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Review

Scientometric review of climate-change extreme impacts on coastal cities

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ABSTRACT

The generalised sea level and temperature rise, along with the increasing frequency and intensity of storms and temperature extremes, trigger a variety of climate-change-related impacts on coastal communities, such as coastal flooding and erosion, pluvial and river flooding, heat waves, cold spells, droughts, and landslides. These events can rapidly cascade into additional challenges and have a profound impact on the coastal zone. Many studies have focused on the causes and consequences of climate change for coastal cities in the past decades. As a result, the number of forecasts, risk assessments, literature reviews, and methodologies has increased. This comprehensive review comprises the key findings of a systematic analysis of the scientific literature on extreme impacts of climate change on coastal cities. After a bibliometric analysis, which yields 2321 papers in 470 journals from 1976 to 2021, a scientometric analysis is carried out. There is wide geographical diversity, with publications from 97 countries. In terms of numbers and nationalities, the USA was followed by China, UK, Australia, and Indonesia. The scarcity of papers from developing countries is apparent. "Storm" and "risk assessment" are the top keywords regarding frequency of occurrence and relationships with other keywords. The main research areas for this topic are risk assessment, climate-change-related hazards and their drivers, modelling tools, disaster control and prevention measures, climate change policies and urban planning. Finally, research gaps are identified, and future research directions proposed, e.g., emerging integrated coastal zone management tools and the impacts on climate change on developing countries.

1. Introduction

The development of coastal cities continues to grow around the world (Neumann et al., 2015), whereas the frequency and severity of extreme events are increasing as a result of climate change (Dale et al., 2001; Knutson et al., 2010). As the population exposed to mean and Extreme Sea Level (ESL) events is expected to grow significantly throughout the 21st century (Oppenheimer et al., 2019), there is a continuous increase of studies focused on climate change and its consequences to coastal populations (Kulp and Strauss, 2019; Lima and Bonetti, 2020; Oppenheimer et al., 2019; Wong et al., 2014).

Research on climate change impacts at global scale dates back approximately to 1970s (Zillman, 2009). Since its roots, the literature on this topic has grown exponentially and is quite well established nowadays. The growth in Environmental, Social, and Governance (ESG) investment, and in particular climate change, have caused more funds to be channelled to the scientific research in the last years and therefore may have contributed to the acceleration in the scientific production. Today, institutional investors participate in a wide-ranging number of initiatives and organizations to address climate-related risks in their portfolios, such as Climate Action 100+, the Montreal Carbon Pledge, the Ceres Investor Network on Climate Risk, UN Principles for Responsible Investment (PRI), Global Sustainable Investment Forums (SIFs), UNEP FI, Institutional Investors Group on Climate Change (IIGCC), and many others. For instance, the G20 Financial Stability Board's Task Force on Climate-related Financial Disclosures released recommendations in June 2017, which highlighted the importance of using scenario analysis to assess climate change-related impacts within the financial sector ("Task Force on Climate-related Financial Disclosures"). Also, the European Commission has recently (March 2018) published a series of measures to enhance the ESG transparency of benchmark methodologies and an initiative to put forward standards for the methodology of low-carbon benchmarks in the Union, in alignment with its action plan *Financing Sustainable Growth*.

Nevertheless, ESG investment by corporations is not the only reason behind the boom of climate-change-related publications. A large set of

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milestones regarding the fight against climate change may have contributed to the social conscience: from the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, bringing together thousands of scientists to assess scientific evidence on climate change and its impacts, and the signature of the United Nations Framework Convention on Climate Change (UNFCCC) by countries around the world in 1992 to the ratification of the European Green Deal in 2020 and the publication of the 6th Assessment Report on Climate Change between 2021 and 2022.

There has not been found a publication analysing the former sources together. In this context, the purpose of this article is to develop a bibliometric and scientometric analysis of the literature regarding extreme climate change impacts on coastal cities, with a particular focus on sea level rise, coastal flooding and coastal erosion, in order to (i) review the spatial and temporal evolution of research, (ii) identify the major themes of current research, (iii) summarize and compare research through meta-analysis and qualitative review, and (iv) suggest future research directions. It is expected that the scientific literature on climate change and coastal cities had grown rapidly in recent decades, reflecting the increasing recognition of the risks and challenges posed by climate change to urban coastal areas. A scientometric analysis of this literature can reveal the patterns, trends, and gaps in research on this topic, providing insights into the knowledge structure and evolution of the field and facilitating evidence-based policy and decision-making.

The increase in the frequency and intensity of storms, in addition to the incessant sea level rise, are the main drivers behind the increase in the number and severity of ESL, coastal flooding and coastal erosion episodes (Crespi et al., 2020; IPCC, 2021; Peduzzi, 2005; Smith, 2017). Information on past events and studies is of interest in assessing the evolution of the problem. In this regard, literature and bibliographic reviews, risk assessments (including hazard, vulnerability and exposure assessments (Nguyen et al., 2016)), climate change reports, and climate projections are valuable information sources.

In general, social, economic, and environmental losses due to the destruction of land, damage to urban assets, seawater intrusion, harmful biological blooms, and pollution are some of the main impacts facing coastal cities and communities. These impacts may stem from either global warming (climate change), human activities, or a combination of both (Fig. 1). However, in this study we will exclude those impacts related exclusively to anthropogenic action.

On the one hand, the extreme impacts enhanced by climate change include heatwaves, cold spells, droughts, heavy precipitation, pluvial floods, river floods, coastal flooding and coastal erosion in general terms (Seneviratne et al., 2021). Moreover, more than one of the extreme events above may occur simultaneously, leading to compound events. Certain impacts are of particular concern to coastal communities, such as coastal flooding, coastal erosion, saltwater intrusion and any others that may affect coastal ecosystems (Costa et al., 2023; González Hernández et al., 2023; Rodriguez-Delgado et al., 2020; Spalding et al., 2014). In this context, coastal flooding is defined as a temporary inundation of a terrestrial area that is not normally submerged and is caused by the combination of Relative Sea Level Rise (RSLR), tides, storm surge and wave setup at the shoreline (Kirezci et al., 2020; Koks et al., 2019; Melet et al., 2018; Pollard et al., 2019; Ranasinghe et al., 2021; Vitousek et al., 2017; Vousdoukas et al., 2018, 2020). Coastal erosion may be defined as the net removal of material from one coastal location to another (Bergillos et al., 2020a, 2020b). It is driven by many natural factors including storm surge, changes in wave energy, sediment supply and sea level rise (Dawson et al., 2009; Hinkel et al., 2013; Mentaschi et al., 2017; Penland et al., 2005; Wong et al., 2014). Coastal erosion is generally accompanied by shoreline retreat, which may occur as a gradual process (e.g., due to sea level rise) or as an episodic event due to ESLs or coastal flooding (Ranasinghe, 2016; Ranasinghe et al., 2021).

On the other hand, as a consequence of socioeconomic development, certain human-related drivers may produce a number of impacts on coastal systems related to sediment delivery, nutrient loads, and hypoxia (He and Silliman, 2019). Human activities in drainage basins and coastal plains impact the coastal zone by changing the delivery of sediment to the coast (Syvitski et al., 2005; Walling, 2006). Shoreline changes as a result of urbanisation, construction of ports, sediment trapping behind dams, water diversion for irrigation, sand and gravel mining in river channels, and soil erosion due to land use changes all affect sediment delivery. Besides, riverine discharge of nutrients (nitrogen, phosphorus) onto coastal areas as a result of fertilizer use in agriculture and fossil fuel emissions may impact coastal ecosystems (Beusen et al., 2016). Indeed, excessive concentrations of nutrients in coastal waters, which cause eutrophication and the subsequent decomposition of organic matter, are the primary cause of decreased oxygen concentration (hypoxia), thereby posing a serious threat to marine life (UN Environment, 2019; Vollenweider, 1992). How the anthropogenic action affects coastal systems is a

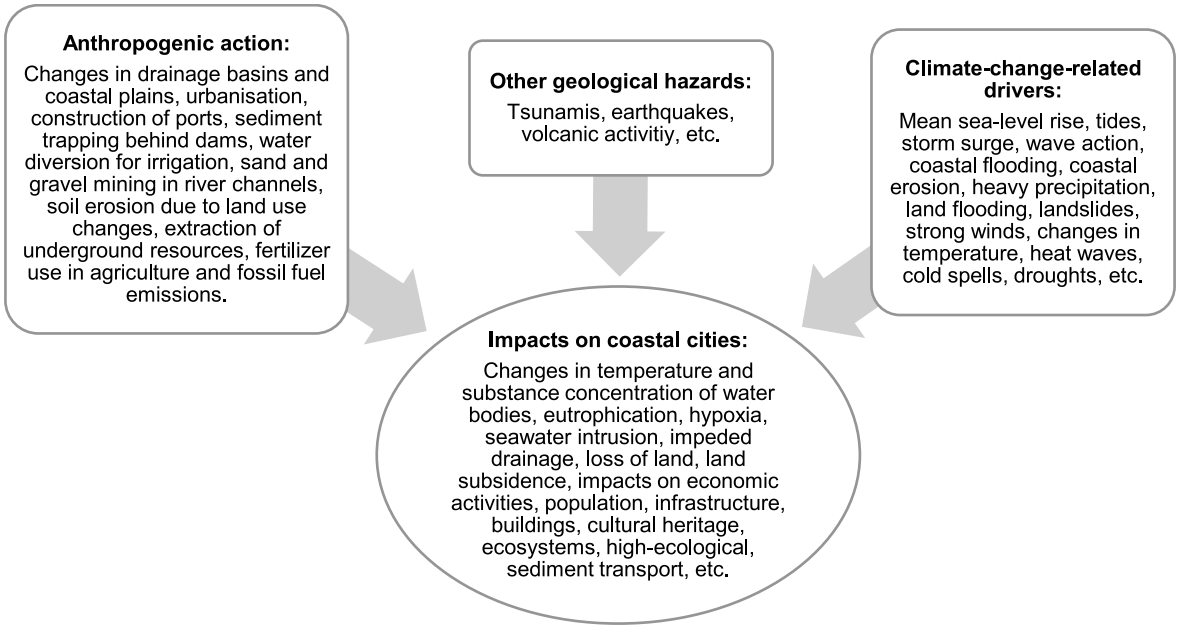

Fig. 1. Summary scheme of the impacts on coastal cities and their drivers.

complex field, and its analysis is out of the scope of this work.

The sub-domain of this field of research focusing on extreme impacts exacerbated by climate change is developing fast, and the analysis in this work will illustrate its momentum. In Data collection, processing and analysis method, we discuss the methodology used to obtain the relevant bibliometric data. In the Results section the meta-analysis of this literature will show that, within the last two decades, the number of scientific studies on the topic has grown exponentially, with the hot topics continually evolving and the geographical distribution of publications retaining the aforementioned diversity. The Discussion section elaborates on these findings and identifies certain topics which are currently underrepresented and may warrant further attention by the research community.

2. Materials and methods

Bibliographic details of the scientific literature on climate change extreme impacts on coastal cities in general and extreme sea levels, coastal flooding and coastal erosion in particular were identified and retrieved from Scopus, one of the main databases of academic publication records (Mingers and Leydesdorff, 2015).

Scopus encompasses a broad range of scientific literature, including journals, conference papers, books, and patents. It covers multiple subject areas, making it a valuable resource for multidisciplinary research. Complementarily, Scopus allows users to track citations, analyse citation patterns, and measure the impact of scholarly works through metrics such as the h-index and citation counts. However, it may not include all journals and publications worldwide, and some niche or regional publications may be underrepresented or absent from the database. Citation data may not capture all forms of scholarly communication, such as preprints, non-peer-reviewed publications, or works outside the Scopus database.

Advanced search capabilities, allowing users to conduct complex queries and refine search results based on various criteria are offered in Scopus. It provides access to abstracts, full-text articles, and bibliographic details. However, the search algorithms and indexing process may occasionally result in false positives or missed relevant articles, necessitating careful selection and interpretation of search results. Moreover, while Scopus indexes open access journals and publications, not all content in the database is freely accessible. Some articles may be behind paywalls or require individual subscriptions, making it challenging for users without institutional access or subscriptions to retrieve full-text versions of certain publications.

While Scopus provides a wealth of bibliographic information, it may lack certain types of data that researchers might require (e.g., detailed experimental data, raw datasets, or supplementary materials associated with publications may not be readily available through Scopus). Although Scopus includes publications from various languages, its coverage is biased toward English-language literature. This language bias may result in the underrepresentation of research published in other languages, limiting access to non-English sources. In addition, as with any bibliographic database, Scopus may be subject to inherent biases in publication patterns, citation practices, and author demographics. These biases can impact the representation of research from certain regions, disciplines, or research communities.

To obtain the reference database for the previous topics, the following combination of search terms was used in a title-abstract-keyword search: *TITLE-ABS-KEY(climate AND change AND extreme AND impact OR event AND coastal OR coast AND city OR town) OR TITLE-ABS-KEY(extreme AND sea OR water AND level AND city OR town) OR TITLE-ABS-KEY(coastal OR coast AND flooding OR flood AND city OR town) OR TITLE-ABS-KEY(coastal OR coast AND erosion AND city OR town)*. The search for establishing the dataset used in this article was last updated in December 2021, considering only texts in English. A total of 3811 results were initially obtained. After screening out the scientific publications which were not relevant to the study – unrelated topics, publications with blank bibliographic fields, and studies regarding human-related drivers exclusively, as mentioned in the Introduction – the final dataset was reduced to 2321 results. The bibliographic details of the reference database, including the list of authors, title, year of publication, source title, volume, issue, page numbers, author affiliations, abstracts, author keywords, index keywords, list of references, document type and some other details, were exported and analysed using scientometric methods.

For the described dataset, scientometric methods are applied in Results to obtain high-level insights into the development of these research domains. Apart from elementary statistics and standard visualization graphs, we apply the VOSviewer software (van Eck and Waltman, 2010). This open-access tool implements the visualization of similarities approach (VOS) (Waltman et al., 2010) and is widely used to map clustered networks of authors, journals, collaborating countries, and co-citations. The VOS clustering methodology employed involves a two-step process: the similarity calculation and the clustering. VOSViewer calculates similarities between pairs of documents using either co-citation or co-occurrence data. Co-citation similarity measures the degree of overlap in the articles cited by two documents, indicating their relatedness. Co-occurrence similarity, on the other hand, quantifies the extent to which two documents share common terms or keywords, reflecting their thematic similarity. These similarity measures serve as the basis for subsequent clustering. Once the similarity matrix is generated, VOSViewer applies clustering algorithms to group similar documents together. The software employs a variant of the MCL (Markov Cluster) algorithm, which is an unsupervised clustering method based on graph theory. The MCL algorithm simulates stochastic flow in a graph, identifying clusters of highly interconnected nodes or documents. The resulting clusters represent groups of documents with significant similarities in terms of citation patterns or thematic content. Finally, three visualizations referred to as the *network* visualization, the *overlay* visualization, and the *density* visualization can be constructed from the results.

The outputs include (i) rankings on the most cited and prolific publishers, the most cited articles, and the most important journals; (ii) visualization graphs illustrating the distribution of scientific publications over the years, and the geographical distribution of both the citations and articles produced using the ArcGIS Pro software; and (iii) the results from the application of the VOSviewer software on the research topic showing the authors network, the countries heat-map network, and heat-maps networks of frequently-occurring terms in the dataset.

Moreover, the relationship between the main milestones on the fight against climate change (Table 1) and the evolution of the number of publications regarding climate change extreme impacts on coastal cities is analysed in Discussion.

3. Results

The yearly distribution of publications from 1976 to 2021 is illustrated in Fig. 2. The first publication, “Effects of Hurricane Eloise on beach and coastal structures, Florida Panhandle”, was published by R.A. Morton in the United States in 1976 (Morton, 1976). Until 1989, when a relative peak of 13 publications was reached, the scientific production regarding extreme climate change impacts on coastal cities remains low. Thereafter, and between 1989 and 1997, the number of publications is not higher than 15 (1991) and significant trends are not observed. However, the graphic starts to show a general uptrend practically at the end of the century. In general, the analysis indicates an increasing research trend in recent years. In fact, the cumulative number of publications from 1976 to 2016 (1024) is less than the number of works published within the last five years (1297). Exceptionally, the number of publications decreased substantially in 2016 compared to 2015. The surge of studies in the last five years (2017–2021) appears to be the most pronounced of all by far.

Despite the boom registered during the last lustrum, most of the

Table 1
Milestones to climate change fight which may be contributed to the social conscience on the matter.

Year	Milestone
1979	First World Climate Conference (WCC-1), as "a world conference of experts on climate and mankind".
1980	Establishment of the World Climate Research Program (WCRP), to help to coordinate global climate research.
1988	Intergovernmental Panel on Climate Change (IPCC) foundation, bringing together thousands of scientists to assess scientific evidence on climate change and its impacts.
1990	IPCC First Assessment Report.
1992	Establishment of the United Nations Framework Convention on Climate Change (UNFCCC), as an international environmental treaty to combat "dangerous human interference with the climate system".
1995	WCRP Coupled Model Intercomparison Project, a collaborative framework designed to improve knowledge of climate change. IPCC Second Assessment Report.
1997	The UNFCCC adopts the Kyoto Protocol, the world's first greenhouse gas emissions treaty.
1998	Launch of the Global Monitoring for Environmental Security (GMES), the EU's Earth monitoring initiative.
2001	IPCC Third Assessment Report.
2005	C40 Cities Climate Leadership Group foundation, a global network of cities fighting climate change. The EU launches its Emissions Trading System.
2007	IPCC Fourth Assessment Report. The EU adopts its 2020 climate and energy package, with three key targets: reduce EU greenhouse gas emissions by 20% compared to 1990; increase the share of renewables to 20% of EU energy use; and improve energy efficiency by 20%.
2009	UN climate change conference in Copenhagen ends without an overall agreement on binding emissions cuts.
2014	IPCC Fifth Assessment Report. Establishment of the Copernicus programme (previously known as GMES)
2015	The Paris Agreement is agreed and entering into force on 4th November 2016. Launch of SDGs.
2017	China launches its carbon emission trading market.
2018	The European Commission (EC) launches a series of measures to enhance the ESG. Countries agree on the detailed rules and guidelines to make the Paris Agreement work in practice across the world.
2020	European Green Deal is approved on the goal to make the EU climate-neutral by 2050.
2021/ 2022	IPCC Sixth Assessment Report.

articles accumulating the highest numbers of citations were published before 2015. In Table 2, the publications accumulating more than 200 total citations in the dataset are sorted. Information on the authors, title, year of publication, source title, number of citations, and document type are also provided. They are 13 in total, of which 10 were published between 2008 and 2014. In the article "Future flood losses in major coastal cities (Hallegatte et al., 2013)", published in the journal Nature Climate Change in 2013, S. Hallegatte, C. Green, R. Nicholls, et J. Corfee-Morlot provide a quantification of present and future flood losses in the 136 largest coastal cities, accumulating up to 1034 citations at the moment of writing this article and ranking the highest in the dataset. The following articles in the list have also a great number of citations – ranging between 459 and 204 –, although substantially lower than the top. Most of the publications included in the table are related to the increasing flood risk in the coastal cities.

An analysis of the sources may provide guidance to identify reputable scholarly journals for publication. The 2231 documents included in the analysis dataset were published in 1271 scientific sources (470 journals), indicating a wide dissemination. The top 20 journals by citations in the field of climate change extreme impacts on coastal cities are presented in Table 3. The top five consists of the journals Natural Hazards, Water (Switzerland), Journal of Coastal Research, Ocean and Coastal Management and Sustainability (Switzerland), with 66, 43, 41, 35 and 28 publications respectively, accounting for the 17% of the published work, approximately. The *h*-index according to Google Scholar and the Impact Factors on Web of Science (WoS) and Scopus are also included in the table. The data have been retrieved from the SCI Journal database and the values were last measured in 2020 (SCI Journal). The five journals with the highest *h*-indices are Science of the Total Environment (244), Journal of Hydrology (226), Water Resources Research (217), Climatic Change (188), and Journal of Environmental Management (179). The previous journals are also the top five regarding the Scopus and WoS Impact Factors, although the order is slightly different: Science of the Total Environment (7.937; 6.551), Journal of Environmental Management (7.058; 5.647), Journal of Hydrology (6.002; 4.500), Water Resources Research (5.549; 4.309), and Climatic Change (5.248; 4.134), with the Scopus and WoS Impact Factors indicated respectively in the brackets. However, it has been observed that some of the most impactful articles had been published in other relevant journals, e.g., *Nature*, *Nature Communications*, *Nature Climate Change* and *Science*.

Altogether, the network of countries associated with publications on climate-change extreme impacts on coastal cities from VOSviewer (showing countries with a minimum of five publications) and the standard graphs illustrating the geographical distribution of the number of citations and publications show that the countries where the research is more productive include the United Stated of America, United Kingdom, China, France, Netherlands, Australia, Italy, India and Indonesia. Fig. 3 illustrates the most active countries in the research domain and their cooperation, including 44 countries (amongst 135 identified in the dataset) with at least 10 publications and 50 citations, and excluding countries that did not have a cooperation relation. The node sizes,

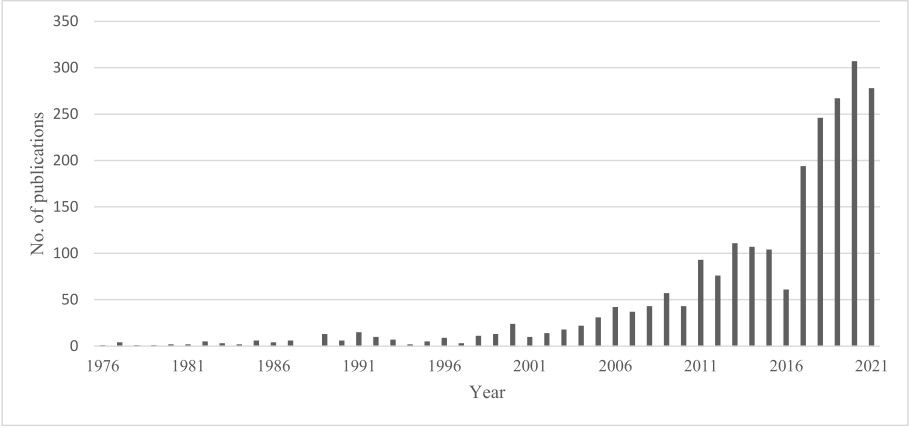

Fig. 2. Evolution of publications on climate-change extreme impacts in coastal cities between 1976 and 2021.

Table 2
Articles accumulating more than 200 citations in Scopus (December 2021).

Authors	Title	Year	Source title	Citation	Reference
Hallegatte, S.; Green, C.; et al.	Future flood losses in major coastal cities	2013	Nature Climate Change	1034	Hallegatte et al. (2013)
Sallenger, A; Doran, K.; and Howd, P.	Hotspot of accelerated sea-level rise on the Atlantic coast of North America	2012	Nature Climate Change	459	Sallenger et al. (2012)
Hanson, S.; Nicholls, R.; et al.	A global ranking of port cities with high exposure to climate extremes	2011	Climatic Change	408	Hanson et al. (2011)
Reid, C; O'Neill, M; et al.	Mapping community determinants of heat vulnerability	2009	Environmental Health Perspectives	359	Reid et al. (2009)
Douglas, I.; Alam K.; et al.	Unjust waters: Climate change, flooding and the urban poor in Africa	2008	Environment and Urbanization	359	Douglas et al. (2008)
Kunkel, K.E.; Pielke Jr., R.A.; and Changnon, S.A.	Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review	1999	Bulletin of the American Meteorological Society	355	Kunkel et al. (1999)
E. Balica. et al.	A flood vulnerability index for coastal cities and its use in assessing climate change impacts	2012	Natural Hazards	326	Balica et al. (2012)
Balica, S.F.; Wright, N.G.; and van der Meulen, F.	Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction	2013	Remote Sensing of Environment	286	Chaussard et al. (2013)
Vitousek, S.; Barnard, P.L.; et al.	Doubling of coastal flooding frequency within decades due to sea-level rise	2017	Scientific Reports	268	Vitousek et al. (2017)
Clark, G.E.; Moser, S.C.; et al.	Assessing the vulnerability of coastal communities to extreme storms: The case of reverse, MA., USA	1998	Mitigation and Adaptation Strategies for Global Change	260	Clark et al. (1998)
Aerts, J.C.J. H.; Botzen, W.J. W.; et al.	Evaluating flood resilience strategies for coastal megacities	2014	Science	258	Aerts et al. (2014)
Gornitz, V.	Global coastal hazards from future sea level rise	1991	Palaeogeography, Palaeoclimatology, Palaeoecology	215	Gornitz (1991)
Revi, A.	Climate change risk: An adaptation and mitigation agenda for Indian cities	2008	Environment and Urbanization	204	Revi (2008)

colours, and connecting lines in the cooperation network reflect the number of publications, collaboration clusters, and strength of collaborations, respectively. Figs. 4 and 5 show the complete geographical distribution of the number of publications and citations by country, respectively. The United States of America dominates the scene with 631 works published and 11362 citations, whereas the second and third place are occupied by the United Kingdom and China, with 5030 and 2551 citations, respectively.

Similarly, Fig. 6 shows the network of authors who have written at least 3 publications and accumulated at least 15 citations. Out of the 6863 authors included in the dataset, 216 meet the threshold. However, the largest set of related authors included 127 of them, represented in figure. As in the previous graph, the node sizes, colours, and connecting lines in the network reflect the number of publications, collaboration clusters, and strength of collaborations, respectively. The author who has accumulated more publications in the research topic is Mohammad Karamouz, from the University of Tehran, with 22 published documents, including articles related to coastal flooding resilience (Karamouz et al., 2019; Mohammad and Zahra, 2017), coastal flooding modelling (Karamouz and Fereshtehpour, 2019; Mohammad et al., 2017), climate change impacts on coastal flood vulnerability (Zahmatkesh and Karamouz, 2017), and coastal flooding risk management (Mohammad and Zahra, 2020), for instance. Ning Lin (Princeton University) has worked on impactful articles studying extreme storms and their consequences on the rainfall; extreme sea levels; and coastal flooding (Garner et al., 2017; Lin and Shullman, 2017; Marsooli et al., 2019; Marsooli and Lin, 2018; Yin et al., 2021). Xiuquan Wang (University of Prince Edward Island) has developed his research on, *inter alia*, regional changes in temperature and precipitation (and other climatic variables) extremes through downscaling methods (Zhou et al., 2018a, 2018b; Zhu et al., 2017, 2018) and occurrences of droughts under climatic change (Sun et al., 2019). Robert J. Nicholls (University of East Anglia) has worked on a number of global studies regarding the impacts of climate change on coastal systems, e.g., coastal zones (Nicholls and Cazenave, 2010), coastal cities (Hallegatte et al., 2013), wetlands (Nicholls, 2004; Nicholls et al., 1999), and the adaptation costs, among other topics (Hinkel et al., 2014). Last, but not least, Zahra Zahmatkesh (McMaster University) has delved into the effects of climate change on urban storm water runoff and their mitigation (Zahra et al., 2015a, 2015b).

A meta-analysis of the keywords included in the scientific publications may be used to reveal the "hot topics". In this vein, Fig. 7 shows the network of keywords associated with publications on climate change extreme impacts on coastal cities, and Fig. 8, the corresponding heatmap. Only the keywords which appeared in at least 15 publications of the dataset are showed in the graph, representing 356 out of the 12142 terms included in the dataset. As previously, the node sizes, colours, and connecting lines reflect the number of keywords, relationship clusters, and strength of the links in the network, respectively. Some of the most recurring terms and their occurrences are presented in Table 4. The analysis of the clusters identified shows how the research topics may be classified within six categories. The largest cluster (red) incorporates a variety of keywords related to policy making and planning (e.g., climate change adaptation, mitigation, adaptative management, sustainable development, urban planning, resilience, water management, regional planning, decision making, risk assessment, strategic approach). "Rivers", "catchments", "water supply", "groundwater", "runoff", "river discharge", "urban flood", "aquifers", "hydrology" and other water-related terms are covered by the green cluster. The third cluster (dark blue) includes keywords corresponding to coastal erosion and coast morphology, such us "accretion", "barrier island", "beach erosion", "beach nourishment", "breakwaters", "coastal engineering", "coastal management", "land reclamation", "satellite imagery", "sediment" and "shoreline change", *inter alia*. Topics related to climatology and meteorology are well covered by the yellow cluster: "air temperature", "climate models", "extreme event/precipitation/rainfall", "forecasting", "frequency analysis", "precipitation", or "return period" are some examples of this. The cluster coloured in light blue is apparently related to climate-related hazards and risk in the USA, as it includes, for example, "coastal flooding", "embankments", "Florida (USA)", "hurricanes", "Hurricane Sandy", "Hurricane Katrina", "levees", "New York", "New Orleans", "storm surge" and "United States". The last cluster (violet) of research hot terms does not seem to focus on any topic in particular and may be understood as a cluster connecting the remaining part of the network.

Finally, it has been observed how the research topics have evolved between 1976 and 1991, 1992–2001, 2002–2006, 2007–2011, 2012–2016 and 2017–2021 (Fig. 9). In the first period (1976–1991), the most recurrent terms are mainly associated to the domain of coastal

Table 3
Twenty journals with the highest number of publications of the dataset, including the scholarly metrics of h-index (from Google Scholar) and Impact Factor (from Web of Science and Scopus) retrieved from the SCI Journal database(https://www.scijournal.org/). Note that some values of the Impact Factor were not available for the Web of Science browser.

Journal	Number of publications	*h*-index (Google Scholar)	Impact Factor (WoS)	Impact Factor (Scopus)
Natural Hazards	66	105	2.427	3.494
Water (Switzerland)	43	55	*Not available*	3.287
Journal of Coastal Research	41	90	0.793	0.885
Ocean and Coastal Management	35	84	2.482	3.581
Sustainability (Switzerland)	28	85	2.576	3.659
International Journal of Disaster Risk Reduction	19	45	2.896	5.145
Science of the Total Environment	17	244	6.551	7.937
Journal of Hydrology	15	226	4.500	6.002
Coastal Engineering	14	110	4.119	5.078
Journal of Coastal Conservation	14	39	1.374	1.823
Natural Hazards and Earth System Sciences	14	99	3.102	4.202
Arabian Journal of Geosciences	13	48	1.327	1.958
Environmental Earth Sciences	13	118	2.180	2.851
Journal of Flood Risk Management	13	36	3.066	3.641
Climatic Change	11	188	4.134	5.248
WIT Transactions on Ecology and the Environment	11	24	*Not available*	0.43
Environmental Monitoring and Assessment	10	109	*Not available*	2.805
Journal of Environmental Management	9	179	5.647	7.058
Water Resources Management	9	100	2.924	3.825
Water Resources Research	9	217	4.309	5.549

erosion (e.g., “coastal engineering”, “shore protection”, “tides”, “beach erosion”, “coastal processes”, “beach”, “dune” and “barrier islands”), but also to the study of storms and floods (“meteorology-storms”, “water waves”, “flood control”, “flood protection” and “storm surges”) and the study cases of the Venice Lagoon (Italy) and Ocean City (Maryland, USA). The second period (1992–2001) introduces a number of new topics related to climate change (“greenhouse”, “global warming”, “climate”, “meteorology”, “pollution control” and “anthropogenic effect”). In the third period (2002–2006), keywords related to the USA and natural disasters are strongly linked, reflecting the impact of Hurricane Katrina (“United States”, “New Orleans”, “North America”, “natural disasters”, “hurricanes” and “disaster planning”). Furthermore, other topics related to probabilistic analysis and hazard modelling (“computer simulation”, “joint probability”, “extreme event”, “geographic information systems” and “GIS”) and large geographical areas (“world”, “Far East”, “Asia”, “South America”, “Eurasia”, “Africa”, “Europe”, “western hemisphere”) are also of relevance in this period. Although the term “risk assessment” was present in the heatmap, it is in the period (2007–2011) when this keyword is most recurrent, including some related topics (“risk management”, “vulnerability”, “risk perception”, and “risk factor”). The last two periods (2012–2016) and (2017–2021) do not show the boom of a new group of keywords as in the previous cases. Instead, the heatmaps are very similar to the one corresponding to the period (2007–2011), although the number of publications per year had significantly grown. This may reflect a period of knowledge consolidation during the last decade.

4. Discussion

The understanding of the impacts of climate change on coastal systems has continuously evolved since the first published studies regarding this matter. In this sense, the chronological alignment of certain milestones and the corresponding variations in the number of publications suggest a connection worth exploring. For example, the relative peak in the number of publications reached in 1989 coincides with the foundation of the IPCC in 1988, which brought together numerous scientists to assess scientific evidence on climate change and its impacts. This correlation could potentially be attributed to a shift in research focus towards collaboration with the IPCC, leading to a temporary increase in publications specifically related to coastal cities. Another noteworthy association is observed around the year 1997 when the United Nations Framework Convention on Climate Change (UNFCCC) adopted the Kyoto Protocol as the world’s first greenhouse gas emissions treaty. This milestone is followed by an increase in the number of publications for subsequent years. The adoption of the Kyoto Protocol likely drew attention to the impacts of climate change, including those on coastal cities, prompting researchers to intensify their investigations and publish findings related to this crucial area. Similarly, in subsequent years, as the adoption of the UN Sustainable Development Goals (SDGs) and agreements such as the Paris Agreement gained prominence between 2015 and 2016, the number of publications related to the impacts of climate change on coastal cities exhibited an upward trend, especially between 2017 and 2021. This suggests that global climate change agreements and initiatives served as catalysts for increased research focus on the specific challenges faced by coastal cities and their vulnerability to climate change, leading to the establishment of cities as relevant actors in the global climate change regime (Aust, 2018). It is important to note that while these observations indicate a general relationship between the milestones and the publication trends, they do not establish a direct cause-and-effect relationship. Numerous other factors, including regional research priorities, funding availability, and evolving scientific paradigms, can also influence publication patterns. Additionally, the number of publications alone does not capture the depth or quality of the research conducted.

In the literature, an event is generally considered extreme if the value of a certain variable exceeds a threshold. The boundary between non-extreme and extreme events is usually defined based on the consequences that these extreme values may trigger (e.g., health impacts, irreversible damage to goods and property, biodiversity loss) (Seneviratne et al., 2012). In this vein, a large number of keywords are closely related with the definition of extreme events and their consequences. For example, keywords from yellow and light blue clusters may reflect that much research is oriented towards these topics.

The frequency and intensity of some climate change extreme events are increasing due to climate change. Climate-change extreme impacts may refer to the harmful effects of short-duration climate-change extreme events which produce a certain level of damage – usually on the economy, society, environment, urbanisation or geomorphology. Climate-change extreme impacts are usually driven by severe storms, which lead to strong winds, high sea levels, intense rainfall, coastal flooding and coastal erosion episodes, loss of ecosystems, salinisation of soils, ground and surface water, and impeded drainage. Moreover, light changes in some magnitudes may also lead to large impacts on fragile coastal systems. Changes in temperature, precipitation, substance concentration or pH may produce large-scale effects, such as droughts and eutrophication, leading to impacts on ecosystems, soil characteristics and water availability, or even forest fires, algal blooms and fish kills

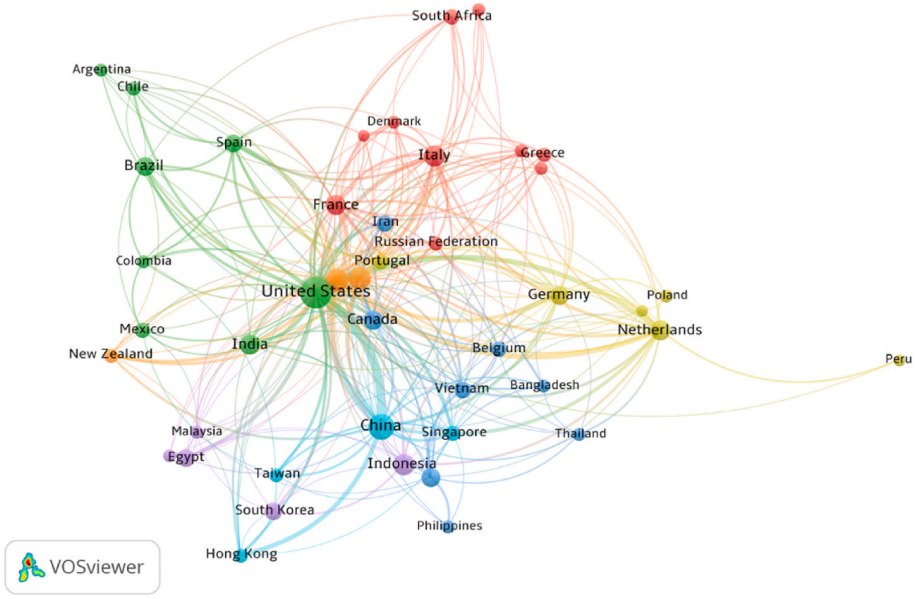

Fig. 3. Network visualization of countries/regions associated with publications regarding climate-change extreme impacts on coastal cities.

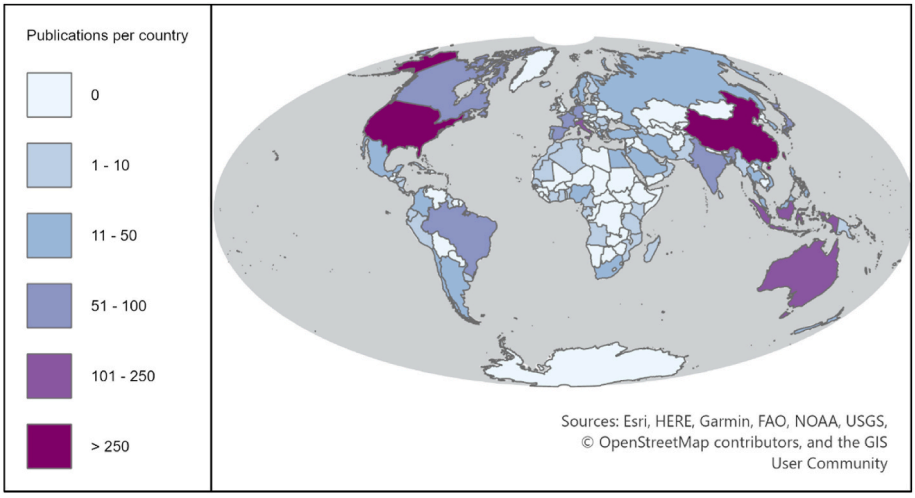

Fig. 4. Geographical distribution of publications.

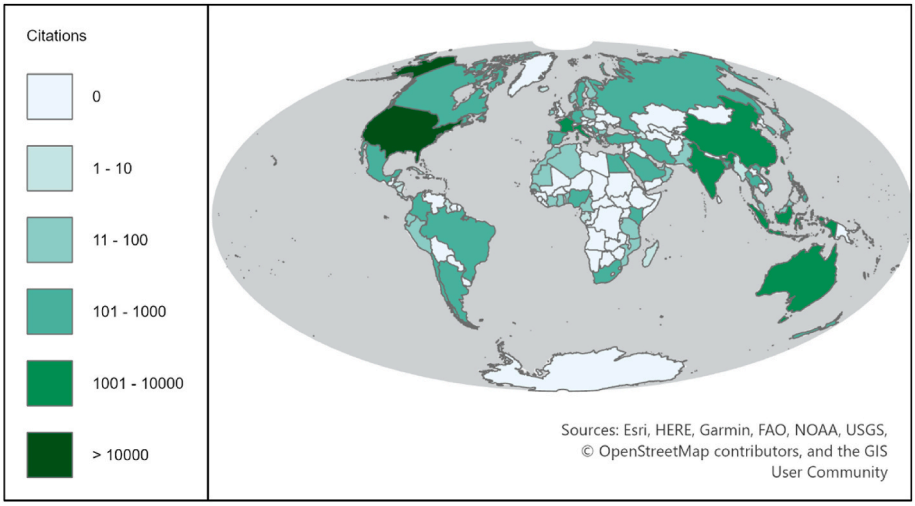

Fig. 5. Geographical distribution of citations.

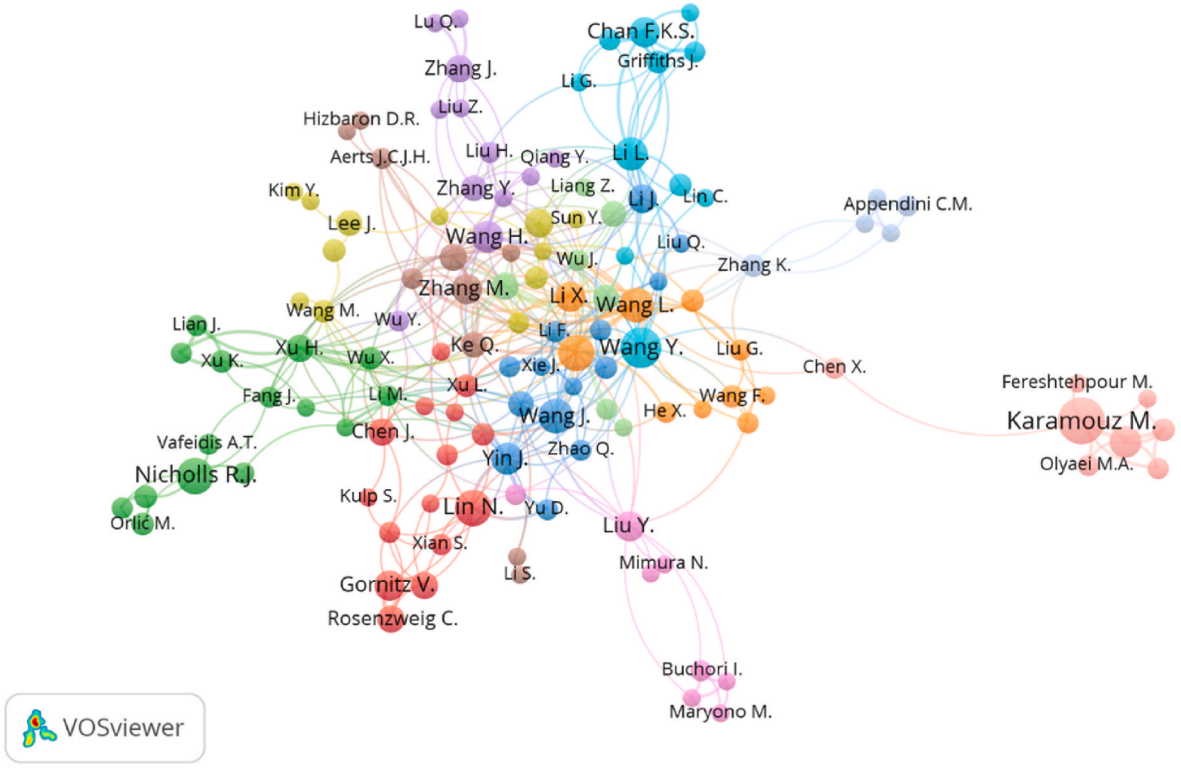

Fig. 6. Network visualization of the authors associated with publications regarding climate-change extreme impacts on coastal cities.

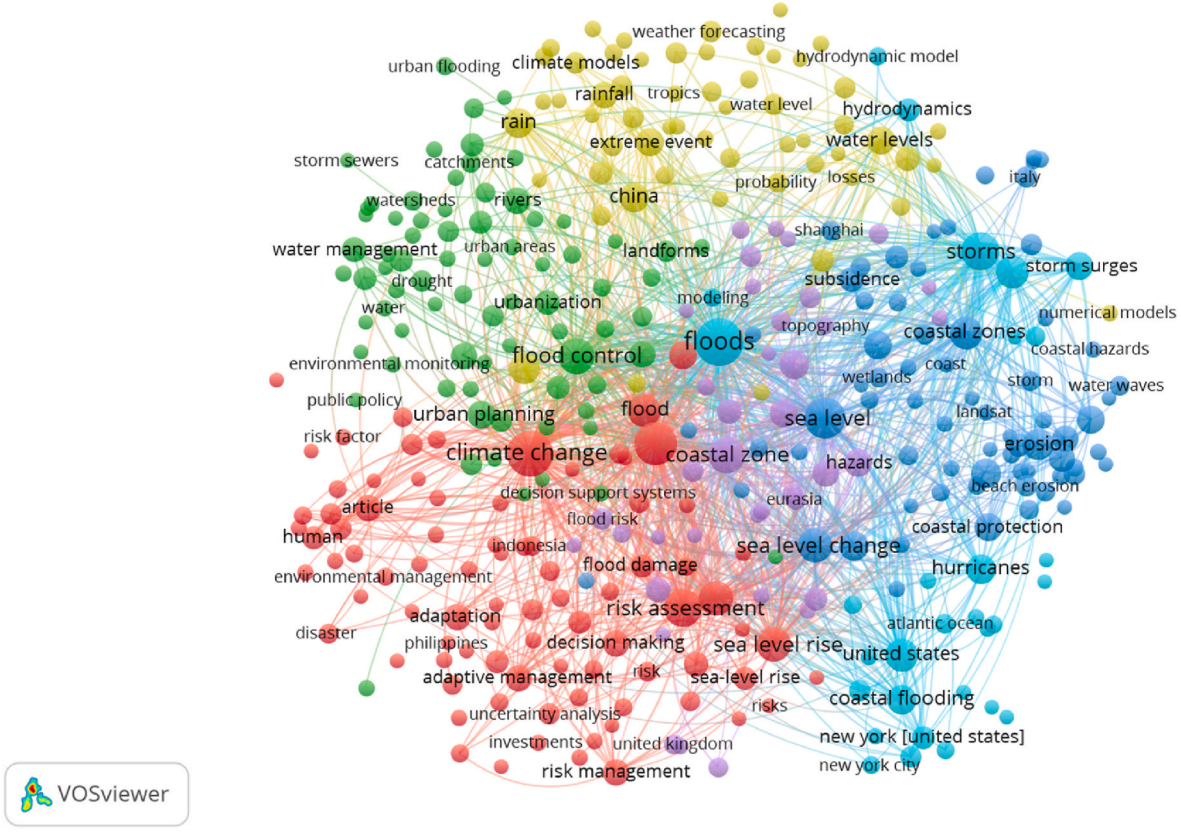

Fig. 7. Network of keywords of publications on climate-change extreme impacts on coastal cities.

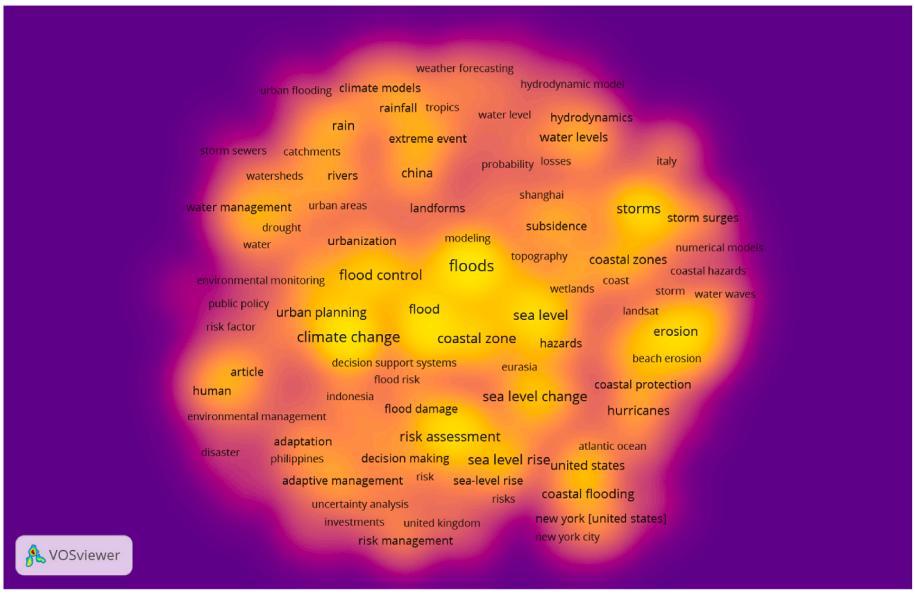

Fig. 8. Heatmap of keywords of publications on climate-change extreme impacts on coastal cities.

Table 4
More frequent keywords of the publications on climate-change extreme impacts on coastal cities.

Keywords	Number of occurrences
Floods	652
Climate change	584
Storms	314
Risk assessment	200
Coastal zone	275
Flood control	252
Sea-level rise	230
Vulnerability	226
United States	207
Storm surge	199
Urban area	165
Erosion	159
Rain	142
Hurricanes	137
Disasters	137

(Vollenweider, 1992). On the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities, the capacity of the urban drainage systems to absorb storm water, the construction of renewable energy infrastructure, and critical infrastructures such as transportation, ports, and naval bases (Hadley, 2009; Zellou and Rahali, 2019). Furthermore, some results and conclusions from research on inland cities may be applied to coastal cities.

Climate change effects do not take place alone. More often than not, the impacts on cities are caused by a combination of climate change effects and human drivers. For instance, the transformation of the coast due to human action (e.g., keywords related to coastal protection schemes, ports and urbanization) modifies the development of climate change extreme events and determines the exposure and vulnerability of nearby cities. Moreover, other geohazards not necessarily related to climate change, such as earthquakes, tsunamis and volcanic eruptions, may increase the harmful potential of climate-change-related hazards (e.g., flood risk (Cavalieri et al., 2015)) as a result of extensive changes in the terrain level, the coastal morphology and the built environment of cities. In addition, the eventual failure of protection systems, e.g., breakwaters, levees and dams, may be expected to increase damage levels.

Conversely, certain human actions, such as beach nourishment to control erosion or, in particular, ecosystem-based approaches (e.g., restoration of vegetation in dune and mangrove habitats) contribute to the resilience of cities to climate change (Jin et al., 2015). However, in the scientometric analysis it is readily seen how most of the publications focus on the characterisation of hazards and assessment of risks, whereas the number of publications relating to the development of coastal adaptation solutions is far smaller. One possible explanation is the complex nature of coastal adaptation solutions. Crafting effective strategies that can withstand the dynamic nature of coastal ecosystems and the multifaceted challenges they face often requires a multidisciplinary approach and extensive collaboration among researchers, policymakers, and stakeholders. The absence of substantial research in this area may suggest a need for enhanced collaboration and interdisciplinary efforts to tackle the intricate issues posed by coastal adaptation. Moreover, it is plausible that the limited availability of funding and resources might be a contributing factor. Research endeavours aimed at developing viable adaptation solutions in coastal regions often demand substantial financial investment and logistical support. The comparatively smaller number of publications in this domain may reflect the challenges that researchers face in securing the necessary resources to undertake comprehensive studies and develop practical solutions. Notwithstanding, the societal conscience is gradually evolving to apprehend new concepts that have emerged in the urban planning and policy-making landscape in recent years, such as climate-change adaptation, climate resilience, adaptative management, sustainable development, or disaster prevention, *inter alia* (Kirby et al., 2021; McClatchey et al., 2014; Petzold and Ratter, 2015).

Climate change has sound impacts on coastal societies and greatly attracts the interest of the scientific community and governments, resulting in a frenetic scientific production. Although the number of publications that relate climate change and its impact on coastal systems is high, as can be deduced from this work, no publication has been found that performs a holistic meta-analysis of said works, in order to understand their momentum. The novelty of this work lies in the unified and systematic meta-analysis of how the study of climate change has developed and evolved from its roots to today throughout the world, by means of a scientometric and bibliometric approach. Due to its complexity, the study of the impact of anthropogenic action on coastal systems has been left aside. Its analysis would complement to that developed here to finish understanding the evolution of the main challenges that coastal cities face.

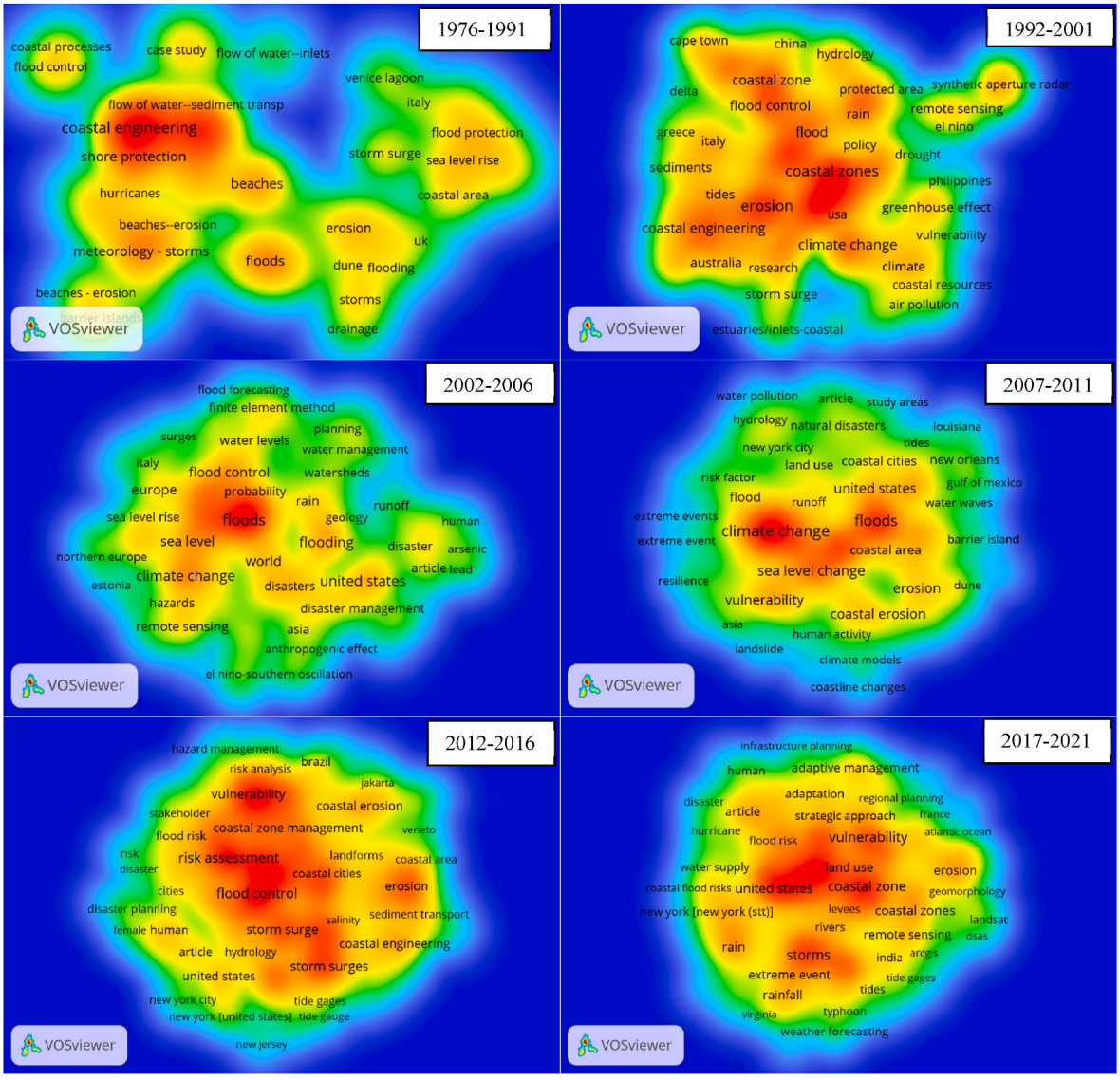

Fig. 9. Temporal evolution of heatmaps of keywords of publications on climate-change extreme impacts on coastal cities.

5. Conclusions

The results shows that scientometric analysis can provide a valuable tool for understanding the research landscape on climate change and coastal cities, including the key themes, contributors, and impacts of the research, as well as the gaps and opportunities for further research.

Scopus offers researchers a powerful tool for accessing, exploring, and analysing scholarly literature. It provides a wide range of features and functionalities for citation tracking, search, and retrieval. However, researchers should be aware of its limitations, including incomplete coverage, language bias, data limitations, and potential biases in the database.

The research interest in extreme impacts of climate change is high, as evidenced by the number of publications, authors and citations. The results show in which manner authors collaborate, and how the keywords analysed are directly related to concepts of sea-level rise and extreme events. The research topics associated to coastal flooding, coastal erosion and sea level rise were covered, and the trending topics and those less pursued so far were indicated. Hot topics of research are mainly related to the assessment of climate-related hazards and risks, policy making and planning, water-related topics, coastal management, climatology and meteorology.

The most relevant publications, authors and research topics have been identified and analysed. The journals Ocean and Coastal Management, Journal of Coastal Research, Natural Hazards, Water (Switzerland) and Sustainability (Switzerland) were the venue for the highest number of documents and considerable scholarly metrics. The five authors who have accumulated more publications in the research topic are Mohammad Karamouz (University of Tehran), Ning Lin (Princeton University), Xiuquan Wang (University of Prince Edward Island), Robert J. Nicholls (University of East Anglia) and Zahra Zahmatkesh (McMaster University). Some of the most impactful publications encompassing the different research areas identified include “Future flood losses in major coastal cities”, “Hotspot of accelerated sea-level rise on the Atlantic coast of North America”, “A global ranking of port cities with high exposure to climate extremes”, “Mapping community determinants of heat vulnerability” and “Unjust waters: Climate change, flooding and the urban poor in Africa” (Douglas et al., 2008; Hallegatte et al., 2013; Hanson et al., 2011; Reid et al., 2009; Sallenger et al., 2012).

Regarding the geographical coverage, works tend to concentrate in a few regions, and there is a serious scarcity of studies published in English in developing countries. USA, China, UK, Australia and Indonesia are the countries which concentrate most of the research. Many of the

publications do not focus on coastal cities exclusively but on long coastal fringes where cities are included.

The results show how climate-change extreme impacts on coastal cities are scoped by research, but also how the concepts and disciplines in the study of these impacts are related to each other through the different keywords and clusters which arose from the scientometric analysis. The number of scientific studies has evolved alongside the growing societal conscience of the need to combat climate change over the last fifty years, since the foundation of the IPCC up to the ratification of the European Green Deal, with an unprecedented surge in the last five years. Many of the keywords and clusters raised are closely related with the characterisation of climate-related extreme events and hazards, rather than with coastal adaptation measures or the development of integrated coastal zone management tools.

The synthesis carried out in this work by means of a bibliometric and scientometric analysis on climate-change extreme impacts on coastal areas contributed to documenting and understanding the momentum of the research to date, but also to helping scientists spot research gaps which might otherwise be missed or to orientating new investigation. The study of emerging integrated coastal zone management tools (e.g., nature-based solutions, ecosystem-based approaches, coastal city living labs, digital twins and smart-sensing technologies) and the impacts of climate change on developing countries are possible opportunities to extend current research. Moreover, key events and agreements in the global climate change fight appear to have influenced research interest and output in studying the effects of climate change on coastal cities. Further investigation and analysis are necessary to ascertain the precise nature and extent of this relationship.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

Aerts, J.C.J.H., Wouter, B.W.J., Kerry, E., Ning, L., Hans, de M., O, M.-K.E., 2014. Evaluating flood resilience strategies for coastal megacities. Science 344, 473–475. https://doi.org/10.1126/science.1248222, 1979.

Aust, H., 2018. The shifting role of cities in the global climate change regime: from Paris to Pittsburgh and back? Rev. Eur. Community Int. Environ. Law 28. https://doi.org/10.1111/reel.12272.

Balica, S.F., Wright, N.G., van der Meulen, F., 2012. A flood vulnerability index for coastal cities and its use in assessing climate change impacts. Nat. Hazards 64, 73–105. https://doi.org/10.1007/s11069-012-0234-1.

Bergillos, R.J., Rodriguez-Delgado, C., Cremades, J., Medina, L., Iglesias, G., 2020a. Multi-criteria characterization and mapping of coastal cliff environments: a case study in NW Spain. Sci. Total Environ. 746, 140942 https://doi.org/10.1016/j.scitotenv.2020.140942.

Bergillos, R.J., Rodriguez-Delgado, C., Medina, L., Iglesias, G., 2020b. Coastal cliff exposure and management. Ocean Coast Manag. 198, 105387 https://doi.org/10.1016/j.ocecoaman.2020.105387.

Beusen, A.H.W., Bouwman, A.F., van Beek, L.P.H., Mogollón, J.M., Middelburg, J.J., 2016. Global riverine N and P transport to ocean increased during the 20th century despite increased retention along the aquatic continuum. Biogeosciences 13, 2441–2451. https://doi.org/10.5194/bg-13-2441-2016.

Cavalieri, F., Franchin, P., Ko, S., Giovinazzi, S., Hart, D., 2015. Probabilistic Assessment of Increased Flooding Vulnerability in Christchurch City after the Canterbury 2010-2011 Earthquake Sequence (New Zealand).

Chaussard, E., Amelung, F., Abidin, H., Hong, S.-H., 2013. Sinking cities in Indonesia: ALOS PALSAR detects rapid subsidence due to groundwater and gas extraction. Remote Sens. Environ. 128, 150–161. https://doi.org/10.1016/j.rse.2012.10.015.

Clark, G.E., Moser, S.C., Ratick, S.J., Dow, K., Meyer, W.B., Emani, S., Jin, W., Kasperson, J.X., Kasperson, R.E., Schwarz, H.E., 1998. Assessing the vulnerability of coastal communities to extreme storms: the case of revere, MA., USA. Mitig. Adapt. Strategies Glob. Change 3, 59–82. https://doi.org/10.1023/A:1009609710795.

Costa, Y., Martins, I., de Carvalho, G.C., Barros, F., 2023. Trends of sea-level rise effects on estuaries and estimates of future saline intrusion. Ocean Coast Manag. 236, 106490 https://doi.org/10.1016/j.ocecoaman.2023.106490.

Crespi, A., Terzi, S., Cocuccioni, S., Zebisch, M., Berckmans, J., Füssel, H.-M., 2020. Climate-related Hazard Indices for Europe.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate Change and Forest Disturbances: climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. Bioscience 51, 723–734. https://doi.org/10.1641/0006-3568(2001)051[0723:CCAFD]2.0.CO, 2.

Dawson, R.J., Dickson, M.E., Nicholls, R.J., Hall, J.W., Walkden, M.J.A., Stansby, P.K., Mokrech, M., Richards, J., Zhou, J., Milligan, J., Jordan, A., Pearson, S., Rees, J., Bates, P.D., Koukoulas, S., Watkinson, A.R., 2009. Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Clim. Change 95, 249–288. https://doi.org/10.1007/s10584-008-9532-8.

Douglas, I., Alam, K., Maghenda, M., Mcdonnell, Y., Mclean, L., Campbell, J., 2008. Unjust waters: climate change, flooding and the urban poor in Africa. Environ. Urbanization 20, 187–205. https://doi.org/10.1177/0956247808089156.

Garner, A.J., Mann, M.E., Emanuel, K.A., Kopp, R.E., Lin, N., Alley, R.B., Horton, B.P., DeConto, R.M., Donnelly, J.P., Pollard, D., 2017. Impact of climate change on New York City's coastal flood hazard: increasing flood heights from the preindustrial to 2300 CE. Proc. Natl. Acad. Sci. USA 114, 11861–11866. https://doi.org/10.1073/pnas.1703568114.

González Hernández, M.M., León, C.J., García, C., Lam-González, Y.E., 2023. Assessing the climate-related risk of marine biodiversity degradation for coastal and marine tourism. Ocean Coast Manag. 232, 106436 https://doi.org/10.1016/j.ocecoaman.2022.106436.

Gornitz, V., 1991. Global coastal hazards from future sea level rise. Palaeogeogr. Palaeoclimatol. Palaeoecol. 89, 379–398. https://doi.org/10.1016/0031-0182(91)90173-O.

Hadley, D., 2009. Land use and the coastal zone. Land Use Pol. 26, S198. https://doi.org/10.1016/j.landusepol.2009.09.014. –S203.

Hallegatte, S., Green, C., Nicholls, R.J., Corfee-Morlot, J., 2013. Future flood losses in major coastal cities. Nat. Clim. Change 3, 802–806. https://doi.org/10.1038/nclimate1979.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., Chateau, J., 2011. A global ranking of port cities with high exposure to climate extremes. Clim. Change 104, 89–111. https://doi.org/10.1007/s10584-010-9977-4.

He, Q., Silliman, B.R., 2019. Climate change, human impacts, and coastal ecosystems in the anthropocene. Curr. Biol. 29, R1021–R1035. https://doi.org/10.1016/j.cub.2019.08.042.

Hinkel, J., Lincke, D., Vafeidis, A.T., Perrette, M., Nicholls, R.J., Tol, R.S.J., Marzeion, B., Fettweis, X., Ionescu, C., Levermann, A., 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. Proc. Natl. Acad. Sci. USA 111, 3292–3297. https://doi.org/10.1073/pnas.1222469111.

Hinkel, J., Nicholls, R.J., Tol, R.S.J., Wang, Z.B., Hamilton, J.M., Boot, G., Vafeidis, A.T., McFadden, L., Ganopolski, A., Klein, R.J.T., 2013. A global analysis of erosion of sandy beaches and sea-level rise: an application of DIVA. Global Planet. Change 111, 150–158. https://doi.org/10.1016/j.gloplacha.2013.09.002.

IPCC, 2021. Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (in press).

Jin, D., Hoagland, P., Au, D.K., Qiu, J., 2015. Shoreline change, seawalls, and coastal property values. Ocean Coast Manag. 114, 185–193. https://doi.org/10.1016/j.ocecoaman.2015.06.025.

Karamouz, M., Fereshtehpour, M., 2019. Modeling DEM errors in coastal flood inundation and damages: a spatial nonstationary approach. Water Resour. Res. 55, 6606–6624. https://doi.org/10.1029/2018WR024562.

Karamouz, M., Taheri, M., Khalili, P., Chen, X., 2019. Building infrastructure resilience in coastal flood risk management. J. Water Resour. Plann. Manag. 145, 04019004 https://doi.org/10.1061/(ASCE)WR.1943-5452.0001043.

Kirby, J.A., Masselink, G., Essex, S., Poate, T., Scott, T., 2021. Coastal adaptation to climate change through zonation: a review of coastal change management areas (CCMAs) in England. Ocean Coast Manag. 215, 105950 https://doi.org/10.1016/j.ocecoaman.2021.105950.

Kirezci, E., Young, I.R., Ranasinghe, R., Muis, S., Nicholls, R.J., Lincke, D., Hinkel, J., 2020. Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. Sci. Rep. 10, 11629 https://doi.org/10.1038/s41598-020-67736-6.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K., Sugi, M., 2010. Tropical cyclones and climate change. Nat. Geosci. 3, 157–163. https://doi.org/10.1038/ngeo779.

Koks, E.E., Rozenberg, J., Zorn, C., Tariverdi, M., Vousdoukas, M., Fraser, S.A., Hall, J. W., Hallegatte, S., 2019. A global multi-hazard risk analysis of road and railway infrastructure assets. Nat. Commun. 10, 2677. https://doi.org/10.1038/s41467-019-10442-3.

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

Kunkel, K.E., Pielke, R.A., Changnon, S.A., 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: a review. Bull. Am. Meteorol. Soc. 80, 1077–1098. https://doi.org/10.1175/1520-0477(1999)080<1077:TFIWAC>2.0.CO, 2.

Lima, C.O., Bonetti, J., 2020. Bibliometric analysis of the scientific production on coastal communities' social vulnerability to climate change and to the impact of extreme events. Nat. Hazards 102, 1589–1610. https://doi.org/10.1007/s11069-020-03974-1.

Lin, N., Shullman, E., 2017. Dealing with hurricane surge flooding in a changing environment: part I. Risk assessment considering storm climatology change, sea level rise, and coastal development. Stoch. Environ. Res. Risk Assess. 31, 2379–2400. https://doi.org/10.1007/s00477-016-1377-5.

Marsooli, R., Lin, N., 2018. Numerical modeling of historical storm tides and waves and their interactions along the U.S. East and gulf coasts. J. Geophys. Res. Oceans 123, 3844–3874. https://doi.org/10.1029/2017JC013434.

Marsooli, R., Lin, N., Emanuel, K., Feng, K., 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nat. Commun. 10, 3785. https://doi.org/10.1038/s41467-019-11755-z.

McClatchey, J., Devoy, R., Woolf, D., Bremner, B., James, N., 2014. Climate change and adaptation in the coastal areas of Europe's Northern Periphery Region. Ocean Coast Manag. 94, 9–21. https://doi.org/10.1016/j.ocecoaman.2014.03.013.

Melet, A., Meyssignac, B., Almar, R., le Cozannet, G., 2018. Under-estimated wave contribution to coastal sea-level rise. Nat. Clim. Change 8, 234–239. https://doi.org/10.1038/s41558-018-0088-y.

Mentaschi, L., Vousdoukas, M.I., Voukouvalas, E., Dosio, A., Feyen, L., 2017. Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. Geophys. Res. Lett. 44, 2416–2426. https://doi.org/10.1002/2016GL072488.

Mingers, J., Leydesdorff, L., 2015. A review of theory and practice in scientometrics. Eur. J. Oper. Res. 246, 1–19. https://doi.org/10.1016/j.ejor.2015.04.002.

Mohammad, K., Forough, A., Zahra, Z., 2017. Distributed hydrologic modeling of coastal flood inundation and damage: nonstationary approach. J. Irrigat. Drain. Eng. 143, 04017019 https://doi.org/10.1061/(ASCE)IR.1943-4774.0001173.

Mohammad, K., Zahra, H., 2020. Conceptual design framework for coastal flood best management practices. J. Water Resour. Plann. Manag. 146, 04020041 https://doi.org/10.1061/(ASCE)WR.1943-5452.0001224.

Mohammad, K., Zahra, Z., 2017. Quantifying resilience and uncertainty in coastal flooding events: framework for assessing urban vulnerability. J. Water Resour. Plann. Manag. 143, 04016071 https://doi.org/10.1061/(ASCE)WR.1943-5452.0000724.

Morton, R., 1976. Effects of Hurricane Eloise on beach and coastal structures. Florida Panhandle. Geology 4, 2. https://doi.org/10.1130/0091-7613(1976)4<277:EOHEOB>2.0.CO.

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding–a global assessment. PLoS One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571.

Nguyen, T.T.X., Bonetti, J., Rogers, K., Woodroffe, C.D., 2016. Indicator-based assessment of climate-change impacts on coasts: a review of concepts, methodological approaches and vulnerability indices. Ocean Coast Manag. 123, 18–43. https://doi.org/10.1016/j.ocecoaman.2015.11.022.

Nicholls, R.J., 2004. Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios. Global Environ. Change 14, 69–86. https://doi.org/10.1016/j.gloenvcha.2003.10.007.

Nicholls, R.J., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517–1520. https://doi.org/10.1126/science.1185782, 1979.

Nicholls, R.J., Hoozemans, F.M.J., Marchand, M., 1999. Increasing flood risk and wetland losses due to global sea-level rise: regional and global analyses. Global Environ. Change 9, S69. https://doi.org/10.1016/S0959-3780(99)00019-9. –S87.

Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B., Sebesvari, Z., 2019. Sea level rise and implications for low-lying islands, coasts and communities. In: Portner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B., Weyer, N.M., N, M. (Eds.), IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

Peduzzi, P., 2005. Is climate change increasing the frequency of hazardous events? Environ. Pover. Times 3, 7.

Penland, S., Connor, P.F., Beall, A., Fearnley, S., Williams, S.J., 2005. Changes in Louisiana's shoreline: 1855–2002. J. Coast Res. 7–39.

Petzold, J., Ratter, B.M.W., 2015. Climate change adaptation under a social capital approach – an analytical framework for small islands. Ocean Coast Manag. 112, 36–43. https://doi.org/10.1016/j.ocecoaman.2015.05.003.

Pollard, J.A., Spencer, T., Brooks, S.M., 2019. The interactive relationship between coastal erosion and flood risk. Prog. Phys. Geogr. Earth Environ. 43, 574–585. https://doi.org/10.1177/0309133318794498.

Ranasinghe, R., 2016. Assessing climate change impacts on open sandy coasts: a review. Earth Sci. Rev. 160, 320–332. https://doi.org/10.1016/j.earscirev.2016.07.011.

Ranasinghe, R., Ruane, A.C., Vautard, R., Arnell, N., Coppola, E., Cruz, F.A., Dessai, S., Islam, A.S., Rahimi, M., Ruiz Carrascal, D., Sillmann, J., Sylla, M.B., Tebaldi, C., Wang, W., Zaaboul, R., 2021. Climate change information for regional impact and for risk assessment. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zho, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Reid, C.E., O'Neill, M.S., Gronlund, C.J., Brines, S.J., Brown, D.G., Diez-Roux, A.V., Schwartz, J., 2009. Mapping community determinants of heat vulnerability. Environ. Health Perspect. 117, 1730–1736. https://doi.org/10.1289/ehp.0900683.

Revi, A., 2008. Climate change risk: an adaptation and mitigation agenda for Indian cities. Environ. Urbanization 20, 207–229. https://doi.org/10.1177/0956247808089157.

Rodriguez-Delgado, C., Bergillos, R.J., Iglesias, G., 2020. Coastal infrastructure operativity against flooding – a methodology. Sci. Total Environ. 719, 137452 https://doi.org/10.1016/j.scitotenv.2020.137452.

Sallenger, A.H., Doran, K.S., Howd, P.A., 2012. Hotspot of accelerated sea-level rise on the Atlantic coast of North America. Nat. Clim. Change 2, 884–888. https://doi.org/10.1038/nclimate1597.

SCI Journal [WWW Document], n.d. URL https://www.scijournal.org/(accessed January.31.2023).

Seneviratne, S.I., Nicholls, N., Easterling, D., Goodess, C.M., Kanae, S., Kossin, J., Luo, Y., Marengo, J., McInnes, K., Rahimi, M., Reichstein, M., Sorteberg, A., Vera, C., Zhang, X., 2012. Changes in climate extremes and their impacts on the natural physical environment. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109–230.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M., Zhou, B., 2021. Weather and climate extreme events in a changing climate. In: Masson-Delmotte, V., Zhai, V.P., Pirani, A., Connors, S.L., Péan, C., Berger, S.N., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Smith, A., 2017. Billion-Dollar U.S. Weather and Climate Disasters 1980-2016 National Centers for Environmental Information. https://doi.org/10.13140/RG.2.2.22686.23368.

Spalding, M.D., Ruffo, S., Lacambra, C., Meliane, I., Hale, L.Z., Shepard, C.C., Beck, M. W., 2014. The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean Coast Manag. 90, 50–57. https://doi.org/10.1016/j.ocecoaman.2013.09.007.

Sun, C.X., Huang, G.H., Fan, Y., Zhou, X., Lu, C., Wang, X.Q., 2019. Drought occurring with hot extremes: changes under future climate change on loess plateau, China. Earth's Future 7, 587–604. https://doi.org/10.1029/2018EF001103.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380. https://doi.org/10.1126/science.1109454, 1979.

Task Force on Climate-related financial Disclosures [WWW Document], n.d. URL. https://www.fsb-tcfd.org/. (Accessed 31 January 2023).

UN Environment, 2019. Global Environment Outlook – GEO-6: Healthy Planet, Healthy People. Cambridge University Press, Cambridge, 10.1017/9781108627146.

van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 84, 523–538. https://doi.org/10.1007/s11192-009-0146-3.

Vitousek, S., Barnard, P.L., Fletcher, C.H., Frazer, N., Erikson, L., Storlazzi, C.D., 2017. Doubling of coastal flooding frequency within decades due to sea-level rise. Sci. Rep. 7, 1399. https://doi.org/10.1038/s41598-017-01362-7.

Vollenweider, Richard A., 1992. Coastal marine eutrophication: principles and control. In: Vollenweider, R.A., Marchetti, R., Viviani, R. (Eds.), Marine Coastal Eutrophication. Elsevier, Amsterdam, pp. 1–20. https://doi.org/10.1016/B978-0-444-89990-3.50011-0.

Vousdoukas, M.I., Mentaschi, L., Hinkel, J., Ward, P.J., Mongelli, I., Ciscar, J.-C., Feyen, L., 2020. Economic motivation for raising coastal flood defenses in Europe. Nat. Commun. 11, 2119. https://doi.org/10.1038/s41467-020-15665-3.

Vousdoukas, M.I., Mentaschi, L., Voukouvalas, E., Bianchi, A., Dottori, F., Feyen, L., 2018. Climatic and socioeconomic controls of future coastal flood risk in Europe. Nat. Clim. Change 8, 776–780. https://doi.org/10.1038/s41558-018-0260-4.

Walling, D., 2006. Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology 79, 192–216. https://doi.org/10.1016/j.geomorph.2006.06.019.

Waltman, L., van Eck, N.J., Noyons, E., 2010. A unified approach to mapping and clustering of bibliometric networks. J. Informetr. 4, 629–635. https://doi.org/10.1016/j.joi.2010.07.002.

Wong, P.P., Losada, I.J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y., Sallenger, A., 2014. Coastal systems and low-lying areas. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), 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, Cambridge, United Kingdom and New York, NY, USA, pp. 361–409.
Yin, J., Lin, N., Yang, Y., Pringle, W.J., Tan, J., Westerink, J.J., Yu, D., 2021. Hazard assessment for typhoon-induced coastal flooding and inundation in shanghai, China. J. Geophys. Res. Oceans 126, e2021JC017319. https://doi.org/10.1029/2021JC017319.
Zahmatkesh, Z., Karamouz, M., 2017. An uncertainty-based framework to quantifying climate change impacts on coastal flood vulnerability: case study of New York City. Environ. Monit. Assess. 189, 567. https://doi.org/10.1007/s10661-017-6282-y.
Zahra, Z., J, B.S., Mohammad, K., Hassan, T.-D., Erfan, G., 2015a. Low-impact development practices to mitigate climate change effects on urban stormwater runoff: case study of New York city. J. Irrigat. Drain. Eng. 141, 04014043 https://doi.org/10.1061/(ASCE)IR.1943-4774.0000770.
Zahra, Z., Mohammad, K., Erfan, G., J, B.S., 2015b. Analysis of the effects of climate change on urban storm water runoff using statistically downscaled precipitation data and a change factor approach. J. Hydrol. Eng. 20, 05014022 https://doi.org/10.1061/(ASCE)HE.1943-5584.0001064.
Zellou, B., Rahali, H., 2019. Assessment of the joint impact of extreme rainfall and storm surge on the risk of flooding in a coastal area. J. Hydrol. (Amst.) 569, 647–665. https://doi.org/10.1016/j.jhydrol.2018.12.028.
Zhou, X., Huang, G., Wang, X., Cheng, G., 2018a. Future changes in precipitation extremes over Canada: driving factors and inherent mechanism. J. Geophys. Res. Atmos. 123, 5783–5803. https://doi.org/10.1029/2017JD027735.
Zhou, X., Huang, G., Wang, X., Fan, Y., Cheng, G., 2018b. A coupled dynamical-copula downscaling approach for temperature projections over the Canadian Prairies. Clim. Dynam. 51, 2413–2431. https://doi.org/10.1007/s00382-017-4020-3.
Zhu, J., Huang, G., Wang, X., Cheng, G., 2017. Investigation of changes in extreme temperature and humidity over China through a dynamical downscaling approach. Earth's Future 5, 1136–1155. https://doi.org/10.1002/2017EF000678.
Zhu, J., Huang, G., Wang, X., Cheng, G., Wu, Y., 2018. High-resolution projections of mean and extreme precipitations over China through PRECIS under RCPs. Clim. Dynam. 50, 4037–4060. https://doi.org/10.1007/s00382-017-3860-1.
Zillman, J., 2009. A history of climate activities. World Meteorol. Organ. Bull. 58.