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An overview of 33 years of trends in space weather research: a bibliometric analysis (1988-2021)

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ABSTRACT

Space weather (SpW) is a phenomenon caused by a variety of solar events and has the potential to disrupt infrastructure systems and technology, putting them at risk. Despite SpW's immense impact, there has been a notable absence of bibliometric analysis studies to understand the research trends, regional distribution, social structure, conceptual structure, and knowledge gaps. This review synthesized scopus documents of SpW domain from 1988 to 2021. In this study, three tools were used, such as Microsoft Excel, VOSviewer, and Harzing's Publish or Perish for statistical analysis, graphical presentation, and citation metrics, respectively. Based on the 3,956 articles, roughly 70% of the articles were published in the last ten years, reveals a rapid growth in SpW research. The study discovered that China ranked third in publication volume, following the United States and the United Kingdom with Russian Federation following closely in fourth place. This study also presents six key findings, including the growth pattern of publications, contributions, and authorship collaboration by countries, most productive and influenced authors, co-authorship status, most influenced journals and articles, research cluster and new SpW subtopics discovered. These findings provide useful insight and aid in the advancement and progress of this field.

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1. INTRODUCTION

Space weather (SpW) events are a combination of an assortment of solar occurrences, such as solar wind, solar particle events, solar flares, coronal holes (CH) as well as coronal mass ejections (CME) [1]. It refers to electromagnetic and particle conditions in space near Earth that can affect both spaceborne and ground-based technological equipment. It results from solar explosions, where the solar wind carries these effects to Earth, interacting with the geomagnetic field and affecting the magnetosphere [2]. This interaction causes disturbances that accelerate charged particles, increase electric currents, and generate electromagnetic

perturbations, impacting various systems on Earth. Solar wind, an ongoing stream of charged particles emitted from the Sun, interacts with Earth's magnetosphere, creating a complex interplay of magnetic fields and radiation. This interaction poses challenges for spacecraft and astronauts due to the potential hazards of solar particle events, characterized by sudden releases of highly energetic particles. Meanwhile, solar flares, intense bursts of energy and radiation from the Sun's surface, have the capacity to disrupt terrestrial navigation and radio systems, adding to the complexities of SpW phenomena. Additionally, CH, regions characterized by exposed magnetic fields on the Sun's surface, can influence Earth's magnetosphere through the solar wind, potentially inducing geomagnetic storms. Finally, CME, massive eruptions of plasma and magnetic fields from the Sun, have the potential to trigger geomagnetic storms and auroras, posing risks to power infrastructures and satellite operations. SpW event is one of the crucial topics that has a wide-ranging effect on the socioeconomic and ecological systems, reducing the reliability of critical systems. As SpW events have garnered increasing attention, they have evolved into a significant scientific endeavour on a global scale. The disruptive effects of SpW events span a wide array of sectors, ranging from pipelines and global positioning systems (GPS) to satellite systems, communication networks, railway system, electric power grids, aviation, spacecraft, and high-frequency communication technology [3]–[8]. The importance of understanding SpW phenomena transcends academic boundaries, with implications reaching into various facets of society and industry [3], [9]. Although the global significance global impact of SpW, a limited amount of comprehensive data on research progress, patterns, and collaborations in this field is available to enable researchers to identify knowledge gaps and future areas of inquiry.

Existing work reviewing on SpW studies provide insightful information about the evolving nature of SpW threats, as well as the difficulties and opportunities such as a detailed review of the historical roots of SpW to its current effects on Earth's technological infrastructure and human health provide by Buzulukova and Tsurutani [10]. It emphasises the changing nature of SpW risks and hazards throughout time, emphasising the importance of readiness. Meanwhile, McGranaghan *et al.* [11], focuses on the Digital Age's impact on SpW studies. This study highlights the challenges and possibilities that arise from the fast-evolving data environment, which is typified by large amounts of data. This article emphasises the significance of adaptable and inventive strategies throughout the whole lifespan of data. In comparison, Gopalswamy [12] explores in more detail the scientific knowledge of solar variability and its implications for SpW and how solar disturbance influences the Earth’s ecology and technological systems due to some events like CME and solar flares. The above publications make the SpW subject more interdisciplinarity, allowing viewpoints from a fresh perspective and different insights. Indeed, where Buzulukova and Tsurutani [10] overview more topics of SpW field in general, this publication provide a better understanding the phenomena of solar physics, and the latter reveals the area of data science, which testifies to the dynamic nature of the field [11], [12].

Additionally, Baki *et al.* [13] assess the status of Africa’s SpW science infrastructure, which indicates gaps in ground-based observing that make it difficult to acquire required data. Furthermore, the rectification of this deficiency is essential for the development of SpW products and services. Conversely, Telloni [14] highlights the importance of monitoring and forecasting Earth-directed heliospheric events, which is designed to formulate empirical laws for the short-term forecasting of SpW with the ultimate aim of reducing the impact of such activity upon human activity and technological infrastructure. Nonetheless, Vourlidas [15] exploration of solar drivers of SpW is centered on coronagraphic sensitivity to CME and flares. It outlines some research gaps and challenges and suggests advances in forecasting capacity and observational facilities. The articles address the issues of the limitations of SpW research in terms of infrastructure growth, forecasting, and understanding the drivers of the Sun. It also argues that SpW research should be more interdisciplinary and state the relationship between reduced industrial capacity and increased solar flares due to weakened observational capacity. These issues are important to predicting and mitigating the impact of SpW on Earth and its technological infrastructure.

A study performed by Tsagouri [16] examines the impact of geomagnetic storms on Earth's upper atmosphere, focusing on middle latitudes. It highlights the changes in ionospheric plasma due to solar wind energy input during these storms. The paper emphasizes the importance of understanding ionospheric storms for their effects on technological systems and solar-terrestrial relations. In comparison, Sousasantos *et al.* [17] investigates the impact of ionospheric dynamics in low latitudes, particularly in Brazil, on global navigation satellite systems. Zenchenko and Breus [18] performed a 25-year review of heliobiological studies reveals connections between solar activity and population disasters, daily morbidity outbreaks, and heart and brain rhythm synchronization with geomagnetic field variations. The review discusses the applicability of SpW indices, the need for meteorological factors, and personalized approaches in heliobiology. The studies explore the intricate relationship between SpW, Earth's atmosphere, and human health, examining geomagnetic storms' impact on the ionosphere, challenges in satellite-based positioning, and potential impacts on human well-being. While all these previous studies investigated on SpW review articles in qualitative analysis, focused on particular aspects of SpW events, can provide important knowledge, they did not explicitly address its influence on quantitative parameters such as growth patterns of publications, characteristics of authorships, citation

networks, and the evolution of topics over time. Bibliometric studies offer a quantitative perspective on the underlying organization and development of scientific research by providing evidence on key authors, journals, publications, and collaboration trends.

This initial examination of a bibliometric analysis, using articles between 1988 to 2021 from the Scopus database covering a 33-year overview, gives a critical insight into the trends in SpW research. Considering the wide array of topics focused on within SpW research, the work aims to find the research gaps that are still to be explored in this dynamically changing and adjusting field. This study hopes to shed light on the different aspects of SpW research thus explaining on the gaps that still has potential for further exploration. Bibliometric analysis in this study quantitatively assesses the growth and spread of the literature and trend in research in SpW. The study expects to identify key authors, journals, and articles while fostering a clear depiction of the research topic through bibliometric mapping and networks. The following research questions (RQ) are addressed in this bibliometric review:

- RQ1: what is the changing trend of the SpW field over a period of time, the growth trajectory, geographic distribution, and volume?
- RQ2: which scholars have emerged as the most productive and influenced authors, its social structure of co-authorship status, the most influenced journals and the most influential articles?
- RQ3: what are the major themes in SpW and what are the potential topics that could be examined in the future?

By investigating these scientific inquiries, this review functions as an essential tool for comprehending the historical development, present situation, and future directions of SpW research. This comprehensive assessment supports informed decision making by researchers, policymakers, funding agencies, and industry stakeholders, guiding resource allocation, policy development, and strategic planning efforts. The subsequent sections of the paper are organised in the following manner, section 2 discussing the methodology employed to conduct the assessment and the software utilized for data analysis. Section 3 presents a critical analysis of the review results, focusing on the bibliometric elements of selected publications. It then combines the main points of the discussion, offering both theoretical and practical insights. Section 4 concludes the study by discussing its consequences and suggesting areas for further research.

2. MATERIALS AND METHODS

This study applied the bibliometric analysis approach [19]–[23], which is a quantitative research approach, centered on examining bibliographic data, including publications, citations, and associated metadata, to uncover insights into the characteristics, patterns, and trends within a specific literature domain [24]. Research by Liang and Liu [25] employing statistical and computational techniques, have shown that this method facilitates the measurement and evaluation of various aspects of scholarly communication and information dissemination. It is an excellent method for addressing the research issues discussed previously. The studies collect metadata on scientific literature, convert it, extract it, check for duplicates, perform descriptive analysis, and perform network analysis. This work will aid in determining the scientific output of authors, the annual growth rate of publications, and citation analysis, among other things. Moreover, research networks and international collaborations, as discussed by Dorovolomo and Dakuidreketi [26], significantly influence scholarly productivity, as it receive higher citation and often yielding higher publication rates and visibility. In addition, well-conducted bibliometric studies can lay the groundwork for novel and meaningful advancements in a field. As noted by Donthu *et al.* [24], such studies allows and encourages researchers to acquire a broad overview, uncover research and knowledge gaps, produce innovative exploratory ideas, and locate their intended contributions for global impact.

This study adheres to a structured methodology based on the modified preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram, as proposed by Moher *et al.* [27]. Initially, all relevant documents were meticulously screened to eliminate duplicates and ensure relevance to the study's topic. The method is illustrated in Figure 1, which outlines three distinct stages:

a. Database searching and extraction, guided by predefined topics, scopes, and search strings.
b. Screening and final selection of documents based on predetermined criteria.
c. Conducting bibliometric analysis to extract valuable insights from the selected literature.

2.1. Database searching and screening

In this work, the Scopus database is used to examine earlier work on web accessibility since Scopus is the largest database of academic articles [28] compared to the Web of Science (WoS) or Pubmed [29]. Scopus database contains information on publications such as the kind of access, the year, the author's name, the topic area, the document type, the title of the source, the keyword, the country, the affiliation, the language, and the source type. To effectively carry out bibliometric research, it is crucial to employ the most

precise keywords that are relevant to the research domain. Therefore, in order to guarantee that publications are obtained from trustworthy sources, this study employed the following search term "space weather" as a one-word search through the title, abstract, and keyword available in Scopus from 1988 until 2021. On the next level of analysis, only publications with journal sources and articles as documents were analysed. With this type of publications, the study is able to maintain uniformity and comparability among investigations, which facilitates meaningful comparisons and meta-analyses.

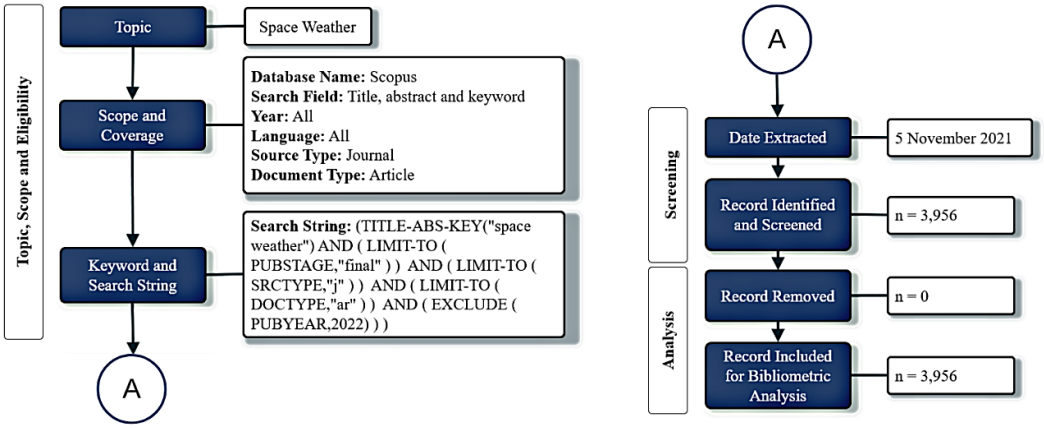

Figure 1. The bibliometric data extraction flow diagram

A total of 3,956 research studies were obtained from the search and. The number of articles is notable, suggesting a significant number of research done on SpW. This vast compilation of articles enables a thorough examination of the subject matter and offers a wide-ranging comprehension of the field's evolution throughout history. At this stage, non-SpW and irrelevant articles and duplicate entries were identified and removed. However, all data are related and there were no duplicate data observed, hence no record was removed in the next phase. This leaves 3,956 data analysed via bibliometric analysis in a variety of ways to provide context for the research questions. The incorporation of papers from different time periods allows for the recognition of historical patterns and the development of research in the field of SpW.

2.2. Tools and analysis

The examine search results feature available in Scopus was used to obtain numerous and more detail results. Ahmi and Nasir [30], the remaining findings were manually added or exported to an Excel file that has been coded to perform statistical computing and basic data analysis. With Excel, the study could assess the impact of SpW publications and authors through metrics like the total publications (TP), number of cited publications (NCP), total citations (TC), citations per paper (C/P), average citations per cited publication (C/CP), h=h-index, and g=g-index. The data, for example, percentages from the files created for all outcomes, are retrieved and after that, the outcome is interpreted. The development of Excel templates tailored for bibliometric analysis allows us to use the most reliable and established methods in the field. Additionally, the data obtained was analysed using visualizations created by VOSviewer [19], [20]. VOSviewer is a software tool widely used to analyse the bibliometric performance of articles, including the visualization of co-authorship networks, topic clusters, and citation patterns within the scholarly literature. VOSviewer was used to visualize complex data and find key authors, topic patterns, and citation network in SpW. In addition to this, Harzing's Publish or Perish (POP) package was used to assess citation metrics. The data was further comprehended using graphics generated by VOSviewer. The analysis included the publication patterns, discover the most productive author, find clusters of related themes, and citation patterns. With the process of identifying, analysing, and synthesizing, the above data was used to compile a comprehensive report that summarized the results, provided reasons, and offered recommendations for research directions in the SpW domain.

3. RESULTS AND DISCUSSION

The outcome of the analysis is presented in this section, which includes an overview of SpW's publication types and citation metrics, along with research trends and growth trajectory, active and influenced authors, journals, articles, and research topics, themes, and future directions that respond to the RQs.

3.1. Research trends and growth trajectory (RQ1)

The list of published studies from 1988 to 2021 is portrayed in Figure 2, along with the total citation by year. Data for the 3,956 Scopus indexed articles released over the past 33 years are denoted by solid blue lines. It signifies a large and rapidly growing knowledge contribution to SpW studies. These publications are separated by the vertical dotted lines, dividing them into three distinct phases, where Phase 1 shows the first starting involvement of SpW studies.

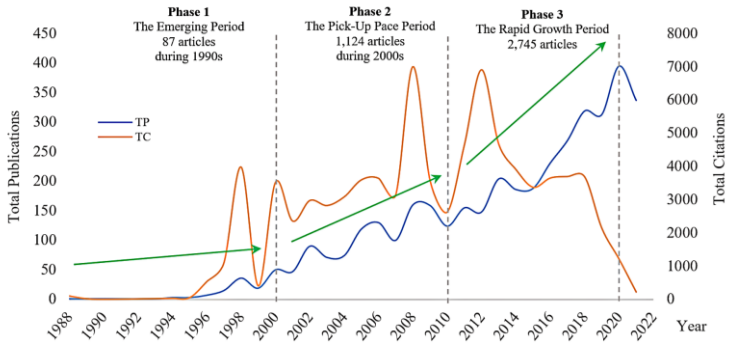

Figure 2. Citations by year and growth trajectory on SpW publications, 1988-2021 (n=3,956)

During Phase 1, 87 records were published on SpW research during the 1990s, but 1,124 documents were released during Phase 2 during the 2000s. The number of articles doubled in phase two, reaching 2,745 articles, indicating a rapid development of literature. Every two years, the number of publications increases by around 2%, indicating an increase in research. The SpW studies started to increase when the first major SpW impact, which was the solar storm, started to hit Earth in the Carrington [31] Event in 1859. The significance of extreme events was not publicly recognized until much later when civilization became more reliant on technology sensitive to such events in the 20th century. This historical context underscores the growing importance of understanding and studying SpW to protect modern technology and infrastructure.

Phase 2 shows a rapid increase in both publication and citation. In this phase, many major SpW events occur and also due to the presence of few solar missions like solar and heliospheric observatory (SOHO) [32], [33], solar terrestrial relation observatory (STEREO) [34], solar dynamics observatory (SDO) [35], [36]) launched during this period. There was a growing recognition of the need to study and understand SpW for both scientific and practical reasons. The launch of solar missions provided scientists with new tools and data to study the Sun and SpW, leading to significant scientific advancements. The availability of this data contributed to the increase in publications and citations. However, there is a huge fluctuation in terms of TC by year, which reflect the dynamic nature of SpW research, which responds to a combination of scientific, technological, environmental, and sociological factors that influence research activity and interest in specific periods. The study of solar radiation and its impact on the element and components in space and how its negative impacts the Earth and its infrastructure is gaining attention. The next decade has shown a tremendous increase in publications and citations. For the year 2021, the number of publications represents scientific literature published till November with 8.52% of the article. There is a potential to increase by 2% from 2020, which will double the previous decade. The maximum number of research outputs is during 2020 which contributed to 10.01% of the TP with 395 documents.

The development of SpW research demonstrates the complex interaction between historical events, technology progress, and societal needs. Phase 1 had modest growth, aided by the Carrington Event, whereas Phase 2 saw an exponential increase, fuelled by solar missions like SOHO and STEREO. Fluctuating citation trends reflect the varied nature of research processes, while the trajectory indicates continued expansion and greater societal relevance.

3.1.1. Publications by country, its volume and collaboration

The analysis of publications by country in the field of SpW provides insights into the worldwide panorama of research contributions and collaborations. Figure 3 provides a visual representation of the nations that are active in SpW publishing, while Table 1 displays the top seven (7) countries along with their citation indexes. China has been a notable contributor, placing third with 434 papers and accounting for 10.97% of the TP. Nevertheless, when evaluating the influence of citations, China's citation index falls below

that of Germany and France, despite its significant publication production. Germany and France hold a higher citation with 6,990 and 7,782, respectively. This suggests that their research outputs have received more attention and impact in the academic world. The United States stands out as the leading contributor to SpW research, with 1,701 papers, making up a significant 42.99% of the TP. The domination of publications in this volume highlights the substantial investment and competence of the United States in the field of SpW. While the United States leads in publication volume, its citation index provides a more nuanced picture of the influence of its research output in comparison to other countries.

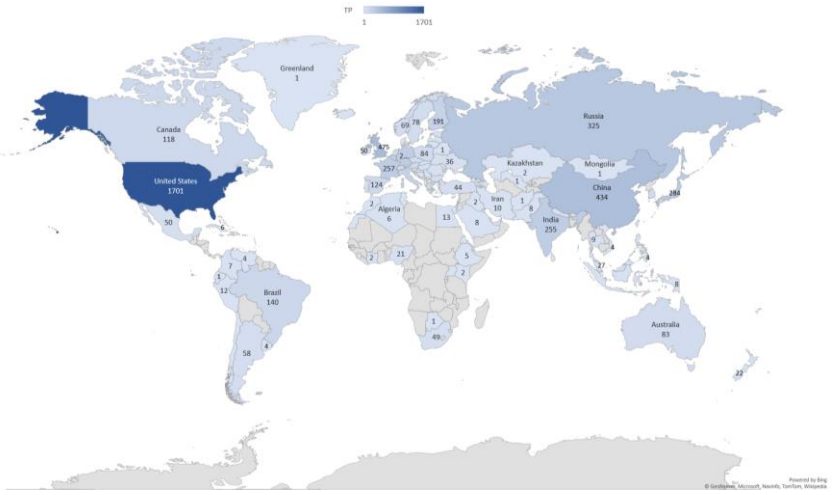

Figure 3. Geographical distribution of publications

Table 1. The top 5 countries assisted in the publications

Country	TP	NCP	TC	C/P	C/CP	h	g
United States	1,701	1,557	56,331	33.12	36.18	101	182
United Kingdom	475	433	10,846	22.83	25.05	49	85
China	434	350	5,604	12.91	16.01	36	61
Russian Federation	325	261	5,120	15.75	19.62	32	62
Japan	284	240	5,368	18.90	22.37	35	64
Germany	259	235	6,990	26.99	29.74	43	73
France	257	238	7,782	30.28	32.70	42	79

Notes: TP is total publications; NCP is number of cited publications; TC is total citations; C/P is citations per paper; C/CP is average citations per cited publication; h is h-index; and g is g-index.

Similarly, the United Kingdom contributes significantly to SpW research, accounting for 475 papers, or nearly 12% of TP. Although the United Kingdom's publishing volume is smaller than that of the United States and China, its research outputs may have considerable influence and impact on the academic community, as reflected in its citation index. Furthermore, it is important to mention that although China is ranked third in terms of the number of publications with 434 counts, its TC is 5,604, which is lower than those of other countries like the Russian Federation and Japan, which have citation counts of 5,120 and 5,368, respectively. This implies that the research output from these countries may have a higher quality and greater impact compared to the number of publications they produce. Less than 10% of the publication's content came from the rest of the countries.

Figure 4 depicts a clear and visually appealing representation of the collaborative landscape for SpW research. It effectively emphasises the international nature of scientific collaboration, particularly in relation to this topic. The map not only shows present collaboration networks but also suggests future paradigms that are expected to influence the network. The current visualisation graphically illustrates the increasing participation of countries from lower latitudes region [37]–[43], as indicated by the colour gradient of the nodes. This trend indicates an increasing engagement and curiosity of countries in SpW research, including those that have not previously participated in scientific collaborations. Studying the distinct elements that initiate and advance this trend, irrespective of scientific cooperation, might offer valuable insights into international collaborative networks and the worldwide dissemination of knowledge. United States serves as the central hub of the cooperative network for SpW. It demonstrates that the nation possesses a robust basis in scientific knowledge, substantial opportunities for financial support, and a high level of proficiency in the field of SpW.

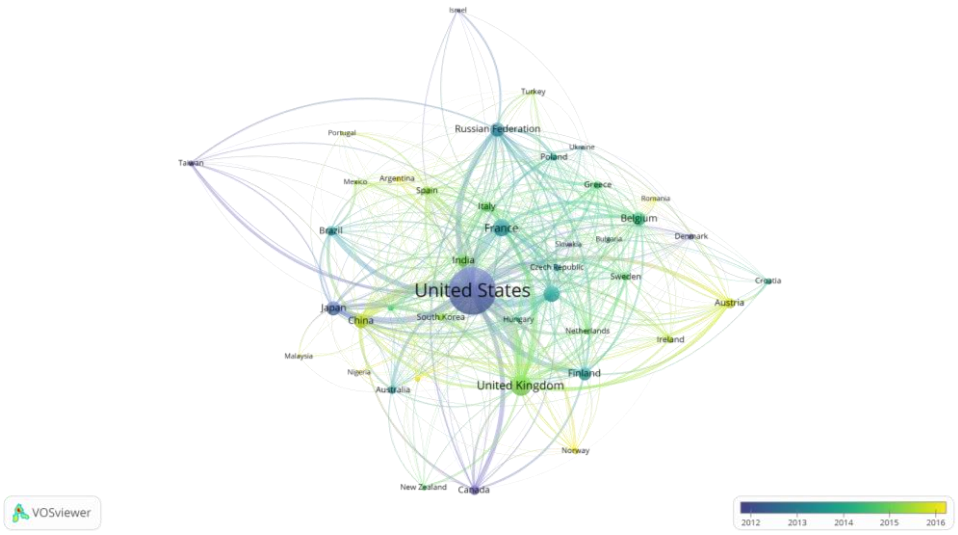

Figure 4. Network visualization map of the country collaborators

The thickness of the link lines indicates the level of collaboration in co-authorship between the countries. The collaborative research conducted by the United States with countries such as Canada, Brazil, Japan, Finland, and the Russian Federation demonstrates the interconnectedness of research endeavours across continents. Therefore, these collaborations not only facilitate the sharing of perspectives and concepts but also foster innovation and scientific advancement in this field. In addition, the collaborative networks Figure 4 illustrates a shared objective among countries to enhance research on SpW. Despite their differences in geographical location, cultural background, and scientific interests, academics around the world share a common goal, to investigate and mitigate the impact of SpW on technology and the global population. Networks play a critical role in accelerating worldwide collaboration and the sharing of knowledge, which enhances our understanding of SpW and improves our ability to anticipate and mitigate its effects.

3.2. Influenced authors, journals, and articles (RQ2)

This section explains the most active and influential authors, co-authorship analysis, most influential journals and most influential articles. Through an exhaustive evaluation of these elements, academics are able to make well-informed choices regarding collaborations in research, approaches to publication, and allocation of resources. This, in turn, promotes the progression of knowledge and the creation of influential scholarly works.

3.2.1. Productive and influential authors

Table 2 presents the eight (8) most significant and prolific authors and the information about their impact on citations and publication histories. The authors exhibit a noteworthy diversity of scientific work, having authored anything 37 to 55 articles pertaining to SpW. Among them, NASA Goddard Space Flight Centre's researcher, Antti A. Pulkkinen stands out as a very active contributor, having authored 55 articles, with an impressive 53 of the papers cited. Among his notable achievements, 25 of his articles have received 25 times or more citations, securing him the 5th rank for citation with 2,009 citations.

Table 2. Ranking of publication and citations status by author

Author's name	Affiliation	CTRY	TP	NCP	TC	C/P	C/CP
Antti A. Pulkkinen	NASA Goddard Space Flight Center, Greenbelt	United States	55	53	2,009	36.53	37.91
Mathew J. Owens	University of Reading, Reading	United Kingdom	44	42	772	17.55	18.38
Tamas I. Gombosi	University of Michigan, Ann Arbor	United States	41	39	2,636	64.29	67.59
Janet G. Luhmann	University of California, Berkeley	United States	40	40	2,379	59.48	59.48
Pete Riley	Predictive Science Inc., San Diego	United States	39	36	2,309	59.21	64.14
Norbert Jakowski	Institute for Solar-Terrestrial Physics, Cologne	Germany	38	37	1,341	35.29	36.24
Stefaan Poedts	Maria Curie-Sklodowska University, Lublin	Poland	37	34	564	15.24	16.59
Angelos Vourlidas	Johns Hopkins University Applied Physics Laboratory	United States	37	37	2,753	74.41	74.41
Norbert Jakowski	Institute for Solar-Terrestrial Physics, Cologne	Germany	38	37	1,341	35.29	36.24

Notes: CTRY is country; TP is total publications; NCP is number of cited publications; TC is total citations, C/P is citations per paper; and C/CP is citations per paper.

The second top productive author is Mathew J. Owens from the University of Reading, Reading, the United Kingdom (UK), with less than 11 articles compared to Antti A. Pulkkinen, but nonetheless, 42 of his articles have been cited. Even though Owens has published less than Pulkkinen, he nevertheless has a high citation rate, which speaks to the calibre and significance of his work. Similarly, Tamas I. Gombosi, the third top author, from the University of Michigan, Ann Arbor, United States (US), boasts 41 articles, with 39 receiving citations. He secures the second rank for TC with a substantial count of 2,636 citations, following Angelos Vourlidas affiliated with Johns Hopkins University Applied Physics Laboratory. The analysis also highlights other notable contributors including Janet G. Luhmann from the University of California, Berkeley, and Angelos Vourlidas from the Johns Hopkins University Applied Physics Laboratory, whose works have received a great deal of attention within the SpW community. Both amassed an impressive 2,753 citations across 37 publications and 2,379 citations across 40 articles respectively, of all of which have been cited. Furthermore, Pete Riley from Predictive Science Inc., San Diego, United States, has 39 articles with 36 of its papers cited. He secures the 4th top author for TC with 2,309 citations.

Figure 5, generated using VOSviewer, offers a visual representation of co-authorship networks within SpW research. It is generated according to co-authorship in SpW with a maximum of 10 co-authorship per paper and 15 minimum documents and citations of an author, giving 36 lists of authors. The explained co-authorship map illustrates how scholars are collaborating with each other. The linkages' thickness indicates how frequently the authors collaborate, while the colour shows which cluster the co-defendants belong to. One interesting pattern from the map is the frequency of its occurrence in research. Each group of scholars in co-authored publications is more frequent than others, and this correlates with the tendency for interdisciplinary research noted by, for example, Dorovolomo and Dakuidreketi [26]. Working together enables researchers to benefit from a wide range of resources and areas of expertise, which enhances the quality and extent of their research. Mathew J. Owens (labled as Owens M.J.) and Antti A. Pulkkinen (labled as Pulkkinen A) deserve special mention as the most collaborative writers with 11 co-authorship links each-such apparent involvement implies their active role in multidisciplinary collaborations. This finding underlines the critical need for cooperative networks to facilitate SpW research development and enable discipline innovation and, most notably, it is clear that few researchers are lone authors. To conclude, the study of well-known writers and the co-authorship dynamics offer valuable information about the character of cooperation and academic clout within the sphere of SpW research. The collaboration and dissemination among authors ultimately make it possible for people to tackle complicated problems together, advance scientific knowledge, and disentangle and prevent the implications of SpW.

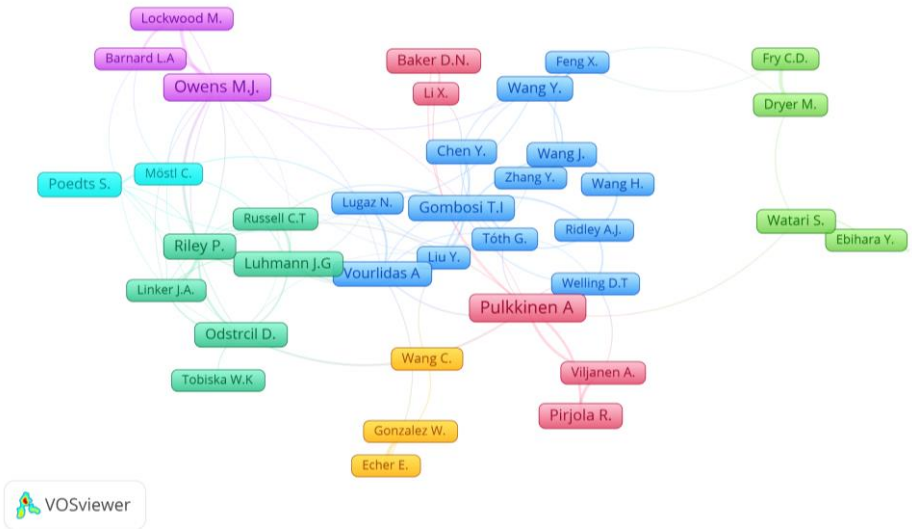

Figure 5. Network visualization map of the author collaborations

3.2.2. Most active and influenced journals

When looking at the landscape of academic publishing, a close assessment of the most active and prominent journals gives fascinating insights into intellectual discussion. Table 3 provides a comprehensive overview of journal activity over a span of 33 years, shedding light on their respective TP alongside key impact metrics. The cite score in the fifth column is the 2020 journal impact statistic that determines the average number of citations per document during the preceding four years, including the computed year.

Additionally, SJR 2020 refers to SCImago Journal Rank that quantifies the serial's weighted citations. The weighting of citations is determined by the topic area and prestige of the referencing periodical. Consequently, the higher the SJR indicator levels, the more prestigious a journal is considered.

Table 3. The most active journal title

Journal title	TP	TC	Publisher	Cite score	SJR 2020	SNIP 2020
SpW	573	9,884	Wiley-blackwell	7.30	1.254	1.254
Journal of geophysical research space physics	387	13,799	Wiley-blackwell	5.30	-1.00	1.112
Advances in space research	341	4,530	Elsevier	4.60	0.682	1.274
Journal of atmospheric and solar terrestrial physics	205	5,325	Elsevier	3.24	0.515	0.990
Astrophysical journal	198	5,199	American astronomical society	9.40	2.376	1.201

Notes: TP is total publications and TC is total citations.

Furthermore, source normalized impact per paper (SNIP) 2020 assesses the number of citations received in comparison with citations predicted for the topic area of the series. SNIP 2020 compares the number of citations obtained with the number expected for the topic area of the serial. Therefore, the "SNIP" of a journal is 1.01 if its articles are cited similarly to those of other journals in the same field. Given that it is lower than 1.01, the journal's articles are not receiving the recognition they deserve, and the journal is not as prominent as it might be. A SNIP of more than 1.5 is usually a sign that a journal is very well-recognized. Among the standout performers, SpW is out as a prominent figure in the subject, with a remarkable record of 573 publications and a high citation total of 9,884. The impressive citation score of 7.30 highlights the substantial influence of this source in the academic world, indicating a strong presence in scholarly discussions.

Additionally, target journal's SJR and SNIP for 2020 are 1.254, reveal the significant degree of acknowledgment and impact and once again underline that this journal is one of the most prominent authorities in the chosen field. Nonetheless, additional insight makes it possible to identify several interesting patterns. Even though the Journal of Geophysical Research Space Physics has fewer articles than SpW, other parameters make it more attractive, proven by the citation count that is 40% higher than that of SpW. Consequently, any article from this journal is likely to receive more attention and acknowledgment, on average. Nonetheless, the lower cite score at 5.30 indicates a lower average citation per publication from 2016 to 2020, highlighting a nuanced aspect of its impact over time. The position of the top tier concludes Advances in Space Research, which has 341 articles and 4,530 citations, confirming that it, too, belongs to the first tier of journals. Its cite score is 4.60, however, the SJR and SNIP for 2020 were different with 0.682 and 1.274 respectively, bring a more complex view of the impact of the journal to the academic discourse.

Although the article has received significant attention, its cite score and SNIP values indicate that it has had relatively low perceived impacts based on its publication dates. Examining the most prominent journals in terms of activity reveals an intricate "ecology" of scientific influence, where quantification measurements provide insights into the realm of academic discourse. Nevertheless, a thorough examination of these tools highlights the necessity of considering situational elements and, more importantly, temporal fluctuations when evaluating a journal's actual influence on its subject matter.

3.2.3. Influential articles

Table 4 depicts the list of seven (7) highly cited articles, a clear detail on their authors, titles, summaries, publication years, citation counts, and citations per year (CY). Notably, it reflected that only one article from the list is coming from a single author while the rest shows a collaborative effort in their authorship. This underscores the collaborative nature of impactful research in the field, emphasizing the collective contributions of multiple researchers for advancing scientific knowledge. Furthermore, the focus shifts in the subsequent discussion to the top five (5) most influential articles, showcasing the significant impact they had with citation ranging from 1,004 to 1,681. Remarkably, the article titled "The SDO" by Pesnell *et al.* [36] stands out as the highly cited article with 1,681 citations and with an average of 186.78 times citations per year (CY). This emphasizes the enduring relevance and impact of the article since its publication in 2012, and the choice of open access publishing on Springerlink.com likely contributed to facilitating to its widespread dissemination and engagement with scholarly works.

The next influential article entitled "HMI Investigation for the SDO" [44] explains the details of the HMI instrument used in SpW studies. Published in 2012, this article is authored by 12 scientists from four different institutions. Until today, this article has garnered significant attention with 1,232 citations and an

average of 136.89 articles being cited per year, which underscores its significance in this field. Similarly, the third in position is the paper with the title "Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI)" Howard *et al.* in 2008 [34] by 46 authors of 9 different institutions, has amassed 1,207 citation counts with an average of 92.85 citations per year. The major focus of this article is the explanation of how the five-telescope system is utilized to understand the CME phenomenon. This article has been established for the STEREO mission. The next most cited paper is "The THEMIS mission," written by Angelopoulos [45], which has gained 1,030 citations with 79.23 annual average citations, underscoring its role in advancing our understanding of SpW phenomena. THEMIS stands for "The time history of events and macroscale interactions during substorms" and is a task under NASA's fifth Medium-class Explorer (MIDEX), deployed in February 2007 to investigate the origin and substorms changes on a massive scale. The mission employs five identical microsatellites aligned along the Earth's magnetotail to trace and understand the movement of particles and plasma.

Table 4. Highly cited articles (more than 500 citations)

Authors	Title	Summary	Year	Cites	CY
Pesnell *et al.* [36]	The Solar Dynamics Observatory (SDO)	SDO mission investigates solar fluctuations, their impact on Earth's climate and technology, examining the Sun's magnetic field, energy emissions, solar wind, and irradiance.	2012	1,681	186.78
Scherrer *et al.* [44]	The Helioseismic and Magnetic Imager (HMI) Investigation for The Solar Dynamics Observatory (SDO)	The NASA solar dynamics observatory's HMI instrument investigates solar dynamo, sunspot origin, active regions, magnetic activity sources, corona and heliosphere dynamics, and precursors for space-weather forecasts, with a brief overview and standard data products.	2012	1,232	136.89
Howard *et al.* [34]	Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)	The article provides information about the STEREO mission's SECCHI project, which consists of a package of five telescopes designed for this purpose.	2008	1,207	92.85
Angelopoulos [45]	The Time History of Events and Macroscale Interactions during Substorms (THEMIS) Mission	The article talks about the THEMIS mission, which THEMIS is the initial micro-satellite constellation developed by NASA, serves as a technological precursor for forthcoming missions related to the connection between the Sun and Earth, while also serving as an intermediate milestone in the pursuit of comprehending SpW.	2008	1,030	79.23
Kaiser *et al.* [46]	The STEREO Mission: An Introduction	An overview of the STEREO mission is given in this article. Launched in 2006, the mission's two spacecraft are used to detect the propagation of CMEs back to Earth, study the acceleration of energetic particles, and create a three-dimensional model of the solar wind's characteristics.	2008	1,004	77.23

Notes: CY is citations per year.

Finally, the fifth most cited article is "The STEREO mission: An introduction", Kaiser *et al.* [46] published in 2008, having 1,004 citations and 77.23 annual average citations, further emphasizing the significance of space missions and their instruments in driving scientific inquiry and collaboration. The STEREO mission's objective is to better comprehend the origins and dynamics of CME and to track their dissemination from the inner heliosphere to Earth. It is noticeable that most of these articles are pertaining to space missions or their instruments which it is expected to gain large number of citations. This is because of their scientific merit, availability of data, international cooperation, public appeal, and technological progress. These articles attract interest from a wide range of readers, which contributes to their lasting influence in the field of space science.

3.3. Research theme and future direction (RQ3)

In exploring the research themes and future directions within the realm of SpW, a critical analysis of keyword co-occurrence data, plotted in Figure 6 via VOSviewer, reveals a complex landscape of interconnected themes. The keyword is synthesized, incorporating each cluster to the surface theme concerning the literature. From the map in Figure 6, it is proposed that the SpW can be grouped into five (5) major themes, "geomagnetic variations", "solar activity", "solar radiation", "space environment", and "ionosphere". The "geomagnetic variations" theme may cover all the geomagnetic changes related to topics from the interplanetary magnetic field to the Earth's magnetic field [44], [47]–[50]. It central to understanding

the Earth's response to external influences from space, including solar activity and solar radiation [1] and encompasses the fluctuations in Earth's magnetic field that can result from solar storms and the dynamic interplay between the solar wind and our planet's magnetosphere [51].

In contrast, the "ionosphere" theme is all related to the effects of interaction between the atmosphere, ionosphere, and magnetosphere layers from the Earth's atmosphere to the latter towards space [52]–[55]. It offers insights into how the Earth's upper atmosphere interacts with space, influencing communication and navigation systems. Vorobev *et al.* [56] solar and geomagnetic factors can lead to ionospheric disturbances, affecting radio signals and GPS accuracy. However, on the other hand, "solar activity" theme is topics associated to solar cycle which are fundamental drivers of SpW. The ebb and flow of solar activity [48], marked by sunspots and solar flares [47], have direct implications for space missions, satellite operations [57], [58], and even the functioning of power grids on Earth. These results "solar radiation" theme, researchers delve into the complex realm of solar energetic particles and their effects on space-based technologies and human health [58], [59]. An understanding of these particles is crucial for safeguarding astronauts in space and ensuring the reliability of spacecraft and satellites. Lastly, the "space environment" theme casts a wide net over the entire ecosystem of space activities, encompassing space exploration, satellite operations, and even space debris management [1], [60]. SpW events can have cascading effects on these endeavours, highlighting the need for a comprehensive approach to managing and mitigating risks.

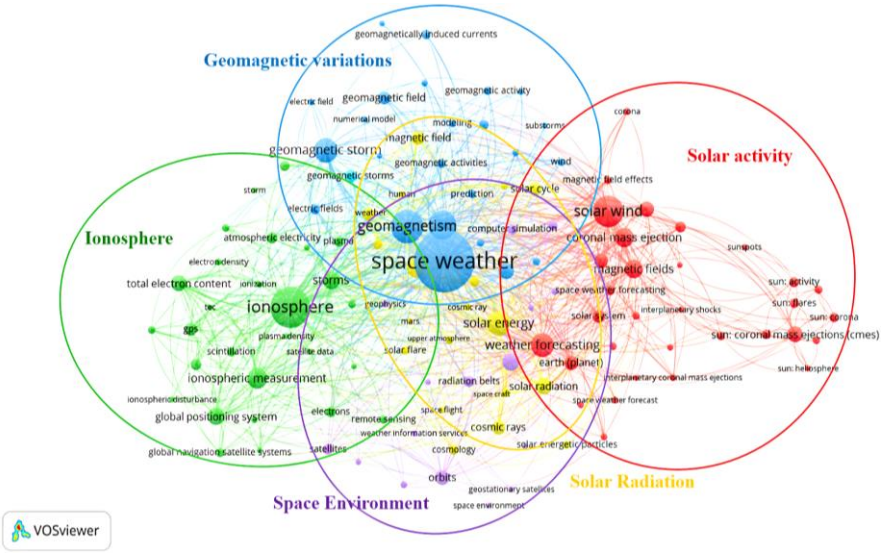

Figure 6. VOSviewer visualization network of a term co-occurrence (from 1988 to 2021) depending on keywords. The keyword is clustered into five category themes

Nevertheless, it is essential to acknowledge that these themes are not isolated silos of research but rather parts of a larger, interconnected system. The intersections between these themes highlight the multidisciplinary nature of SpW research. Collaborations between experts in these different areas are not only beneficial but essential for developing a holistic understanding of SpW and for devising effective strategies to address its challenges. The themes, therefore, serve as a roadmap for SpW researchers, guiding them toward the most pressing questions and areas of study. As the field continues to evolve, it is these interconnections and collaborative efforts that will shape the future of SpW research, enhance our SpW forecasting capabilities, and ultimately bolster the resilience of our technological infrastructure in the face of space-related threats.

3.3.1. Potential future topics in SpW study

Based on the author's keyword with a minimum occurrence of 5, Figure 7 represents the current keyword trend in the SpW study. A larger node size signifies more frequent use of a keyword. We identified 168 keywords from 2017 to 2021, based on the extraction. This analysis identifies keywords, terms, or topics that have not been widely explored in recent years. There's a prospect for the researcher to investigate further in the future. It's important to note that these are not novel concepts or keywords used in this research field.

They might be used differently and depends mostly on the authors' scope of study [61]. From the map, the keywords identified used in recent years but not that frequently include “space radiation”, “equatorial plasma bubble”, “LSTM”, “deep learning”, “space weather forecasting”, “neural network”, “GIC” which refers to geomagnetically induced currents, “telescopes”, and “Sun: UV radiation”. These keywords show the potential topic to be further explored in the future. It is suggested that current research work can focus on SpW modelling for, but not limited to space radiation, equatorial plasma bubble, GIC and UV radiation. Moreover, with the ongoing advancement and widespread adoption of artificial intelligence (AI) tools across various scientific domains, including SpW research, there exists a significant opportunity for them to profoundly alter our approaches to studying and comprehending SpW phenomena. AI methodologies, such as machine learning algorithms, recurrent neural networks, and deep learning models, offer robust means for analysing data, identifying patterns, and making forecasts in SpW research. By leveraging AI, researchers can refine the accuracy and efficiency of SpW forecasting models, bolster our capability to anticipate and mitigate the effects of SpW events on critical infrastructure and technology, and uncover novel insights into the complex subtleties of the space environment. Therefore, the integration of AI methodologies into SpW research holds immense potential for future exploration and advancement within the discipline.

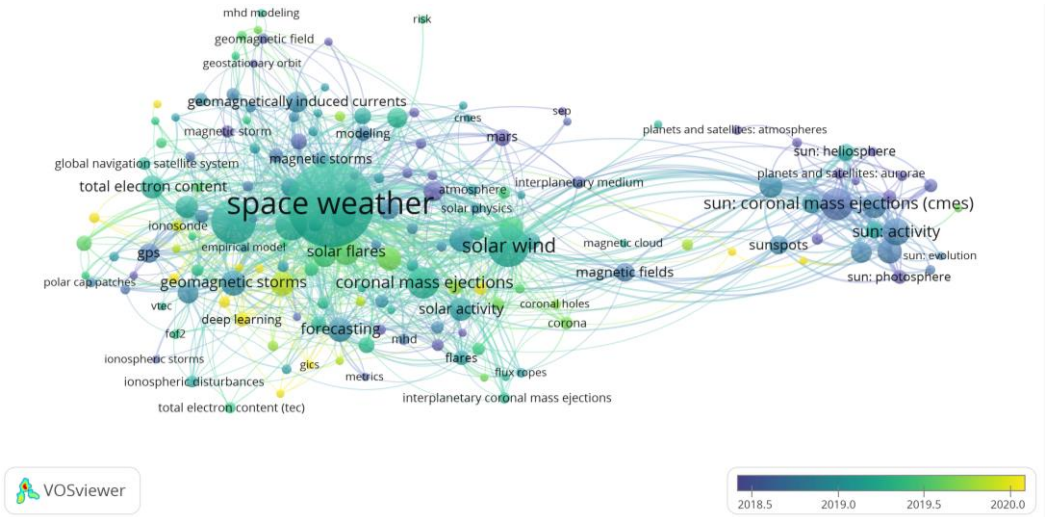

Figure 7. VOSviewer visualization of author’s keyword co-occurrence network from the year 2017 to 2021

4. CONCLUSION

Overall, the researched analysis presents an exhaustive description of the rapid evolution within the field of SpW research. The paper reveals all the vital in-depth knowledge concerning the field’s development, strong contributions, leading articles and publications, and “signals” or perspectives. It is supported by rigorous evidence on the explosive proliferation of academic SpW literature worldwide due to the growing public concern and recognition about the need to know more about SpW. Examples like the Carrington Event send a strong signal to protect modern civilization through its technology and infrastructure from a space-related natural disaster. The paper highlights the dominance of contributions and publications in the field of SpW by researchers. Secondly, it has a global perspective, noting the nature of the collaboration among all countries who participate in intellectual exchange and inquiry. Thirdly, while some countries write more research papers, subtly, all the countries write the most influential work, quality over quantity. Furthermore, the study of prominent authors, journals, and articles proves that SpW research is multidisciplinary and sheds light on the most influential contributors to the field. Ultimately, visioning on the research themes and future targets will serve as a guide for SpW researchers, helping them focus on the most pressing issues and knowledge gaps regarding the SpW phenomenon. Therefore, reviewing upcoming enquiries, such as space radiation, equatorial plasma bubble, and AI applications, is a promising opportunity for further research and development. Given the above justifications, it is agreeable that collaboration, an inter-disciplinary approach, and employing advanced methodologies such as AI would go a long way in strengthening space forecasting and protecting the technological infrastructure for space from destruction. For these reasons and even more, the SpW community has the potential to enhanced and expand exploration in this field.

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