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*Original Scientific Paper*

# Bibliometric Analysis of Atmospheric Simulation Trends in Meteorology and Atmospheric Science Journals

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*Abstract.* This study was designed to evaluate the global scientific output of simulation research in "meteorology and atmospheric sciences" for the past 16 years and to assess the characteristics of the atmospheric simulation research patterns, tendencies and methods in the papers, from leading countries and institutes. Data were based on the online version of Science Citation Index, Web of Science from 1992 to 2007. Articles referring to atmospheric simulation were assessed by exponential regression fitting the trend of publication outputs with $r^2 = 0.9996$, distribution of source countries, source institutes, source titles, author keywords, and keywords plus, and the four most cited articles in these years. By synthetic analysis of the three kinds of keywords, it was concluded that atmospheric simulation research related to "ozone", "climate", "circulation", "transport", "parameterization" and "assimilation" will be foci of atmospheric simulation research in the 21st century.

*Keywords:* atmospheric simulation, scientometrics, SCI, research trend, exponential model

## INTRODUCTION

Simulation research in meteorology and atmospheric sciences originated in the early 1950s,[1] and today it is one of the most important areas in atmospheric research. The rapid progress of urbanization and economic development resulted in a burst of pollutants all over the world, which threaten human health,[2–4] influence climate,[5,6] and hinder future development. A large majority of warming over the last century can be attributed to human activities rather than natural factors.[7] At present global warming, greenhouse gases, and limitations of carbon dioxide emissions are on the top political agenda,[8,9] such as the international environmental treaty – Kyoto Protocol.[10] The U.S. House of Representatives passed historic legislation to cut emissions linked to global warming for the first time in 2009. Pollution sources are concentrated in cities and their suburbs,[11,12] while atmospheric pollutants are transported between cities resulting in correlations among different areas and high spatial overlap of pollutants.[13] A limitation of most observations is that measurements are either made at a fixed point (ground), or on platforms not necessarily moving along with the same air parcel.[14]

Models have been used to assess our knowledge of atmospheric processes, including meteorological variations,[15] chemical and physical transformation of pollutants,[16,17] air quality forecasts and variations of pollutants.[18] Moreover, regional air quality modeling has been used to develop control strategies designed to reduce levels of pollutants such as ozone,[19] particulate matter,[20,21] and nitrogen oxides.[22,23] Recently, results of regional models have been integrated into epidemiological studies that aim to assess the health impact of atmospheric pollutants.[24,25] Continuing research on atmospheric simulation has increased our understanding of transport,[26] formation,[27] deposition,[28] and reactions of pollutants.[13]

Despite the high growth rate of publications, there have been few attempts at gathering systematic data on the global scientific production of atmospheric simulation research.[29] A common research tool for this analysis is the bibliometric method[30] which has already been widely applied to scientific production and research trends in topics such as aerosols,[29] adsorption technology,[31] water research,[32] microbiology,[33] and geostatistics.[12] The Science Citation Index (SCI), from the Institute for Scientific Information (ISI) Web of Science databases, is the most important and frequently used

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source database for a broad review of scientific accomplishment in all fields.[34] Conventional bibliometric methods often evaluate research trends by the publication outputs of countries, research institutes, journals, and research fields[35–37] or by citation analysis.[38,39] However, merely depending on changes in the citations or publication counts of countries and organizations cannot completely reveal the developmental trends or future orientation of a research field. More information, closer to the research itself, such as source titles,[40] author keywords,[29] and keywords plus[41] should be introduced. The keywords plus in the SCI database supply additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes.[42] Data were separated into 4 four-year periods to analyze the variations of trends thoroughly and precisely.[29,40]

In this study, a traditional bibliometric method, analysis of language, source country, source institute, and the most cited papers to describe the performance in atmospheric simulation was used. Moreover, the innovative method - analysis of selected topics in the combination of source titles, author keywords, and keywords plus, was applied to map the global research trends during the period of 1992−2007. Findings from these investigations can help researchers to realize the breadth of atmospheric simulation research and to establish further research directions.

## DATA SOURCES AND METHODOLOGY

The data were from the online version of SCI, Web of Science. According to Journal Citation Reports (JCR), it indexed 6 426 major journals with citation references across 172 scientific disciplines in 2007. "Model*" and "simulat*" were used as search keys in the category of meteorology and atmospheric science, which included (http://admin-apps.isiknowledge.com/JCR/JCR) 51 jo-urnals. The word "model*" might stand for "model", "models", "modeling", and "modelling", while "simulat*" might represent "simulate", "simulation", and "simulating".

Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as from the United Kingdom (UK). Articles from Hong Kong were not included in China. Besides, the reported impact factor (IF) of each journal was obtained from the 2007 JCR.

All articles referring to atmospheric simulation during the past 16 years were assessed according to: type of publication, characteristics of publication outputs, distribution of outputs in journals, publication outputs of source country, source institute, author number per single country or institute publication, and analysis of source titles, author keywords, and keywords plus.

Keywords were defined as comma-separated items of one or more words. All keywords (1992−2007), both those reported by authors and those attributed by ISI, as well as the words in the title were identified and separated into 4 four-year periods, then their ranks and frequencies were calculated. Different words with identical meaning and misspelled keywords were grouped and considered as a single keyword. An innovative method, combination of the words in the title, author keywords, and keywords plus was used in this analysis.

## RESULTS AND DISCUSSION

### Characteristics of Publication Outputs

In the total 38 295 publications (36 869 with author addresses), the article was the most frequently used document type with 96 % of total publications, followed by reviews (717; 1.9 %), and editorial materials (237; 0.62 %). As journal articles represented the majority of peer-reviewed document types within this field, only the 36 912 original articles were used for further analysis in this study.

During the last 16 years, the average number of references cited grew gradually, from 26 in 1992 to 37 in 2007 (Table 1), showing that researchers referred to more articles and relied more on the work of others. Another possible reason was that communication technologies and the ISI database made it easier for researchers to find relevant results. The average length of an article fluctuated slightly, the average being 14 pages. The average number of authors per article rose from 2.4 in 1992 to 4.0 in 2007. The author number per publication differed little among countries, varying between 2.3 (Australia and Norway) and 3.8 (Spain). Thirty-two pertinent articles were published per journal in 1992, compared to 78 in 2007, with the numbers varying through the years.

A publication model was used to evaluate research performance. The relationship between the cumulative number of articles published each year ($P$) and the number of consecutive years ($Y$) was expressed as:

$$P = AY^B$$

where $A$ is the growth potential, $B$ is the publication rate. The progression in the number of articles from 1992 to 2007 is illustrated in Figure 1. We simulated the growth pattern by an exponential regression, and the plots of the data revealed coefficients of determination as high as $r^2$ = 0.9996. The relationship between the cumulative number of articles published each year ($P$) and the number of consecutive years ($Y$) studied from

**Table 1.** Characteristics of outputs by year of publication during 1992–2007

| Year | TP | NR | NR/P | PG | PG/P | AU | AU/P | J | P/J |
|---|---|---|---|---|---|---|---|---|---|
| 1992 | 834 | 21 891 | 26 | 13 814 | 17 | 1,989 | 2.4 | 26 | 32 |
| 1993 | 1 204 | 32 569 | 27 | 18 694 | 16 | 3,001 | 2.5 | 29 | 42 |
| 1994 | 1 336 | 35 998 | 27 | 21 715 | 16 | 3 567 | 2.7 | 36 | 37 |
| 1995 | 1 976 | 55 510 | 28 | 27 759 | 14 | 5 568 | 2.8 | 62 | 32 |
| 1996 | 1 618 | 51 369 | 32 | 25 826 | 16 | 4 546 | 2.8 | 34 | 48 |
| 1997 | 2 012 | 60 384 | 30 | 28 826 | 14 | 5 938 | 3.0 | 56 | 36 |
| 1998 | 1 904 | 59 092 | 31 | 28 624 | 15 | 5 594 | 2.9 | 53 | 36 |
| 1999 | 2 151 | 66 680 | 31 | 32 216 | 15 | 6 680 | 3.1 | 59 | 36 |
| 2000 | 2 276 | 73 684 | 32 | 34 930 | 15 | 7 613 | 3.3 | 52 | 44 |
| 2001 | 2 477 | 77 643 | 31 | 35 325 | 14 | 8 284 | 3.3 | 62 | 40 |
| 2002 | 2 526 | 81 569 | 32 | 35 736 | 14 | 8 729 | 3.5 | 63 | 40 |
| 2003 | 2 803 | 91 919 | 33 | 39 868 | 14 | 9 860 | 3.5 | 65 | 43 |
| 2004 | 3 141 | 102 700 | 33 | 43 688 | 14 | 11 549 | 3.7 | 68 | 46 |
| 2005 | 3 314 | 111 094 | 34 | 47 452 | 14 | 12 805 | 3.9 | 69 | 48 |
| 2006 | 3 593 | 128 669 | 36 | 52 608 | 15 | 14 717 | 4.1 | 63 | 57 |
| 2007 | 3 747 | 137 467 | 37 | 53 589 | 14 | 14 986 | 4.0 | 48 | 78 |

TP: total number of publications; NR: cited reference counts; PG: page counts; AU, and J: number of authors, and journals; NR/P, PG/P, and AU/P: references, pages, and authors per publication; P/J: papers per journal.

1992 to 2007 was: $P = 816Y^{1.34}$ until 2002, and $P = 437Y^{1.60}$ for 2002−2007. $B_1$ = 1.24, $B_2$ = 1.60, and the relationship that $B_2 > B_1$ meant that the growth rate of the publication number during 2002−2007 was faster than that during 1992−2002.

However, some articles on atmospheric simulation might have been published in journals in the subject categories of environmental sciences and multidisciplinary geosciences. Thus the absolute article numbers shown here did not reflect the true situation in terms of all atmospheric simulation articles, but estimates of the characteristics and trends in these papers were probably not far from the real situation.

## Analysis of Source Titles, Author Keywords and Keywords Plus

*Source titles*

Rodríguez and Moreiro[43] primarily assessed the growth and development of research by dissertation title analysis. They used the length and key words per title to compare the complexity of titles between countries. Moreover, analysis of word distribution in the title was used to evaluate research trends.[40] The title of an article always includes the information that the author would most like to express to the readers. In our study, all words in the titles of atmospheric simulation-related articles were statistically analyzed. Some prepositions such as "of", "in", and "on" were discarded, as they were meaningless for further analysis. As a result, the 25 most frequently used substantives in titles were grouped in 4 four-year periods (Table 2). Besides the search keys "model*" and "simulat*", "climate", "data", "surface" and "variability" had the highest frequencies, which indicated that "climate" change, land/sea/air "surfaces", and pollutants on earth "surface" as well as their "variability", were the mainstream issues.[44,45] Meanwhile, meteorological and atmospheric simulations call for quantities of "data" to validate the results of models, to be interpolated into models as initial conditions, and to raise simulation accuracy.[46] Moreover,

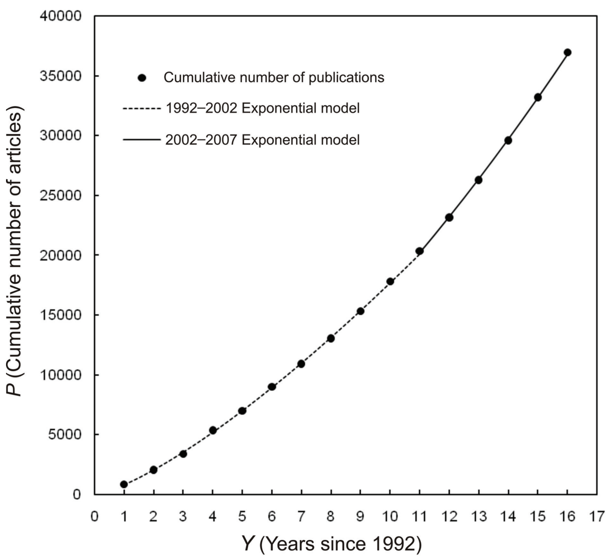


**Figure 1.** Cumulative number of publications by year during 1992−2007.

**Table 2.** Top 25 most frequent substantives in source titles during 1992−2007 and 4 four-year periods

| Words in Title | TP | 92−07 R (%) | 92−95 R (%) | 96−99 R (%) | 00−03 R (%) | 04−07 R (%) |
|---|---|---|---|---|---|---|
| model | 5 883 | 1 (16) | 1 (17) | 1 (17) | 1 (16) | 1 (15) |
| climate | 2 812 | 2 (7.6) | 4 (4.9) | 2 (7.6) | 2 (7.8) | 2 (8.6) |
| model*ing | 2 366 | 3 (6.4) | 2 (5.6) | 5 (5.6) | 3 (6.6) | 3 (7.0) |
| atmospheric | 2 184 | 4 (5.9) | 2 (5.6) | 3 (6.4) | 4 (6.0) | 5 (5.7) |
| data | 1 996 | 5 (5.4) | 5 (4.6) | 6 (5.5) | 6 (5.2) | 4 (5.8) |
| surface | 1 879 | 6 (5.1) | 12 (3.2) | 4 (6.0) | 5 (5.6) | 6 (4.9) |
| models | 1 593 | 7 (4.3) | 7 (4.0) | 7 (5.0) | 8 (4.4) | 10 (4.0) |
| simulation | 1 526 | 8 (4.1) | 11 (3.3) | 8 (4.2) | 9 (4.4) | 8 (4.3) |
| analysis | 1 473 | 9 (4.0) | 10 (3.4) | 10 (4.0) | 12 (3.8) | 7 (4.3) |
| variability | 1 417 | 10 (3.8) | 16 (2.8) | 12 (3.8) | 10 (4.1) | 9 (4.1) |
| global | 1 402 | 11 (3.8) | 6 (4.2) | 9 (4.2) | 17 (3.3) | 13 (3.8) |
| tropical | 1 389 | 12 (3.8) | 9 (3.6) | 14 (3.7) | 12 (3.8) | 12 (3.8) |
| observations | 1 305 | 13 (3.5) | 15 (2.9) | 22 (3.0) | 11 (3.9) | 11 (3.8) |
| effects | 1 289 | 14 (3.5) | 8 (3.7) | 15 (3.6) | 14 (3.5) | 17 (3.3) |
| numerical | 1 264 | 15 (3.4) | 14 (3.1) | 11 (3.9) | 16 (3.4) | 19 (3.3) |
| ocean | 1 162 | 16 (3.1) | 29 (2.3) | 18 (3.2) | 18 (3.2) | 16 (3.4) |
| temperature | 1 159 | 17 (3.1) | 18 (2.7) | 17 (3.3) | 20 (3.2) | 20 (3.2) |
| measurements | 1 158 | 18 (3.1) | 21 (2.6) | 20 (3.0) | 15 (3.5) | 21 (3.2) |
| precipitation | 1 120 | 19 (3.0) | 32 (2.1) | 29 (2.6) | 21 (3.1) | 14 (3.6) |
| simulations | 1 119 | 20 (3.0) | 22 (2.6) | 24 (2.8) | 23 (3.0) | 18 (3.3) |
| comparison | 1 102 | 21 (3.0) | 13 (3.1) | 25 (2.8) | 22 (3.1) | 24 (3.0) |
| cloud | 1 096 | 22 (3.0) | 17 (2.8) | 16 (3.5) | 26 (2.9) | 29 (2.8) |
| impact | 1 045 | 23 (2.8) | 40 (1.9) | 33 (2.3) | 28 (2.8) | 15 (3.5) |
| circulation | 1 037 | 24 (2.8) | 37 (1.9) | 13 (3.7) | 24 (3.0) | 36 (2.5) |
| water | 1 026 | 25 (2.8) | 68 (1.3) | 26 (2.7) | 19 (3.2) | 22 (3.1) |

TP: total number of publications; R (%): rank and percentage of words in the titles in total publications. The word "model*ing" represented "modeling" and "modelling".

three adjectives "global", "tropical", and "numerical" all had stably high ranks, #11, #12, and #15. It was inferred that atmospheric simulation mainly focuses on "global" variation and interaction,[47,48] "tropical" meteorology, and "numerical" methods.[49] Some nouns such as "air", "sea", "layer", "aerosol", "ozone", and "boundary" had a higher growth rate than any others, and were more frequently used in recent times. The rank and percentage of articles related to atmospheric simulation research with "aerosol" in the title went up from #108 (1.0 %) in 1992−1995 to #23 (3.1 %) in 2004−2007, in accord with the attention given to aerosol simulation in the past decade because of its potential impact on global and regional climate change[8,50] and negative effects on human health.[51] Understanding these effects requires detailed information on how aerosol particles enter the atmosphere and how they are transported there before being removed by dry or wet deposition.[14] Several models simulate aerosol distribution and transportation,[29] such as the Models-3 Community Multiscale Air Quality modeling system (Models-3 CMAQ)[52] and general circulation models.[53] Meanwhile, the rank and percentage of articles with "layer" and "boundary" in the title went up from #251 (0.54 %) and #587 (0.24 %) to #33 (2.7 %) and #37 (2.5 %). Since the boundary layer is important, but knowledge of it was very limited, more and more research projects focused on its vertical profile and variations.[54,55]

On the other hand, the ranks of words such as "boundary-layer", "interaction", and "large-scale" markedly descended from #230, #155, and #167, to #702, #255, and #263. Two possible explanations for these decreases are (a) some were general words which were replaced by more specific or definite single words in the titles of articles ("boundary-layer" belongs to this case, and was replaced by "boundary" and "layer", separately), and (b) some title words were gradually disregarded, or fell out of the mainstream of atmospheric

**Table 3.** Top 25 most frequent author keywords used during 1992−2007 and 4 four-year periods

| Author Keywords | TP | 92−07 R (%) | 92−95 R (%) | 96−99 R (%) | 00−03 R (%) | 04−07 R (%) |
|---|---|---|---|---|---|---|
| ionosphere | 413 | 1 (3.0) | N/A | N/A | 3 (2.5) | 1 (4.6) |
| climate change | 355 | 2 (2.6) | 1 (4.8) | 1 (3.9) | 1 (2.7) | 4 (1.9) |
| model*ing | 352 | 3 (2.6) | 3 (3.8) | 3 (3.0) | 2 (2.6) | 3 (2.3) |
| ozone | 312 | 4 (2.3) | 2 (4.7) | 2 (3.5) | 4 (2.2) | 5 (1.7) |
| magnetospheric physics | 292 | 5 (2.1) | N/A | N/A | 6 (1.8) | 2 (3.2) |
| precipitation | 219 | 6 (1.6) | 16 (1.3) | 4 (2.2) | 5 (1.9) | 10 (1.2) |
| turbulence | 200 | 7 (1.5) | 16 (1.3) | 5 (2.1) | 10 (1.1) | 7 (1.5) |
| remote sensing | 162 | 8 (1.2) | 42 (0.83) | 27 (0.81) | 8 (1.4) | 10 (1.2) |
| air pollution | 159 | 9 (1.2) | 4 (2.7) | 8 (1.3) | 9 (1.3) | 14 (0.94) |
| temperature | 155 | 10 (1.1) | 67 (0.67) | 7 (1.3) | 7 (1.4) | 13 (1.0) |
| space plasma physics | 143 | 11 (1.0) | N/A | N/A | 14 (0.87) | 6 (1.6) |
| data assimilation | 136 | 12 (1.0) | N/A | 21 (0.86) | 19 (0.77) | 9 (1.3) |
| aerosol | 124 | 13 (0.91) | 24 (1.2) | 27 (0.81) | 12 (1.0) | 18 (0.88) |
| model | 122 | 14 (0.89) | 7 (2.2) | 9 (1.2) | 11 (1.0) | 31 (0.61) |
| particulate matter | 121 | 15 (0.88) | 87 (0.50) | 75 (0.50) | 13 (0.89) | 12 (1.0) |
| numerical simulation | 110 | 16 (0.80) | 16 (1.3) | 21 (0.86) | 17 (0.79) | 23 (0.75) |
| large-eddy simulation | 110 | 16 (0.80) | 162 (0.33) | 14 (1.0) | 17 (0.79) | 21 (0.79) |
| meteorology and atmospheric dynamics | 108 | 18 (0.79) | N/A | N/A | 55 (0.47) | 8 (1.3) |
| air quality | 106 | 19 (0.77) | 67 (0.67) | 45 (0.63) | 26 (0.62) | 15 (0.92) |
| dry deposition | 101 | 20 (0.74) | 6 (2.5) | 6 (1.4) | 38 (0.55) | 51 (0.50) |
| climate | 97 | 21 (0.71) | 42 (0.83) | 27 (0.81) | 21 (0.67) | 27 (0.69) |
| deposition | 97 | 21 (0.71) | 9 (2.0) | 14 (1.0) | 14 (0.87) | 72 (0.41) |
| convection | 93 | 23 (0.68) | 162 (0.33) | 11 (1.1) | 23 (0.65) | 36 (0.58) |
| aerosols | 91 | 24 (0.66) | 33 (1.0) | 39 (0.72) | 38 (0.55) | 27 (0.69) |
| model evaluation | 89 | 25 (0.65) | 16 (1.3) | 33 (0.77) | 33 (0.57) | 33 (0.60) |

TP: total number of publications; R (%): rank and percentage of author keywords in total publications. The word "model*ing" represented "modeling" and "modelling".

simulation research ("interaction" is a case in point).

*Author keywords*

Author keywords analysis offers information about research trends that concern researchers. Bibliometric methods concerning author keywords analysis are only found in recent years,[56] and using them to analyze research trends is rare.[29,31] Examination of author keywords in this study revealed that altogether 28 122 were used, among which, 21 075 (75 %) appeared only once, and 3 123 (11 %) appeared twice. The large number of once-only author keywords probably indicates a lack of continuity in research and a wide disparity in research foci.[57] Furthermore, these keywords might not be standard or widely accepted by researchers.[38] The lack of standardization among keywords assigned by authors greatly hampered our analysis since the use of synonymous terms, spelling variations, abbreviations, and more or less specific terms made the exact interpretation of the author's intended meaning difficult.

Author keywords that appeared in articles referring to atmospheric modeling from 1992 to 2007 were counted and ranked in 4 four-year periods. Keywords that appeared altogether more than 90 times during the last 16 years are listed in Table 3. Other than "model*" and "simulat*", the search keywords in this study, the top three most frequently used keywords were "ionosphere", "climate change", and "ozone", which indicate hot spots in atmospheric simulation research worldwide.[19,45] On the contrary, a decline in the ranking of the keywords "dispersion", "dry deposition", "wet deposition", "acid deposition", "dispersion", and "atmospheric dispersion" is evident.

Unlike segmenting a whole title into single words as in source title analysis, in this section, precise words that the authors wanted to transmit to the readers were preserved. Synonymous single words or phrases there-

**Table 4.** Top 25 most frequent keywords plus used during 1992-2007 and 4 four-year periods

| Keywords Plus | TP | 92−07 R (%) | 92−95 R (%) | 96−99 R (%) | 00−03 R (%) | 04−07 R (%) |
|---|---|---|---|---|---|---|
| Model | 6 502 | 1 (19) | 1 (19) | 1 (20) | 1 (20) | 1 (19) |
| Variability | 2 117 | 2 (6.3) | 13 (3.1) | 5 (5.4) | 2 (6.9) | 2 (7.5) |
| Simulation | 1 813 | 3 (5.4) | 3 (5.2) | 3 (5.6) | 4 (5.2) | 3 (5.5) |
| General-circulation model | 1 654 | 4 (4.9) | 2 (5.4) | 2 (5.7) | 3 (5.3) | 10 (4.1) |
| Precipitation | 1 605 | 5 (4.8) | 10 (3.6) | 9 (4.6) | 5 (5.1) | 4 (5.1) |
| Parameterization | 1 584 | 6 (4.7) | 4 (5.0) | 4 (5.5) | 7 (4.6) | 6 (4.3) |
| Temperature | 1 519 | 7 (4.5) | 12 (3.5) | 6 (5.3) | 6 (4.8) | 8 (4.3) |
| Climate | 1 506 | 8 (4.5) | 7 (4.5) | 7 (4.9) | 9 (4.4) | 7 (4.3) |
| Atmosphere | 1 471 | 9 (4.4) | 6 (4.9) | 8 (4.7) | 10 (4.2) | 9 (4.2) |
| Sensitivity | 1 468 | 10 (4.4) | 9 (3.8) | 10 (4.5) | 8 (4.5) | 5 (4.4) |
| Circulation | 1 322 | 11 (3.9) | 8 (4.2) | 11 (4.1) | 11 (3.9) | 12 (3.8) |
| Dynamics | 1 279 | 12 (3.8) | 5 (4.9) | 12 (3.6) | 12 (3.8) | 14 (3.5) |
| Models | 1 046 | 13 (3.1) | 14 (3.1) | 13 (3.2) | 14 (3.2) | 18 (3.1) |
| Boundary-layer | 1 025 | 14 (3.1) | 20 (2.5) | 17 (3.0) | 13 (3.3) | 16 (3.2) |
| Flow | 1 001 | 15 (3.0) | 11 (3.5) | 15 (3.1) | 22 (2.8) | 21 (2.9) |
| Simulations | 996 | 16 (3.0) | 31 (2.0) | 24 (2.2) | 18 (2.9) | 11 (3.8) |
| System | 985 | 17 (2.9) | 36 (1.7) | 22 (2.4) | 16 (3.0) | 13 (3.6) |
| Sea-surface temperature | 974 | 18 (2.9) | 28 (2.0) | 14 (3.2) | 15 (3.1) | 20 (2.9) |
| Transport | 969 | 19 (2.9) | 21 (2.3) | 20 (2.6) | 17 (3.0) | 15 (3.2) |
| Prediction | 959 | 20 (2.9) | 24 (2.2) | 18 (2.9) | 18 (2.9) | 19 (3.1) |
| Ocean | 920 | 21 (2.7) | 18 (2.6) | 19 (2.8) | 20 (2.9) | 23 (2.7) |
| El-nino | 910 | 22 (2.7) | 17 (2.7) | 16 (3.0) | 21 (2.9) | 25 (2.5) |
| United-States | 846 | 23 (2.5) | 46 (1.4) | 32 (1.8) | 23 (2.7) | 17 (3.1) |
| Evolution | 838 | 24 (2.5) | 16 (2.8) | 20 (2.6) | 24 (2.6) | 28 (2.3) |
| Turbulence | 707 | 25 (2.1) | 28 (2.0) | 26 (2.1) | 27 (2.1) | 29 (2.2) |

TP: total number of publications; R (%): rank and percentage of keywords plus in total publications.

fore could be seen in different author keywords. For instance, of among the 36 912 atmospheric simulation-related articles in the last 16 years, more than 441 (3.2 %) were related to "particle", comprising "particulate matter" (121), "$PM_{2.5}$" (short for particulate matter 2.5; 89), "$PM_{10}$" (short for particulate matter 10; 68), "pm" (short for particulate matter; 7), "organic particulate matter" (5), "particulates" (5), "suspended particulate matter" (5), and another 110 different author keywords with the single word "particulate". Hence our data are only an approximate reflection of scientific attention. The rank and percentage of "remote sensing" rose from #42 (0.83 %) in 1992−1995 to #9 (1.2 %) in 2004−2007, which indicated the greater importance of remote sensing technology and research results in recent years. Indeed, space and the atmosphere are too expansive to do in-situ measurements everywhere, while satellite remote-sensing provides more complete spatial coverage and a vertically integrated measure of atmospheric components.[58]

*Keywords plus*

Keywords plus provides search terms extracted from the titles of papers cited in each new article in the ISI database.[42] The distribution of keywords plus with their ranks and percentages in different periods is listed in Table 4. As in the author keywords ranking, some words, such as "precipitation", "temperature", "climate", and "turbulence" were also emphasized in keywords plus. Among those keywords plus listed, "variability" has ranked number one for the last 16 years. Keywords plus as an additional search term, is usually more concerned about novel research directions than the mature direction in the field.[42] According to the bibliometric analysis by Xie *et al.*,[29] "model" ranked fourth in the keywords plus frequency list of world aerosol research, indicating that atmospheric modeling has become a promising research method for aerosols and may develop further in the near future. Through the keywords plus analysis (Table 4), it can be concluded that additional spikes of attention were given to “circulation”, “dynamics”, “flow”, “precipitation”, “transport”, and “prediction” in our study period. As air pollution becomes more serious and climate change develops, regional transport and the global cycle of pollutants among cities, countries and even continents attracted special attention. Prediction of meteorological parameters and variations in pollutants has become even more important for policy makers to take effective measures in time.[18,59]

**Analysis of Research Trends**

In order to overcome the weak points of the three separate types of keywords analysis, the words in the title, author keywords, and keywords plus were combined, then synonymic single words and congeneric phrases were summed and grouped into categories, so as to analyze the historical development of the science and programs more completely and precisely, and more importantly, to discover the directions the science is taking.

Research trends in atmospheric simulations were separated into three categories - simulated items, types of variation and research methods. The words listed in Figures 2−4 all include their plural forms, abbreviations, and other transformations, as well as words with similar meanings.

Referring to the items that atmospheric simulation research focused on, “ozone” had a distinctly higher incidence, being mentioned in 36 798 publications at a rate of about 200 articles per year. Since photochemical smog first appeared in Los Angeles, many megacities in Asia, Europe, and other parts of North America also

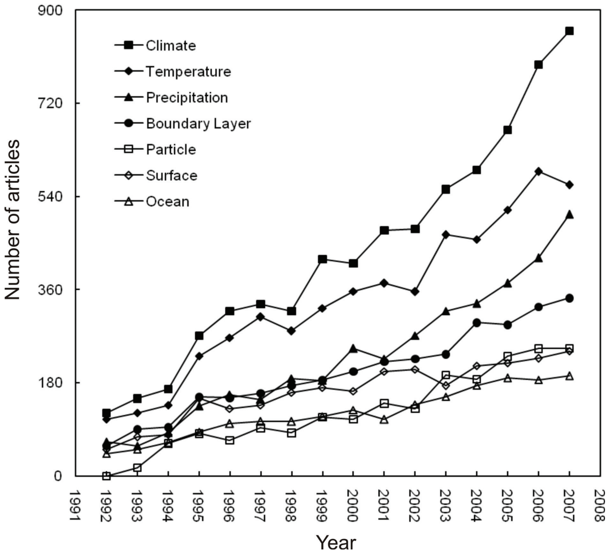

**Figure 2.** Comparison of the trends of simulated items, including “climate”, “temperature”, “precipitation”, “boundary layer”, “particle”, “surface” and “ocean” during 1992−2007.

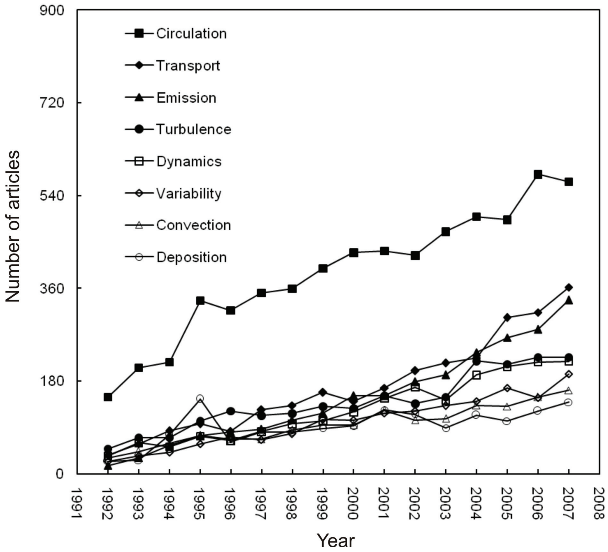

**Figure 3.** Comparison of the trends of types of variation including “circulation”, “transport”, “emission”, “turbulence”, “dynamics”, “variability”, “convection” and “deposition” during 1992-2007.

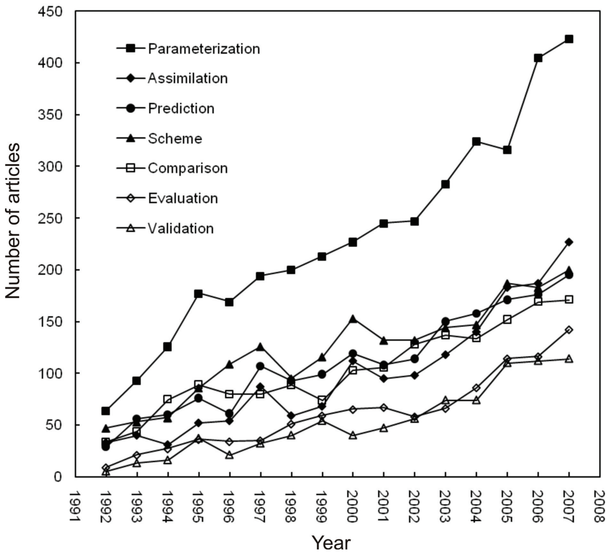

**Figure 4.** Comparison of the trends of research methods including “parameterization”, “assimilation”, “prediction”, “scheme”, “comparison”, “evaluation” and “validation” during 1992-2007.

faced the same problems due to rapid urbanization and too many vehicles. Although great progress has been made in the simulation of ozone, including the level of process descriptions and computational implementation, it still lacks thorough evaluation and comparison. Model advances were seen in the use of new tools for extending the interpretation of their results, systems to facilitate their use, and extension of their capabilities.[19] Therefore, ozone-related simulation remained vigorous all the way through 1992−2007, and is predicted to remain a top research emphasis in the near future.

Topics including "climate" and "precipitation" grew rapidly until 2007 (Figure 2), which could be partly interpreted as due to Climate Change 2007.[8] Starting with 66 in 1992, the number of articles related to "particle" grew markedly and surpassed "surface" and "ocean" in 2005, because of particulate influence on climate[50] and health.[51] In the past 16 years, with the fast development of measurement technology, "$PM_{2.5}$" and "$PM_{10}$" rose high in the rankings. Besides, "$PM_1$" first appeared as a source author keyword in 2005,[60] due to a great deal of progress made in aerosol sampling and monitoring techniques,[61] and their composition and characterization.[62,63] Particle size distribution has been extensively studied, shifting from total suspended particulate (TSP)[64] to inhalable particles ($PM_{10}$),[65] $PM_{2.5}$,[66] and even ultrafine particles ($PM_1$).[67]

It is evident that "circulation" of items in the atmosphere was investigated most, whereas articles related to "deposition" in the atmosphere peaked in 1995, and then changed little until 2007 (Figure 3). The decrease of "deposition" might be attributed to the fact that the mechanism of acid deposition was already quite clear, and it had been controlled well;[19] whereas, urbanization and overuse of motor vehicles resulted in serious pollution by ozone and particulate matter,[22,66] which attracted attention and research has rocketed in the 21st century.[19] Moreover, "transport" and "emission" followed "circulation" in attracting increasing attention after 2002[32,68]. Other types of variation, such as "turbulence" and "convection" changed little between 1992 and 2007.

"Parameterization" was the most popular research method in atmospheric simulations from 1992 to 2007 (Figure 4). Improvements in parameterization ensure more reasonable atmospheric parameters for precise meteorological simulation as well as air quality modeling, such as cloud properties,[69] boundary layer structures,[70] and diurnal cycles of surface winds and temperatures,[71,72]. Meanwhile, publications related to "assimilation" increased with years and ranked second in 2007, which indicates that this is close to "parameterization" as a mainstream research method.[73] "Comparison", "evaluation" and "validation" were also important methods in atmospheric simulation research,[28,45] whose numbers of articles increased steadily.

The four most cited papers were further analyzed. The two papers by Mellor and Yamada[54] (1 063 citations until 2007) and Louis[55] (1 016 citations until 2007) had rather long article lives, and the boundary layer-related models they developed as well as their results on boundary layer structures still have a profound impact today. This also demonstrated that boundary layer research is a hot spot. The other two articles, by Kalnay *et al.*[44] (5 452 citations until 2007) and Kistler *et al.*[46] (912 citations until 2007) had the same corresponding author (Kalnay), but at different institutes (NCAR and University of Maryland). Both papers introduced the NCEP/NCAR reanalysis project, which involved the recovery of land surface, ship, rawinsonde, pibal, aircraft, satellite, and other data. These data were then quality controlled and assimilated with a system kept unchanged over the reanalysis period. They had large numbers of citations, especially the first paper[44] with a peak of about 800 citations per year. The citations of all these four articles are still rising, which indicates continuing research in the atmospheric simulation area.

**Distribution of Output in Journals, Countries and Institutes**

Articles were published in 51 searched journals in the subject category of meteorology and atmospheric sciences. The book series - Advances in Space Research - had about 244 source journals, which led to a bias in journal-related analysis. Seven journals had more than 1 000 articles referring to atmospheric simulation from 1992 to 2007. Approximately 40 % of all articles were from these 7 core journals, whereas the remainder was from another 44 journals. As the flagship journal of this particular research field, *Atmospheric Environment* (*AE*) published the most articles (3 217; 8.7 %), while *Journal of the Atmospheric Sciences* (*JAS*) ranked second with 2 922 (7.9 %). Close on *JAS*'s heels was *Journal of Climate* (*JC*) with 2 762 (7.5 %). A new, international and interactive journal - *Atmospheric Chemistry and Physics* (*ACP*) of the European Geosciences Union (EGU) - deserves special attention. It is published by the Copernicus Society and was just launched in 2001 (www.atmos-chem-phys.net), yet it multiplied at the rate of 40 publications per year. According to JCR (2007), the IF of *ACP* reached 4.865, which was higher than all the other four mainstream journals: *AE* (2.549), *JAS* (2.755), *JC* (3.55) and *Monthly Weather Review* (2.267). It was also the highest of all journals in the category of meteorology and atmospheric sciences and one of the highest across the fields of environmental and geosciences.

The contribution of different countries/territories was estimated by the location of the affiliation of at least one author. Of all articles with author addresses, 27 814 (75 %) were single country publications and 9 055 (25 %) were internationally collaborative. The USA showed the greatest counts (47 %), followed distantly by other countries. "BRIC" countries - Brazil, Russia, India, and China have the fastest growing economies in the world, and it was predicted that in less than forty years, the BRIC economies collectively will be larger than the G6 (the USA, Japan, the UK, Germany, France and Italy).[74] Publications from China and Russia grew sharply, while those of Brazil and India increased slowly during 1992−2007, which might be evidence of the remarkable differences in their development of technologies. In 1997, when the National Basic Research Program (also called the 973 Program) was approved by the Chinese government (www.973.gov.cn), publications from China started growing. After 2005, publications for China had a higher growth rate than others, and quickly became the fourth most productive country. This might also have resulted from the positive influence of high environmental requirements for important activities, such as the Beijing 2008 Olympic Games, the Shanghai 2010 World Expo, and the Guangzhou 2010 Asian Games. There is no doubt that a series of positive policies motivated the rapid development of atmospheric simulation research in China.[75,76] Croatia too shows development of such research recently.[77,78]

The contributions of different institutes were estimated by the affiliation of at least one author. Of the 36 869 articles with author addresses, 17 421 (47%) were independent publications and 19 448 (53%) were collaborations by two or more institutes. Among the top 20 institutes, 15 (75 %) were in the USA. Leading were NASA (National Aeronautics and Space Administration; 1 638), NOAA (National Oceanic and Atmospheric Administration; 1 624), and NCAR (National Center for Atmospheric Research; 1 555) in the USA, which had a large disparity with the others, and whose publication numbers were about twofold that of University of Colorado (USA; 800; #4). Most popular meteorological, emission and air quality models were derived from these institutes, such as MM5[79] (the fifth generation Penn State/NCAR mesoscale model), WRF[80] (Weather Research and Forecast model), MRF[81] (Medium-Range Forecast), Models-3 CMAQ,[82] RAMS[83] (Regional Atmospheric Modeling System), and ARPS[15] (Advanced Regional Prediction System). However, a bias appeared because both the Chinese Academy of Sciences (CAS) and the Russian Academy of Sciences (RAS) have over 100 branches in different cities. At present, the publications of these two institutes were pooled as one heading, and publications divided into branches would result in different rankings. For instance, one branch of the CAS, Institute of Atmospheric Physics, contributed 550 articles (89 %) to its total publications. Whereas, different from the pattern in China, the A.M. Obukhov Institute of Atmospheric Physics published only 223 articles (35 %) for the RAS, with the Institute for Numerical Mathematics contributing 14 % of its total publications. This kind of identity raised these two institutes' ranks in global atmospheric simulation research, especially the RAS. The ratio of collaborations to total publications in institutes was greater than 55 %, indicating that atmospheric simulation research calls for teamwork among institutes. In order to compare the research performance of institutes by country, publication per institute (PPI) in a country was used as an indicator. The PPI of a country is the ratio of total publications to the number of related institutes. It should be noted that, for one article, the sensitivity of the PPI mainly depended on the number of institutes. If the number of institutes was not large enough, the uncertainty resulting from the number of institutes affected PPI considerably. In order to reduce the possible error, countries with at least 50 related institutes were selected, so the effect of one article on PPI was less than 2 %. In atmospheric simulation research, the UK ranked first with a PPI of 8.6, followed by the USA, Sweden, Canada, and Australia, similar to the situation in contingent valuation research.[39] A bias was introduced by both the CAS and the RAS having more than 100 institutes. The limitation of this system would reduce the number of institutes greatly and thus raised their PPIs.

## CONCLUSION

In this study on atmospheric simulation publications listed in SCI, significant points on worldwide research performance from 1992 to 2007 were obtained. A total of 51 journals were listed in the subject category of meteorology and atmospheric science. The highest number of articles was in *Atmospheric Environment*, and the numbers in *Atmospheric Chemistry and Physics* grew rapidly, with the highest IF in 2007. China had the most rapid growth since 2005, which might be a result of positive policies. NASA, NOAA, and NCAR in the USA were the flagships in this field, distinctly followed by other institutes. Analysis of the four most cited articles revealed that the boundary layer continued to be an important research topic during these 16 years.

By synthetically and innovatively analyzing the distribution and changes of words in the title, author keywords, keywords plus and the most cited articles, the development of research on atmospheric simulation during last decade were described, and the future orientation of atmospheric simulation research were also predicted. It can be concluded that atmospheric simulation research related to "ozone", "climate", "circulation", "transport", "parameterization", and "assimilation" are major directions of atmospheric simulation research in the 21st century. Analysis by this new bibliometric method can help researchers realize the panorama of global atmospheric simulation research, and establish further research directions.

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# SAŽETAK

## Bibliometrijska analiza trendova atmosferske simulacije u znanstvenim časopisima područja meteorologija i atmsferske znanosti

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Razmatrana je globalna znanstvena produkcija u područjima "meteorologija i atmosferske znanosti" kroz proteklih 16 godina kako bi se utvrdile karakteristike istraživanja simulacije atmosfere te opći smjerovi i metode u znanstvenim radovima iz vodećih zemalja i instituta. Podaci se temelje na mrežnoj verziji Scienece Citation Index-a i Web of Science za 1992. do 2007. godinu. Osim što je ukupni broj radova iz tog područja eksponencijalno rastao ($r^2$ = 0,9996) dana je i njihova distribucija po zemljama, institutima i naslovima, autorskim ključnim i ključnim riječima. Navedena su po četiri najcitiranija rada u tim godinama. Statističkom analizom ključnih riječi zaključeno je da su istraživanja atmosferskom simulacijom koja se odnose na riječi "ozon", "klima", "cirkulacija", "transport", "parametrizacija" i "asimilacija" u središtu zanimanja u 21. stoljeću.