

# Impacts of Storm Surges on a Changing Climate: a Global Bibliometric Analysis of the Coastal Zone

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## Research Article

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# Abstract

An increase in the global mean sea is predicted during the 21st century as a consequence of global average temperature projections. In addition, changes in the strength of atmospheric cyclonic storms may alter the development of storm surges, exacerbating the risks to coastal communities. Based on the fact that the interest and range of papers are growing on this topic, this study aims to present the global scientific production status of studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation) via a bibliometric analysis. We analyzed 429 papers published in journals between 1991 and February 2021 from the Scopus database. Through the VOSviewer and Bibliometrix R package, we describe the most relevant countries, affiliations, journals, authors, and keywords. Our results demonstrate that there has been an exponential growth in the research topic, and that authors from the United States and the United Kingdom are the most prolific. Among the 1454 authors found, 10 researchers published at least 5 papers on the topic and obtained at least 453 citations in the period. The most represented journals were the Journal of Coastal Research, Climatic Change, and Natural Hazards. We also found, and discuss, the lack of standardization in the choice of keywords, of which climate change, storm surge, and sea level rise are the most frequent. Finally, we have written a guide to facilitate the authors' bibliographic review.

## 1. Introduction

Global predictions project an increase of 4°C to 6°C in the global average temperature by 2100 on the most extreme greenhouse gas representative concentration pathway (Collins et al. 2013). This may lead to a hydrological cycle acceleration, consequently increasing the intensity and frequency of extreme events, such as coastal storms and storm surges (Coco and Ciavola 2017; Oppenheimer et al. 2019). In this extreme scenario (RCP8.5), it is estimated that global mean sea level (GMSL) may increase by approximately 1.10 m in the 21st century (Oppenheimer et al. 2019). A recent study conducted by Nicholls et al. (2021) shows that, in the last two decades, the GMSL has risen  $2.5 \text{ mm yr}^{-1}$  and that the impact in subsiding coastal areas is four times faster with an average relative sea-level rise varying from  $7.8 \text{ mm}$  to  $9.9 \text{ mm yr}^{-1}$ . Thus, as a result, we know that coastal systems will increasingly flood and experience erosion during the 21st century, if adaptation or mitigation measures to sea level rise and extreme events are not taken (Nicholls 2002; Nicholls and Cazenave 2010; Wong et al. 2014; Oppenheimer et al. 2019; Nicholls et al. 2021).

A fundamental aspect of coastal storms that distinguishes them from other extreme events is their genetic process, which is driven by atmospheric disturbances over the open ocean. Tropical cyclones and extra-tropical cyclones are the main synoptic systems responsible for the vast majority of coastal storms worldwide. Depending on several factors, related to both the cyclonic system as well as the coastal setting in which it occurs, these systems may also generate storm surges (Harley 2017). Storm surges refer to the abnormal rise in seawater level caused by low atmospheric pressure and the force exerted on the sea surface by strong winds. By definition, it is measured as the height of the water above the normal predicted astronomical tide (Lowe and Gregory 2005; Harley 2017; NOAA 2021).

During a changing climate, changes in the number, path, and strength of atmospheric cyclonic storms may alter the formation and development of storm surges (Lowe and Gregory 2005). The amplitude and impact at any given location depend on the intensity, size, and speed of the storm, coastline orientation, and the local topobathymetric characteristics (Lowe and Gregory 2005; Resio and Westerink 2008; De Lima et al. 2020; Leal et al. 2020; NOAA 2021). In addition, hazards and disasters associated with this abnormal rise in seawater level, are highly correlated with storm frequency and characteristics (Harley 2017; Lin et al. 2019). Severe coastal flooding usually happens when wind-induced waves and storm surges coincide with high tides (Resio and Westerink 2008; Kumbier et al. 2017; Chen et al. 2021). In addition, these storms are the main driver for coastal flooding, and responsible for extensive coastal erosion (Resio and Westerink 2008; Leal et al. 2020). Their impacts can be different and more destructive on densely urbanized coasts, in terms of human and economic losses (Neumann et al. 2015). Although the impacts of sea-level rise and, consequently, of storm surges, are potentially strong, the application and success of adaptation are large uncertainties that require more assessment and consideration (Nicholls and Cazenave 2010). Therefore, the scientific community's interest in studies on those impacts and possible adaptations to climate change is growing.

Based on the fact that the range of published papers is growing exponentially on this topic, we see a bibliometric analysis as an important tool, which can facilitate and expand the capacity of researchers in a given subject. For instance, in some cases, the bibliographic review process can take a long time, since it is essential to select relevant papers for the scientific community, thus the results of the bibliometric study can be a quick solution. In addition to the accelerated production, control, and dissemination of information, the development of computer programs for bibliometrics and the creation of databases facilitates the gathering of data in the same place, streamlining information processing and access to new papers. Moreover, synthesizing past research findings is one of the most important tasks for advancing a particular research line. Quantitative analysis for given scientific research, through bibliometric studies, determines the scientific knowledge derived from publications and represents the current research trends, through which the direction of science and related institutions is defined. Besides, bibliometrics can connect published papers, authors, or journals; identify research substreams; and produce published research maps (Davyt and Velho 2000; Zupic and Čater 2015).

Thus, this study aims to present the global scientific production status of studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation). Through a bibliometric analysis, we resolve the following fundamental topics: 1) the most relevant countries, affiliations, authors, and journals; 2) the most cited papers; 3) direct scientists to the research area in their bibliographic reviews. To the best of our knowledge, the present study combines, for the first time, climate change and the impacts of storm surges in the coastal zones to conduct a bibliometric analysis.

## **2. Approach And Methodology**

The compilation between systematic literature review and bibliometric analysis provides a rigorous and formal methodical procedure, which seeks to minimize bias and possible errors when selecting studies to characterize an area of knowledge (Denyer and Tranfield 2009; Zupic and Čater 2015; Keathley-Herring et al. 2016; Carrión-Mero et al. 2020). The methodology for the bibliographic review and bibliometric analysis was adapted from Zupic and Čater (2015). It has been used by several studies from different research areas (Barnes et al. 2019; Ji et al. 2019; Fan et al. 2020; Lima and Bonetti 2020; Feng and Cui 2021; Majeed and Ainin 2021; Maldonado-Erazo et al. 2021). Four main steps were followed to address the research objective (Fig. 1).

In the first step, researchers need to define their research aim (Zupic and Čater 2015). The main intention of the bibliometric analysis was to present the global scientific production status of studies that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation), as well as direct scientists to the research area in their bibliographic reviews.

A bibliographic database was selected and compiled during the second step. First of all, considering the three main databases (Google Scholar, Web of Science, and Scopus), we found out that Scopus is the most relevant database, indexing 25,751 journal titles, and it also has the largest number of publications related to the topic, outperforming the other databases. Therefore, the review was based on the Scopus database. According to Lima and Bonetti (2020), the selection of a single database is the actual best alternative to perform a bibliometric analysis, although it must be highlighted that it will never cover all the existing information and limits will always exist on using this approach.

It is necessary to clarify that the present study has only considered the papers that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation). Studies that did not consider such disasters (i.e., erosion and flooding) were not included in this paper. Four criteria were defined for choosing the terms to be included in the systematic review: 1) the study area should be impacted by *storm surge* and *flooding (inundation)* or *erosion*; 2) the area must be located along a *coastal* zone; 3) the impact must be associated with *climate change*; 4) papers with biological bias were disregarded. Thus, the query expression applied to the *Advanced paper search* in the Scopus database was:

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( TITLE-ABS-KEY ( "climat* chang*" ) AND TITLE-ABS-KEY ( coast* ) AND TITLE-ABS-KEY ( erosion OR flood* OR inundation ) ) AND TITLE-ABS-KEY ( "storm surge*" ) AND ( LIMIT-TO ( LANGUAGE, "English" ) ) AND ( LIMIT-TO ( DOCTYPE, "ar" ) ) AND ( LIMIT-TO ( SRCTYPE, "j" ) )
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The terms were searched in the *titles*, *abstracts*, and *keywords* (TITLE-ABS-KEY) of each indexed paper. We select only *papers* (LIMIT-TO (DOCTYPE, "ar")) published in *journals* (LIMIT-TO (SRCTYPE, "j")) and written in *English* (LIMIT-TO (LANGUAGE, "English")). No periods (dates) were determined. Thus, the search has considered all papers in the historical series. In the same step, all abstracts were read practically, using the *Show all abstracts* option. The intention was to select only the papers of interest, based on the four pre-established criteria. Finally, the file with selected papers was exported in two extensions, *.csv* e *.bib*, which are automatically recognized by the bibliometric analysis software.

The third step consisted of data refinement (i.e., data cleaning) and analysis. Based on the studies already carried out (Lima and Bonetti 2020; Majeed and Ainin 2021), we opted for a more robust analysis with results generated by both the Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16 software. The Bibliometrix package provides various routines for importing bibliographic data from Scopus and others, performing bibliometric analysis, and building data matrices for co-citation, coupling, scientific collaboration analysis, and co-word analysis. It is a unique tool, developed in the statistical computing and graphic R language, according to a logical bibliometric workflow (Aria and Cuccurullo 2017). In the same sense, VOSviewer is a software tool for creating maps based on network data and visualizing and exploring these maps (Jan van Eck and Waltman 2020).

In addition, during the third step, the appropriate bibliometric methods were chosen to respond to the first stage. Table 1 presents the relational and evaluative methods that were generated by using the Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16. The choice of methods was based on the proposed objective of presenting the global scientific production status on the topic. Moreover, Zupic and Čater (2015) discuss the pros and cons of presenting each method in the results, which also contributed to the decision on the final results of the present study.

The *co-authorship method* is established when two authors co-publish a paper. It can provide evidence of collaboration and produce the social structure of the field. *The citation method* is used as a measure of influence. If an paper or journal is heavily cited, it is considered important. In addition, it can quickly help to find important works in the research field. The *co-citation method* by the author is defined as the frequency in which two authors are cited together. This analysis uses co-citation counts to construct measures of similarity between authors or journals. A fundamental assumption of co-citation analysis is that the more two items are cited together, the more their contents are related. The *co-occurrence method* by author keywords connects words when they appear in the same keyword list. The idea underlying the method is that when words frequently co-occur in papers, it means that the concepts behind those words are closely related (White and McCain 1998; Small 1999; Lu and Wolfram 2012; Zupic and Čater 2015; Grácio 2016).

Finally, in the fourth step, all the results generated for scientific production were interpreted by the following units of analysis: countries, affiliations, journals, authors, and keywords. In addition, a table was attached as supplementary material to facilitate the literature review of other researchers. For each paper analyzed, the following information was tabulated: authors, title, year of publication, journal, and DOI.

### 3. Global Scientific Production Status

We found 486 papers written in English and published in journals between 1991 and February 2021 in the Scopus database. However, 429 papers were selected according to the abstracts and pre-established criteria in the second step of the methodology. The analysis resulted in papers produced in 57 countries,

182 journals, 660 affiliations, by 1454 authors, who used a total of 1075 keywords. The first and most relevant results for each unit of analysis were listed to make the data presentation clarify.

As shown in Fig. 2, during the period between 1991 and February 2021, there was an increase in annual scientific publications according to the Scopus database. The first paper was written in 1991, and the second in 1992, with an interval without publication in 1993. Since 1996, more than one paper has been published each year, except for 1998, when there were no publications related to the topic. From 2011 onwards, at least 14 papers per year started to be published (disregarding the year 2021), showing the growth trend. Although a significant decrease in publications was observed between 2012 and 2014, during the following years, fewer differences in the number of publications were observed, indicating a more balanced scenario (i.e., between 2014 and 2018). On the other hand, the peak of publications was observed in 2020, the year in which authors published 60 papers related to the topic. In January and February 2021, 11 papers had already been published, which is a higher number than in the whole year of 2009 and the period before 2007. This result demonstrates a recent increase in studies on that have correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation). Thus, the annual growth rate of publications related to the topic is 8.94%.

### 3.1 Analysis by country

Among 57 countries, at least 10 have 18 papers or more published. Table 3 shows the first 10 countries, in which the authors published more between 1991 and February 2021. Researchers from the United States published 132 papers, that is, 30.77% of the total of 429. Next is the United Kingdom, in which 54 papers were published. Authors from unlisted countries have published 36 papers or less. Table 2 also highlights the first 10 countries, in which the authors were most cited. Among 19,753 citations, the countries listed reached 15,821, which represents 80% of the total citations. The United States authors had 4,844 citations counted until February 2021: this reflects a percentage of 24.52%. The United Kingdom authors were cited 3,494 times (17.69%); whereas German researchers were cited 1,586 times (8.03%). In contrast, papers published by the authors from the Netherlands have 78 fewer citations. In France and Australia, citations reach 1,103 and 1,016, respectively. Papers published by researchers from Italy, Canada, India, and Bangladesh reach 11.49% of the total. The unlisted countries have 422 citations or less.

Comparing the number of published papers and citations, the United States and United Kingdom authors lead the rank, with 132 and 54 papers and 4,844 and 3,494 citations, respectively. However, the Netherlands has more papers than Germany, but no more citations. France researchers are not on the top of the papers list, but they have 1,103 citations in their 13 papers. Australia has fewer papers compared to Italy but has more citations, 1,016 and 917, respectively. Canada, India, and Spain have fewer papers than China but account for a greater number of citations, 470, 458, and 380, respectively. Finally, Bangladesh has fewer papers (14) than Spain (18) but adds 45 more citations.

Figure 3 shows the co-authorship network by country using a cluster approach. Colors separate countries into different clusters by collaborations; the size of the circle represents the number of publications, and

the line thickness represents how strong the relationship between countries is. For example, lines are thicker between countries with more co-authorships. The results of co-authorship by countries are represented by 10 different clusters, in which 43 authors have at least two co-authorships (Fig. 3). A larger network among researchers was observed in 39 countries. The United States researchers were the most productive (132 papers) in the period and have established co-authorship with 22 different countries. Among them, China, the United Kingdom, Italy, Australia, and India presented a high relationship.

Researchers from the United Kingdom have 54 published papers and at least two co-authorships with 24 other countries. Among them, Ghana, China, Germany, and the Netherlands. Authors from the Netherlands, Germany, and Italy have 36, 35, and 33 papers (respectively) and at least two co-authorships with researchers from 17 countries. Authors from these three countries have a strong relationship. Both Australia and China had strong relationship, co-authoring with 11 countries. In Canada, two co-authorships occur with 8 countries, and in India, with 6, which are represented in the same cluster as Iran. Despite being in tenth place in the publication ranking, Spain has at least two co-authorships with 18 countries. Brazil, which has 4 published papers, has a strong relation with Portugal and the United States.

### **3.2 Analysis by affiliations**

Authors' addresses recorded a total of 660 affiliations. It was found that 490 affiliations (74.24%) published only 1 paper. Figure 4 lists the 12 organizations with which authors were affiliated in terms of the most papers published in the period between 1991 and February. Pennsylvania State University is the most prolific affiliation with 20 papers, followed by Deltares and Princeton University, which published 15 papers each. The 12 affiliations represent 29.84%, with 128 papers out of a total of 429 publications on the topic. The other affiliations published 6 papers or less. Regarding countries, 7 affiliations are located in the United States. The Netherlands is the second country that most appeared in the rank, with 2 affiliations. The United Kingdom, Greece, and Taiwan are host countries for one affiliation.

### **3.3 Analysis by journals**

The 429 selected papers were published in 182 individual journals. Table 3 shows the first 10 journals that published more papers on the topic in the period between 1991 and February 2021. The first paper published in our time series (Paw and Thia-Eng 1991) was published in *Ocean and Coastal Management*, which has only this paper related to the topic and 15 citations. The second and third (Daniels 1992, Toppe and Fiihrboter 1994) were published in the *Journal of Coastal Research*, in which a subsequent 22 further papers were published. *Natural Hazards* has published 20 papers, the first in 2003 (Danard et al. 2003); *Climatic Change* has published 21 papers the first in 2008 (Kirshen et al. 2008). These first three journals represent 14.69% of the total number of published papers. The other 7 listed total 19.11%, with 82 papers published. In addition, 119 journals published only one paper, 24 journals published 2, and another 39 published 3 or more papers in the analyzed period.

The annual occurrence of papers related to the theme in the 7 most relevant journals is presented in Fig. 5. The journal *Natural Hazards* has become a greater focus on the vulnerability to, and impact of, storm surges over the years. It was the journal that published the most in January and February 2021. *Water* (Switzerland) also grew exponentially over the period and it was the second to publish more related papers in 2021. The *Journal of Coastal Conservation* published more in the period between 2017 and 2019. On the other hand, *Climatic Change* published more between 2013 and 2015, and *Ocean and Coastal Management* obtained the highest number of publications in the year 2017. The *Journal of Coastal Research*, which took an initial interest in the topic, has maintained this with a relatively consistent since 2009. *Global and Planetary Change* published less than the other 6 journals, with the peak between 2011 and 2015. Concerning all the highlighted journals, it can be seen that there has been a marked increase in publications with a focus on impacts of the storm surges commencing in 2007.

The rank of the journals that have been published more is different, regarding the most cited journals. Table 4 shows the first 10 most cited journals by the 429 selected papers. *Climatic Change*, which published 21 papers, is the most cited journal. On the other hand, the *Journal of Coastal Research*, with 22 papers, is the fifth most cited journal (705). *Plos One*, which has 6 published papers, obtained 789 citations. *Natural Hazards*, third in the publications rank, appeared in the tenth position, with 443 citations. Journals, such as *Global Environmental Change*, *Climate Research*, *Nature Climate Change*, also do not appear in the ranking of those that have published more on the topic, but they total 763, 648, and 619 citations, respectively. The other journals, which are not in the rank of the first 10, were cited 412 times or less. Among the 13,548 citations, the first 10 journals have 6,778 (50.03% of the total). The results also demonstrate that 16 journals did not obtain citations, 14 had 1 citation, and 152 were cited 2 times or more.

Figure 6 shows 10 journals, in which at least 7 papers have been cited 65 times. In three clusters, represented by different colors, there are the journals that have the highest citation network. The *Natural Hazards* and *Climatic Change* have a greater relationship, forming a cluster represented by the color blue. In the green cluster are represented *Water* (Switzerland), *Global and Planetary Change*, *Journal of Geophysical Research*, and *Science of the Total Environmental*. Finally, the red group lists *Ocean and Coastal Management*, *Journal of Coastal Research*, *Journal of Coastal Conservation*, and *Coastal Engineering*. The size of the circles shows that among the journals with the highest citation network, *Climatic Change*, *Global and Planetary Change*, and *Journal of Coastal Research* were the three most cited journals.

### **3.4 Analysis by authors**

The results indicate a total of 1,454 authors. The 10 most productive authors were highlighted, according to the number of publications on the topic. In addition, the number of citations, affiliations, country, and gender of the author is presented in Table 5. In our analysis, we have only selected the authors who have

correlated climate change and the impact of storm surges on the coastal zone leading to erosion and flooding (inundation) in their papers.

Nicholls published the most papers on the topic. His first paper was published in 1996 in *Ocean and Coastal Management Journal* (Nicholls and Hoozemans 1996). Until February 2021, this paper obtained 31 citations of a total of 1,965 citations of the author. The author's most cited paper was published in 2015 in the *Plos One* journal and obtained 713 citations (Neumann et al. 2015). The second author of the rank is Lin, who has published 9 papers. The first paper produced having Lin as the main author was in 2010 (Lin et al. 2010) in the *Journal of Geophysical Research: Atmospheres*. That paper obtained 161 citations out of the 414 citations that have been reached by the researcher. Other authors are recorded in the database as having published 7 or fewer papers in the period.

The affiliations presented were described based on the profile of each researcher in Scopus. They were updated, according to the last paper published by the author until March 31, 2021. Thus, some authors may have more than one affiliation. According to Table 5, two prominent authors are affiliated with the Euro-Mediterranean Center on Climate Change: Critto and Torresan. The other authors are affiliated with different universities/centers. Regarding the countries, three authors develop researches in Italy (Critto, Marcomini, and Torresan), another three in the United States (Lin, Hagen, and Medeiros). Nicholls and Lowe are from the United Kingdom. Belgium and Germany also appear in the rank with the authors Vousdoukas and Weisse, respectively.

The discussion about gender aims to demonstrate that the frequency in which men and women occur in the field is mostly different. Holmam et al. (2018) found that prestigious journals have fewer female authors. Additionally, the authors estimated that men are invited by journals to submit papers at approximately double the rate of women. Gender equity guarantees women the same opportunities as men in benefiting from the fruits of research, contributing to society, earning a living, and choosing a fulfilling profession (Huyer 2015; Vila-Concejo et al. 2018). In the current times, in which gender equality is sought, it is necessary to present and show that women still do not dominate ranks, such as those presented in Table 5 and Table 6. Concerning the largest number of publications, Lin (female) occupies the second position. In the same sense, Torresan occupies the ninth position of the rank. However, the results point out that women are the minority compared to men, who account for 80% of the 10 authors on the top ranking.

Figure 7 shows the clusters of researchers who are co-authors in at least two papers. Among the 1454 authors, 183 are co-authors in the 429 papers analyzed. However, the largest set of connecting co-authorship consists of 49 authors. In this case, the cluster analysis allows the identification of the niches of co-authors. In the light blue cluster, Nicholls was the author who published the most, with 13 papers, and he is co-author with 10 other researchers. Among his strongest relationships are Brown, Hanson, and Vafeidis. Lin published 9 papers, thus being the author who has most published in the yellow cluster, co-authoring with 8 researchers. In the green cluster, Lowe, who published 7 papers, was the researcher with the highest co-authorship number (15). In the dark blue cluster, Weisse was the most prolific author with 5

published papers, and is a co-author with 10 researchers. Gonnert published 3 papers, hence is the most productive author in the red cluster, being the co-author with 9 other researchers. In the purple cluster, Kirshen, which published 4 papers, is co-authored with 5 researchers. Sterl was the most prolific publisher in the brown cluster with 3 published papers, and is co-author with 9 other authors. In the orange cluster, Dawson, which has 2 publications, is co-author with 4 researchers. Finally, in the pink cluster, Xian was the author who has written the most number of papers (3) and is co-author with 3 researchers.

Table 6 presents the first 10 most cited authors. The first 4 authors, Nicholls, Vafeidis, Neumann, and Zimmermann are co-authors of the same paper (Neumann et al. 2015), which obtained 713 citations until February 28, 2021. Lowe is the fifth author of the rank, with 529 citations in his 7 published papers. Dingman, Ericson, Meybeck, Vörösmarty, and Ward are also co-authoring of the same paper (Ericson et al. 2006), which has 453 citations to the same date.

Regarding affiliations, Vafeidis and Zimmermann are affiliated with Christian-Albrechts-Universität zu Kiel in Germany. Dingman and Ward are part of the University of New Hampshire Durham, located in the United States. The other authors of the rank are affiliated with different universities/centers. The first country in the rank is the United States, with four researchers. Next is Germany, with three authors, and the United Kingdom, with two researchers. France appears only once, in the seventh position in the ranks. As in the analysis of the number of papers published by the author (Table 5), the results related to gender in Table 6 also indicate that women occupy only 20% of the rank of most cited researchers. It is also noteworthy that Neumann and Zimmermann were co-authors of the same work, with Neumann being the first author. Again, it is shown that women are not the majority among the 10 authors on the top ranking.

Figure 8 presents the cluster analysis of the authors, in which at least 3 published papers were cited 4 times by other researchers. Divided into six clusters, the authors are associated with other authors, among whom they were cited. Nicholls was the most cited author, among the analyzed researchers. This author also presents a connection with the authors represented by the light blue, red, and purple clusters. This indicates that he also cites a significant number of authors from those clusters. Lowe appears as the second author who obtained at least 4 citations in 3 published papers. He was the researcher most cited by the authors of the light blue cluster. Lin was the third most cited author from the 429 papers in the database. The author was a reference, mainly of the works written by Emanuel, Xian, Donnelly, Horton, Kopp, Yin, and McInnes.

The co-citation patterns indicate the history of recognition and academic impact of publications since a publication can be relevant for future research and can, thus, potentially be cited (Hjørland 2013). The co-citation analysis by the author presents the group of researchers who are cited by a group of authors. Therefore, it becomes important to demonstrate to the authors that it is also related to the topic. The analysis of co-citation by the author demonstrates, from four clusters, the set of authors that were most cited by the 1454 authors of the 429 papers analyzed. In the selected papers, 24,623 researchers were cited, and the 36 researchers represented in Fig. 9 were cited at least 65 times. The authors' proximity to

clusters refers to the list of their proposed themes within the general topic of storm surges and climate changes.

Nicholls appears as the most cited author, with 552 citations. In the same papers, authors, such as Woodroffe, Hinkel (the fifth most cited, with 144), Tol, Vafeidis, Hallegatte, and Corfee-Morlot are also cited. It does not exclude the fact that the authors of other clusters are also cited in the same paper, in which Nicholls appears. Emanuel is in the second position, with 247 citations. The authors most cited by the same paper are represented in the green cluster, in which Lin, fourth-most cited is part, with 146. Church is the third in rank, with 147 citations by base papers. The author is represented by the yellow cluster, in which also appears Cazenave, the sixth most cited author, with 141 papers. The other researchers were cited 121 times or less.

The paper entitled *Sea-level rise and its impact on coastal zones* (Nicholls and Cazenave 2010) was the most cited by the 429 papers analyzed. The authors discuss important issues in it, such as *Global Sea-Level Rise in the 21st Century*, *Main Impacts of Sea-Level Rise*, and *Adaptation*. The publication obtained 40 citations among the selected papers. The paper totaled 1.256 citations until April 2, 2021. Between January and April 2, 2021, the paper had already been cited 49 times, as indicated by Scopus.

### 3.5 Keywords' analysis

The evolution of the first 5 keywords between 1991 and 2021 is shown in Fig. 11. The keywords plus (i.e., most commonly used words in titles, abstracts, and keywords list) were represented according to their annual and noncumulative occurrence. The main keywords are highlighted: *Climate Change*, *Storm Surge*, *Floods*, *Sea Level*, and *Sea Level Change*. In general, the terms appeared considerably since 2007. The most used keyword per year was climate change. Between the period of 2019 to February 2021, the curve is stable, with an annual occurrence of approximately 35. It shows that its use is constant and more elevated, concerning the other highlighted keywords.

*Storm surge* is the second most used keyword since 2007. Its usage peak occurred between 2017 and 2019. However, it must be considered that only papers from January and February of the year 2021 were selected. Studies related to the topic are growing exponentially until the year 2020, as seen in Fig. 2. In addition, only two months in 2021 account for more publications than several other years, such as 2009. The growth occurs due to the current situation of climate change and environmental impacts. *Sea level change* was the most used keyword in the papers since 2007. However, between 2015 and 2018, it remained stable, with a drop in its employment in 2019. After 2016, *floods* started to have a higher annual occurrence in keywords. Its peak was in the first two months of 2021. The use of the term *sea level* in keywords was stable between 2017 and 2019, slightly decreasing in 2020.

Among the 1075 keywords established by the authors, 17 occurred in at least 10 papers out of 429 analyzed. The co-occurrence network based on keywords occurrences in papers is shown in Fig. 12. The size of the node is proportional to the frequency of occurrence of the keyword, and the thickness of the line represents the intensity of co-occurrence between individual keywords (Mishra et al. 2020). Zupic and

Čater (2015) point out the negative aspect of presenting co-word analysis. The authors show that words can appear in different forms, as well as they can have different meanings.

The keywords determined by the authors did not follow a pattern. It can occur in different research fields since different words can have the same interpretation meaning. In the case of the present study, words, such as *sea level rise* and *sea-level rise*, were found among the authors' the 17 most used keywords. The researchers used it in 64 and 53 papers, respectively. Another example of duplicity is *storm surge* and *storm surges*, which appeared 82 and 26 times, respectively. Moreover, words like *coastal flooding* (24) and *flooding* (22) were used. Considering that the research only delimited studies related to the coastal area, the two terms can be classified as synonyms. The keyword *inundation* (13) may or may not give rise to the same interpretation as *flooding*. There is no consensus, among authors in the research area. In the same sense, *erosion* and *coastal erosion* appeared (both 13 times), which probably refer to the same topic. It should be noticed that, logically, when one of these keywords is used, the other one will not be used. It justifies the fact that they have the same interpretation.

An analysis of some papers by the three authors who published more on the topic revealed divergences in the keywords pattern. Nicholls (2002) used words like *sea-level rise* and *flooding*, while Lin et al. (2016) employed *storm surge* and *sea level rise*. On the other hand, Lin and Shullman (2017) used *storm surge* and *sea-level rise*. In the paper by Lowe and Gregory (2005), the expression *storm surge* may appear as a keyword. It is understood that the use of words in the singular or plural, as *storm surge*, may be related to the number of events that were analyzed by the authors. The three keywords most used by the researchers were *climate change* (168 times), *sea level rise* (*sea-level rise*), and *storm surge* (*storm surges*). The highlighting of these keywords is justified, as they are directly related to the keywords used in the query expression determined in the present study. Regarding keywords that did not show duplicity, there is *vulnerability* and *adaptation*, which appeared in 18 papers each, next to *the sea level* keyword, which was used 14 times. *Risk assessment* appeared in 11 papers, while the words *coastal hazards*, *coastal management*, and *flood risk* appeared in 10 papers. The other keywords were used 9 times or less.

Four clusters are represented in Fig. 12. In papers that the authors opted for the keyword *climate change*, the other 16 keywords presented were also used at least once. In the same green cluster, terms, such as *sea level rise*, *coastal flooding*, *storm surge*, *sea level*, and *flood risk*, appear. *Storm surges* appear related to the words represented in the blue cluster, considering its strong relationship with climate change and sea level rise, as well as *sea-level rise*, being more used in conjunction with words belonging to the red cluster, in addition to having a strong relationship with *storm surge*. *Erosion* and *coastal hazards* appear in the yellow cluster. Terms considered as synonyms appear in different clusters, which shows the fact that they are not used together in the keyword lists.

## 4. Guide For Authors: Bibliographic Review

For researchers who intend to make a significant bibliographic review or even publish on the topic, it is worth looking for authors, papers and journals with significant recognition among the scientific community. Two countries occur as the most productive and cited: the United States and the United Kingdom. The United States is the country with the largest number of authors who publish on the topic. In addition, the country hosting important universities is highlighted in Fig. 4. Authors, such as Lin and Hagen publish a lot and do have their works considerably cited by the scientific community. The second is the United Kingdom, the country has important researchers in the study area, such as Nicholls and Lowe, in addition to hosting significant universities. Nicholls, according to the results, is the most relevant researcher in the area. The author published the largest number of papers and obtained the highest number of citations and co-citations. One of his works was the most cited of the 429 selected papers (Nicholls and Cazenave 2010).

In addition, the Netherlands hosts two prominent affiliations for the study area, Deltares and Delft University of Technology. It should be noticed that several other countries and authors presented in the results also have scientific relevance, in which researchers publish important papers that contribute substantially to the issue. Readers are strongly encouraged to find the supplementary material listing all 429 selected papers, which are available in this document.

Regarding journals, the 14 that published more or had papers with the highest number of citations on the topic are highlighted in alphabetical order: Climatic Change, Climate Research, Coastal Engineering, Global and Planetary Change, Global Environmental Change, Journal of Coastal Conservation, Journal of Coastal Research, Natural Hazards, Natural Hazards, and Earth System Science, Nature Climate Change, Ocean and Coastal Management, Plos One, Science of The Total Environment and Water (Switzerland).

## 5. Final Considerations

The bibliometric analysis was presented as an alternative approach to demonstrate the global scientific production status. Both software used, the Bibliometrix package for R and VOSviewer generated important results that complemented each other and, thus, have supported a better understanding of the scientific knowledge in the research field. The results showed that there is an exponential growth in the publication of papers written and published in journals since 1991. The peak in the publication of papers related to the topic was observed in 2020, but in the first two months of 2021, it has been published more papers than the entire period before 2007.

According to the query expression applied in the Scopus database, which was based on four preestablished criteria, 429 papers were selected. The evaluation through the units of analysis countries, affiliations, journals, authors, and keywords highlighted significant issues about the current situation of research in the world. We have found that authors from the United States, the United Kingdom, Italy, Germany, and the Netherlands stood out in the number of publications on the topic. In terms of numbers, the United States presented the highest number of publications published between 1991 and February 2021. On the other hand, the most relevant author for the research field is Nicholls, from the United

Kingdom. This author published more papers in the period, obtaining the highest number of citations in one of his papers. In addition, our results showed that only 20% of women are in the rank of the 10 authors who most produced and were cited. Steps to improve gender diversity were proposed by women researchers in areas related to this study (Vila-Concejo et al. 2018) and deserve the attention of all researchers.

Regarding affiliations, we highlighted the 10 most relevant, which have published more in the research area. Of the 660 affiliations found, only 170 published more than two papers in the analyzed period. At the top of the rank, it is The Pennsylvania State University from the United States and Deltares from the Netherlands. The same countries host the most relevant journals of the area, with more publications and citations on the topic.

The analysis of the keywords co-occurrence network, based on keywords occurrences in papers, showed the lack of standardization on the choice of terms. We highlighted the most used keywords by the authors, such as climate change, sea level rise, and storm surge. Based on this result, the authors can understand and choose the terms that are being more used in publications related to the topic.

Finally, we understand that the study can support researchers in the investigation field on the following issues: 1) to identify the global scientific production between 1991 and February 2021; 2) to understand which countries, affiliations, journals, and authors are the most relevant; 3) to identify papers with greater relevance, among the scientific community of the research area; 4) to recognize the lack of standardization in the use of keywords and, possibly, create standardization mechanisms, at least, among research groups; 5) to facilitate and speed up bibliographic reviews in the research area. Besides, the proposed methodology of this study can be reapplied to any other research area, collaborating with the advancement of scientific knowledge.

## **6. Declarations**

### **Funding**

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### **Conflicts of interest/Competing interests**

Not applicable.

### **Availability of data and material**

Not applicable.

### **Code availability**

Not applicable.

## Authors' contributions

All authors contributed to the study's conception and design. KBL performed the bibliographic search, generated the results through bibliometric tools, analyzed the data, and wrote the first version of the manuscript. LESR and ASL analyzed the data and contributed to the review of the manuscript in all versions. All authors read and approved the final manuscript.

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## 8. Tables

Table 1

Relational and evaluative methods generated through Bibliometrix package for R version 4.0.4 and VOSviewer version 1.6.16

VOSviewer version 1.6.16					
Relational Methods	Co-authorship	Citation	Co-citation	Co-occurrence	
Units of Analysis	By country	By journal	By author	Author Keywords	
	By author	By author			
Bibliometrix package for R version 4.0.4					
Evaluative Method	Annual Scientific Publications	Country Scientific Production	Journal Growth	Affiliations	Keywords Growth

Table 2

Total papers and citations according to the 10 most relevant countries

Papers			Citations		
Rank	Country	N. Papers	Rank	Country	N. Citations
1	United States	132	1	United States	4,844
2	United Kingdom	54	2	United Kingdom	3,494
3	Netherlands	36	3	Germany	1,586
4	Germany	35	4	Netherlands	1,508
5	Italy	33	5	France	1,103
6	Australia	32	6	Australia	1,016
7	China	29	7	Italy	917
8	Canada	22	8	Canada	470
9	India	21	9	India	458
10	Spain	18	10	Bangladesh	425

Table 3  
Total papers according to the 10 most relevant journals

Rank	Journal	N. Papers	SJR Index (Scimago 2019)	H-INDEX
1	Journal of Coastal Research	22	0.36	84
2	Climatic Change	21	1.91	175
3	Natural Hazards	20	0.81	96
4	Journal of Coastal Conservation	18	0.4	36
5	Ocean and Coastal Management	16	0.82	77
6	Global and Planetary Change	10	1.76	124
7	Natural Hazards and Earth System Science	10	1.01	90
8	Water (Switzerland)	10	0.66	42
9	Coastal Engineering	9	1.82	100
10	Science of The Total Environment	9	1.66	224

Table 4  
The first 10 most cited journals by the 429 selected papers

Rank	Journal	Citations	SJR Index (Scimago 2019)	H-INDEX
1	Climatic Change	1,087	1.91	175
2	Plos One	789	1.02	300
3	Global Environmental Change	763	4.3	162
4	Global and Planetary Change	708	1.76	124
5	Journal of Coastal Research	705	0,36	84
6	Climate Research	648	0.8	101
7	Nature Climate Change	619	7.74	160
8	Ocean and Coastal Management	547	0.82	77
9	Coastal Engineering	469	1.82	100
10	Natural Hazards	443	0.81	96

Table 5

Top 10 most productive authors by the number of papers from 1991 to February 2021

Author	Papers	Citations	Affiliation*	Country	Gender
Nicholls R.J.	13	1965	University of East Anglia	United Kingdom	Male
Lin N.	9	414	Princeton University	United States	Female
Lowe J.A.	7	529	Met Office	United Kingdom	Male
Hagen S.C.	6	236	Louisiana State University	United States	Male
Vousdoukas M.I.	6	269	European Commission Joint Research Centre	Belgium	Male
Critto A.	5	113	Euro-Mediterranean Center on Climate Change	Italy	Male
Marcomini A.	5	113	Università Ca' Foscari Venezia	Italy	Male
Medeiros S.C.	5	219	Embry-Riddle Aeronautical University	United States	Male
Torresan S.	5	113	Euro-Mediterranean Center on Climate Change	Italy	Female
Weisse R.	5	366	Helmholtz-Zentrum Geesthacht	Germany	Male

\* Affiliations were filled out, according to each author's profile at Scopus, which considers the affiliation of the most recent paper published until March 31, 2021. Some authors may have more than one affiliation.

**Table 6** Top 10 most productive authors by the number of citations from 1991 to February 2021

Author	Citations	Papers	Affiliation*	Country	Gender
Nicholls R.J.	1965	13	University of East Anglia	United Kingdom	Male
Vafeidis A.T.	714	2	Christian-Albrechts-Universität zu Kiel	Germany	Male
Neumann B.	713	1	Institute for Advanced Sustainability Studies	Germany	Female
Zimmermann J.	713	1	Christian-Albrechts-Universität zu Kiel	Germany	Female
Lowe J.A.	529	7	Met Office	United Kingdom	Male
Dingman S.L.	453	1	University of New Hampshire Durham	United States	Male
Ericson J.P.	453	1	Virginia Department of Conservation and Recreation	United States	Male
Meybeck M.	453	1	Sorbonne Université	France	Male
Vörösmarty C.J.	453	1	City College of New York	United States	Male
Ward L.G.	453	1	University of New Hampshire Durham	United States	Male

\* Affiliations were filled out, according to each author's profile at Scopus, which considers the affiliation of the most recent paper published until March 31, 2021. Some authors may have more than one affiliation.

## Figures

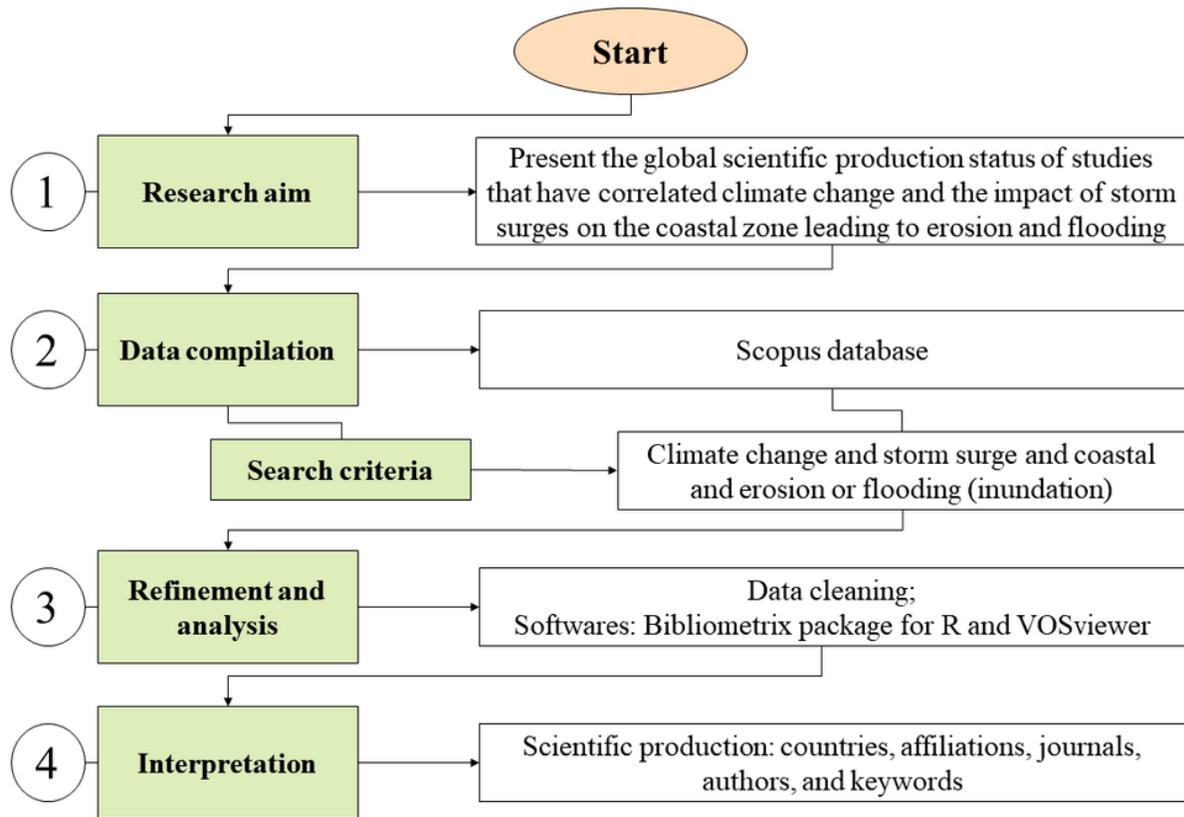


Figure 1

Main stages of the research process. Adapted from Zupic and Čater (2015)

# Annual Scientific Production

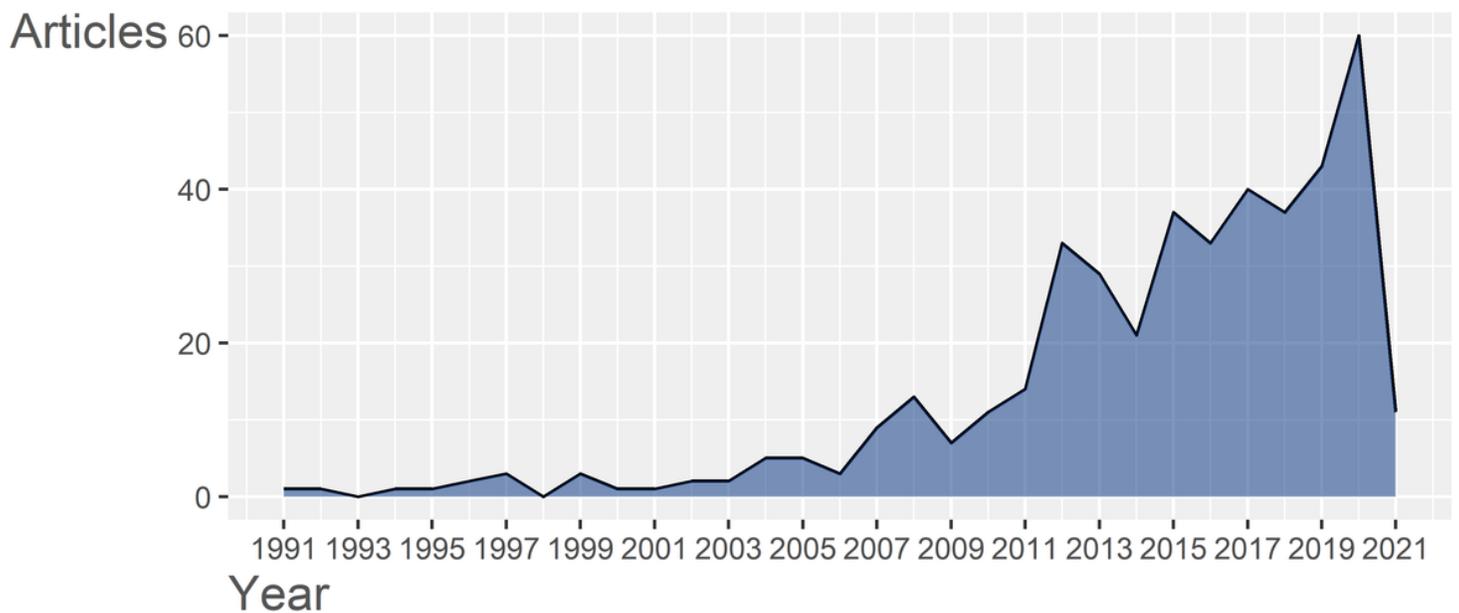


Figure 2

Annual scientific publications on the impact of storm surges related to coastal erosion and flooding under climate change

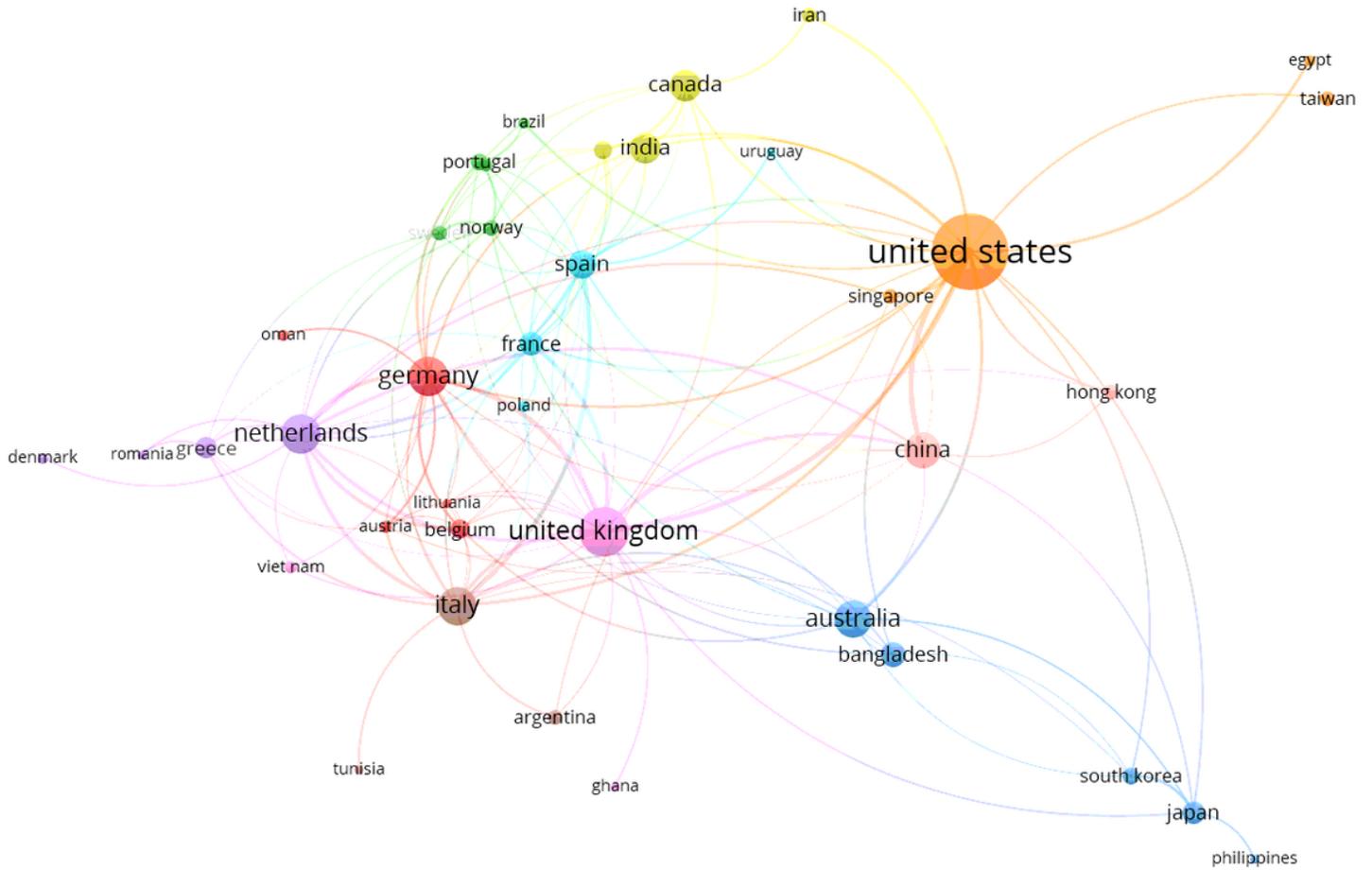


Figure 3

Co-authorship network by country

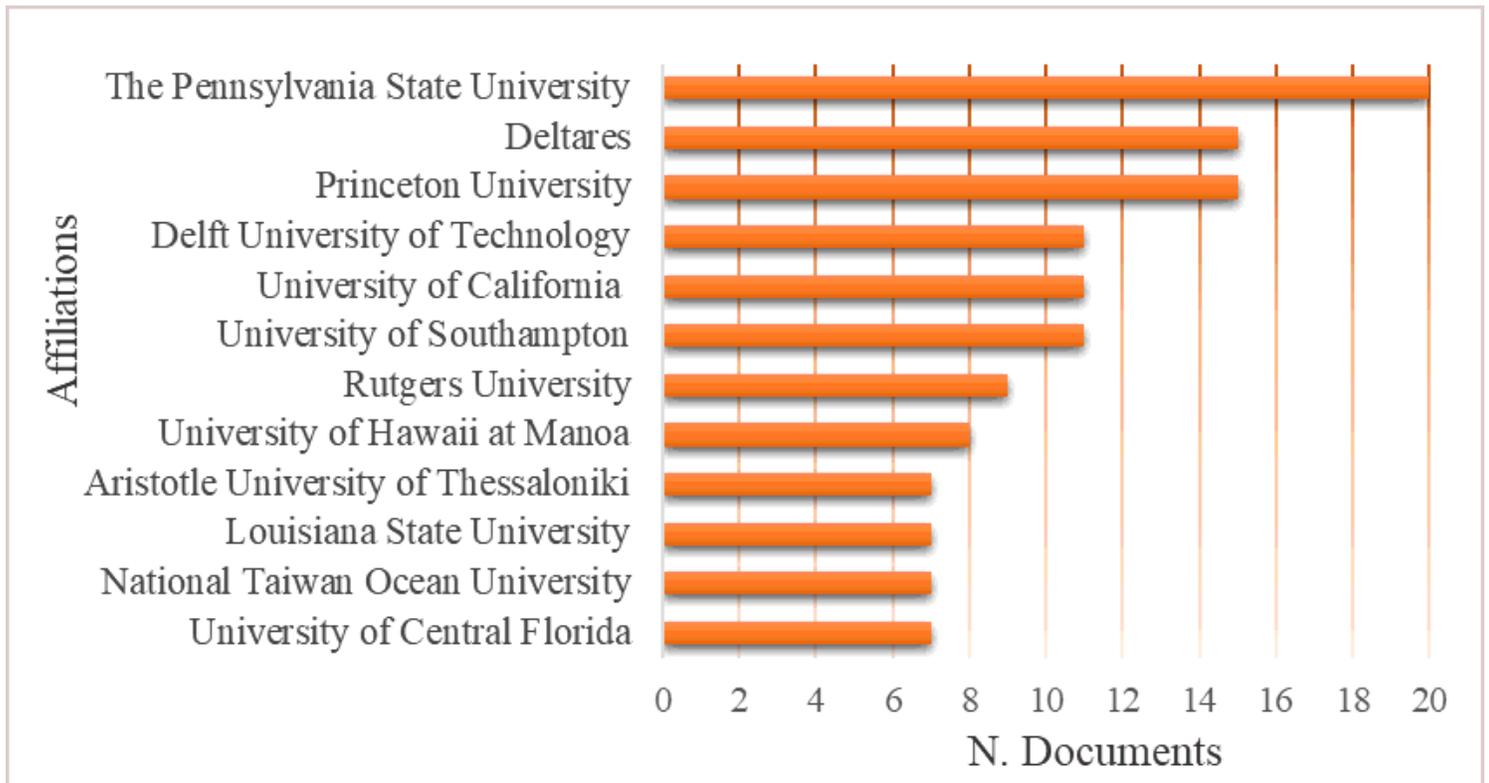


Figure 4

Total papers according to the 12 most relevant affiliations between 1991 and February 2021

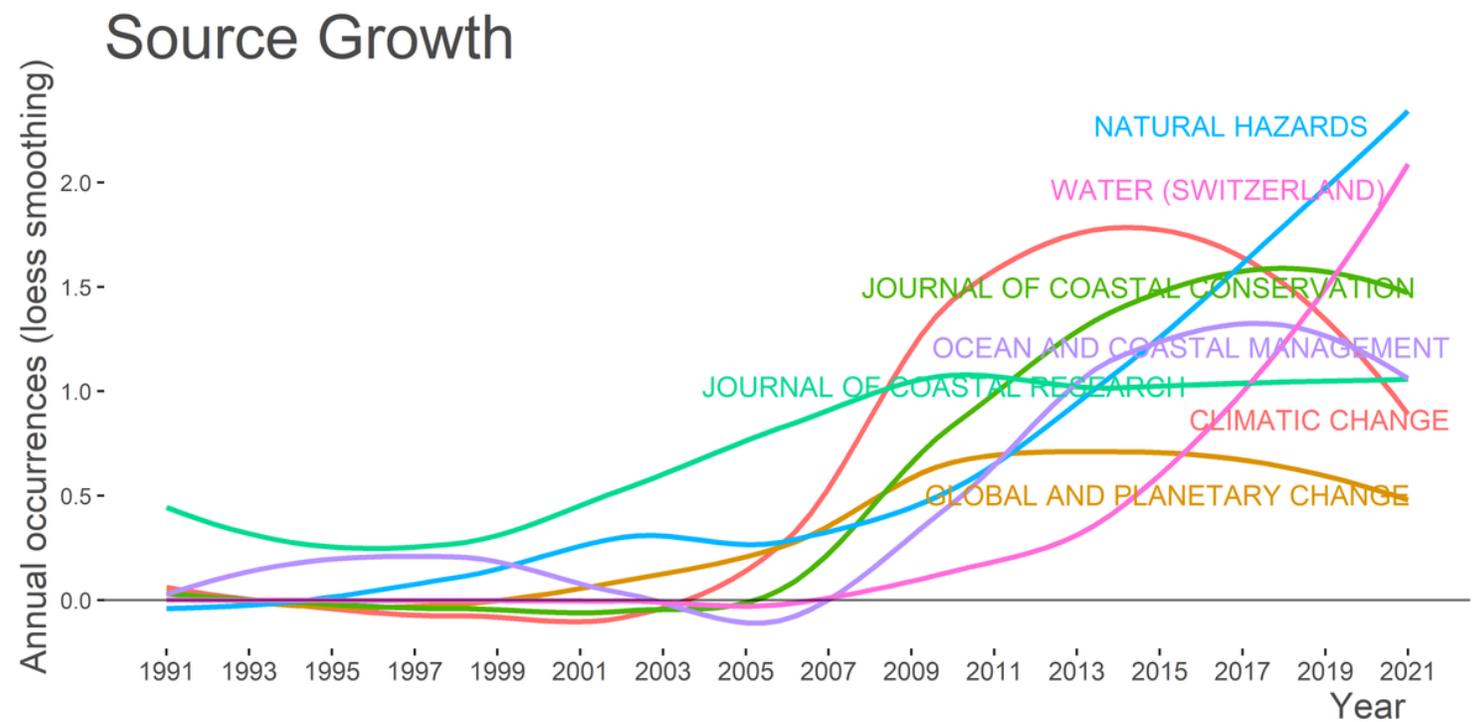


Figure 5

Journal growth between 1991 and February 2021

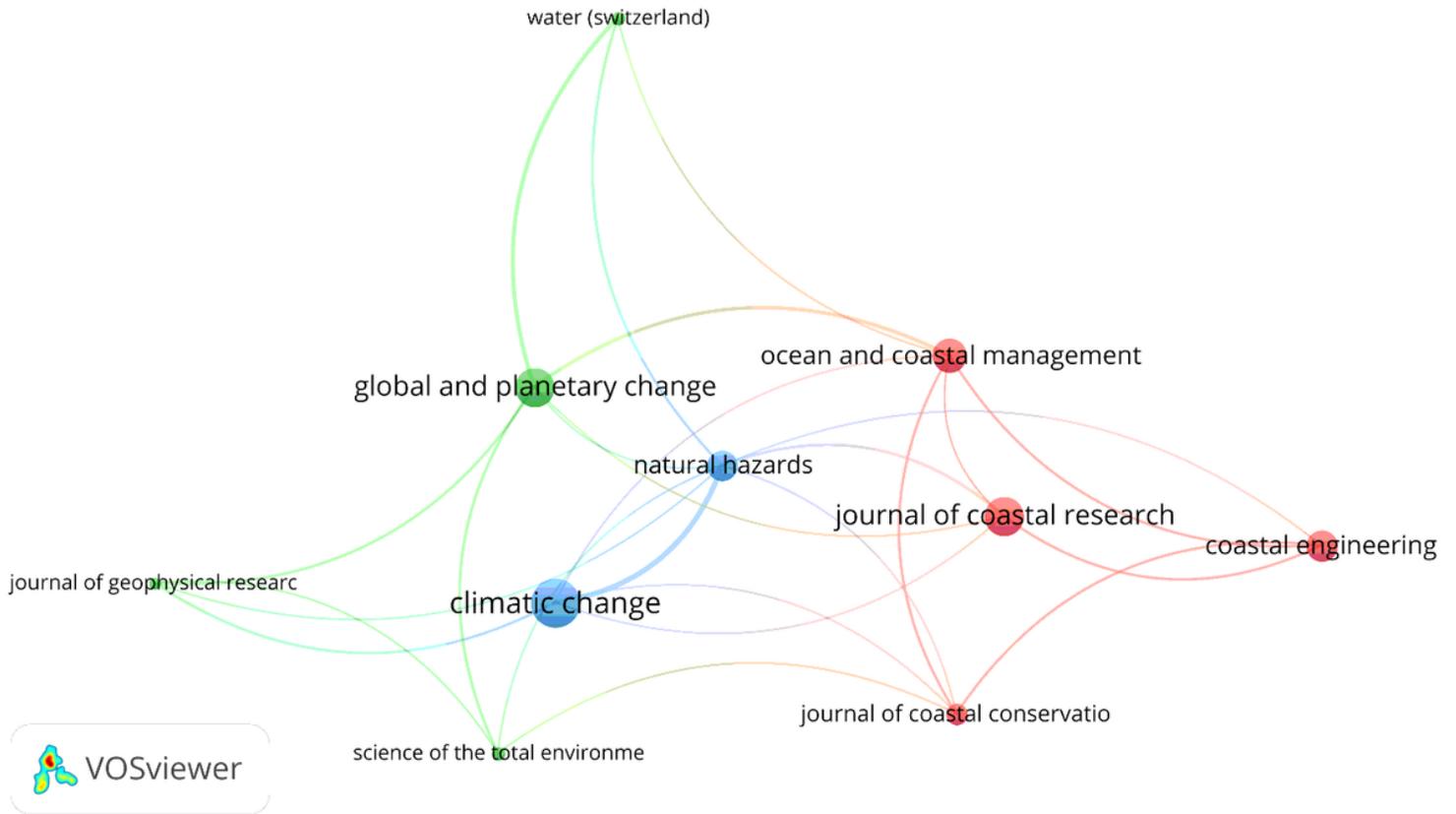


Figure 6

Citation network by journals

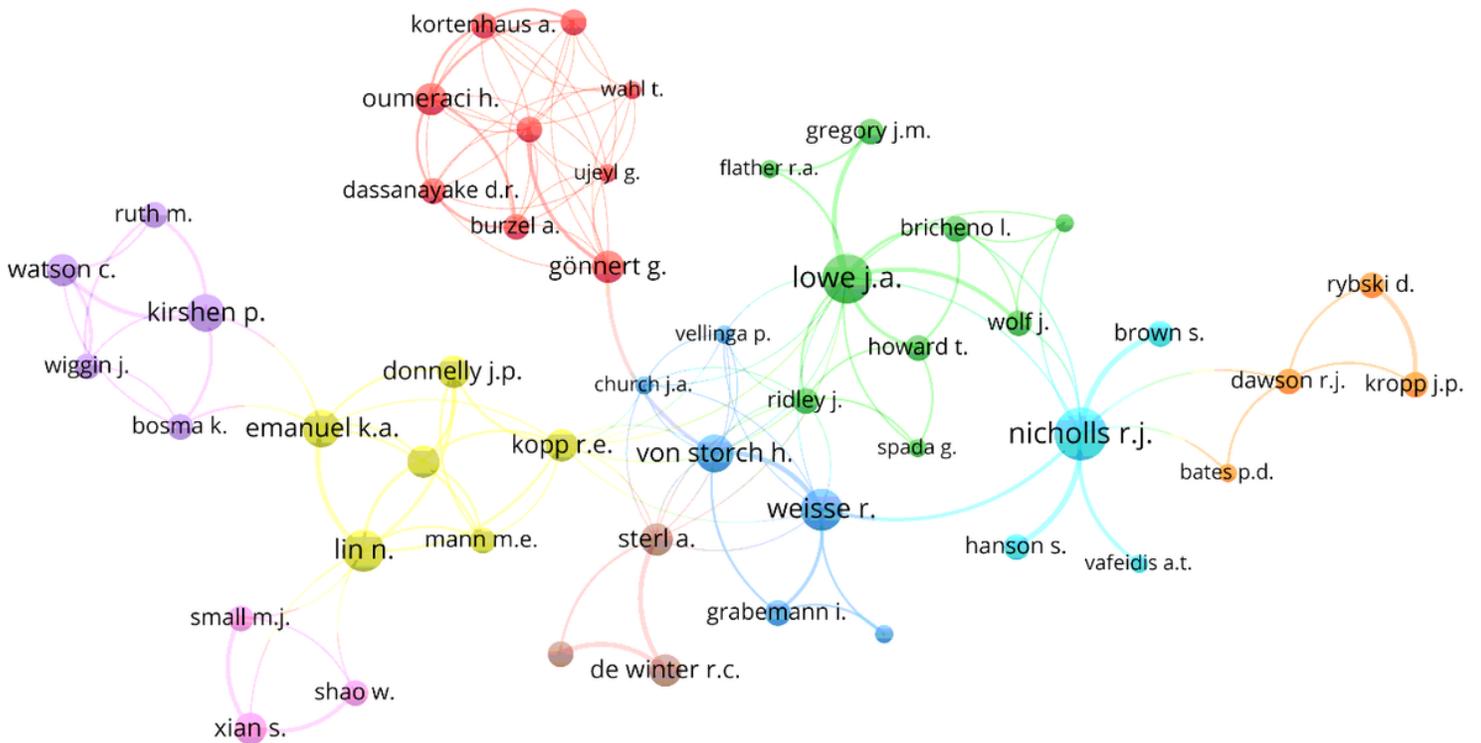
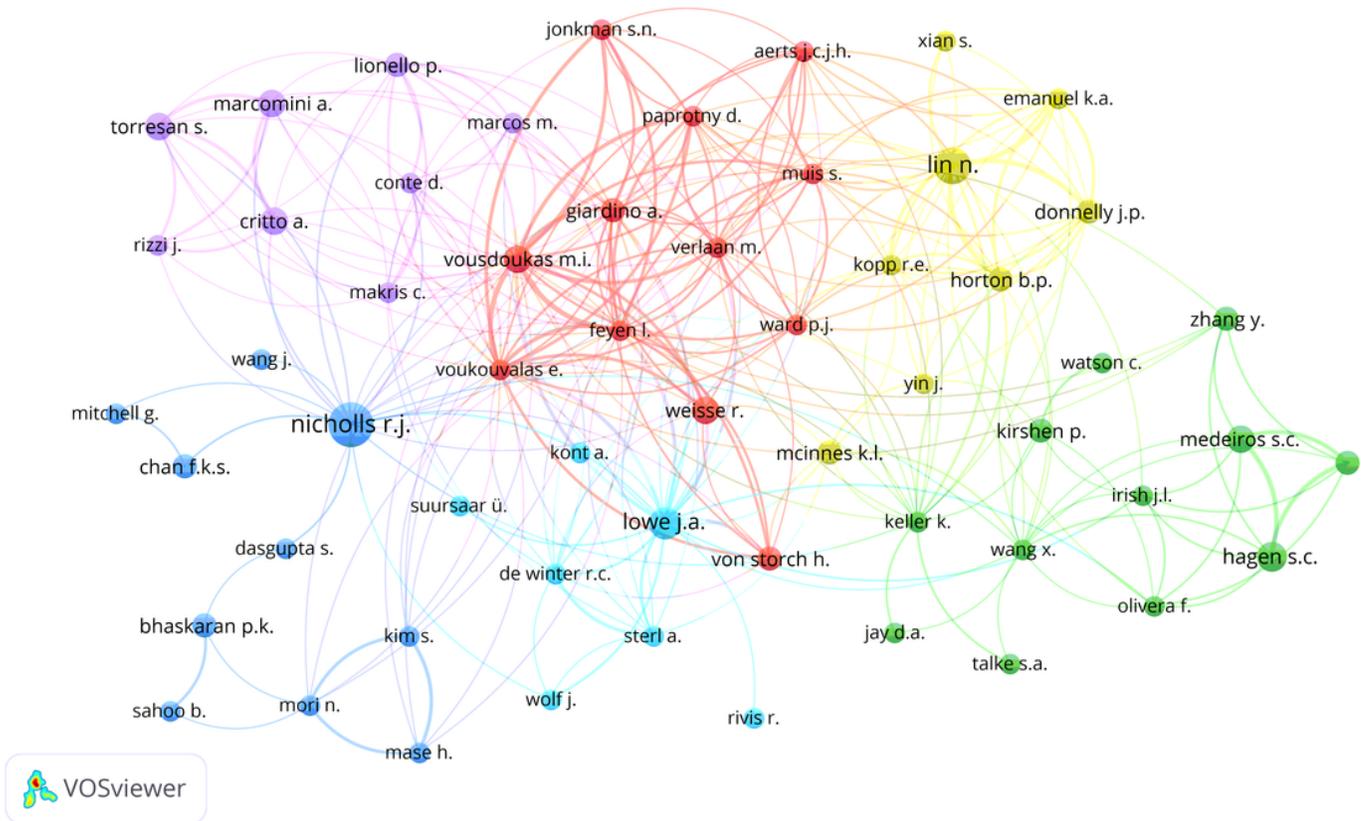


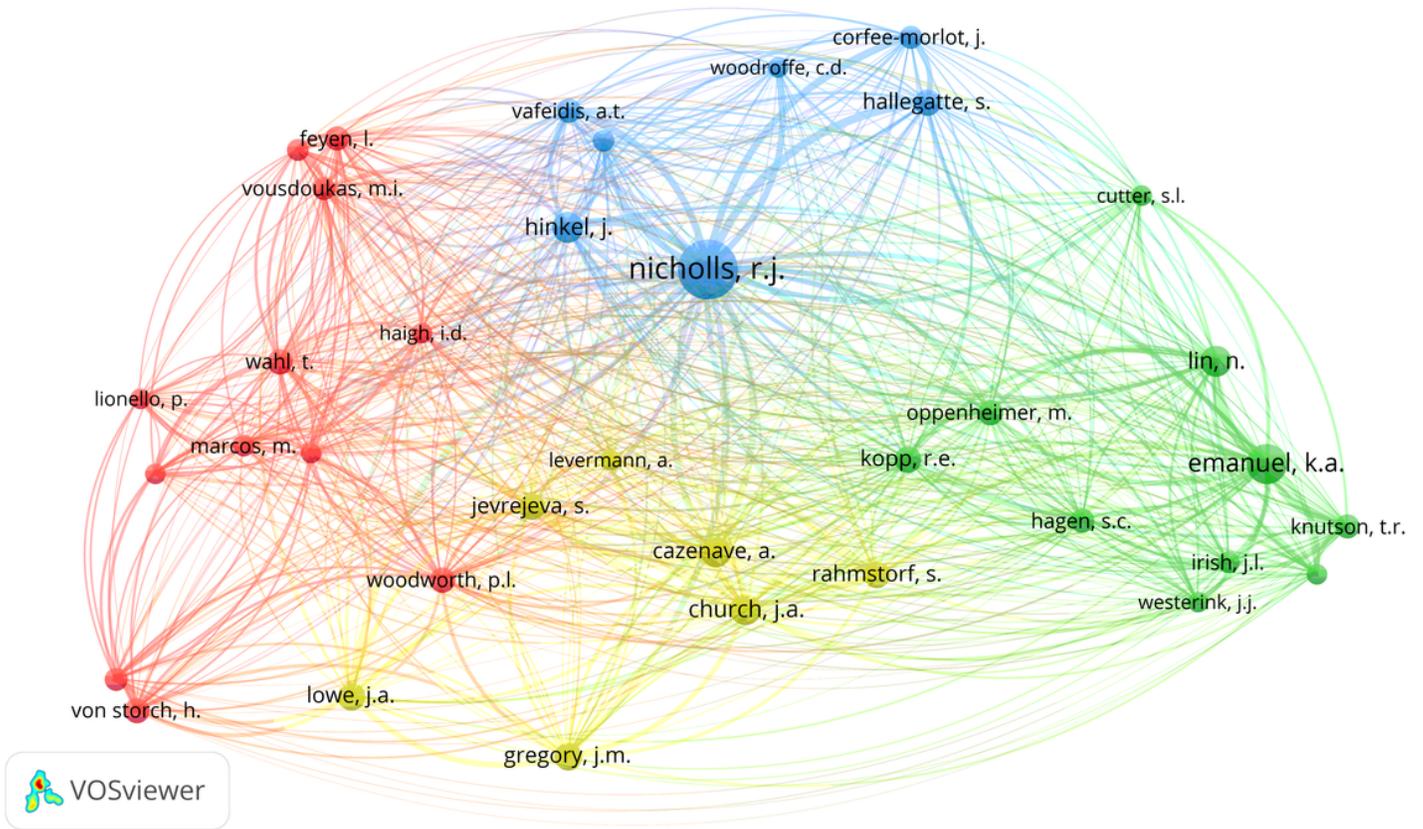
Figure 7

## Co-authorship network by author



**Figure 8**

Citation network by author



**Figure 9**

Co-citation network by author

Image not available with this version

**Figure 10**

Figure 10

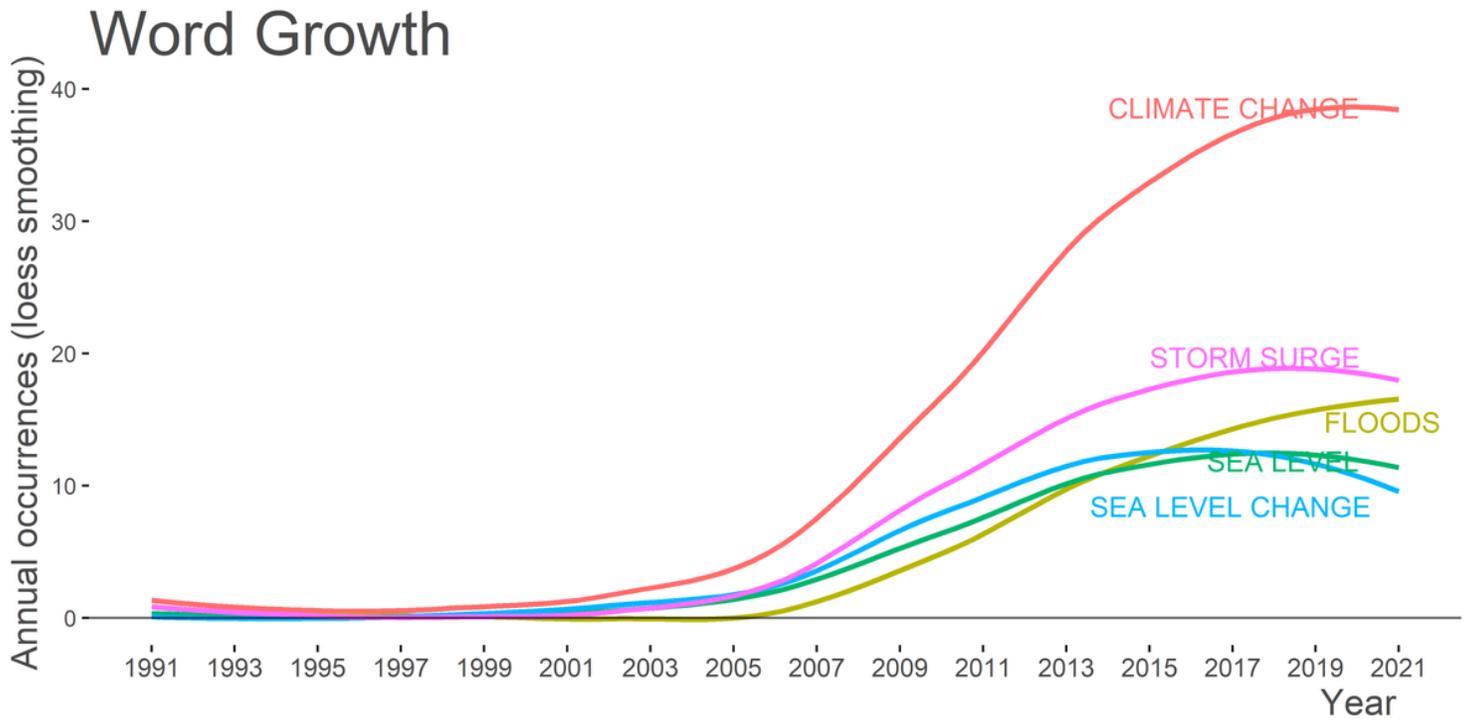


Figure 11

Keywords usage growth from 1991 to February 2021

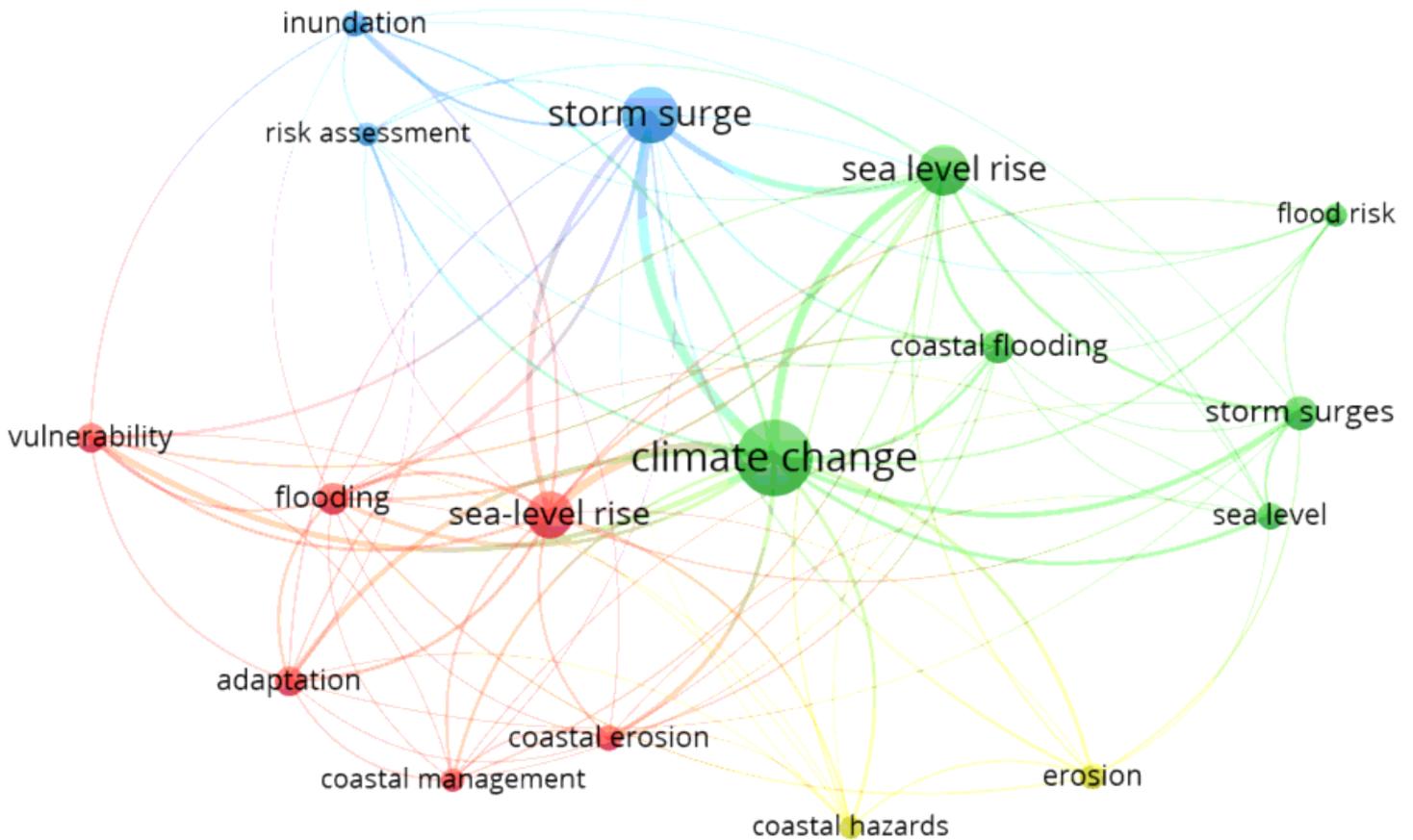


Figure 12

The keywords co-occurrence network based on incidences of keywords in paper

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supplementarymaterial.xlsx](#)