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ORIGINAL ARTICLE

Bibliometric analysis: global research trends in biogenic volatile organic compounds during 1991–2014

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Abstract Bibliometric analysis was applied to identify global patterns and trends in the research of biogenic volatile organic compounds (BVOCs), which are important to atmospheric ozone formation and secondary organic aerosol formation. Yearly publications, mainstream subject categories and journals, leading countries and institutions, research emphases and trends were identified. Number of publications and times of citation were used as indicators to evaluate publication performances. A summary of the most frequently used keywords obtained from author keywords and *KeyWords Plus* provided clues for research emphases in different periods. A network of keywords was drawn to visualize the cross-relationship of keywords. Results indicated that annual output of the related scientific papers increased notably during 1991–2014. Atmospheric Sciences, Environmental Sciences & Ecology, Environmental Sciences & Engineering, and Chemistry were the main subject categories. *Journal of Geophysical Research-Atmospheres* was the most competitive journal in productivity and academic impact. The USA and the National Center for Atmospheric Research (NCAR) were, respectively, the leading country and leading institution in BVOC research. "Emissions," "isoprene," and "model" were the leading research emphases in BVOC field in terms of word frequencies and centrality driven from the network structure. The three leading research hotspots cross-fields, emissions-isoprene, emissions-model, and isoprene-model showed substantial growth in scientific outputs during the study period. These trends were evidenced by the evolution of research contents in various studies.

Keywords BVOCs · Bibliometric · SCI-expanded · Research trend · Ozone · SOA

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Introduction

Volatile organic compounds (VOCs) have aroused widespread concern due to their adverse effects on human health (Liu et al. 2009) and significant role in tropospheric ozone (O_3) and SOA formation via photochemical reactions (Derwent et al. 2010). VOCs are emitted from anthropogenic and biogenic sources (Li et al. 2013). Globally, 1150 Tg C/yr of VOCs from biogenic sources are emitted annually, much more than those emitted from anthropogenic sources, accounting for ~90% of total annual VOC emissions (Guenther et al. 1995, 2006). BVOCs dominate the total annual flux of organic compounds into the atmosphere (Guenther et al. 2012). Additionally, BVOCs are far more reactive than anthropogenic VOCs (Emanuelsson et al. 2013). Owing to their high emission loads and reactivity, there is a considerable body of research on BVOCs.

Research related to BVOCs is multidisciplinary, as they interact with the atmosphere, hydrosphere, lithosphere, and biosphere, and covers a wide range of topics, including environmental sciences (Fu et al. 2014), ecology (Hewitt et al. 2011), plant physiology (Loreto and Schnitzler 2010), and atmospheric chemistry (Situ et al. 2013). The publication “Blue hazes in the atmosphere” (Went 1960) in *Nature* pioneered scientific research on BVOCs. Since then, studies on BVOCs have ranged in different scales, including leaf (Bracho-Nunez et al. 2013), canopy (Potosnak et al. 2013), regional (Wong et al. 2013), and global scales (Harrison et al. 2013). Studies have focused on diverse topics, including the biosynthesis mechanism of BVOCs (Harrison et al. 2013), environmental factors influencing BVOC emissions (Rasulov et al. 2010), and environmental impacts of BVOCs (Ryerson 2001; Pacifico et al. 2009). Both measurements of BVOC emission rates (Helmig et al. 2004) and fluxes (Kalogridis et al. 2014), and modeling of BVOCs (Unger et al. 2013; Harley et al. 2014) have been performed worldwide. However, there have been few attempts to collect systematic data on the global scientific production and distribution of research on BVOCs. Garfield (1970) indicated that a recent research focus could be reflected on its publication output. Therefore, there is an urgent need to trace the global trends in BVOC research quantitatively to obtain an overview of this field and identify the research hotspots.

Bibliometric study is useful for mapping the literature related to a research field (Fu et al. 2013). Bibliometrics refers to research methodology used in informatics and library sciences that uses quantitative analysis and statistical methods to depict distribution patterns of publications in a particular research field, topic, country or institute (Hu et al. 2010; Campanario et al. 2006; Almind and Ingwersen 1997; Schubert et al. 1989). Bibliometric studies have been extensively performed in a number of science and engineering fields. For example, Vergidis et al. (2005) employed a bibliometric approach to assess trends in research productivity in microbiology from 1995 to 2003 quantitatively and to investigate correlations between research productivity and gross domestic product (GDP) in different regions. Kumari (2006) combined scientific output with an activity index and drew comparisons among countries to evaluate their performances in synthetic organic chemistry research. Traditional bibliometric studies tended to emphasize an individual aspect of research trend in a particular research topic, such as assessing only publications, journals or subject categories. It has been suggested that this approach does not thoroughly reflect the development trends or future directions of a research field (Chiu and Ho 2007). More information, such as times of citation, author keywords, and *KeyWords Plus*, should be included in bibliometric evaluations of the scientific performances in different countries or institutions and global research trends. More comprehensive analyses should be performed to obtain a more integrated understanding (Khan and Ho 2012; Ho 2014).

In this study, the number of scientific publications and times of citations were examined to describe quantitatively the productivity and academic impact, respectively, of journals, countries and academic institutions. In addition, popular topics in BVOC research during different time intervals in the study period were identified via a synthetic analysis of author keywords and *KeyWords Plus*. A network of the most common keywords was created to identify research hotspots at different times and to visualize the cross-relationship between each keyword. Furthermore, a time series of the cross-fields of the leading research hotspots was studied to clarify and describe global research trends. The results provide insights into the impacts of BVOC research and offer a basis for a more comprehensive understanding of the global research situation on BVOC research.

Methods

Search strategy

The publications used in this study were retrieved from the Thomson Reuters Web of Science, which is based on the online version of Science Citation Index (SCI)-Expanded (Xie et al. 2008; Fu et al. 2013). Because documents before 1991 did not include an abstract, only those published in the period beginning with 1991 were discussed in order to use the same standard (Hu et al. 2010).

For bibliometric study, keywords, including “biogenic volatile*,” “biogenic hydrocarbon*,” “biogenic VOC*,” BVOC*, “biogenic emission*,” biogenic isopren*, biogenic *terpen*, were searched in titles, abstracts and keywords of documents published in 1991–2014. The keywords were connected with the logical connector OR. Quotation marks were added to some of the keywords, as shown above, so as not to separate the individual words. We performed truncated searches of some keywords by including asterisks to include multiple related terms. For instance, “biogenic volatile*” can represent “biogenic volatiles,” “biogenic volatile organic compounds,” “biogenic volatile organic species,” and so on. The search yielded 2659 documents, from which we collected the following information: titles, keywords, publication years, author names, contact address, subject categories, and document source.

Analytical methods

The full records were exported to Microsoft Excel 2013 (Microsoft Corporation, Redmond, WA, USA) for further analysis. For the country analysis, documents from England, Scotland, Wales, and Northern Ireland were grouped as the United Kingdom (UK) (Zhang et al. 2010; Hu et al. 2010). Documents originating from Hong Kong published before 1998 were grouped as Hong Kong, while those published in 1998 or later were grouped with China, due to the return of Hong Kong to China after 1997. We further manually processed the country and keyword data by including necessary substitutions for certain regional codes and breaking down keyword clusters. In addition, the impact factor (IF) of each journal was derived from 2014 Journal Citation Reports (JCR).

In evaluating journal performances, total published papers is an indicator of journal productivity, while times of citation is an indicator of journal impact, i.e., the larger the times of citation of a certain journal is, the more academically influential the journal is. Average times of citation equals times of citation divided by total published papers, which combines the indicators of journal productivity and journal impact. Hence, both total published papers and average times of citation as well as impact factors (IF) were compared to comprehensively evaluate journal performances.

All documents referring to BVOC research during 1991–2014 were assessed with the following aspects: yearly publications, document types and languages, output distribution in subject categories, journals, countries and institutions, and keyword analysis to distinguish research hotpots and global research trend in this field. Centrality analysis of author keywords and *KeyWords Plus* was performed to establish the network of important keywords, study the relationships among the keywords, and identify the keywords that were most frequently connected with other keywords. The network of keywords was built by a social network analysis tool, UCINET (Analytic Technologies, Lexington, KY, USA), which was embedded with frequency analysis, matrix analysis, dichotomization, and centrality measures (Silva and Saraiva 2015; Mohammadfam et al. 2015).

Results and discussion

Scientific outputs

In total, there were 2659 documents under the search strategy described above. Figure 1 depicts the number of publications by year from 1991 to 2014. The number of documents on BVOCs increased substantially during 1991–2014 (Fig. 1a). There were only 26 documents published in 1991, while nearly eight times more were published in 2014. Yearly publications rose sharply from 1994 to 1997, likely due to the increasing frequency of academic exchanges and conferences among scientists worldwide acting as crucial drivers of BVOC research. Another factor that may have enhanced the number of publications in recent years is the introduction of online submission systems, which are more convenient than

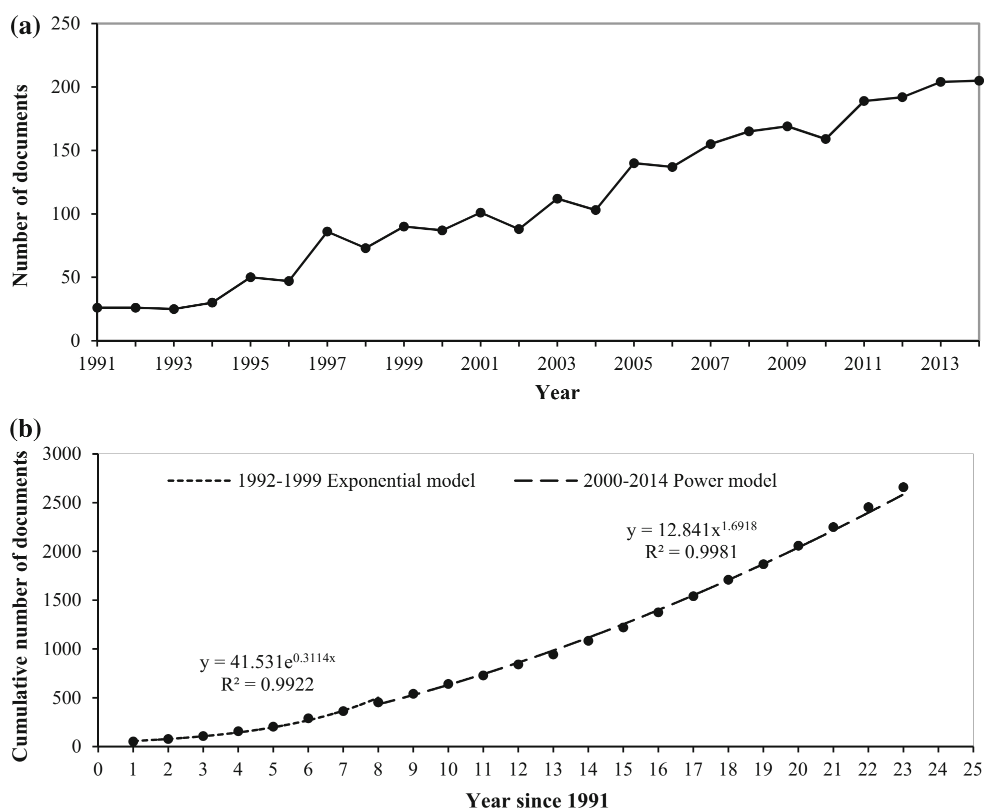


Fig. 1 Publication patterns during 1991–2014 (**a**) yearly publications (**b**) yearly cumulative number of publications

traditional systems, and the faster review processes employed by peer-reviewed journals (Zhi et al. 2015). A significant correlation was found between the yearly cumulative number of documents and the year since 1991 (Fig. 1b). The cumulative progression was represented by an exponential model and a power model, respectively, for 1992–1999 and 2000–2014. Equations (1) and (2) exhibited good fits with the trends in the yearly published papers for the two respective time periods, with high coefficient of determinations (r^2) (1992–1999: $r^2 = 0.9922$; 2000–2014: $r^2 = 0.9981$). In both equations, y represents the cumulative number of scientific papers and x represents the number of year since 1991. For instance, 1992 and 2000 corresponds to the x value of 1 and 9, respectively. It can be predicted from the cumulative progression that the number of scientific outputs on BVOCs will increase at a high rate in the future.

$$y = 41.531e^{0.3114x} \quad (1)$$

$$y = 12.841x^{1.6981} \quad (2)$$

Document types and languages

Scientific papers retrieved in this study comprised nine document types. Article (2331 papers) was the dominant type, accounting for 87.7% of total publications, followed distantly by proceedings paper (142, 5.3%) and review (134, 5.0%). Other document types included meeting abstract (23, 0.9%), editorial material (17, 0.6%), correction (5, 0.2%), note (3, 0.1%), letter (2, 0.1%), and book chapter (2, 0.1%).

In addition, the 2659 documents were published in eight languages, including English, German, Spanish, Chinese, Japanese, Portuguese, Czech, and French. English was the dominant written language. Documents written in English made up 99.1% of total publications, followed by German (0.2%), Spanish (0.2%), Chinese (0.1%), Japanese (0.1%), Portuguese (0.1%), Czech (0.1%), and French (0.1%). This was expected because English is the international language of choice in BVOC research, according to the SCI database (Xie et al. 2008). Cultural and linguistic factors are less significant in affecting publications owing to the global dominance of English, as it is the standard language for conducting research and the strict writing format for academic papers, although geographic factors played a significant role in global publication on BVOC research (Zhi et al. 2015).

Subject categories

Based on the JCR subject categories classifications, the publications on BVOC research were distributed among 133 subject categories during 1991–2014. Table 1 summarizes the ten subject categories with the largest number of documents. The most productive subject categories, each containing more than 100 documents, were: Atmospheric Sciences, Environmental Sciences & Ecology, Environmental Sciences & Engineering and Chemistry. These subject categories, which are all branches of chemical and environmental science, included a total of 1060 publications, accounting for 40% of all BVOC publications.

Atmospheric Sciences dominated yearly publications from 1991 to 2014, indicating that it is a well-developed field in BVOC research (Fig. 2). However, there was no significant increase in the number of documents in Atmospheric Sciences from 2011 to 2014, and a decline was observed in comparison with the number of publications in 1997. In addition, publications in Environmental Sciences & Ecology, Environmental Sciences & Engineering and Chemistry experienced distinct fluctuations during the investigated period. Environmental Sciences & Ecology exhibited the greatest instability in scientific output, followed by Environmental Sciences & Engineering and Chemistry. It should be noted that Chemistry and Atmospheric Sciences are also broader research fields besides subject categories in BVOC research. Trends in yearly publications in these subject categories are comparable to those in their broader fields, indicating that faculty and participant interest have changed in similar manners. The use of statistics in any scientific discipline could be considered a key element in evaluating its degree of maturity (Palmer et al. 2005), and therefore, the result provided a current overview of the BVOC research patterns.

Table 1 Top 10 most productive subject categories during 1991–2014

Subject categories	TP[a]	R[b]	Percentage[c]
Atmospheric Sciences	569	1	21.4
Environmental Sciences & Ecology	224	2	8.4
Environmental Sciences & Engineering	142	3	5.3
Chemistry	125	4	4.7
Plant Sciences	83	5	3.1
Geology	67	6	2.5
Environmental Sciences & Meteorology	46	7	1.7
Ecology & Geology	45	8	1.7
Geochemistry & Geophysics	44	9	1.7
Chemistry & Physics	42	10	1.6

[a] Total published papers in a certain subject category during 1991–2014

[b] Ranking of total published papers

[c] Percentage in total publications, unit: %

Fig. 2 Yearly publications of the four most productive subject categories during 1991–2014

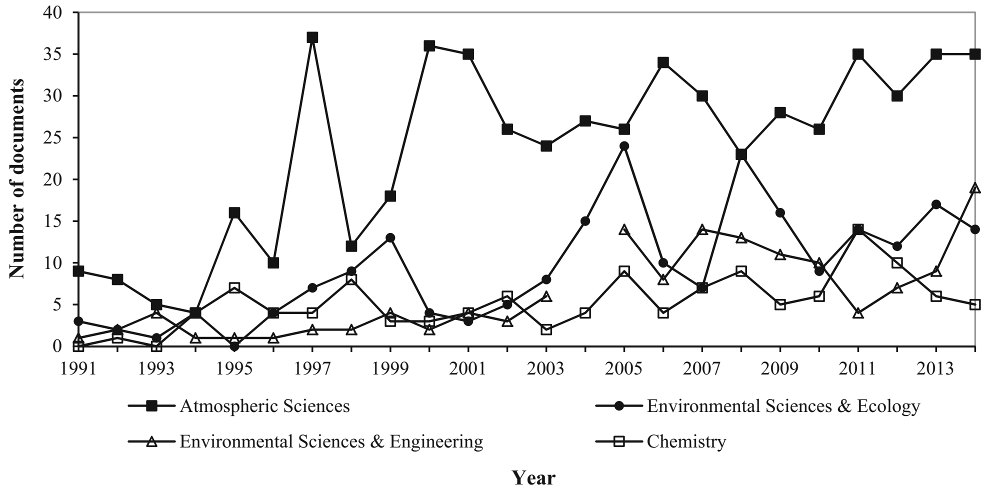


Table 2 Top 10 most productive journals during 1991–2014

Journals	TP	R of TP[a]	Percentage	TC[b]	Ave TC[c]	R of Ave TC[d]	IF (2013)[e]
Atmospheric Environment	482	1	18.1	17,610	36.5	5	3.062
Atmospheric Chemistry and Physics	378	2	14.2	12,325	32.6	6	5.298
Journal of Geophysical Research-Atmospheres	355	3	13.4	23,819	67.1	1	3.440
Environmental Science & Technology	124	4	4.7	6057	48.8	4	5.481
Journal of Atmospheric Chemistry	62	5	2.3	3892	62.8	2	1.632
Geophysical Research Letters	50	6	1.9	2743	54.9	3	4.456
Chemosphere	36	7	1.4	1001	27.8	7	3.499
Biogeosciences	34	8	1.3	779	22.9	8	3.753
Journal of the Air & Waste Management Association	28	9	1.1	374	13.4	10	1.171
Science of the Total Environment	27	10	1.0	442	16.4	9	3.163

[a] Ranking of total published papers

[b] Times of citation

[c] Average times of citation, Ave TC = TC/TP

[d] Rankings of average times of citation

[e] Impact factors of 2013, derived from 2014 JCR

Journal performances

In total, the 2659 scientific papers were published in 373 journals covering 133 subject categories, as described above. Table 2 lists the ten journals with the largest scientific outputs during the investigated period, which accounted for ~60% of the total scientific output. Among these journals, *Environmental Science & Technology* (EST) and *Science of the Total Environment* (STOTEN) belong to the Web of Science category of environmental sciences (Fu et al. 2013) and cover a wide range of disciplines; most of the other journals are related to atmospheric sciences. The most productive journals, which published more than 100 scientific papers, were: *Atmospheric Environment* (AE), *Atmospheric Chemistry and Physics* (ACP), *Journal of Geophysical Research-Atmospheres* (JGR-A), and *Environmental Science & Technology* (EST). AE ranked first with respect to total number of published papers and had an IF of 3.062. AE was also the most productive journal in world VOCs research during 1992–2007 (Zhang et al. 2010) and world aerosol research during 1991–1994 (Xie et al. 2008). The leading position in scientific output of this journal is due to its aim and scope regarding atmospheric composition and its impacts (http://www.journals.elsevier.com/atmospheric-environment/), which is in accordance with the scope of BVOC research. JGR-A, with a total number of published papers and IF comparable to those of AE, had an average number of citations nearly twice that of AE. JGR-A ranked first for the average times of citation. The competitiveness of JGR-A was due to its publication of articles which improve understanding of atmospheric properties and processes, including the interaction of the atmosphere with other components of the Earth system (http://jgr-atmospheres-submit.agu.org/cgi-bin/main.plex). It should be noted that journal performance is also related to factors such as editorial goals, readership, scientific fundamentals, and time to publication.

Figure 3 shows the yearly publications of the three most productive journals. The yearly publications in AE reached a peak of 31 in 1997, which remained stable with slight fluctuations for 10 years, with an average of 28. Before 2007, the yearly number of publications in JGR-A slowly increased and was comparable to that of AE, but underwent an acute decline from 2007 to 2008. The total number of yearly publications of JGR-A also decreased during this period. This is possibly due to changes in management policy and short-term economics of this journal. Meanwhile, ACP experienced an expeditious increase in the number of publications after its establishment in 2001, indicating a strong preference by researchers to contribute to this journal. This is possibly due to its publication approach of interactive open access (Pöschl and Koop 2008). The average number of yearly publications in ACP in the final 5 years of the study period was 1.7 times greater that of AE. In bibliometric studies, the total number of published papers and average times of citation can be analyzed to evaluate journal performance comprehensively.

Country and institution contributions

In total, 2562 documents contained information of reprint author addresses, which were distributed in 60 countries. Table 3 summarizes the ten countries with the highest scientific output during the study period. These countries contributed 77% of world publications, showing that the academic predominance was shared among a minority of countries. The United States of America (USA) showed marked predominance in both total number of published papers and average times of citation, indicating that the USA not only led BVOC research in terms of productivity, but also in terms of influence. Germany and the UK were also competitive in productivity and academic impact. China ranked fifth in total number of published papers; however, it fell to tenth place for the average times of citation. This sharp contrast showed that China was relatively competitive in the number of published papers, but had a long way to go to enhance its academic impact.

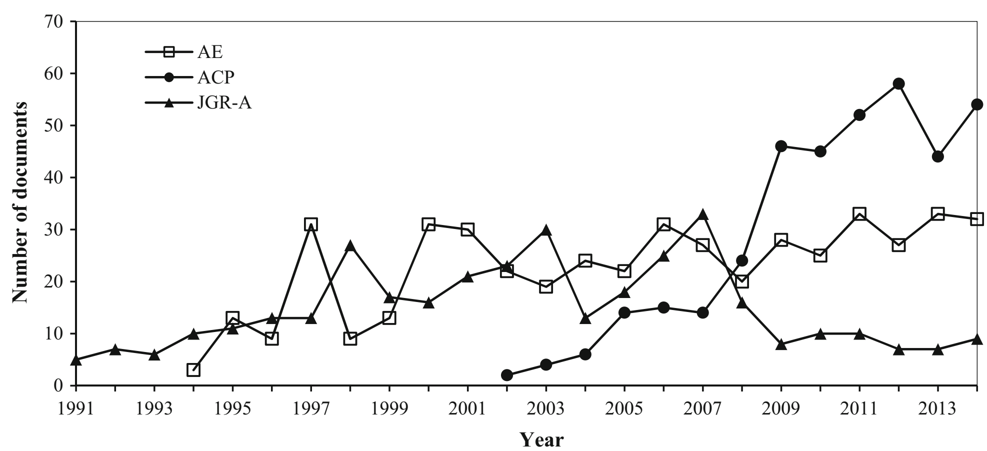


Fig. 3 Yearly publications of the three most productive journals during 1991–2014 (*AE* Atmospheric Environment, *ACP* Atmospheric Chemistry and Physics, *JGR-A* Journal of Geophysical Research-Atmospheres)

Table 3 Top 10 most productive countries during 1991–2014

Country	TP	R of TP	Percentage	TC	Ave TC	R of Ave TC
USA	929	1	36.3	47,978	51.6	1
Germany	245	2	9.6	9356	38.2	2
UK	164	3	6.4	5380	32.8	4
France	123	4	4.8	3289	26.7	6
China	122	5	4.8	1514	12.4	10
Italy	88	6	3.4	2671	30.4	5
Finland	88	6	3.4	3066	34.8	3
Spain	77	8	3.0	1585	20.6	8
Canada	72	9	2.8	1858	25.8	7
Japan	67	10	2.6	1260	18.8	9

Figure 4 presents the yearly number of publications of the five most productive countries, which published more than 100 scientific papers during 1991–2014. In 1991 and 1992, the numbers of publications were comparable among the USA, Germany, the UK, and France. However, beginning in 1993, the USA far surpassed the other countries, whose publications increased rapidly from 1993 to 2007. Before 1999, there were no publications from China on BVOC research; however, the number of publications from China has since shown a substantial increase, especially after 2006. This is in contrast with Germany, which experienced successive declines in the number of publications from 2006 to 2011, although Germany produced more publications than the UK, France, and China before 2006. The UK and France followed similar trends in number of publications, increasing after 2004, declining after 2007, and reaching a peak in 2011.

In total, 759 scientific institutions took part in BVOC research during the investigated period. Figure 5 provides a comparison between the total number of published papers and times of citation among the ten most productive institutions. Six of the ten institutions were located in the USA, including the National Center for Atmospheric Research (NCAR), University of California Berkeley (UC Berkeley), the National Oceanic and Atmospheric Administration (NOAA), the US Environmental Protection Agency (USEPA), California Institute of Technology (Caltech), and University of Colorado, while the remaining four institutions were located in Germany, the UK, China, and Finland. Obviously, the USA possessed a stronger base for BVOC research. NCAR was the largest contributor, with 82 publications, followed by Max Planck Institute for Chemistry, the Chinese Academy of Sciences, UC Berkeley, and NOAA, with 62, 56, 48, and 46 scientific papers, respectively. NCAR was competitive in terms of average times of citation, indicative of its strong research. Caltech ranked eighth in the number of publications and was comparable to the institutions ranking sixth through tenth, but predominated in average times of citation. This indicated that papers published by Caltech were far more frequently referred to than those published by other institutions. By analyzing the number of publications and times of citations, we obtained an overview of the research scale, competence and contribution of different countries and institutions.

Fig. 4 Yearly publications of the five most productive countries during 1991–2014

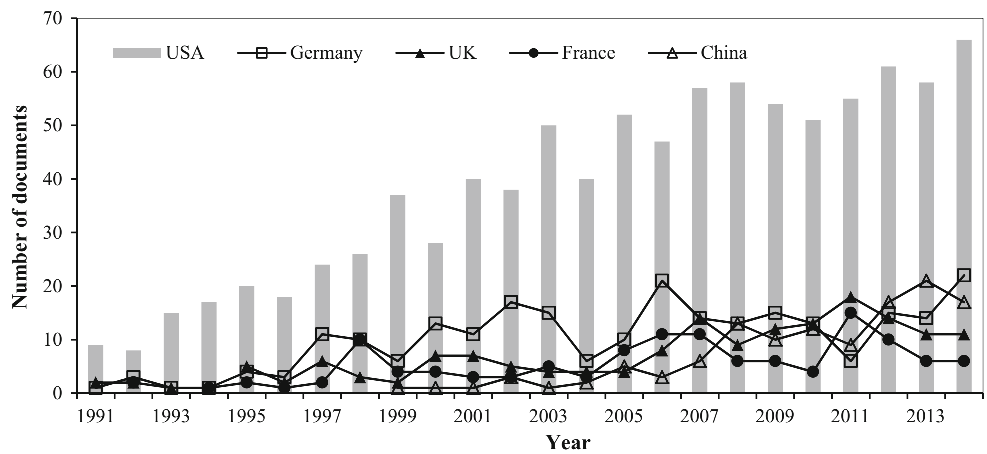
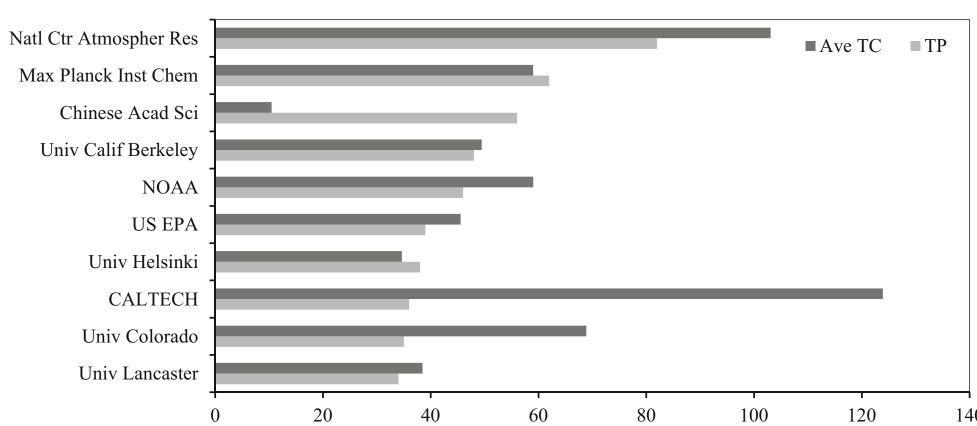


Fig. 5 Total published papers and average times of citation of the ten most productive institutions



Keywords analysis

Bibliometric studies with keywords analysis have been used to identify research hotspots and analyze research trends (Tan et al. 2014; Zhi et al. 2015). Two kinds of keywords are commonly studied: author keywords and *KeyWords Plus*. Analysis on author keywords can provide information on trends in researcher focuses (Hu et al. 2010). Bibliometric reviews have analyzed author keywords in a specific time period (Chiu and Ho 2007; Zhi et al. 2015) and the distribution of author keywords in different time intervals (Xie et al. 2008; Zhang et al. 2010) to identify research trends over time. *KeyWords Plus*, which are generated independently from author keywords and have an indirect relationship with an article's content (Garfield 1990), provide additional information on research emphasis and trends. A synthetic analysis of both author keywords and *KeyWords Plus* was only recently established and has proven to be an effective method for identifying research hotspots and trends (Xie et al. 2008; Li et al. 2009; Fu et al. 2013). It should be noted that keywords are not only a reflection on research priorities, but also on social, political, and economic interests, since they may reflect a researcher's views within the larger scientific community, ability of funds, and interest in supporting their objectives.

Among the 2659 examined documents, 1320 (49.6%) had records of author keywords and 2587 (97.3%) had *KeyWords Plus*. Ultimately, 2612 (98.2%) documents with author keywords or *KeyWords Plus* were analyzed synthetically, yielding 9770 keywords used from 1991 to 2014. Among them, 6619 (67.7%) appeared only once, and 1248 (12.8%) appeared twice. These results are similar to those of Xie et al. (2008) (74 and 11%, respectively) and Hu et al. (2010) (81 and 10%, respectively). The large number of keywords used only once probably represents a lack of continuity in research and a wide disparity in research focuses (Chuang et al. 2007).

Table 4 lists the 20 most frequently used keywords. We divided the study period into three 8-year intervals (1991–1998, 1999–2006, and 2007–2014) to ensure a reasonable time span for performing temporal analysis. The overall word frequency increased over time, implying that BVOC research has received increasing attention. Results show that "isoprene," an important chemical in biogenic emissions, remained within the top three keywords in all time intervals, indicating that it was a constant focus of research throughout the examined period. Isoprene has

Table 4 Top 20 keywords with the highest word frequency in 1991–1998, 1999–2006, and 2007–2014

1991–1998		1999–2006		2007–2014	
Keywords	F[a]	Keywords	F	Keywords	F
Isoprene	101	VOCs	247	VOCs	362
Ozone	78	Biogenic hydrocarbons	237	Isoprene	234
Biogenic emissions	64	Isoprene	207	Biogenic hydrocarbons	218
Hydrocarbons	47	Ozone	150	Emissions	182
Monoterpenes	47	Hydrocarbons	107	Ozone	180
Air	44	Biogenic emissions	102	Secondary organic aerosol	179
Gas phase reactions	44	Emissions	102	Model	165
Biogenic hydrocarbon emissions	42	α-pinene	96	United States	156
Emissions	40	Model	93	Monoterpenes	151
Organic compounds	39	Monoterpenes	92	α-pinene	140
VOCs	39	United States	92	Biogenic emissions	126
Model	37	Chemistry	74	Organic compound emissions	100
United States	36	Organic compound emissions	68	Atmospheric chemistry	99
Biogenic hydrocarbons	35	Gas phase reactions	67	Chemistry	97
Atmosphere	32	Atmospheric chemistry	65	Oxidation	95
Rate variability	30	β-pinene	64	Particulate matter	95
Inventory	28	Atmosphere	61	Isoprene emission	87
Forest	27	Oxidation	60	Atmosphere	84
Photosynthesis	26	Isoprene emission	53	Source apportionment	84
Temperature	26	Forest	51	Chemical composition	82

[a] Word frequency

significant effects on atmospheric chemistry (Monson 2002), and more isoprene is emitted to the atmosphere form vegetation than all other BVOCs combined (Arneth et al. 2007; Guenther et al. 2006, 2012). In addition to "isoprene," "monoterpenes" such as "α-pinene" and "β-pinene" are important chemicals emitted mainly from coniferous trees (Kim et al. 2005; Zhang et al. 2012); based on the temporal analysis, they were researched more in the most recent interval. The frequency of several keywords increased continuously over time, including "VOCs," "emissions," and "model." Apart from "VOCs" and "emissions," which were included in our search terms, the advancement of "model" reflects that model-based research was given increasing scientific attention during the study period, a trend that we expect to continue in the future. On the contrary, the frequency of some keywords decreased over time. "Ozone," formed by BVOCs via photochemical reactions (Situ et al. 2013; Singh et al. 2014), ranked second, fourth, and fifth in the three respective time intervals. Likewise, "biogenic emissions" and "atmosphere" experienced a continuous decrease. Several keywords were only among the top 20 during 1991–1998, including "air," "rate variability," "inventory," "photosynthesis," and "temperature." The relative declines described above were possibly due to the increasing variety in research topics, diluting the significance and dominance of these relatively traditional topics (Zhi et al. 2015). For instance, new research areas arose in atmospheric chemistry during 2007–2014, including "secondary organic aerosol" (SOA) and "particulate matter." SOA has caused widespread concern because of its adverse effects on public health and air quality. A number of BVOCs, including isoprene, monoterpenes, sesquiterpenes, and other reactive chemicals, are important precursors of SOA (Ehn et al. 2014; Wells et al. 2014). The formation mechanisms of SOA from various BVOCs have been investigated by researchers worldwide (Yassaa et al. 2012; Meng et al. 2014). In addition, studies on particulate matter, including contribution of BVOCs to particle growth (Zhou et al. 2015) and the chemistry behind new particle formation (Setyan et al. 2014), became increasingly popular research topics in the past decade.

Research emphases and research trends

To visualize the correlation of one keyword with other keywords and determine the centrality of each keyword, we created a network structure using UCINET based on the number of papers in which both investigated keywords appeared. Of the top 20 keywords in the three time intervals, 12 keywords that appeared relatively more frequently and represented research hotspots of the time were selected. The 12 keywords are: "isoprene," "monoterpenes," "biogenic hydrocarbons," "model," "emissions," "inventory," "ozone," "secondary organic aerosol," "particulate matter," "atmospheric chemistry," "VOCs," and "photosynthesis." The numbers of papers containing both investigated keywords were determined by refining the original search results (2659 papers), using both keywords to limit the search further. The numbers of papers for each two keywords were then compiled in a matrix as the input for UCINET processing. In total, 937 papers contained both "emissions" and "isoprene," which were the most abundant, followed by those containing both "emissions" and "model" (887), "emissions" and "ozone" (799). The network was drawn based on a cut-off value embedded in UCINET to dichotomize the input matrix into "1" and "0," where "1" denotes that the two investigated keywords were correlated and "0" denotes that they were not correlated. In this study, the cut-off value of the input numbers of papers was determined to be 100 by studying the distribution of all numbers. If the number of papers containing both keywords was larger than 100, the two keywords were correlated, and if it was smaller than 100, there was no relationship between the two keywords.

Figure 6 exhibits the cross-relationship of the 12 selected keywords, in which each node represents a keyword, and the lines with arrows display the correlation of each two keywords. The size of each node characterizes the centrality of the keyword. Specifically, larger nodes represent stronger centralities, and more correlation with other keywords. In this network, "emissions" correlated with all other keywords and had the strongest centrality, indicating that this area was a well-rounded cross-domain area. For example, it was related to various chemicals, including "isoprene," "monoterpenes," and "biogenic hydrocarbons," as well as the environmental impacts of BVOCs, including "ozone," "secondary organic aerosol" and "particulate matter." The centralities of "isoprene" and "model" followed that of "emissions." "Isoprene" correlated with all other keywords except "particulate matter," and "model" correlated with all other keywords except "photosynthesis." This does not necessarily indicate that they did not correlate with these keywords at all, but in this network, their relationship may have been covered up and the centrality of the keyword could have been relatively weakened because the number of papers was smaller than 100. Keywords including "inventory," "atmospheric chemistry," and "particulate matter" had weaker centralities compared to those described above. "Photosynthesis" showed the weakest centrality and was only correlated with "emissions" and "isoprene," indicating that "photosynthesis" was a relatively narrow area and was likely to fall outside the scope of mainstream BVOC research over time. In summary, "emissions," "isoprene," and "model" were the most comprehensive research hotspots and represented the leading edges of BVOC research during 1991–2014.

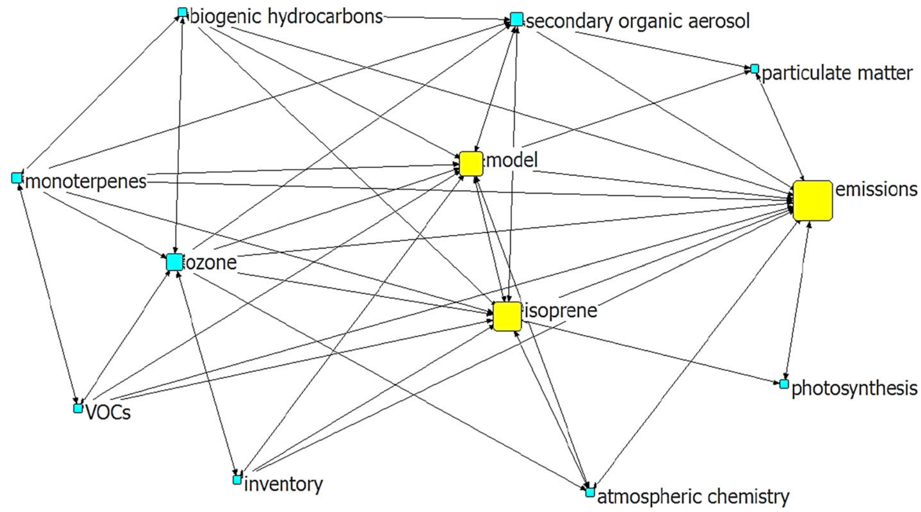


Fig. 6 Network structure of cross-relationship of 12 keywords during 1991–2014

By synthetic analysis of author keywords and *KeyWords Plus*, we obtained clues for the research hotspots. We performed further analyses of yearly publications in each leading hotspots cross-field (i.e., emissions-isoprene, emissions-model, and isoprene-model) to improve our identification of research trends. Publications on emissions-model grew substantially during 1991–2014 (Fig. 7). Evidences were found for this trend in several papers on BVOC research in the area concerning both isoprene and emissions. In terms of plant physiology, understanding the physiological effects of isoprene synthesis (i.e., why isoprene is emitted) in plants may aid in predicting how plants will respond to global changes, such as global warming (Monson et al. 2013; Sharkey 2013). With respect to atmospheric chemistry, atmospheric oxidation of isoprene produces reaction products that contribute directly to aerosols (Ervens et al. 2008; Paulot et al. 2009). The fields of both global warming and aerosols witnessed substantial development (Zhi et al. 2015; Xie et al. 2008). Since topics concerning isoprene and emissions in BVOC research were closely correlated with global warming and aerosols, it is well-reasoned that the emissions-isoprene research has shown rapid growth during the investigated period. Regarding publications on emissions-model, modeling on BVOC emissions has improved from empirical models to emission mechanism-based models. The earliest approaches for modeling BVOC emissions used algorithms on empirical relationships between key drivers (e.g., temperature and light) and emission (Guenther et al. 1993). Additional driving factors of BVOC emissions were later added to the models, including leaf age (Guenther et al. 1999), soil moisture, and carbon dioxide (Guenther et al. 2006). More recent efforts introduced the mechanistic treatment of photosynthesis in vegetation emission models, including photosynthetic electron transport (Arneth et al. 2007) and calculation of a cascade of intermediate compounds (Zimmer et al. 2000; Grote 2007). Empirical models have been widely used to investigate the impact of changing environmental conditions on BVOC emissions. However, there are considerable uncertainties in predicting changes under environmental conditions outside the range used to derive the empirical relationships (Pacifico et al.

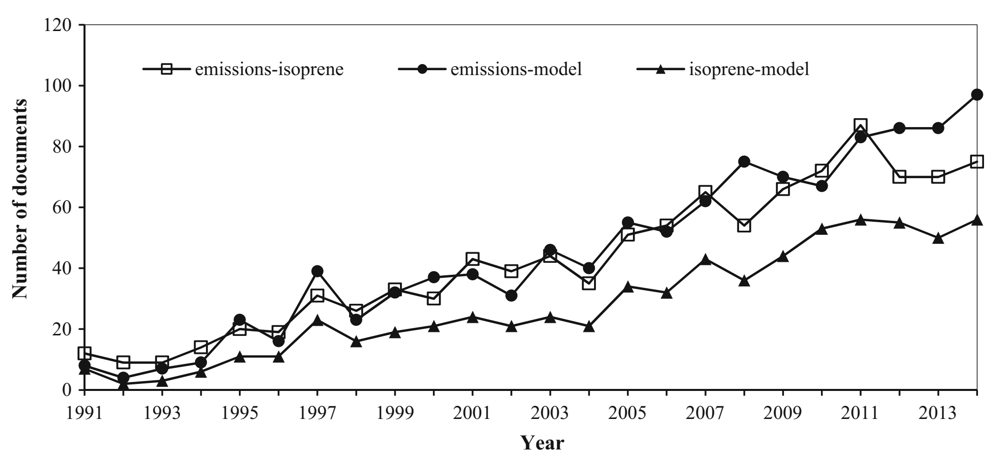


Fig. 7 Trends in cross-fields of the three leading research emphases during 1991–2014

2009). The development of models based on BVOC emission mechanisms is an improvement. However, these mechanistic models have additional limitations, such as a lack of validation data (Pacifico et al. 2009). BVOC modeling has undergone successive modifications to incorporate more valuable parameters and minimize uncertainties. There has been a lot of research interest in this area, as evidenced by the continuing growth of scientific outputs. The scientific output of isoprene-model exhibited similar growth, albeit with fewer publications. From the research trends of the three leading research hotspots cross-fields, it is expected that global scientific output in these mainstream areas will continue to grow in the future.

Conclusions

A bibliometric overview of the BVOC research was presented based on information related to yearly publications, document types and languages, subject categories, journals, countries, institutions, research emphases and trends. Scientific outputs increased substantially during 1991–2014. The 2659 scientific papers in this study were published in 373 journals covering 133 diverse subject categories. The main subject categories included Atmospheric Sciences, Environmental Sciences & Ecology, Environmental Sciences & Engineering, and Chemistry. The USA exhibited high productivity and influence in BVOC research, ranking first in both the number of publications and times of citation. NCAR took the leading position among the institutions in total publications, followed by Max Planck Institute for Chemistry, the Chinese Academy of Sciences, UC Berkeley, and NOAA. NCAR was also competitive concerning times of citation.

The synthetic analysis of author keywords and *KeyWords Plus* provided insight into BVOC research focuses. The overall word frequency increased over time. "Isoprene" was the most frequently used keywords in the study period. "Model" was increasingly important during 1991–2014. In addition, "secondary organic aerosol" and "particulate matter" were recent emphases in BVOC research. The network of the identified keywords showed that "emissions," "isoprene," and "model" had the strongest centralities and were considered to represent the leading edges of BVOC research. The cross-fields of the three leading research emphases showed substantial growth in the number of publications over time and were expected to grow in the future. We performed the analysis of research emphases and trends in a stepwise manner, from the single dimension of keyword frequency to the network of keywords and time series analysis to identify trends. Results of this study provide insights into patterns and trends in global BVOC research and help expand our understanding of the situation of global BVOC research. Moreover, the bibliometric approach used in this study can be applied to trend analyses of other research fields.

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