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Research trend the in meteorology and atmospheric sciences category based on essential science indicators during 2011–2021

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Abstract— This study analyzed 1,636 top papers in the subject category of meteorology and atmospheric sciences about eleven years from 2011 to 2021, which included 1,636 highly cited papers and 24 hot papers in the field belonged to 20 Web of Science categories and 14 research areas. All top papers, written in English, were from 13,878 authors, 2,913 organizations, and 124 countries or territories, and published in 72 journals in the field. The top five journals are the *Nature Climate Change* (15.9% of the studied paper), *Atmospheric Chemistry and Physics* (12.1%), *Journal of Climate* (7.0%), *Bulletin of the American Meteorological Society* (6.7%), and *Journal of Geophysical Research Atmospheres* (4.6%), each published more than 76 papers. Top five countries were the USA, England, PR China, Germany, and France. Furthermore, top five organizations of National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), National Aeronautics and Space Administration (NASA), Chinese Academy of Sciences, and University Colorado were popular based on contribution of articles more than 134 papers each. All keywords were separated into eight clusters for different research topic. Visualizations offer exploratory information on the current state in a scientific field or discipline, as well as can indicate possible developments in the future.

Key-words: bibliometric analysis, essential science indicators (ESI), meteorology and atmospheric sciences, top papers, VOSviewer

1. Introduction

According to the category description for meteorology and atmospheric sciences in Scope Notes of Science Citation Index Expanded, it covers those resources that deal with the atmosphere and its phenomena, especially weather and weather forecasting. Resources in this category are concerned with the atmosphere's temperature, density, winds, clouds, precipitation and other characteristics, as well as the structure and evolution of the atmosphere in terms of external influences and the basic laws of physics. This category also includes resources dealing with climatology (*Clarivate,* 2022, Categories & Collections (Scope Notes)).

Bibliometric analysis are useful tools to collect, analyze, and get a better understanding of the progress in specific areas of science and technology, and to assess the outcomes of research efforts and investments (*Eito-Brun*, 2021). Bibliometrics technique has been adopted in Web of Science category of meteorology and atmospheric sciences such as, atmospheric simulation trends in meteorology and atmospheric science journals (*Li*, 2018), scientific production on coastal communities' social vulnerability to climate change and to the impact of extreme events (*Lima* and *Bonetti,* 2020), disaster and climate change resilience (*Rana*, 2020), multidimensional flood risk management under climate changes (*da Silva et al*., 2020), research on carbon price in emissions trading scheme (*Ji et al.*, 2019), tsunami in the last 15 years (*Jain et al*., 2021), mapping the evolution and current trends in climate change adaptation science (*Nalau* and *Verrall*, 2021), knowledge mapping analysis of integrated disaster risk management in a changing climate (*Wang et al*., 2021), evolution of disaster nursing research in the past 30 years (1990–2019) (*Molassiotis et al*., 2021), a quantitative approach to the scientific production on radar altimetry (*Eito-Brun*, 2021), waste-to-energy technologies towards circular economy (*Boloy et al*., 2021), bibliometric analysis of global trends on soil moisture assessment using the remote sensing research study from 2000 to 2020 (*Badaluddin et al*., 2021), a large-scale bibliometric analysis of global climate change research between 2001 and 2018 (*Fu* and *Waltman*, 2022), the use of local climate zones in the urban environment (*Aslam* and *Rana*, 2022), coastal impacts of storm surges on a changing climate (*Leal et al*., 2022), disasters triggered by natural hazards and terrorism (*Battikh et al*., 2022), bibliometric analysis of rice and climate change publications based on Web of Science (*Yuan* and *Sun*, 2022a), and others.

Top papers are the sum of hot papers and highly cited papers, based on Clarivate Analytics' Essential Science Indicators (ESI). A bibliometric evaluation of highly cited papers with high-level representation was conducted during the period from 1999 to 2009 based on the essential science indicators (ESI) database (*Fu et al*., 2011), highly cited papers in the field of Economics and Business based on the Essential Science Indicators database (*Zhang et al.*, 2018), highly cited papers in operations research and management science from 2008 to 2017 (*Liao*

et al., 2019), highly cited papers in environmental sciences (*Ma et al*., 2020), macro-level collaboration network analysis and visualization with Essential Science Indicators (*Yang et al*., 2020). *Sun* and *Yuan* have analyzed the top papers in library and information science (*Sun* and *Yuan*, 2020), agronomy category (*Sun* and *Yuan*, 2021), green and sustainable science and technology category (*Yuan* and *Sun*, 2019), scientific research on maize or corn (*Yuan* and *Sun,* 2020), research trend and status of forestry category based on Essential Science Indicators during 2010–2020 (*Yuan* and *Sun,* 2021), trend and status of food science and technology category based on the Essential Science Indicators during 2011–2021(*Yuan* and *Sun*, 2022b), and others.

The purpose of this paper was to use bibliometric methods to analyze top papers in the subject category of meteorology and atmospheric sciences during 11-year-long period from 2011 to 2021 through publication year, category, author, affiliations, country, journals, all keywords, and other key features. Co-authorship network visualization of authors, organizations, and countries, co-occurrence network visualization of all keywords were done by the VOSviewer software tool.

2. Materials and methods

2.1. Essential Science Indicators (ESI)

Article counts for ESI are derived from the Web of Science (WoS) core collection over an 11-year-long period. Here, the database has been updated on March 10, 2022, to cover the period from January 1, 2011 to December 31, 2021 (Clarivate, Essential Science Indicators Help, 2022).

2.2. Data collection

Data collection was completed on the single day on March 28, 2022 to avoid the bias. Firstly, it was conducted an advanced search in the WoS category of meteorology and atmospheric sciences. Then, the results were used to identify the highly cited papers and hot papers in the field (Hot papers are papers that receive citations soon after publication, relative other papers of the same field and age.). There were 1,636 top papers from the WoS Core Collection. The records were downloaded and saved as plain text format by selecting the export format "full records and cited references", and then imported into VOSviewer (version 1.6.18, 2022, Leiden University, Leiden, the Netherlands) for further citation analysis. The impact factors (IF 2021 and IF 5year) were taken from the Journal Citation Report (JCR 2021) that was updated on June 28, 2022 (Clarivate, Journal Citation Reports ™ 2021, 2022). The Journal Citation Reports™ includes journals from the Science Citation Index Expanded (SCIE) and the Social Science Citation Index (SSCI).

2.3. VOSviewer

VOSviewer is a freely available computer program developed to construct and view bibliometric maps with detailed approach in an easy-to-interpret way (www.vosviewer.com). In this work, VOSviewer were used to show the international collaboration between the authors, organizations, countries and the research trends through all keywords (*Van Eck* and *Waltman*, 2010). The graphs represent a network of items through circles, whose size differs according to the significance of the element, whereas the network connections represent the proximity of the link between items. The distance position of the circles and distinct colors are used to cluster the elements. In this paper, default parameters values of the VOSviewer are usually used in the analysis (*Van Eck* and *Waltman*, 2022).

3. Results and discussion

3.1. Document types and language of publication

From the WoS Index, all of the 1,636 top papers were identified in SCIE (1,633 papers, ratio of total papers is 99.817%), SSCI (391, 23.9%), and Conference Proceeding Citation Index-Science (CPCI-S, 7, 0.428%). The document types of all 1,636 top papers were articles (1,440, 88.02%), review articles (196, 11.98%), and also included data papers (19, 1.161%) and proceedings papers (7, 0.428%). Among the total 1,636 top papers, there were 24 hot papers and 1,636 highly cited papers, which means that the 24 hot papers are both hot papers and highly cited papers. All top papers were published in English language.

3.2. Publication output

Fig. 1 shows the top paper of the meteorology and atmospheric sciences category for eleven years from 2011 to 2021. The mean publication was 148.73 each year, and the highest value was 186 in 2013. The *h*-index was initially proposed as a measure of a researcher's scientific output based on counting the number of publications (N) by that researcher cited N or more times (*Hirsch*, 2005). For the total 1,636 papers, the *h*-index is 342, and the average citation per item is 279.87 till to March 28, 2022.

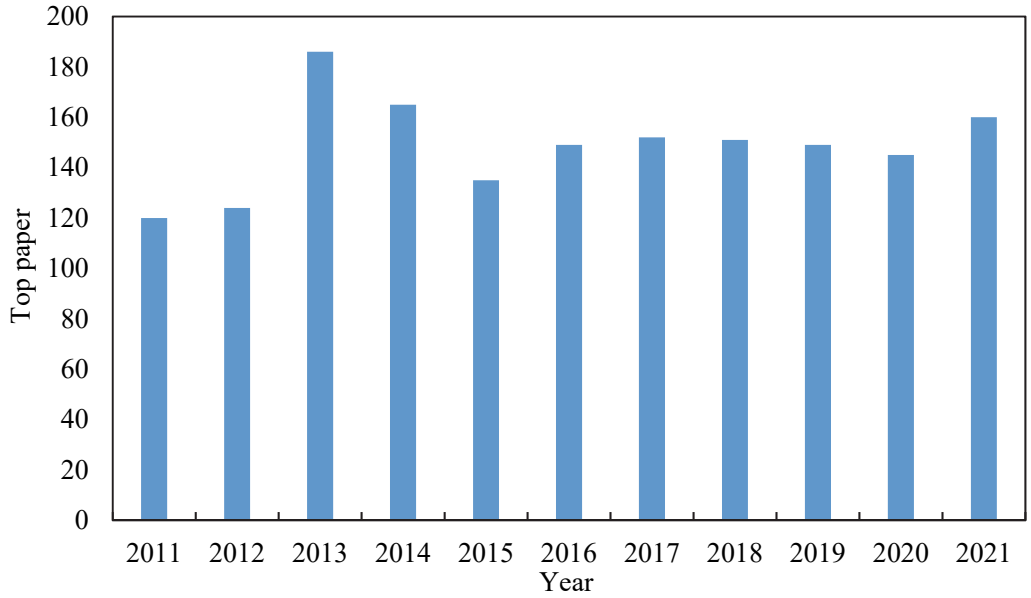

Fig. 1. Number of top papers for the meteorology and atmospheric sciences category per year from 2011 to 2021.

3.3. Web of Science categories and research areas

Based on the WoS categories, the total 1,636 papers were all in the meteorology and atmospheric sciences category, they also belong to other 19 WoS subject categories and total 14 research areas (*Table 1*).

The top six categories included meteorology atmospheric sciences (1,636 papers, 100% of 1,636 papers), environmental sciences (724, 44.254%), environmental studies (320, 19.56%), geosciences multidisciplinary (148, 9.046%), agronomy (67, 4.095%) and forestry (67, 4.095%). The top five research areas included meteorology atmospheric sciences (1,636 papers, 100% of 1,636 papers), environmental sciences ecology (779, 47.616%), geology (148, 9.046%), agriculture (67, 4.095%) and forestry (67, 4.095%). Journals or papers may be classified into two or more categories in the WoS, showed the multidisciplinary character of this research field (*Elango* and *Ho*, 2017).

Table 1. WoS categories and research areas for the meteorology and atmospheric sciences category during 2011-2021

Rank	WoS categories			Research areas		
	Categories	**No. papers**	**% Total papers**	**Areas**	**No. papers**	**% Total papers**
1	Meteorology Atmospheric Sciences	1,636	100	Meteorology Atmospheric Sciences	1,636	100
2	Environmental Sciences	724	44.254	Environmental Sciences Ecology	779	47.616
3	Environmental Studies	320	19.56	Geology	148	9.046
4	Geosciences Multidisciplinary	148	9.046	Agriculture	67	4.095
5	Agronomy	67	4.095	Forestry	67	4.095
6	Forestry	67	4.095	Water Resources	45	2.751
7	Water Resources	45	2.751	Engineering	27	1.65
8	Oceanography	21	1.284	Oceanography	21	1.284
9	Astronomy Astrophysics	11	0.672	Astronomy Astrophysics	11	0.672
10	Engineering Chemical	9	0.55	Geochemistry Geophysics	5	0.306
11	Engineering Mechanical	9	0.55	Biophysics	4	0.244
12	Engineering Aerospace	7	0.428	Physiology	4	0.244
13	Engineering Environmental	6	0.367	Remote Sensing	1	0.061
14	Geochemistry Geophysics	5	0.306	Telecommunications	1	0.061
15	Biophysics	4	0.244			
16	Engineering Ocean	4	0.244			
17	Physiology	4	0.244			
18	Engineering Civil	1	0.061			
19	Remote Sensing	1	0.061			
20	Telecommunications	1	0.061			

3.4. Core journals

All the 1,636 top papers were published in 72 journals. The top 20 core journals are displayed in *Table 2* with total articles each more than 14 top papers. The table showed the journal impact factor as IF 2021 and IF 5year, quartile in category (QC) and quartile rank (QR) among the total 94 journals in the meteorology and atmospheric sciences category from the Journal Citation Reports ™ 2021.

The top 5 journals, top 10 journals, top 15 journals, and top 20 journals published about 46.454%, 64.302%, 78.238%, and 84.84% of the total 1,636 top papers, respectively. The top five journals are the *Nature Climate Change* (260, 15.892%), *Atmospheric Chemistry and Physics* (199, 12.164%), *Journal of Climate* (115, 7.029%), *Bulletin of the American Meteorological Society* (110, 6.724%) and *Journal of Geophysical Research Atmospheres* (76, 4.645%), each published more than 76 papers. Based on the results of quartile category in *Table 2*, among the top 20 journals, sixteen journals were in quartile 1, three journals were in quartile 2 and one journal was in quartile 3.

Table 2. The top 20 core journals on meteorology and atmospheric sciences category research indexed in the WoS

Rank	Journal	TP	Ratio (%)	IF 2021	IF 5year	QC	QR
1	*Nature Climate Change*	260	15.892	28.66	32.35	Q1	1
2	*Atmospheric Chemistry and Physics*	199	12.164	7.197	7.32	Q1	12
3	*Journal of Climate*	115	7.029	5.38	6.549	Q1	20
4	*Bulletin of the American Meteorological Society*	110	6.724	9.116	10.009	Q1	6
5	*Journal of Geophysical Research Atmospheres*	76	4.645	5.217	5.302	Q1	22
6	*Atmospheric Environment*	69	4.218	5.755	6.027	Q1	19
7	*Agricultural and Forest Meteorology*	67	4.095	6.424	7.021	Q1	17
8	*Environmental Research Letters*	53	3.24	6.947	8.414	Q1	13
9	*Wiley Interdisciplinary Reviews Climate Change*	52	3.178	10.072	10.452	Q1	3
10	*Earth System Science Data*	51	3.117	11.815	12.88	Q1	2
11	*Atmospheric Research*	48	2.934	5.965	5.97	Q1	18
12	*Climate Dynamics*	48	2.934	7.901	4.742	Q2	24
13	*Climatic Change*	48	2.934	5.174	6.058	Q1	23
14	*International Journal of Climatology*	44	2.689	3.651	4.914	Q2	45
15	*Atmospheric Measurement Techniques*	40	2.445	4.184	4.473	Q2	40
16	*Journal of Advances in Modeling Earth Systems*	39	2.384	8.469	7.008	Q1	8
17	*Quarterly Journal of the Royal Meteorological Society*	22	1.345	7.237	5.303	Q1	11
18	*Natural Hazards*	18	1.1	3.158	3.685	Q3	58
19	*Global Biogeochemical Cycles*	15	0.917	6.5	7.067	Q1	16
20	*Earths Future*	14	0.856	8.852	9.274	Q1	7

Note: TP: Total publications; Ratio: ratio of 1,636 (%); IF 2021: journal impact factor in 2021; IF5 year: journal impact factor of 5 years; QC: quartile in category; QR: quartile rank of 94 journals in the meteorology and atmospheric sciences category from the Journal Citation Reports ™ 2021.

According to the citation sources analyzed by the VOSviewer, for the publication data in the citation of 72 journals, there were 43 journals that meet the thresholds of 5 publications, and were connected to each other in *Fig. 2*. The network map of citation for 43 journals in the field of meteorology and atmospheric sciences category is shown six clusters with different colors in *Fig. 2*, the size of circles reflects a total number of journal publication records. Journals in the same color cluster usually suggested that they published the similar content papers and had close relations with each other. The first cluster (red) had twelve journals and centered as *Journal of Climate*, the second cluster (green) had nine journals and centered as *Atmospheric Chemistry and Physics*, the third cluster (blue) had eight journals and centered as *Nature Climate Change*, the fourth cluster (yellow) had eight journals and centered as *Earth System Science Data*, the fifth cluster (violet) had four journals and centered as *Atmospheric Research*, and the sixth cluster (light blue) had two journals both the *Atmospheric Research* and *Climate Risk Management*.

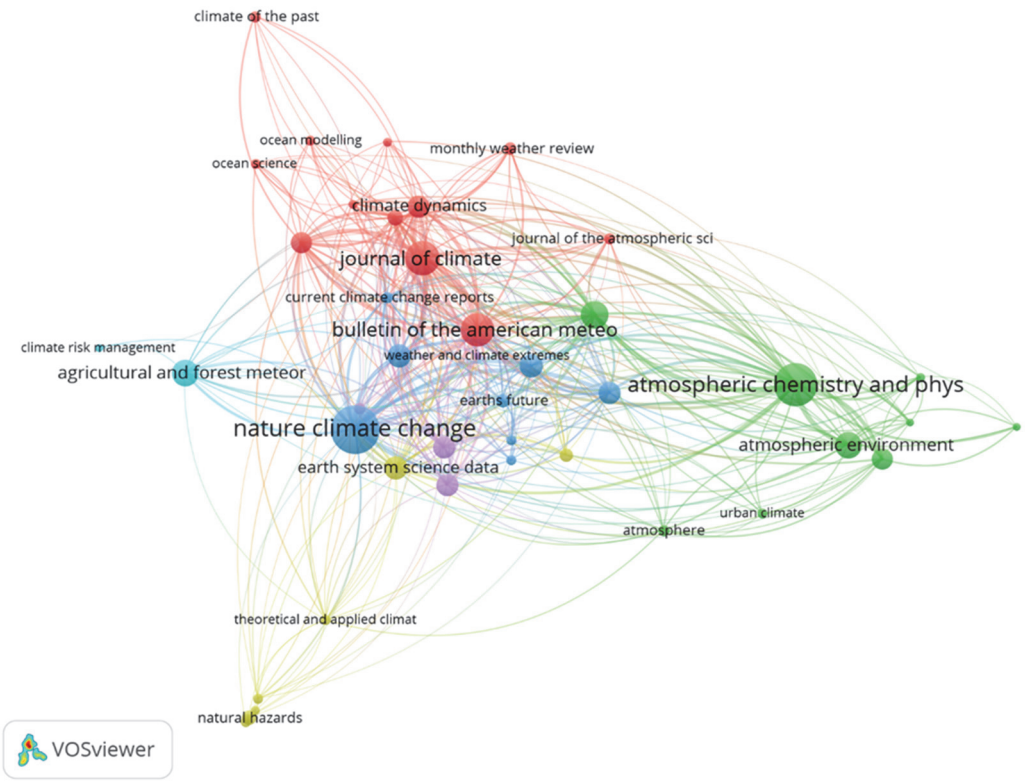

Fig. 2. Network visualization maps of citation journals in the field of meteorology and atmospheric sciences category based on WoS with 43 circles and 6 clusters.

3.5. Authors co-authorship analysis

A total of 13,878 authors have dedicated to all 1,636 top papers, and 291 authors met the thresholds of five publications, but 283 authors were connected with each

other and were separated into ten clusters. The network of the authors co-authorship analysis is represented in *Fig. 3*. Authors in the same cluster usually suggested that they studied in a similar field or worked at the same institute or had close cooperation with each other. The strong linkages between authors show that within the cluster, the collaboration is strong.

The details of the author information in the published articles from 2011 to 2021 along with citation, average citations, affiliations, and countries are provided in *Table 3*. The top five authors published more than 15 papers. Based on the average citations, each published paper of the top five mostly cited authors were cited more than 479.7 times.

There were five authors from the USA, the organizations were the State University of New York, Stanford University, University of Colorado, National Center for Atmospheric Research (NCAR), National Oceanic and Atmospheric Administration (NOAA); three authors from the Netherlands, the organizations were the University of Utrecht and the Vrije Universiteit Amsterdam; two authors from Tsinghua University of China; two authors from the University of Exeter and the Imperial College London of England; one author from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia; one author from the University of Paris Saclay of France; one author from Center for International Climate Research, Norway; one author from the Environment and Climate Change Canada.

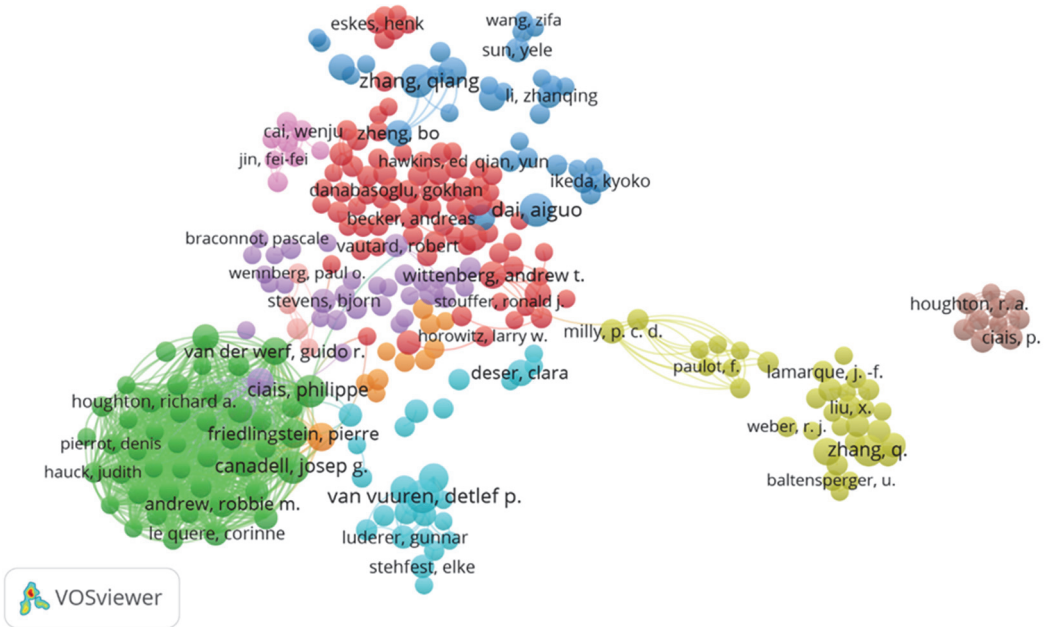

Fig. 3. Network visualization map of top authors in meteorology and atmospheric sciences category from 2011 to 2021.

Table 3. The top sixteen most prolific authors in the field of meteorology and atmospheric sciences category from 2011 to 2021

Rank	Author	Papers	Citations	Average citations	Affiliations	Country
1	Dai, Aiguo	16	7,675	479.7	State University of New York	USA
2	Van Vuuren, Detlef P.	16	9,096	568.5	University of Utrecht	Netherlands
3	Zhang, Qiang	16	3,177	198.6	Tsinghua University	China
4	Canadell, Josep G.	15	6,669	444.6	CSIRO Oceans & Atmosphere	Australia
5	Ciais, Philippe	15	6,833	455.5	University of Paris Saclay	France
6	Riahi, Keywan	13	6,416	493.5	University of Utrecht	Netherlands
7	Friedlingstein, Pierre	12	6,294	524.5	University of Exeter	England
8	He, Kebin	12	2,664	222.0	Tsinghua University	China
9	Jackson, Robert B.	12	4,092	341.0	Stanford University	USA
10	Peters, Glen P.	12	5,036	419.7	enter for International Climate Research	Norway
11	Jimenez, J. L.	11	2,878	261.6	University of Colorado	USA
12	Rogelj, Joeri	11	3,405	309.5	Imperial College London	England
13	Trenberth, Kevin E.	11	5,573	506.6	National Center Atmospheric Research	USA
14	van der Werf, Guido R.	11	4,972	452.0	Vrije Universiteit Amsterdam	Netherlands
15	Wittenberg, Andrew T.	11	3,635	330.5	National Oceanic and Atmospheric Administration (NOAA)	USA
16	Zhang, Xuebin	11	2,737	248.8	Environment and Climate Change	Canada

3.6. Countries/regions co-authorship analysis

Co-authorship with countries as unit is the relation of items based on the number of co-authors in papers highlighting their respective countries. There were 124 countries or regions that contributed 1,636 top papers from 2011 to 2021 based on WoS, and 56 countries or regions that met the requirement threshold of five papers.

Table 4 represents the list of the top 20 countries or regions that published more than 55 papers. Among the 20 countries, the USA, England, Peoples

Republic of China, Germany, and France were the major article contributors. From the average citations, the top five countries were South Korea, Austria, Japan, Sweden, and England, whose citations are more than 311.7 times per paper.

Table 4. Top 20 countries/regions publishing top papers in the field of meteorology and atmospheric sciences category from 2011 to 2021.

Rank	Countries/Regions	Records Count	Cluster	Total link strength	Citations	Average citations
1	USA	984	3	2,837	286,090	290.7
2	England	459	3	2,314	143,077	311.7
3	Peoples Republic of China	419	1	1,333	85,528	204.1
4	Germany	368	2	2,130	110,255	299.6
5	France	272	2	1,800	70,562	259.4
6	Australia	243	1	1,441	66,309	272.9
7	the Netherlands	222	2	1,401	62,128	279.9
8	Canada	212	3	1,258	59,941	282.7
9	Japan	181	3	1,305	73,050	403.6
10	Switzerland	177	2	1,217	51,249	289.5
11	Italy	164	2	1,224	41,545	253.3
12	Spain	145	2	1,083	36,937	254.7
13	Norway	136	2	1,074	41,023	301.6
14	Austria	115	2	827	54,576	474.6
15	Sweden	107	2	842	39,494	369.1
16	Finland	83	2	686	19,858	239.3
17	Belgium	67	2	506	14,419	215.2
18	Denmark	63	2	596	15,947	253.1
19	South Korea	58	1	411	29,216	503.7
20	Scotland	55	3	498	15,497	281.8

There were 56 countries or regions that met the requirement threshold of five papers(*Fig. 4*). The VOSviewer divided these circles into three clusters. According to *Fig. 4*, the first cluster consisted of twenty-seven countries or regions (red color) including the Peoples Republic of China, Australia, South Korea, India, Brazil, South Africa, Russia, Saudi Arabia, Malaysia, Argentina, Iran, Mexico, Chile, Singapore, Taiwan, Turkey, Colombia, Peru, Indonesia, Pakistan, Vietnam, Kenya, Romania, Egypt, Morocco, Ecuador, Estonia. The

second cluster consisted of twenty-two countries or regions (green color) including Germany, France, the Netherlands, Switzerland, Italy, Spain, Norway, Austria, Sweden, Finland, Belgium, Denmark, Greece, Portugal, Israel, Ireland, Poland, Czech Republic, Hungary, Cyprus, Slovenia, Croatia. The third cluster consisted of seven countries (blue color) including USA, England, Canada, Japan, Scotland, New Zealand, Wales. Taiwan as a region of China showed the stronger research ability in the field.

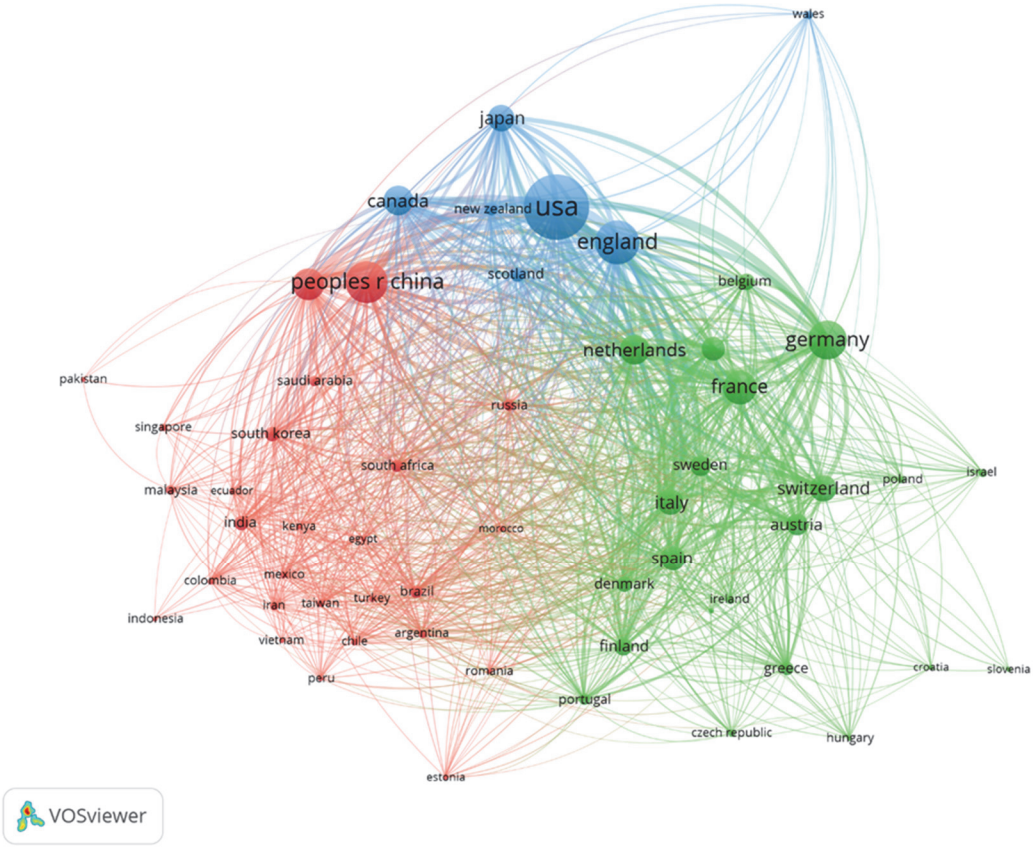

Fig. 4. The country co-authorship network of the meteorology and atmospheric sciences related top papers from 2011 to 2021 with 56 nodes and 3 clusters.

3.7. Organizations (author affiliation) co-authorship analysis

The affiliations presented were described on the profile of each researcher in WoS. They were updated according to the last paper published by the author until March 28, 2022. A total of 2,913 organizations had 1,636 top papers, there were 437 organizations met the minimum thresholds of five citations.

Table 5 represents the top 21 organizations and institutions ranked by the number of total publications (more than 52 papers), and also showed the total link of strength, citations, average citations, and country. These 21 organizations were mainly in USA (11 organizations), England (5 organizations), China (3 organizations), Germany (1 organization), and the Netherlands (1 organization). Furthermore, top five organizations of NOAA, NCAR, NASA,

Chinese Academy of Sciences, and University Colorado were popular based on contribution of articles more than 134 papers each. Similarly, in case of average citations of papers, the University of Leeds, University of Utrecht, NCAR, NOAA and University of Maryland, showed the higher average citations, more than 346.1 times per paper.

Table 5. Top twenty-one organizations published papers in the field of meteorology and atmospheric sciences category from 2011 to 2021.

Rank	Organizations	Records	Total link strength	Citations	Average citations	Country
1	National Oceanic and Atmospheric Administration	205	1940	73149	356.8	USA
2	Natlional Center for Atmospheric Research	181	1395	66657	368.3	USA
3	National Aeronautics and Space Administration (NASA)	163	1658	46048	282.5	USA
4	Chinese Academy of Sciences	160	902	32581	203.6	China
5	University of Colorado	134	1581	41081	306.6	USA
6	Columbia University	104	1167	23698	227.9	USA
7	University of Maryland	97	1179	33571	346.1	USA
8	University of Reading	82	853	19147	233.5	England
9	Princeton University	75	595	19748	263.3	USA
10	University of Washington	70	829	18074	258.2	USA
11	Tsinghua University	64	349	13279	207.5	China
12	University ofExeter	64	859	18851	294.5	England
13	Met Office Hadley Center	63	1042	20643	327.7	England
14	CALTECH	61	784	11297	185.2	USA
15	Max Planck Institute	60	1066	17600	293.3	Germany
16	Nanjing University	57	324	8172	143.4	China
17	Colorado State University	55	521	13187	239.8	USA
18	University of Leeds	53	518	30054	567.1	England
19	University of Oxford	53	515	11054	208.6	England
20	University of Calif Irvine	52	702	15428	296.7	USA
21	University of Utrecht	52	728	21182	407.3	Netherlands

Among the total 2,913 organizations, there were 437 organizations which met the minimum threshold of five papers, and connected to each other (*Fig. 5*). The VOSviewer software divided these 437 institutes into seven clusters with different colors. Within the context of network formation, organizations tend to form bonds with other institutions in the same region.

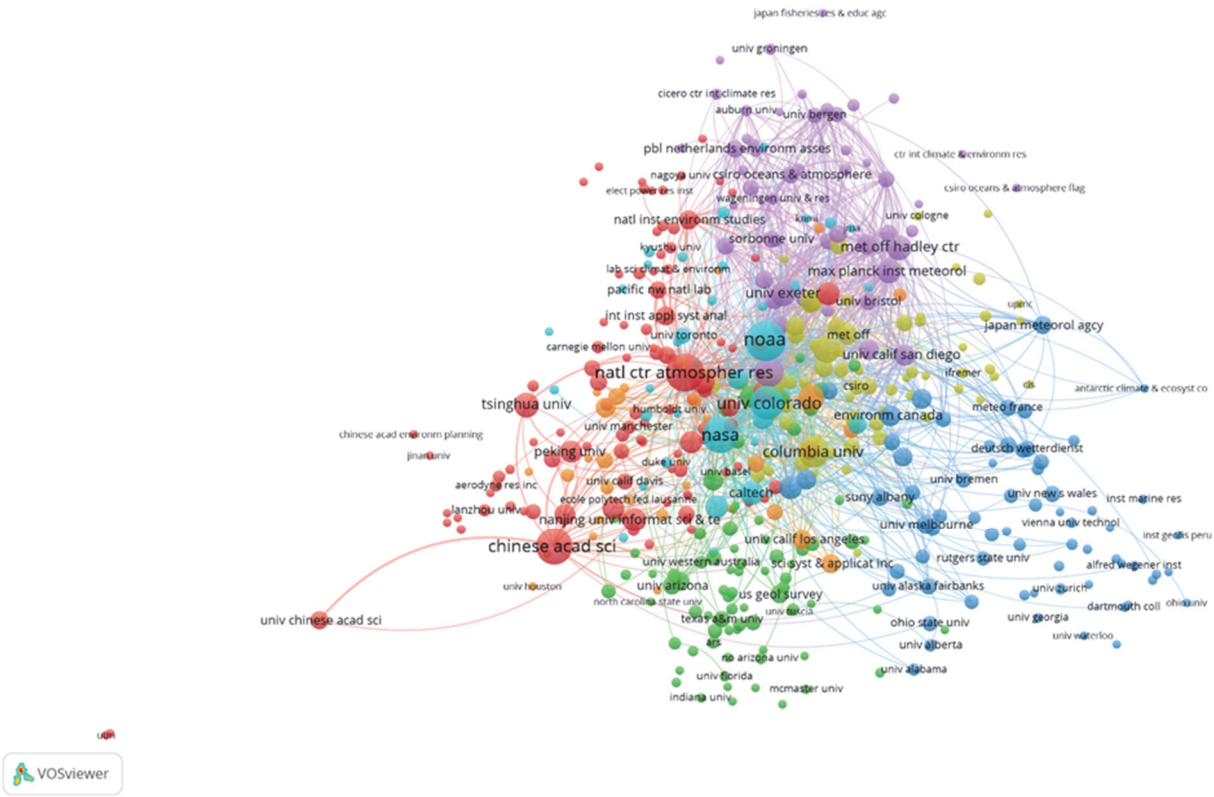

Fig.5. The organizations co-authorship network of the meteorology and atmospheric sciences related publications from 2011 to 2021 with 437 circles and 7 clusters.

3.8. All keywords co-occurrence analysis

For a specific scientific field study, keyword plays a large role as it can reflect the root contents of articles, and the compilation of keywords can reveal the pattern and trends of specific academic research (*Badaluddin et al*., 2021). To analyze the co-occurrence of the keywords, author keywords, keywords plus, and all keywords as unit were chosen and analyzed.

For the author keywords by full counting method for co-occurrence analysis, there were total 2,097 author keywords, and 72 keywords which met the threshold level of more than five times, and they were separated into eight cluster. The top twenty-four co-occurrence author keywords were climate change, precipitation, drought, China, remote sensing, CMIP6, PM2.5, climate models, climate, climate variability, CMIP5, air pollution, air quality, Covid-19, source apportionment, data assimilation, extreme events, trends, ENSO, arctic, particulate matter, carbon cycle, global warming, and agriculture, each keywords occurred more than 10 times.

For the keywords plus by full counting method for co-occurrence analysis, there were total 4,864 keywords plus, and 503 keywords which met the threshold level of more than five times, and they were separated into seven cluster. The top twenty-three co-occurrence keywords plus were variability, model, climate change, temperature, climate, impact, precipitation, trends, impacts, United

States, emissions, circulation, rainfall, ocean, sensitivity, sea-surface temperature, particulate matter, projections, air pollution, performance, soil moisture, source apportionment, and El Nino, each keywords plus occurred more than 40 times.

For the all keywords by full counting method for co-occurrence analysis, there were total 6,466 all keywords, only 599 keywords met the threshold level of more than five times included in the map. There are eight main clusters that represent different viewpoints on the meteorology and atmospheric sciences category research (*Fig. 6*). 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 (*Leal et al*., 2022). The top twenty co-occurrence all keywords were variability, model, climate change, temperature, precipitation, climate, impact, trends, climate change, impacts, United States, rainfall, emissions, circulation, China, drought, ocean, particulate matter, sensitivity, CMIP5, each all keywords occurred more than 50 times. The same data in *Fig. 6* were then arranged by a period of meteorology and atmospheric sciences category research as overlay map for most frequent all keywords (*Fig. 7*). Blue colors indicated earlier research topics, whereas, yellow and green colors indicated more recent topics of interest. Yellow and green circles present those which are research fronts.

Here, for 599 all keywords, about twenty keywords were listed and ranked in each cluster based on *Fig. 6*.

The first cluster (red) has 161 all keywords and focused on source apportionment of emissions and air pollution, and the 20 most frequently used keywords are United States, emissions, particulate matter, source apportionment, pollution, air pollution, PM2.5, transport, aerosols, air quality, aerosol, black carbon, secondary organic aerosol, optical properties, ozone, retrieval, tropospheric ozone, mortality, boundary layer, chemical composition, *et al*., each keywords occurred more than 20 times.

The second cluster (green) has 107 all keywords and represents climate change impacts, and are 20 most frequently used keywords climate change, climate change, impacts, CO_2, patterns, energy, scenarios, carbon, uncertainty, land, vegetation, responses, vulnerability, adaptation, risk, agriculture, time-series, land-use, framework, management, each key-words occurred more than 19 times.

The third cluster (blue) has 91 all keywords and is focused on climate variability and circulation impact, and the 22 most frequently used keywords are variability, climate, impact, circulation, ocean, sea-surface temperature, El-Nino, sea ice, interannual variability, ENSO, weather, atmospheric circulation, surface temperature, North-Atlantic, southern ocean, climate variability, sea-level rise, pacific, atmosphere, north-atlantic Oscillation, each keywords occurred more than 18 times.

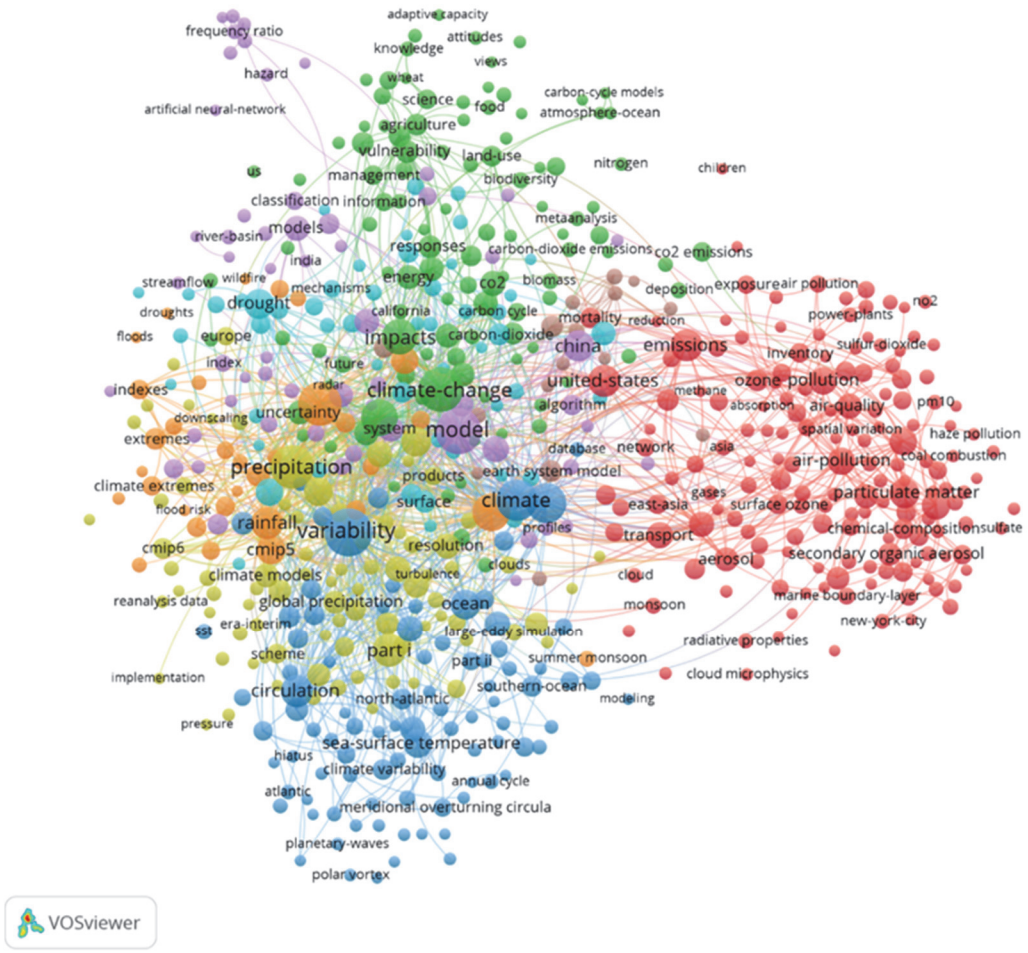

Fig. 6. VOSviewer co-occurrence network visualization mapping of all keywords (minimum 5 occurrences) in the meteorology and atmospheric sciences category from 2011 to 2021. Co-occurrence network of all keywords includes author keywords and keywords plus. The size of the circles correlates with the number of articles using that keyword such that a higher number of articles is represented by a bigger circle. Circle color denotes different clusters.

The fourth cluster (yellow) has 83 all keywords and represents precipitation, and the 20 most frequently used keywords are precipitation, part i, sensitivity, performance, simulations, resolution, simulation, data assimilation, climate models, parameterization, global precipitation, general-circulation model, reanalysis, Madden-Julian oscillation, CMIP6, convection, scheme, numerical weather prediction, Europe, assimilation, each keywords occurred more than 16 times.

The fifth cluster (violet) has 58 all keywords and is focused on climate models, and the 20 most frequently used keywords are model, China, satellite, water, system, models, prediction, validation, events, remote sensing, algorithm, extreme precipitation, area, classification, energy balance, fluxes, index, air temperature, trmm, basin, each keywords occurred more than 12 times.

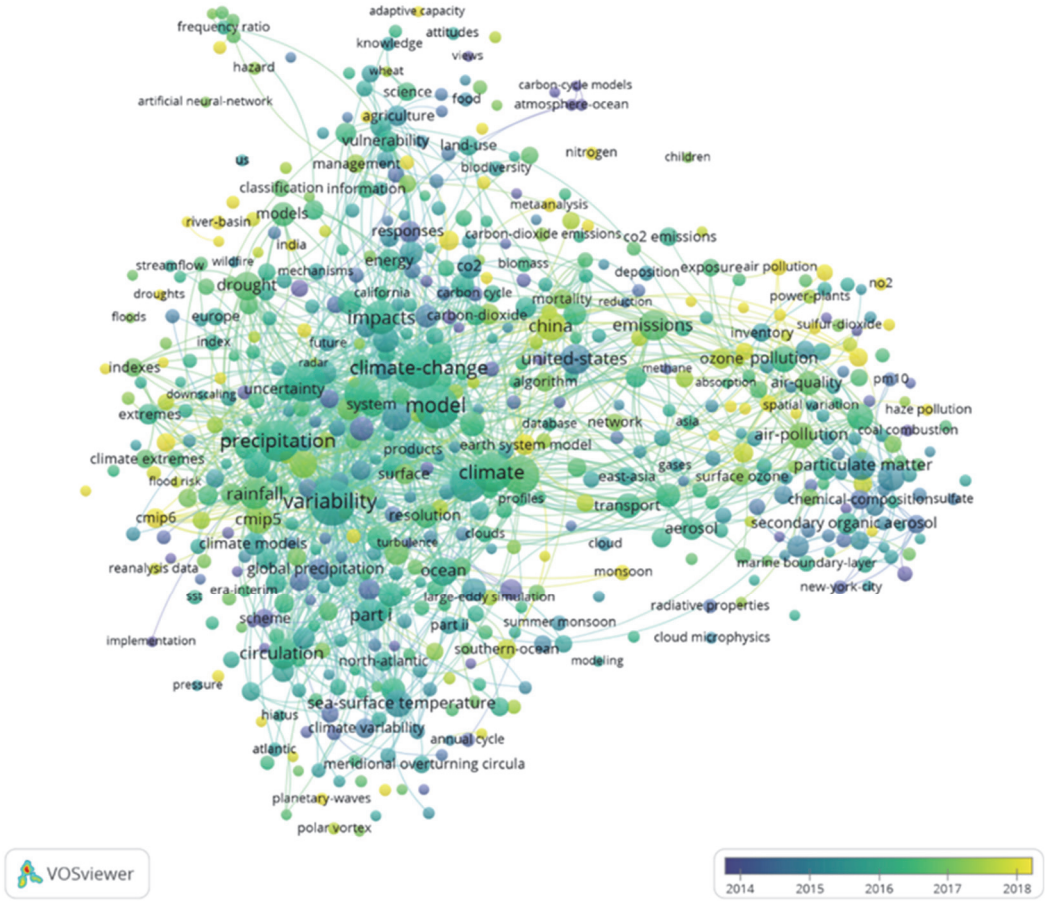

Fig. 7. VOSviewer co-occurrence overlay visualization mapping of all keywords in the meteorology and atmospheric sciences research (minimum of five occurrences) from 2011 to 2021.

The sixth cluster (light blue) has 51 all keywords and is focused on drought and soil moisture, and the 22 most frequently used keywords are drought, soil moisture, MODIS, surface, carbon-dioxide, water-vapor, dynamics, forest, evapotranspiration, evaporation, stomatal conductance, photosynthesis, NDVI, mechanisms, Tibetan Plateau, potential evapotranspiration, runoff, snow, soil, global warming, carbon cycle, spatial variability, each keywords occurred more than 10 times.

The seventh cluster (orange) has 32 all keywords and is focused on the temperature change trends, and the 20 most frequently used keywords are temperature, trends, rainfall, CMIP5, projections, ensemble, extremes, hydrological cycle, frequency, indexes, climate extremes, 20th century, dataset, future changes, increase, summer, extreme events, attribution, region, climate change impacts, each keywords occurred more than 11 times.

The eighth cluster (brown) has 16 all keywords and is focused on global climate change on earth system model, and the keyword are earth system model, atmospheric CO_2 cycle, dioxide emissions, environment simulator JULES, leaf area index, anthropogenic CO_2 uptake, land-use change, global climate, fire

emissions, land-cover change, model description, dependence, flux variability, South-America, terrestrial ecosystems, each keywords occurred more than 5 times.

3.9. The most frequently cited articles

Although many articles have been published, a relatively small number of individuals account for a large proportion of the citations within the period. The annual citations of the eight papers showed an increasing trend after the year of publication (*Fig. 8*). Here, the total citations for the most frequently cited articles were more than 3,123. The eight papers were authored by *Dee et al*. (2011), *Taylor et al*. (2012), *Alvares et al*. (2013), *Harris et al.* (2014), *Fick* and *Hijmans* (2017), *van Vuuren et al*. (2011), *Rienecker et al.* (2011), *Bond et al*. (2013). The total citations of the eight most cited papers were 16971, 9215, 4079, 4073, 3544, 3538, 3339, and 3123. From the publication year to 2022, the average number of citations per year of the most cited eight papers were 1414.25, 837.73, 407.9, 452.56, 590.67, 294.83, 278.25, 312.3. Among the eight articles, the highest average citation per year (1,414.25, blue color) was observed for the article of *Dee et al.* (2011) published in the *Quarterly Journal of the Royal Meteorological Society* (*Fig. 8*).

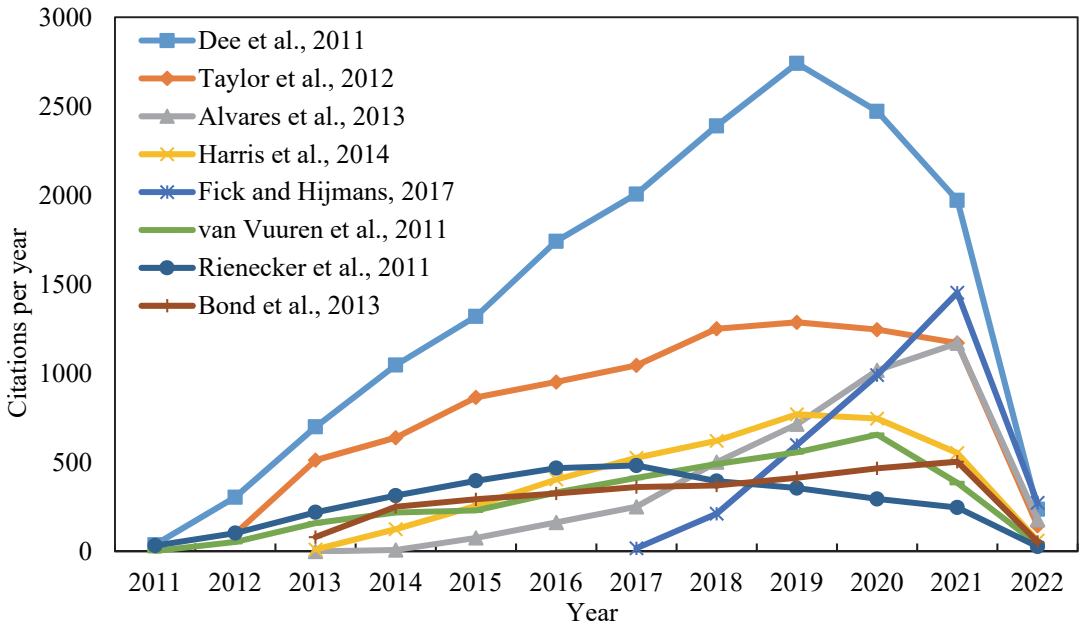

Fig. 8. Comparison of the citations per year of the most cited eight papers from their initial publications to March 28, 2022.

4. Conclusions

This study analyzed 1,636 top papers in the subject category of meteorology and atmospheric sciences published in the period from 2011 to 2021, which included 1,636 highly cited papers and 24 hot papers in the field and belonged to 20 Web of Science categories and 14 research areas. All top papers written in English were from 13,878 authors, 2,913 organizations and 124 countries or territories, and published in 72 journals. The top five journals are the *Nature Climate Change*, *Atmospheric Chemistry and Physics*, *Journal of Climate*, *Bulletin of the American Meteorological Society,* and *Journal of Geophysical Research Atmospheres*. Top five countries and regions were the USA, England, Peoples Republic of China, Germany, and France. Top five organizations were the National Oceanic and Atmospheric Administration (NOAA), National Center for Atmospheric Research (NCAR), National Aeronautics and Space Administration (NASA), Chinese Academy of Sciences, and University of Colorado. The top five authors were *Aiguo Dai, Detlef P. Van Vuuren, Qiang Zhang, Josep G. Canadell,* and *Philippe Ciais*. All keywords were separated into eight clusters for different research topic. This work is also useful for student identifying graduate schools and for researchers selecting journals.

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