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Assessment of world aerosol research trends by bibliometric analysis

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This study was to explore a bibliometric approach to quantitatively assessing current research trends on atmospheric aerosol, using the related literature in the Science Citation Index (SCI) database from 1991 to 2006. Articles were concentrated on the analysis by scientific output, research performances by individuals, institutes and countries, and trends by the frequency of keywords used. Over the years, there had been a notably growth trend in research outputs, along with more participation and collaboration of institutes and countries. Research collaborative papers shifted from national inter-institutional to international collaboration. The decreasing share of world total and independent articles by the seven major industrialized countries (G7) was examined. Aerosol research in environmental and chemical related fields other than in medical fields was the mainstream of current years. Finally, author keywords, words in title and keywords plus were analyzed contrastively, with research trends and recent hotspots provided.

Introduction

Atmospheric aerosol research is an ancient topic, dating back to ancient Roman Empire times [NRIAGU, 1996]. It is also a forefront and hotspot subject of current international atmospheric sciences [CRUTZEN, 1998]. Scientific articles on aerosol research have demonstrated an expeditious increase in quantity over the past several decades, and a number of papers presenting the latest research achievements have been

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published in the authoritative scientific journals such as *Nature* and *Science* [MASON, 1960; MEINEL & MEINEL, 1975; RAHN & LOWENTHAL, 1984; CHARLSON & AL., 1992; ANDREAE & CRUTZEN, 1997; JACOBSON, 2001; ANDREAE & AL., 2005]. Atmospheric aerosol is closely connected with environmental deterioration and the quality of human life, and thus has aroused abroad concern all over the world. More and more countries have invested abundant scientific funds in investigating the properties and behavior of aerosol [MURELEY, 1991], mainly including the chemical composition of aerosols, the formation and transformation mechanisms and its effects on climate and human health.

Aerosol research has been obtaining increasing scientific attention first due to its negative effects on health [DRINKER & HATCH, 1936; DOCKERY & AL., 1993; VEDAL, 1997], which was early highlighted in the 12th century by a prominent physician Moses Maimonides [ROSNER, 2002]. The role of aerosol particles in the global and regional climate change has also been studied increasingly in the international scientific community [IPCC 4TH ASSESSMENT REPORT, 2007]. Atmospheric aerosols are proposed as climate-forcing constituents by exerting direct and indirect influences on the radiation balance: scattering or adsorbing solar radiation, and changing the optical characteristics, spatial and temporal distributions of cloud in the form of cloud condensation nuclei [TWOMEY, 1977; CHARLSON & AL., 1990; MITCHELL & AL., 1995; TANG, 1996; SEINFELD & PANDIS, 1998; JACOBSON, 2001].

Over the years, a great deal of progress was made in aerosol sampling and monitoring techniques [HINDS, 1982; CHOW, 1995; WILLEKE & BARON, 1993; JAYNE & AL., 2000], and the composition and characterization of aerosols [HILDEMANN & AL., 1991; DECESARI & AL., 2000; FINE & AL., 2001]. Particle size distribution had been extensively studied, shifting from bulk particle to individual particle [GIERAY & AL., 1997]; total suspended particulate (TSP) to inhalable particles (PM10), PM2.5 and even ultrafine particles [PETERS & AL., 1997; HUGHES & AL., 1998; KLEEMAN & AL., 2000]. Source apportionment studies were performed to identify possible sources and their relative spatial and temporal contributions, with the focuses changing from the emission of anthropogenic activities to natural productions and biogeochemistry sources [GARTRELL & FRIEDLANDER, 1975; ODOWD & AL., 1997; GRIFFIN & AL., 1999; GINOUX & AL., 2001]. In recent years, a great deal of detailed studies addressing mechanism aspects in the formation of aerosols and chemical reactions between aerosols and gaseous substances were conducted [PANKOW, 1994; MENG & AL., 1997; RAVISHANKARA, 1997; ELLISON & AL., 1999; RAES & AL., 2000; KULMALA & AL., 2004]. Furthermore, the present aerosol research has developed from local, regional to intercontinental and even global scale. For example, the International Global Atmospheric Chemistry (IGAC) project has organized three regional Aerosol Characterization Experiments (ACE) during the 1990s [QUINN & BATES, 2005].

Today, researchers are carrying out more comprehensive studies on aerosol, leading to the unusual breadth of topics. Despite increasing interest, there have been few attempts at gathering systematic data on the nature and extent of aerosol research. Garfield indicated that a recent research focus could be reflected on its publication output [GARFIELD, 1970]. A common research tool is the bibliometric method which has already been widely applied to many disciplines of science and engineering. Moreover, the Science Citation Index (SCI), from the Institute for Scientific Information (ISI), Web of Science databases, is the most important and frequently used source database of choice for a broad review of scientific accomplishment [BAYER & FOLGER, 1966; KOSTOFF, 2000].

In this study, we attempted to bibliometrically evaluate the SCI scientific literature on atmospheric aerosol. Hopefully, this paper will provide some additional insights into the current state of aerosol research during the time span from 1991 to 2006, such as the characteristics of research activities, publication patterns, research hotspot tendencies or irregularities, and basis for future projection.

Methodology

Documents used in this study were based on the online database of the Science Citation Index (SCI) retrieved from the ISI Web of Science, Philadelphia, PA, USA. "Aerosol*" was used as the keyword to search titles, abstracts, and keywords from 1991 to 2006. Document information included names of authors, contact address, title, year of publication, keywords, subject categories, and names of journals publishing the articles. The records were downloaded into Microsoft Excel software, and additional coding was manually performed for the number of authors, and origin country of the collaborators.

Articles originating from England, Scotland, Northern Ireland, and Wales were grouped under the UK heading. Contributions of different institutes and countries were estimated by the location of the affiliation of at least one author for the published articles. The term "international collaboration" was assigned if the article was cosigned by authors' addresses from multiple countries.

Results and discussion

There were 39,528 publications that met the selection criteria mentioned, including 16 document types. Article (36,047) was the most-frequently used document type comprising 91% of the total production, followed distantly by reviews (1,411, 3.6%). Others showing less significance were meeting abstracts (811), editorial materials (401), notes (348), letters (319), corrections (82), news items (55), addition corrections

(28), reprints (15), discussions (3) items about an individual (3), biographical-items (2), bibliography (1), book review (1), and software review (1). As journal articles represented the majority of document types that were also peer-reviewed within this field, 36,047 articles were identified and further analyzed in this study. The emphasis of the following discussion was to determine the pattern of scientific production; research activity trends which consisted of authorship, the institutes, countries; and the trends in the research subjects addressed.

Languages of publication

Written languages of all aerosol related scientific publications were grouped. The results showed that English had a clear monopoly, making up 97% of all article publications. For all practical purposes, the English language was the international language of choice in aerosol research, at least according to the SCI database. We left the debate of whether or not English was the lingua franca of international scientific communication [GARFIELD, 1989] to other commentators.

As atmospheric aerosol which had owned a long research history generated greater and greater worldwide interest, increasing share of articles in languages other than English appeared. Totally 16 languages were included in the non-English SCI publishing world for the 16 years. Similar phenomena were found in other scientific fields that were getting mature gradually [SELF & AL., 1989; NAVARRO, 1996; LIN & ZHANG, 2007]. The top three languages with respect to non-English articles were German (247; 0.69%), Russian (233; 0.65%), and French (180; 0.5%). The remaining included Japanese, Chinese, Spanish, Polish, Hungarian, Portuguese, Rumanian, Czech, Italian, Dutch, Finnish, Korean, and Slovenian.

Scientific output

The aerosol research developed expeditiously over the last century, from 1 SCI article in 1904 to 1,095 articles in 2006 by using "aerosol*" that included aerosol, aerosols, aerosolized, aerosolised, aerosolization, aerosolisation, aerosolize, aerosolsin, aerosols99, aerosolresearch, aerosolic, aerosolizing, aerosola, aerosole, aerosol-disinfection, aerosoltherapy, aerosolar, aerosolotherapy, aerosolionization, aerosoles, aerosoled, aerosolgenerator, aerosoliser, aerosolpackungen, aerosolen, aerosolteilchen, aerosolkonzentration, aerosolmessung, aerosolove, aerosolstreuung, aerosolovych, aerosoltherapie, aerosolisees, aerosolica, aerosolot, and aerosolie to search title words (Figure 1). It could be seen that the world academic publication had a steady growth after the 1960s.

Table 1. Characteristics of aerosol scientific articles from 1991 to 2006

Year	A	PG	PG/A	NR	NR/A	J	A/J
1991	1,491	12,487	8.4	31,770	21	495	3.0
1992	1,429	12,130	8.5	34,505	24	458	3.1
1993	1,539	13,980	9.1	38,556	25	465	3.3
1994	1,778	16,694	9.4	45,049	25	498	3.6
1995	1,785	17,132	9.6	48,316	27	531	3.4
1996	2,038	19,798	9.7	59,015	29	592	3.4
1997	2,140	21,100	9.9	63,680	30	572	3.7
1998	2,148	21,159	9.9	63,360	29	581	3.7
1999	2,281	23,772	10	66,773	29	611	3.7
2000	2,267	23,586	10	69,829	31	617	3.7
2001	2,478	24,846	10	75,110	30	651	3.8
2002	2,618	27,394	10	85,183	33	673	3.9
2003	2,710	30,618	11	88,961	33	679	4.0
2004	2,903	30,054	10	92,991	32	690	4.2
2005	3,080	32,193	10	103,632	34	702	4.4
2006	3,362	36,142	11	116,301	35	753	4.5
Total	36,047	363,085		1,083,031		2,656	
Average			10		30		3.8

A: Number of articles; PG: Page count; NR: Cited reference count; J: Number of journals; PG/A: The average page count per article; NR/A: The average cited reference count per article; A/J: The average number of articles published per journal.

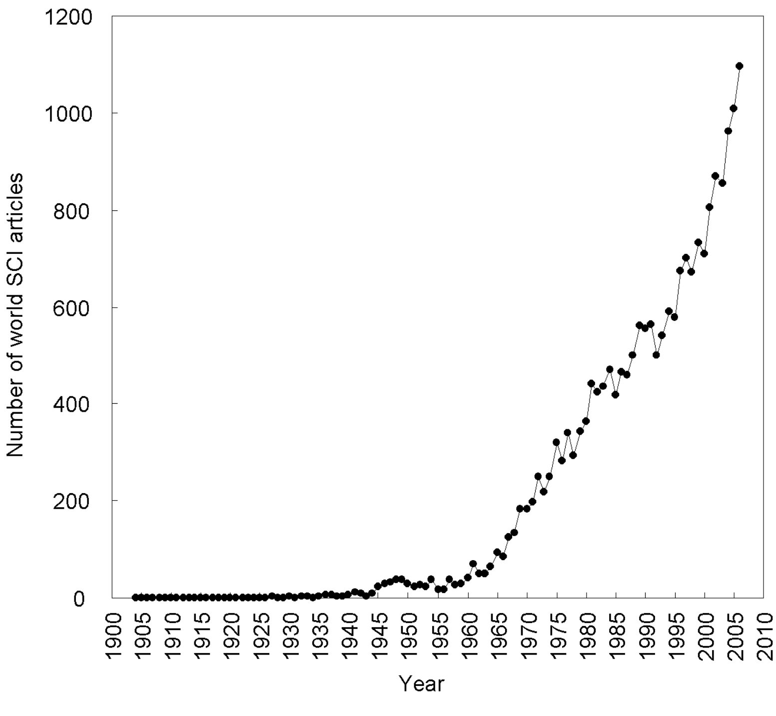

Figure 1. World SCI publications on aerosol since 1900 to 2006

The publication output of current aerosol research during the time span of 1991 through 2006 was summarized in Table 1. The annual number of articles, the number of cited references, pages and the number of journals publishing aerosol-related literature increased considerably. One thousand four hundred and ninety-one articles were published in 1991, while the number of publication rose to 3,080 in 2005 and 3,362 in 2006. The average article lengths fluctuated slightly, with an overall average of 10 pages. Twenty-one references were cited per article in 1991, compared to 35 references per article in 2006, with the number steadily increasing through the 16 years. Furthermore, the mean number of articles published per journal also varied over the years, from a minimum of 3.0 articles per journal in 1991 to a maximum of 4.5 in 2006.

A significant correlation was found between the yearly cumulative number of publications and the year from 1991 to 2006 (Figure 2).

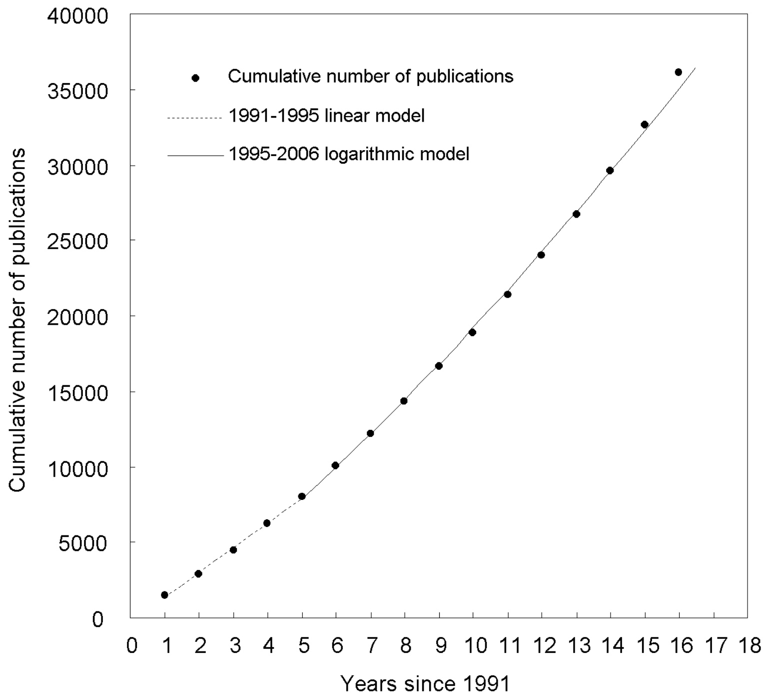

Figure 2. Cumulative number of publications by year from 1991 to 2006

The cumulative progression was represented by a linear model and a logarithmic model. The plot of the data revealed high coefficient of determinations in the period 1991 to 1995 (r^2 = 0.997) and 1995 to 2006 (r^2 = 0.999). The publication growth in the later period was even higher compared to the period from 1991 to 1995. It can be predicted that the number of scientific papers on the topic of aerosol is still growing at a high rate in the future. In fact, 17,151 articles have been published in the six years after 2000, almost as many as from 1991 to 2000.

Publication performances: authorship, institutes, and countries

Except for the 83 articles for which the author information was missing in the ISI, there were 64,358 authors devoting publications to aerosol from 1991 to 2006. Besides, 35,785 articles were included in the research activity analysis of countries and institutes, as 262 cases did not have author address information. The increasing trend in the number of authors, institutes and countries worldwide participating in aerosol research could be observed in Table 2. Moreover, the mean number of authors, countries and institutes per article also rose up steadily.

Table 2. Authors, institutes and countries participating in aerosol research from 1991 to 2006

Year	A (AU)	AU	AU/A	A (In, C)	In	In/A	C	C/A
1991	1,488	4,162	3.4	1,473	1,090	1.5	56	1.1
1992	1,425	4,317	3.8	1,407	1,118	1.6	56	1.1
1993	1,535	4,620	3.8	1,526	1,180	1.6	64	1.1
1994	1,771	5,209	3.8	1,748	1,326	1.7	68	1.2
1995	1,776	5,661	4.0	1,767	1,376	1.7	66	1.2
1996	2,034	6,615	4.2	2,011	1,509	1.8	72	1.2
1997	2,134	6,864	4.3	2,116	1,594	1.9	67	1.2
1998	2,144	6,667	4.1	2,140	1,724	1.9	68	1.2
1999	2,272	7,476	4.3	2,262	1,872	2.0	69	1.3
2000	2,262	7,482	4.4	2,250	1,854	2.1	73	1.3
2001	2,472	8,098	4.4	2,467	2,103	2.1	84	1.3
2002	2,614	8,476	4.5	2,609	2,054	2.1	73	1.4
2003	2,703	9,083	4.8	2,700	2,197	2.3	84	1.3
2004	2,897	9,753	4.8	2,887	2,275	2.2	79	1.3
2005	3,077	10,631	4.8	3,070	2,504	2.2	89	1.4
2006	3,360	11,324	4.9	3,352	2,616	2.3	91	1.4
Total	35,964			35,785	12,569		149	
Average			4.4			2.0		1.3

A (AU): Articles with author information; AU: Number of authors participating in; AU/A: Average number of authors per article; A (In, C): Articles with author address information; In: Number of institutes participating in; In/A: Average number of institutes per article; C: Number of countries participating in; C/A: Average number of countries per article.

Collaboration, playing an ever growing role in contemporary scientific research, can usually manifest itself in internationally co-authored papers tracked by bibliometric tools [SCHUBERT & BRAUN, 1990; MOED & HESSELINK, 1996]. Among the 35,785 articles with address information, 48% were publications by single institute, and others were inter-institutional collaborative work, both national and international collaborations included. As could be seen from Figure 3, collaborative articles were more prevalent in recent years than earlier years, from a 33% percentage of world SCI articles in 1991 to 62% in 2006. In general, the ascending trend of collaborative article proportion to world publication was somewhat owing to the rising number of institutes and countries that engaged in the research.

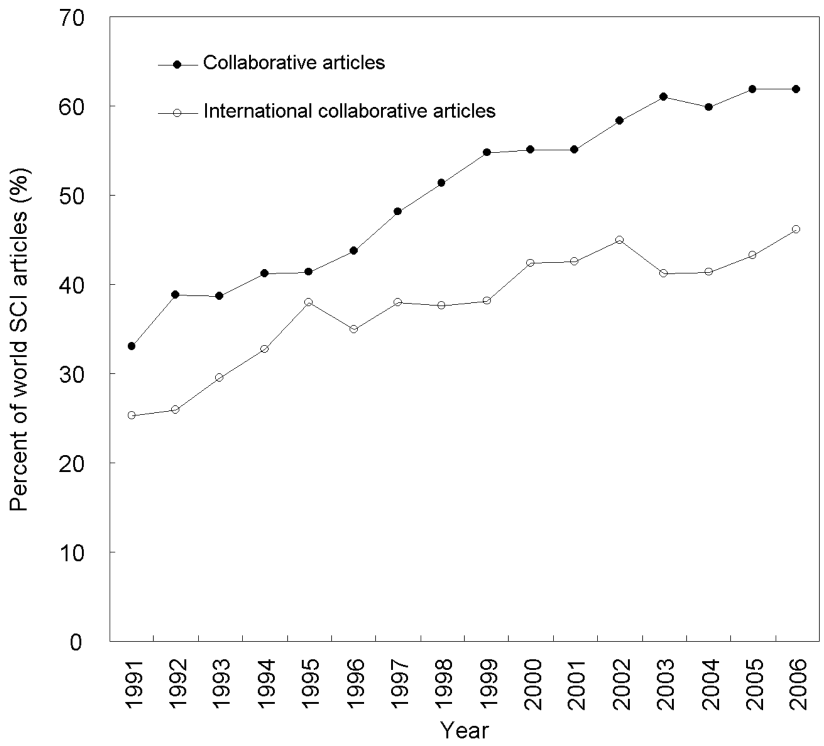

Figure 3. Collaboration share of world articles, international share of world collaboration articles per year

Simultaneously recent proportion of international articles to world collaborative articles showed a gradual increase, though collaborative productivity within the country took the majority, with an overall average 60% of collaboration. Scientific productivity resulting from national inter-institutional collaboration was stronger, as by our common sense it was much easier to network with similar research groups attached to other institutions in the country. Using 4-year intervals to minimize the year-to-year fluctuations, the proportions of articles with international co-authorship to world collaboration were 29%, 37%, 42%, and 43% for the periods 1991–1994, 1995–1998, 1999–2002, and 2003–2006, respectively. It was clear that collaborative work of aerosol research shifted from domestic inter-institute to international collaboration. It would be reasonable to assume that the increased ease of communication in a technologically connected world contributed to the increasing collaboration.

Analyzing all the countries producing SCI papers in detail, the mainstream of participation and collaboration on aerosol research was obtained. Among the total 149 countries/territories over the investigation period, 50 countries/territories had no publication output during 1991–1995, and 27 countries/territories just began to publish papers after the year 2000. It was obvious that aerosol research became more globally concerned. As obtained from the ISI database, the seven major industrialized countries (G7: Canada, France, Germany, Italy, Japan, the UK, and the USA), with USA leading the top, held the majority of total world production. This domination pattern in publication from mainstream countries occurred in most scientific fields [MELA & AL., 1999].

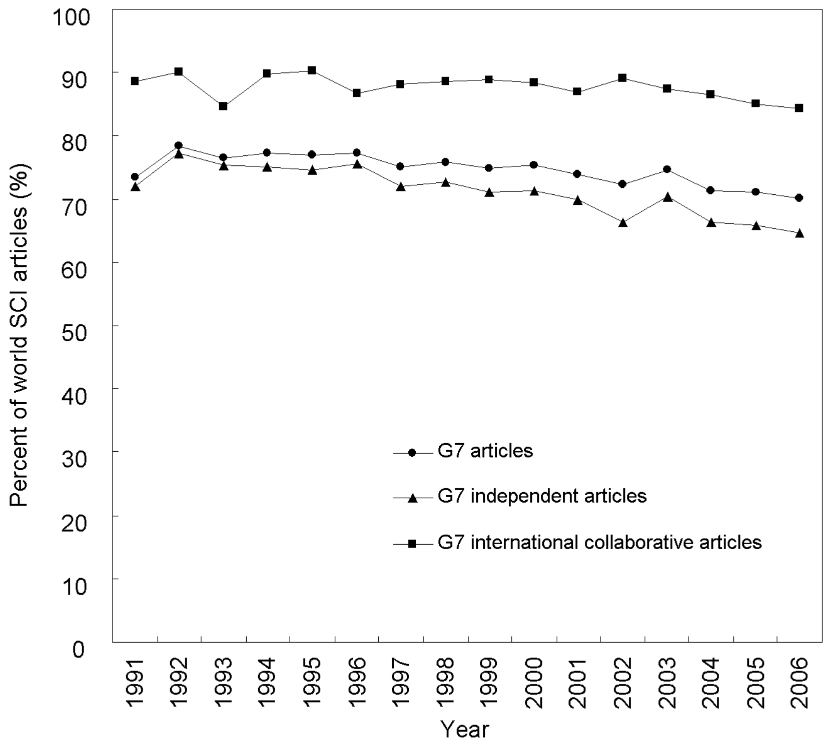

Figure 4. G7 share of world total articles, independent articles and international collaborative articles per year

Figure 4 showed the trend of G7 total articles, single country articles, and internationally collaborated articles share of world publication. The absolute ascendancy in quantity reflected that the academic levels of these countries were high. Since the early atmosphere aerosol pollution occurred in industrial countries, they conducted the earliest and the most relative research performances. Moreover, the G7 kept a high percentage of world total international collaborative articles, with a slight fluctuation by year, which meant they were the most-frequent partners stable all the while. On the other hand, however, gradual decreases were found for the proportions of both the G7's total output and independent output to world publications by year, also presented in Figure 4. In recent years more scientists from developing countries had begun to focus on aerosol research, occupying a larger and larger proportion of world publication. For instance, the number of SCI publications by China after 2000 had significantly reached 741, compared to 203 in the previous 10 years. In addition, the none-G7 independent articles increased, making up 28% of world total single-country publications in 1991 to 35% in 2006, which might indicate their independent productivity also boosted up to a certain extent.

Publication patterns: Subject categories and journals

In the research topic of aerosol, there was a great diversity including 182 subject categories identified by ISI. The use of statistics in any scientific discipline could be considered a key element in evaluating its degree of maturity [PALMER & AL., 2005]. Table 3 showed categories which had at least 1,000 articles, including the ranking of paper quantities in four periods: 1991–1994, 1995–1998, 1999–2002, and 2003–2006. The result provided a current view of the research emphasis of this topic. Aerosol was mostly presented in medical, environmental, and chemical related fields, though the proportion of scientific articles per category exhibited some variation during the time span covered. A decrease of ranking appeared in the yearly publications of the medical categories: respiratory system; and public, environmental & occupational health. On the contrary, the publication quantities in multidisciplinary geosciences, physical chemistry, and environmental engineering had such a significant growth that they ranked 3, 6, and 7 respectively in the period of 2003–2006.

In total, 36,047 articles were published in 2,654 journals including specialty journals, but also journals of other disciplines. Table 4 presents the 22 journals publishing more than 200 aerosol-related articles through the 16 years. *Atmospheric Environment Part A-General Topics* and *Atmospheric Environment Part B-Urban Atmosphere* were incorporated as *Atmospheric Environment* in 1994, and articles published by these three journals were analyzed together under *Atmospheric Environment*. As the flagship journal of this particular research field, *Journal of Geophysical Research-Atmospheres* published the most articles.

Table 3. The top 12 subject categories with the most publications, including the ranking and respective percentages for four-year periods

Subject categories	91–06 TA	91–06 R (%)	91–94 R (%)	95–98 R (%)	99–02 R (%)	03–06 R (%)
Meteorology & Atmospheric Sciences	10,787	1 (30)	2 (24)	1 (27)	1 (31)	1 (34)
Environmental Sciences	8,728	2 (24)	1 (25)	2 (21)	2 (24)	2 (26)
Mechanical Engineering	2,450	3 (6.8)	3 (9)	4 (7)	3 (6.3)	3 (6)
Chemical Engineering	2,247	4 (6.2)	5 (8.6)	5 (6.1)	5 (5.7)	5 (5.5)
Respiratory System	2,177	5 (6)	4 (8.7)	3 (8.1)	6 (5.7)	11 (3.6)
Multidisciplinary Geosciences	1,987	6 (5.5)	8 (5)	6 (5)	4 (5.7)	3 (6)
Physical Chemistry	1,749	7 (4.9)	10 (3.8)	7 (4.9)	7 (4.9)	6 (5.4)
Public, Environmental & Occupational Health	1,586	8 (4.4)	7 (5.4)	8 (4.8)	8 (4.4)	10 (3.7)
Pharmacology & Pharmacy	1,560	9 (4.3)	6 (5.6)	8 (4.8)	12 (3.8)	9 (3.8)
Analytical Chemistry	1,550	10 (4.3)	9 (4.2)	10 (4.5)	10 (4)	8 (4.4)
Environmental Engineering	1,360	11 (3.8)	14 (2.5)	13 (2.9)	9 (4.1)	7 (4.8)
Immunology	1,313	12 (3.6)	11 (3.5)	11 (3.9)	11 (3.9)	12 (3.3)

TA: total published articles in the 16 years; R (%): ranking of publications (percentage of all articles published in the years).

Table 4. The top 22 most published journals on aerosol, including the ranking and respective percentages for four-year periods

Journal	91–06 TA	91–06 R (%)	91–94 R (%)	95–98 R (%)	99–02 R (%)	03–06 R (%)
Journal of Geophysical Research-Atmospheres	3,441	1 (9.5)	3 (5.4)	1 (10)	1 (11)	1 (9.9)
Atmospheric Environment	2,427	2 (6.7)	1 (6.4)	2 (4.5)	2 (6.8)	2 (8.3)
Journal of Aerosol Science	1,282	3 (3.6)	2 (6.1)	3 (3.4)	4 (3.1)	6 (2.7)
Geophysical Research Letters	1,249	4 (3.5)	4 (3.9)	4 (3.4)	3 (3.3)	3 (3.5)
Aerosol Science and Technology	1,039	5 (2.9)	5 (2.7)	5 (3.4)	5 (2.7)	5 (2.8)
Environmental Science & Technology	652	6 (1.8)	9 (1.4)	9 (1.3)	6 (1.9)	7 (2.2)
Applied Optics	493	7 (1.4)	10 (1.3)	6 (1.7)	7 (1.5)	9 (1.1)
Journal of Aerosol Medicine- Deposition Clearance and Effects in the Lung	433	8 (1.2)	11 (1.3)	8 (1.5)	8 (1.3)	12 (0.94)
Atmospheric Chemistry and Physics	420	9 (1.2)	–	–	86 (0.17)	4 (3.4)
Journal of the Air & Waste Management Association	322	10 (0.89)	46 (0.32)	28 (0.52)	9 (1.1)	8 (1.3)
Chest	295	11 (0.82)	7 (1.8)	11 (0.94)	18 (0.65)	33 (0.37)
Atmospheric Research	270	12 (0.75)	–	12 (0.92)	14 (0.78)	11 (1)
American Journal of Respiratory and Critical Care Medicine	264	13 (0.73)	35 (0.4)	7 (1.5)	12 (0.85)	49 (0.3)
Science of the Total Environment	260	14 (0.72)	19 (0.64)	18 (0.68)	15 (0.74)	13 (0.78)
Journal of Applied Physiology	249	15 (0.69)	8 (1.5)	13 (0.86)	25 (0.51)	53 (0.29)
Journal of the Atmospheric Sciences	247	16 (0.69)	31 (0.48)	24 (0.58)	11 (0.96)	16 (0.64)
Journal of Physical Chemistry A	238	17 (0.66)	–	40 (0.38)	12 (0.85)	10 (1)
Tellus Series B-Chemical and Physical Meteorology	230	18 (0.64)	24 (0.55)	20 (0.67)	10 (1)	32 (0.38)
Inhalation Toxicology	222	19 (0.62)	43 (0.34)	18 (0.68)	16 (0.71)	15 (0.65)
Journal of Atmospheric Chemistry	216	20 (0.6)	12 (0.88)	25 (0.57)	21 (0.57)	25 (0.5)
Analytical Chemistry	203	21 (0.56)	33 (0.46)	28 (0.52)	21 (0.57)	16 (0.64)
European Respiratory Journal	201	22 (0.56)	21 (0.58)	10 (1)	20 (0.6)	75 (0.21)

TA: total published articles in the 16 years; R (%): ranking of publications (percentage of all articles published in the years).

A decline in the ranking of the medical journals *Chest*, *Journal of Applied Physiology* and *European Respiratory Journal* was visible, consistent with the trend of category pattern analyzed previously. We may make a conjecture that aerosol research in the medical topic had continuously developed to a mature state. Researchers began to focus more on the physical chemical mechanism and engineering of atmospheric aerosols than on their induced health problems. The growth of yearly aerosol publications within *Analytical Chemistry*, *Journal of Physical Chemistry A*, and *Journal of the Air & Waste Management Association* speeded up in recent years (Table 4).

Research emphasis: Author keywords, words in title, and keywords plus

The technique of statistical analysis of keywords and title-words might be aimed at discovering directions of science [GARFIELD, 1990]. In this sense it proved to be important for monitoring development of science and programs. Examination of author keywords revealed that 31,916 keywords were used. Among them, 23,354 (74%) appeared only once, and 3,669 (11%) keywords appeared twice. The large number of once-only author keywords probably indicated a lack of continuity in research and a wide disparity in research focuses [CHUANG & AL., 2007]. Most of the research articles were not considered to be mainstream aerosol research by their authors. Table 5 showed distributions of the top 25 most active author keywords. Except for "aerosol" and "aerosols", the most frequently used keyword for all periods was "asthma". Several keywords referring to particulate matters such as "PM2.5", "PM10", "nanoparticles", and "size distribution" had extremely high increasing rates in ranking of frequency, which might be identified as current aerosol research hotspots [WINKLMAYR & AL., 1991; IMHOF & AL., 2006]. Finally, the ranking of a few author keywords did not fluctuate distinctly, showing the aerosol-related research was basically steady in the past 16 years. However, what should be noted was that the comparisons of the keywords frequency would somewhat produce inexact or spurious conclusions. For example, the term PM 10 had three expressed forms: PM-10, PM (10), and PM 10, and even "inhalable particles" were with the same sense as author keywords. Besides, the analysis was only for a total of 16,274 aerosol articles with author keywords records, accounting for 45% of the publications in the investigated 16 years. Hence, our data were only an approximate reflection of scientific attention.

An analysis of words in title was also undertaken for it could be used to make inferences of the scientific literature or to identify the subjective focus and emphasis specified by authors. The prepositions, articles, and conjunctions in title were excluded from the statistic analysis. Title words which had appeared in over 1,000 articles were presented in Figure 5. "Measurements", "model", 'deposition", "size", "organic", "chemical", "lung", and "dust" were most frequently used in the period of 1991–2006.

Table 5. Frequency of author keywords used

Author keywords	91–06 TA	91–06 R (%)	91–94 R (%)	95–98 R (%)	99–02 R (%)	03–06 R (%)
aerosol	1489	1 (4.1)	1 (3)	1 (3.3)	1 (4.5)	1 (4.9)
aerosols	1069	2 (3)	2 (2.4)	2 (2.6)	2 (2.9)	2 (3.5)
asthma	594	3 (1.6)	3 (1.5)	3 (2)	3 (1.9)	5 (1.3)
particulate matter	264	4 (0.73)	165 (0.096)	37 (0.22)	5 (0.8)	4 (1.4)
PM 2.5	263	5 (0.73)	–	418 (0.049)	6 (0.79)	3 (1.5)
air pollution	251	6 (0.7)	12 (0.34)	4 (0.73)	7 (0.77)	10 (0.8)
ozone	242	7 (0.67)	26 (0.26)	6 (0.62)	4 (0.81)	9 (0.81)
PM 10	199	8 (0.55)	393 (0.048)	120 (0.12)	8 (0.67)	6 (1)
inhalation	198	9 (0.55)	6 (0.43)	8 (0.54)	8 (0.67)	18 (0.51)
deposition	194	10 (0.54)	6 (0.43)	9 (0.47)	11 (0.61)	15 (0.58)
lung	191	11 (0.53)	17 (0.29)	7 (0.59)	10 (0.64)	17 (0.52)
size distribution	182	12 (0.5)	13 (0.32)	12 (0.39)	17 (0.43)	11 (0.74)
remote sensing	173	13 (0.48)	58 (0.18)	25 (0.28)	26 (0.34)	7 (0.88)
lidar	158	14 (0.44)	8 (0.38)	11 (0.44)	17 (0.43)	21 (0.47)
cystic fibrosis	153	15 (0.42)	101 (0.13)	5 (0.67)	13 (0.52)	42 (0.34)
sulfate	151	16 (0.42)	5 (0.45)	34 (0.25)	20 (0.4)	16 (0.53)
nanoparticles	142	17 (0.39)	–	418 (0.049)	23 (0.36)	8 (0.85)
atmospheric aerosol	140	18 (0.39)	10 (0.35)	19 (0.31)	22 (0.38)	22 (0.46)
atmospheric aerosols	131	19 (0.36)	13 (0.32)	35 (0.23)	15 (0.46)	29 (0.4)
dust	130	20 (0.36)	101 (0.13)	77 (0.16)	30 (0.29)	12 (0.67)
black carbon	128	21 (0.36)	66 (0.16)	88 (0.15)	14 (0.48)	19 (0.5)
biomass burning	123	22 (0.34)	601 (0.032)	66 (0.17)	36 (0.28)	13 (0.66)
source apportionment	118	23 (0.33)	45 (0.21)	88 (0.15)	61 (0.22)	14 (0.6)
nitrate	117	24 (0.32)	30 (0.24)	25 (0.28)	23 (0.36)	37 (0.36)
particle size distribution	117	24 (0.32)	88 (0.14)	35 (0.23)	21 (0.39)	26 (0.42)

TA: total published articles in the 16 years; R (%): ranking of publications (percentage of all articles published in the years).

Furthermore, keywords plus, which supplied additional search terms, was extracted from the titles of papers cited by authors in their bibliographies and footnotes in the ISI database [GARFIELD, 1990]. The keywords plus substantially augmented title-word and author-keyword indexing. 32,494 articles in all were found to include keywords plus information. Table 6 showed the 30 most frequently used keywords plus with their rankings and percentages. Research emphasis and changes could be roughly found. The keywords plus “model”, “ozone”, “chemistry”, and “size distribution” ranked top of the list, in accordance with the frequency of author keywords and title-words. Withal, “deposition”, “transport”, “emissions”, and “size distribution” were popular topics all along as additional search terms. It might be concluded that the migration, transfer and global cycle of some aerosol contaminations received additional spikes of attention [GUENTHER & AL., 1995; CAPALDO & AL., 2000]. The topic might have developed to a significant subgroup of atmosphere aerosol research.

Table 6. Frequency of keywords plus used

Keywords plus	91–06 TA	91–06 R (%)	91–94 R (%)	95–98 R (%)	99–02 R (%)	03–06 R (%)
aerosol	3006	1 (8.3)	1 (7.3)	1 (8.3)	1 (8.6)	2 (8.7)
aerosols	2820	2 (7.8)	2 (6.7)	2 (7.6)	2 (8)	3 (8.5)
particles	2530	3 (7)	3 (4.4)	3 (5.5)	3 (7.3)	1 (9.1)
model	1718	4 (4.8)	5 (2.8)	4 (4.1)	4 (5.2)	4 (5.9)
deposition	1286	5 (3.6)	4 (3.3)	5 (3.6)	5 (3.9)	10 (3.4)
atmosphere	1170	6 (3.2)	9 (2.4)	7 (2.9)	6 (3.6)	5 (3.6)
transport	1049	7 (2.9)	13 (1.9)	9 (2.7)	8 (3)	6 (3.5)
air	987	8 (2.7)	12 (2)	10 (2.6)	7 (3)	13 (3)
water	961	9 (2.7)	6 (2.7)	6 (2.9)	10 (2.6)	18 (2.5)
ozone	889	10 (2.5)	11 (2.2)	11 (2.5)	11 (2.5)	20 (2.5)
chemistry	874	11 (2.4)	14 (1.9)	12 (2.3)	9 (2.7)	18 (2.5)
size	851	12 (2.4)	24 (1.3)	16 (1.9)	13 (2.4)	12 (3.2)
emissions	828	13 (2.3)	26 (1.2)	23 (1.5)	12 (2.5)	11 (3.2)
climate	814	14 (2.3)	19 (1.5)	14 (2.1)	15 (2)	14 (2.9)
growth	770	15 (2.1)	21 (1.3)	19 (1.8)	14 (2.2)	16 (2.7)
asthma	752	16 (2.1)	7 (2.5)	8 (2.8)	20 (2)	46 (1.4)
air–pollution	738	17 (2)	62 (0.8)	43 (1.1)	22 (1.9)	7 (3.5)
system	729	18 (2)	18 (1.6)	13 (2.1)	17 (2)	22 (2.2)
optical–properties	716	19 (2)	141 (0.5)	30 (1.3)	25 (1.8)	8 (3.4)
aerosol–particles	688	20 (1.9)	43 (1)	28 (1.4)	17 (2)	17 (2.6)
sulfate	673	21 (1.9)	16 (1.7)	18 (1.8)	16 (2)	31 (1.8)
united–states	649	22 (1.8)	66 (0.7)	34 (1.2)	23 (1.8)	15 (2.7)
temperature	644	23 (1.8)	26 (1.2)	20 (1.8)	26 (1.7)	23 (2.1)
size distribution	623	24 (1.7)	78 (0.7)	26 (1.4)	21 (1.9)	21 (2.3)
inhalation	611	25 (1.7)	10 (2.2)	15 (2)	27 (1.6)	56 (1.3)
particulate matter	586	26 (1.6)	126 (0.5)	166 (0.5)	62 (1)	8 (3.4)
lung	583	27 (1.6)	8 (2.5)	17 (1.9)	34 (1.4)	71 (1.1)
clouds	537	28 (1.5)	37 (1)	25 (1.5)	30 (1.6)	38 (1.7)
pollution	537	28 (1.5)	34 (1.1)	38 (1.1)	31 (1.5)	29 (1.9)
scattering	535	30 (1.5)	22 (1.3)	24 (1.5)	24 (1.8)	51 (1.3)

TA: total published articles in the 16 years; R (%): ranking of publications (percentage of all articles published in the years).

In addition, "optical-properties" had become a new focus, the frequency of which ranking from 141st in 1991–1994 to 8th in the last 4 years. By contrast, the keywords plus "asthma" and "lung" decreased markedly from 7th and 8th in 1991–1994 to 46th and 71st in 2003–2006 respectively. This agreed with the trend of publication patterns analyzed for subject categories and journals, namely that more and more research attention was paid from medical fields to the physical chemistry fields on aerosol.

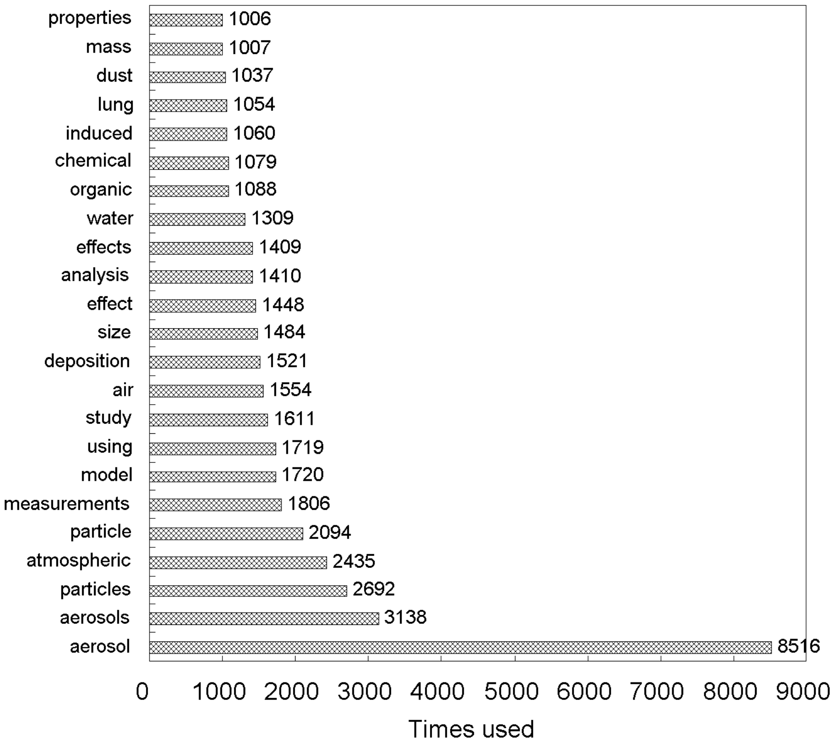

Figure 5. The top 23 title-words appearing more than 1,000 times

Conclusion

In this study dealing with aerosol SCI papers, we obtained some significant points on the worldwide research trends throughout the period from 1991 to 2006. The effort provided a systematically structural picture, as well as clues to the impacts of the aerosol topic. English was by far the dominant language; while 16 other languages were also used, indicating that aerosol research became more globally connected. A linear and a logarithmic model were applied to illuminate the relations between cumulative number of articles and the year. Significant growth was observed, particularly in the recent period 1995–2006. Apparently more and more authors, institutes, and countries engaged in the research over the years. Collaborative articles, the number of which increasing conspicuously, had shifted from domestic collaboration to international collaboration. The G7, owning a longer research tradition in this field, had not only the absolute ascendancy of production, but also the most-frequent partners. However, the proportion of their total and independent publication to world overall began to decrease to some extent. For the overall 36,047 articles, there were totally 2,654 journals listed in the 182 subject category with a great diversity. The mainstream of aerosol research was in medical, environmental and chemical related fields, whereas research in the medical categories somewhat played a less important role than before. "Asthma" headed the most frequently used author keywords in the 16 years. "PM2.5", "PM10", "nanoparticles", and "size distribution" were recent emphasis of aerosol research. Another sign of concern was that research covered a wide range of sub-topics, as indicated by the large number of one-time-only author keywords used in these articles. Title words and keywords plus were also examined, the results of which proved good accordance with author keywords. The migration and global cycle of atmosphere aerosols had become a significant research subgroup, suggested by the keywords plus analyses. Finally, it was proved that more research attention was transferred from medical fields to physical chemistry fields, agreeing with the previous publication pattern analysis for subject categories and journals.

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