10% of data retrieved) from each search unit to ensure no (or very limited) false positives were captured or created. The overall aim of the term-based search approach is to generate many particular search units rather than a few broad search units in order to reduce false positives. This is particularly important for a large, diverse multidisciplinary literature such as SLR science. The following search query was used:

TI = (“sea level rise” OR “sea-level rise”) OR AB = (“sea level rise” OR “sea-level rise”) OR AK = (“sea level rise” OR “sea-level rise”).

As per Supplementary Fig. S3, the developed query string was inserted into the Web of Science Core Collection in January 2022, with the search time span restricted to 1st of January 1990 to 31st of December 2021, returning $N = 14,951$ unique publications, called “citing articles”. The bibliographic information (e.g. list of authors, keywords, journals, publication year, references, etc) for these articles was obtained from the Web of Science and was stored as text files. Bibliometric methods were then applied to the dataset to obtain high level insights on the development of SLR literature and its research streams. The method of Visualisation of Similarities (VOS) and the VOSviewer software[88] which is a popular tool for mapping clustered networks of authors, journals, and citations were used to illustrate the similarities[89]. In addition, VOSviewer uses text mining algorithms to identify specific phrases from an article’s title and abstract from which major clusters and networks could be developed. In this context, VOS provides a visualisation such that the similarity between two objects $i$ and $j$ is depicted by their Euclidean distance $\delta_{i,j}$. This similarity, which is also referred to as Proximity Index or Association Length, is measured as[90]:

$$\delta_{ij} = \frac{\alpha_{ij}}{\varepsilon_i \varepsilon_j} \quad (1)$$

where $\alpha_{i,j}$ is the number of co-occurrences of objects $i$ and $j$, and $\varepsilon_i$ and $\varepsilon_j$ denote their respective number of total occurrences.

The VOS mapping method creates a two-dimensional network by minimising the weighted sum of the squared Euclidean distances between all pairs of elements (Eq. 2). A higher degree of similarity would be indicated by heavier weights[90,91]:

$$Min\ V(\boldsymbol{M}_1, \ldots, \boldsymbol{M}_n) = \sum_{i<j} \delta_{ij} \|\boldsymbol{M}_i - \boldsymbol{M}_j\|^2 \quad (2)$$

This is subject to the requirement that the average distance between pairs of objects be equal to unity[90,91]:

$$\frac{\sum_{i<j} \delta_{ij} \|\boldsymbol{M}_i - \boldsymbol{M}_j\|}{n(n-1)/2} = 1 \quad (3)$$

As a result, Eqs. (2, 3) are used to find the spatial locations of items where $\boldsymbol{M}_i = (x_i, y_i)$ is the vector of position for item $i$ in a two-dimensional map, and $\|\bullet\|$ signifies the Euclidean norm. VOSviewer uses a majorization approach to derive the answer numerically.

**Data analysis techniques**. The occurrence and co-occurrence of terms in the title and abstract of articles were used to determine the broad scientific structure and major research themes of SLR science. When the VOS method was applied to the key terms of the titles and abstracts of this field, four major themes were identified including (I) geological dimensions and sea-level indicators, (II) impacts, risks, and adaptation, (III) physical components of sea-level change, and (IV) coastal ecosystems and habitats (Fig. 2a). In Fig. 2, the frequency of co-mention and similarity of terms determine their placement in the figure, and the size of a node represents the frequency of its occurrence.

Authors’ keywords were also analysed with a focus on three set of periods including 1990–2009, 2010–2015, and 2016–2021 (due to the disproportionate distribution of SLR articles from 1990 to 2021), and for six different continents of Africa, Asia, Europe, North and Central America, Oceania, and South America identified based on authors’ affiliation (i.e. countries of all authors in any given article are considered) (Fig. 1b). In each period, the top 10 keywords most widely used were identified and presented to provide an overview on the trends of change in SLR research topics.

A more detailed analysis on the dataset, referred to as Document Co-citation Analysis[68], was also conducted. This analysis determines key sub-themes of SLR science, provides a greater level of resolution, and identifies temporal and spatial trends and evolution of those sub-themes and their respective fundamental cited references (Fig. 3). This analysis makes the approach robust to possible missing items in the original dataset. To illustrate this point, if a fundamental reference has been cited enough times within a large dataset, it will be detected, regardless of whether it exists in the dataset or not. This refers to a set (cluster) of references that have been jointly cited (cited references) by researchers publishing in the SLR science space. The principal logic behind this approach is that references which are routinely co-cited (cited together) by articles that have a SLR theme can be grouped together as they would be thematically similar. Each cluster of co-references (cited references) form the knowledge foundation of certain research sub-themes within the SLR literature. In other words, the formed clusters (that have a similar theme) represent distinct sub-themes of research in SLR science. It should be noted that research sub-themes containing fewer than 50 cited references were not considered nor presented (i.e. removed from visualisations).

The document co-citation methodology explained by Chen[68] and the CiteSpace software[92] were used to classify the references, categorise its spatio-temporal trends during the development of its disciplines, and identify the most influential references in the SLR science domain (Fig. 3). In Fig. 3a, each node represents an individual reference, the node size indicates the local citation count (i.e. the frequency of being referenced by SLR articles solely), and links represent instances of co-citation. A K-means clustering algorithm was used with a g-index criterion for the selection of references and the number of look-back years of 30 and time slices of 1 year.

Clusters (sub-themes) were then ranked based on the number of cited references within each of them. The degree of activities of each cluster over time was quantified based on the number of citing articles of each cluster during each year as well as the total number of citations (i.e. total coverage) from the citing articles to the references of each cluster (Fig. 3b–e). Influential references of each cluster (sub-theme) were determined based on three primary metrics, namely, (1) *local citation counts*, (2) *bursts* of (sudden spikes in) local citation count to the references, and (3) *reference centrality*, which is the extent to which a reference receives citations across various sub-themes of SLR literature (Supplementary Table S2). It is fundamental to note the difference between citing articles and cited references as the citing articles are directly related to SLR science, whereas the cited references are those cited by the citing articles and could be from different disciplines, even from outside SLR domain (e.g. policy, economy). Further, sub-themes were labelled such that the labels employed best characterise the contents of each sub-theme based on the topics of citing articles incorporated in them (e.g. see "Highest coverage SLR citing articles" column of Supplementary Table S2). These labels were predominantly inspired by the IPCC reports, sea-level terminology[93], and authors' knowledge of SLR literature.

It should be noted that the IPCC reports were not considered in the dataset of citing articles retrieved from the Web of Science as they may have distorted the analyses. However, these reports are inevitably captured in the analyses as "cited references" of many SLR "citing articles" and thereby contributed to shape up the research sub-themes. All the cited references were analysed and reported as described and cited in the citing articles. For some sources such as the IPCC reports, they were cited in multiple ways (chapter, synthesis, or full report). However, this does not influence the analysis and cluster formation processes due to the robustness of the document co-citation methods (see above and below).

Similar to almost all clustering algorithms, while belonging to a cluster (sub-theme) indicates closer association with other items of that cluster, this does not rule out the possibility of a weaker association with the items of other clusters (sub-themes). When cited reference "X" is found affiliated with sub-theme "Y", for instance, this does not indicate that the reference has only been cited together with other references belonging to sub-theme "Y". The reference might have had instances of co-citation with items of other sub-themes (see, for example, links that are often drawn between items of one sub-theme to an item of another sub-theme on the document co-citation map depicted in Fig. 3a). However, for the purpose of clustering, each "cited reference" has to be identified with one unique sub-theme, the one with which it has the closest relationship. More importantly, note that, while references of SLR papers can only identify with a unique sub-theme, the citing articles (i.e. SLR papers themselves) are not under this constraint. This is reflected under the concept of "coverage" (i.e. the (partial) contribution of each citing article to the formation of a sub-theme), as presented in Table S2. While a citing article may have a dominant role in the formation of sub-theme "Y" (i.e. a high degree of coverage), for example, it can also have contributed to the formation of another sub-theme such as "Z" (most likely to a lesser degree, through a smaller degree of coverage). The methodology considers all these contributions to sub-themes formation into account.

In summary, different citing articles can potentially contribute to the formation of more than one sub-theme (see Supplementary Fig. S2), whereas the cited references extracted from reference lists of SLR articles can only identify with a single sub-theme. However, these cited references can also have instances of co-citation with references from other sub-themes and the method adopted had considered this concept. In fact, the *centrality* metric that has been adopted in the analyses is a direct reflection of this aspect (see Supplementary Table S2). By the nature of clustering, each reference identifies with one single sub-theme, but the references that are frequently co-cited with references of other sub-themes (i.e. sub-themes other than the main sub-theme that they have identified with) receive a high score on centrality, highlighting the multidisciplinary nature of the references as well as the analyses.

**Average growth rate and doubling time of SLR articles**. In this study, the average yearly growth rate (i.e. growth over a series of equally spaced time periods) and doubling time (i.e. the duration of time it takes for a population—here, SLR articles— to double), which are valuable indicators for evaluating long-term trends in science, were evaluated (Fig. 4). The annual growth rate percentage $\beta$ was first computed as:

$$\beta = \left(\left(E_V - B_V\right)/B_V\right) \times 100\% \qquad (4)$$

where $E_V$ and $B_V$ are ending and beginning values (here articles), respectively. $\beta$ was calculated between 2 successive years to compute the annual growth rate. The average growth rate for the entire period was then evaluated by averaging the values of $\beta$ for all the periods considered (i.e. 1990–2021). The doubling time $\tau$ was then estimated as:

$$\tau = \frac{\ln(2)}{\ln(1+\beta)} \qquad (5)$$

## Data availability

In addition to dataset presented in Supplementary Information, underlying data for the paper figures and the bibliographic information of SLR articles can be accessed at https://doi.org/10.5281/zenodo.8013630.

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## Author contributions

D.K., M.H., R.J.N., and H.M. conceived the study. D.K. and M.H. designed and performed the analyses. D.K., M.H., and R.J.N. wrote the original paper. D.K., M.H., and A.S. produced the figures and tables. D.K., M.H., R.J.N., H.M., M.S., K.J.M., S.F., A.T.V., E.B., A.S., and W.G. contributed to the discussion and checked the analyses, as well as reviewed and revised the paper.

## Competing interests

The authors declare no competing interests.

## Additional information

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