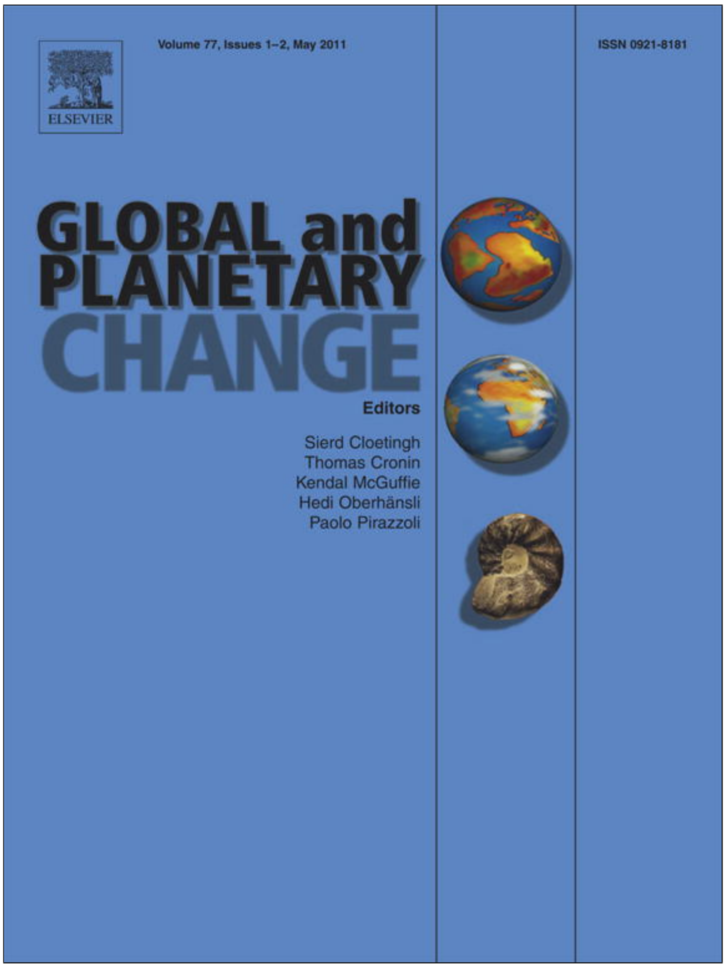
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Trends in research on global climate change: A Science Citation Index Expanded-based analysis

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This study was conceived to evaluate the global scientific output of climate change research over the past 18 years and to assess the characteristics of the research patterns, tendencies, and methods in the papers. Data were based on the online version of Science Citation Index Expanded from 1992 to 2009. Articles referring to climate change were assessed by distribution of source countries, source institutes, paper titles, author keywords, KeyWords Plus, abstracts, and the most cited articles in these years. By synthetic analysis of the four kinds of keywords, it was concluded that the items "temperature", "environment", "precipitation", "greenhouse gas", "risk", and "biodiversity" will be the foci of climate change research in the 21st century, while "model", "monitoring", and "remote sensing" will continue to be the leading research methods. A novel method, "phylogeography", may have a strong application potential in the near future.

1. Introduction

Climate change refers to an alteration in the state of the climate that can be identified by changes in the mean and/or the variability of its properties that persists for an extended period, typically decades or longer (IPCC, 2007). Climate change reflects abnormal variations in the Earth's atmosphere and subsequent effects on other parts of the planet, such as on crop lands, reducing the annual yield (Challinor et al., 2007), and the melting of polar ice leading to a rise in sea level and flooding of low-lying countries and the plains that provide food (Wassmann et al., 2004). The oceans are growing more acidic because of CO_2 absorption, which makes it harder for animals like corals and clams to build and maintain their shells and skeletons (Hoegh-Guldberg, 1999). Moreover, climate change can result in higher future ozone levels over polluted areas (Nolte et al., 2008). At the end of the nineteenth century, Svante Arrhenius and Arvid Högbom suggested that temperature might be affected by greenhouse gases (Heimann, 2005). In an early study, there were arguments about whether the Indian climate had changed (Lockyer, 1910). Hubert Horace Lamb (1913–1997) was among the first to alert the scientific community to the natural vagaries of climate over recent centuries and millennia, and to point to their possible effects on human societies (Kelly, 1997). The first and now iconic examples documenting global climate change were the precise measurements of the concentration of CO_2 in the atmosphere made at the mountain station on Mauna Loa, Hawaii, by Charles David Keeling (1928–2005) (Heimann, 2005). This work prepared the ground for the public and political acceptance of the threat that would, in 1992, result in the United Nations Framework Convention on Climate Change — the international community's initial response to this pressing environmental problem (Kelly, 1997). Climate change has become a major scientific, political, economic, and environmental issue during the last decade (Hoegh-Guldberg, 1999; Walther et al., 2002; Watson, 2003; IPCC, 2007). Scientific articles on climate change have demonstrated a rapid increase in quantity over the past several decades, and a number of papers presenting the latest research achievements have been published in authoritative scientific journals such as *Nature* (Walther et al., 2002; Harte et al., 2004; Thomas et al., 2004) and *Science* (Crowley, 2000; Watson, 2003; Lobell et al., 2008). Global warming, greenhouse gases, and limitations on CO_2 emissions are at the top of the political agenda. With the international environmental treaty – the Kyoto Protocol (Bohringer, 2003) – some countries have committed to reducing their anthropogenic greenhouse gas emissions, namely CO_2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride, by at least 5% below 1990 levels, during the commitment period 2008 to 2012. James Hansen of America's National Aeronautics and Space Administration, the first scientist to warn about global warming more than two decades ago, concluded that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm in order to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted (Hansen et al., 2008).

Despite the high growth rate of publications, there have been few attempts to gather systematic data on the global scientific production of research on climate change, except for a scientometric study by Stanhill (2001). Garfield (1970) indicated that a recent research focus should be reflected in its publication output. A common research tool for this

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analysis is the bibliometric method, which has already been widely applied in many disciplines of science and engineering (Braun et al., 1995; Ho, 2008; Li et al., 2009a). The Science Citations Index Expanded (SCI-EXPANDED), from the Institute of Scientific Information (ISI) Web of Science databases, is the most important and frequently used source for a broad review of scientific accomplishment in all fields (Ugolini et al., 2001; Li et al., 2009b). Conventional bibliometric methods often evaluate research trends by the publication outputs of countries (Braun et al., 1995), research institutes (Xie et al., 2008), journals (Colman et al., 1995), and research fields (Ugolini et al., 1997), as well as by citation analysis (Li and Ho, 2008). 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 paper titles (Li et al., 2009b), author keywords (Ugolini et al., 2001), KeyWords Plus (Qin, 2000), and abstracts (Zhang et al., 2010) have been introduced.

In this study, a traditional bibliometric method, analysis of language, source country, source institute, and the most cited papers was used to describe the latest advances in climate change research. Moreover, an innovative method – word cluster analysis of selected topics in the combination of paper titles, author keywords, KeyWords Plus, and abstracts (Li et al., 2009a; Mao et al., 2010) – was applied to map the global research trends during the period 1992–2009. Findings from these investigations can help researchers to realize the breadth of climate change research and to establish future research directions.

2. Materials and methods

The data were based on the online version of SCI-EXPANDED. According to Journal Citation Reports (JCR), this indexed 7387 major journals with citation references across 174 scientific disciplines in 2009. However, a limitation is that most abstracts before 1991 are not included in SCIE. “Climate change”, “climate changes”, “climatic change”, and “climatic changes” were used as the keyword to search titles, abstracts, and keywords from 1992 to 2009. Articles originating from England, Scotland, Northern Ireland, and Wales were reclassified as being from the United Kingdom (UK). Articles from Hong Kong were not included in China. All articles referring to climate change during the past 18 years were assessed according to: type of publication, characteristics of publication outputs, distribution of outputs in journals, publication outputs of source country, source institute, and analysis of paper titles, author keywords, KeyWords Plus, and abstracts.

The words in titles and abstracts were separated, and then conjunctions and prepositions such as “and”, “of”, “in”, and “on” were discarded, as they were meaningless for further analysis. Keywords were defined as comma-separated items of one or more words. All keywords (1992–2009), both those reported by authors and those attributed by ISI as well as the words in titles and abstracts, were identified and separated into 3 six-year periods, and then their ranks and frequencies were calculated in order to thoroughly and precisely analyze the variations of trends. Different words with identical meaning and misspelled keywords were grouped and considered as a single keyword. A word cluster analysis combination of the words in titles, author keywords, KeyWords Plus, and words in abstracts was used in the analysis (Li et al., 2009a; Mao et al., 2010).

3. Results and discussion

3.1. Characteristics of publication outputs

From this study, 16 document types were found in the total 41457 publications during the 18-year study period. Article was the most-frequently used document type comprising 74% of the total production. Only 30843 original articles were used for further analysis as relevant citable items. Ninety-eight percent of the journal articles were published in English. Twenty other languages also appeared; the most frequent were French (0.62%), German (0.46%), Russian (0.19%), Spanish (0.17%), and Chinese (0.17%). This reflects the limitation of evaluation of climate change research in SCI-EXPANDED, most papers in which are in English.

Climate change research developed rapidly over the last century (Fig. 1), from 1 article in 1907 to 862 articles in 2009 with “climate change”, “climate changes”, “climatic change”, and “climatic changes” as the search keywords in titles only. World academic publications had a notable growth after the 1990s. There are some papers related to climate change published before 1907, but due to the limitation of SCI-EXPANDED and the methods used here, they are not included in our discussions.

Based on the classification of subject categories in JCR 2009, the publication output data of climate change research was distributed into 154 SCI subject categories during 1992–2009. Subject categories containing more than 5000 articles were environmental sciences (7022; 23%), multidisciplinary geosciences (22%), meteorology and atmospheric sciences (18%), and ecology (17%). From 1992 to 2002, environmental sciences, meteorology and atmospheric sciences, and multidisciplinary geosciences held primacy; however since 2002 the number of articles in ecology grew quickly and ranked second in 2009 (Fig. 2). This indicates the recent emphasis on the impact of climate change in ecology (Hoegh-Guldberg, 1999; Walther et al., 2002).

Articles were published in a wide range of 2023 journals. In this particular research field, *Geophysical Research Letters* published the most articles (921; 3.0%), while *Climatic Change* ranked second with 891, *Global Change Biology* ranked third with 788, and *Journal of Climate* ranked fourth with 659. Close on *Journal of Climate*'s heels was *Journal of Geophysical Research-Atmospheres* with 649. The percentage of the top journal was not high, which indicates the breadth of article distribution in climate change research as well as the broad interest in climate change from various research angles. This phenomenon also appears in other research areas, such as *Atmospheric Environment* (8.7%) in atmospheric simulation (Li et al., 2009a), *Journal of Geophysical Research-Atmospheres* (9.5%) in aerosol (Xie et al., 2008), and *Water Research* (19%) in biosorption technology for water treatment (Ho, 2008).

Of the 30606 articles with author addresses, 21425 (70%) were single country articles and 30% were internationally collaborative articles. To a certain extent, the number of research articles reflected

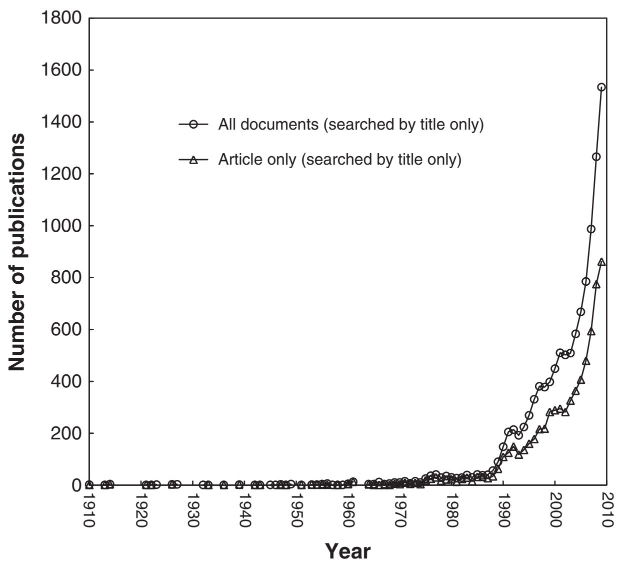

Fig. 1. World SCI-EXPANDED journal publications with climate change, climate changes, climatic change, or climatic changes in titles during 1900–2009.

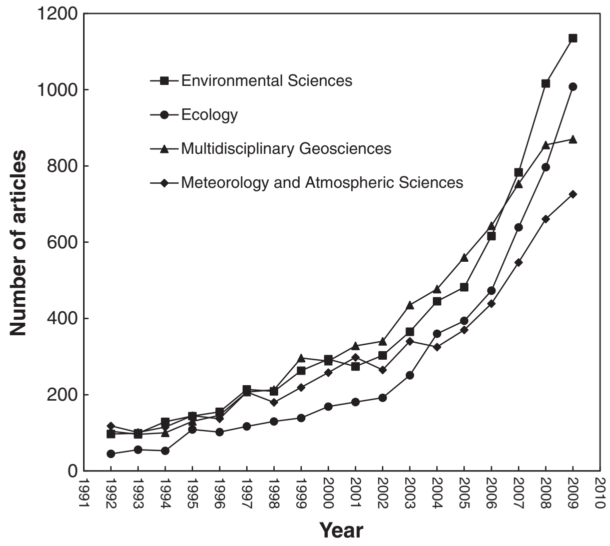

Fig. 2. Comparison the growth trends of the top four productive subject categories.

the activity and academic level of these countries, which were likewise high. The USA showed the highest counts (39%), followed distantly by other countries, as in other research fields, such as the rapid development of stem cell research (Li et al., 2009b). In addition, the USA published the most single-country articles (36%), internationally collaborative articles (47%), first author articles (32%), and corresponding author articles (32%). Among the top 20 most productive countries, India (32%) and the USA (36%) had lower percentages of internationally collaborative articles, while 74% of the articles from Denmark resulted from international collaborations. Among the seven most productive countries besides the USA, the UK maintained an accelerating growth rate, especially after 2003. A comparison of the publication trends of the top seven countries which included at least 1800 articles is shown in Fig. 3. Most of these countries had a sharp increase in articles after 2002. The USA was a signatory to the 1997 Kyoto Protocol, but the Bush administration abandoned the pact after coming to power in 2001. In the same year, the Intergovernmental Panel on Climate Change (IPCC) published

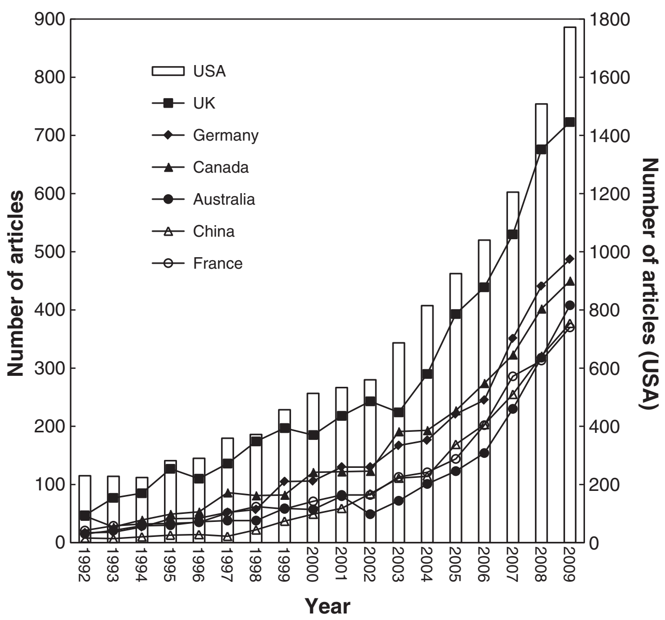

Fig. 3. Comparison of growth trends of the top seven productive countries.

their Third Assessment Report (IPCC, 2001). These two issues attracted extensive research on the causes and effects of climate change, which led to the faster increase of publications after 2002.

In 2000, authors from the UK reported acceleration of global warming due to carbon-cycle feedback (Cox et al., 2000) and represented 20th-century space–time climate variability by the development of monthly grids of terrestrial surface climate and mean monthly terrestrial climatology (New et al., 1999, 2000). At the same time, authors in the USA pointed out that the 21st-century global warming projection far exceeds the natural variability of the past 1000 years and is greater than the best estimate of global temperature change for the last interglacial (Crowley, 2000), and the 20th century warming counters a millennial-scale cooling trend which is consistent with long-term astronomical forcing (Mann et al., 1999). Moreover, China, from 8 to 22 articles during 1992–1998, showed great interest in climate change research, quickly catching up with developed countries in 2009, with 377 articles which ranked among the top 6 in the world. According to China's Policies and Actions for Addressing Climate Change released by the State Council of the People's Republic of China in 2008 (http://www.gov.cn/english/2008–10/29/content_1134544.htm), China invested over 2.5 billion RMB in climate change research during 2001–2005 through various technology development programs, such as the National High-Tech Research and Development Program (863 Program) and the National Basic Research Program (973 Program). Until the end of 2007, the National Science and Technology Pillar Program in the Eleventh Five-Year Plan period (2006–2010) had planned 7.0 billion RMB for emission reduction, energy saving, and climate change research. At the Copenhagen Climate Change Summit in 2009, China clearly put forward the target of cutting CO_2 emissions per unit of GDP by 40–45% by 2020 from the 2005 level. This series of positive policies and funding contributed to the rapid development of climate change research in China.

Of all articles with author addresses, 11711 (38%) were single institute articles and 18895 (62%) were inter-institutionally collaborative articles, again indicating that climate change research calls for teamwork among institutes. The top 20 institutes were ranked according to the total number of articles (Table 1). This included five indicators: total number of articles, single institute articles, inter-institutionally collaborative articles, first author articles, and corresponding author articles (Malarvizhi et al., 2010). The percentage of inter-institutionally collaborative articles among the total articles for each institute (%C) was also considered. Among the top 20 institutes, 13 (65%) were in the USA. Leading was the Chinese Academy of Sciences in China (1066), which had a large disparity with the others, and whose number of articles was more than double that of the University of Colorado in the USA (465). It should be noted that the University of East Anglia in the UK ranked 11th in total articles, but ranked third in single institute articles, 6th in first author articles, and 5th corresponding author articles. The Climatic Research Unit (CRU) at this university provided the world's land-based, gridded (currently using 5° by 5° latitude/longitude boxes) temperature data set in 1978 (Jones et al., 1999; Brohan et al., 2006). Besides, CRU constructed high-resolution (0.5° by 0.5°) monthly datasets (for maximum and minimum temperature, precipitation, rainday counts, vapour pressure, cloudiness and wind speed), for all the world's inhabited land areas (New et al., 1999, 2000). In the USA, the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) provided a 40-year record of global analyses of atmospheric fields that were widely used (Kalnay et al., 1996).

The result of institutes' output should be interpreted in the context of bias. The Chinese Academy of Sciences and the Russian Academy of Sciences have over 100 branches in different cities. At present, the articles of these two institutes are pooled under one heading, and articles divided into branches would result in different rankings (Li et al., 2009a; Malarvizhi et al., 2010).

Table 1
Top 20 most productive institutes based on total number of articles.

Institute	TA	TAR (%)	SAR (%)	CAR (%)	FAR (%)	RAR (%)	% C
Chinese Academy of Sciences, China	1066	1 (3.5)	1 (2.1)	1 (4.3)	1 (2.3)	1 (2.3)	77
University of Colorado, USA	465	2 (1.5)	11 (0.50)	2 (2.1)	8 (0.62)	12 (0.57)	87
US Geological Survey, USA	450	3 (1.5)	5 (0.74)	5 (1.9)	3 (0.68)	3 (0.71)	81
National Center for Atmospheric Research, USA	446	4 (1.5)	7 (0.71)	5 (1.9)	11 (0.59)	4 (0.66)	81
National Aeronautics and Space Administration (NASA), USA	440	5 (1.4)	22 (0.44)	3 (2.1)	10 (0.61)	9 (0.59)	88
Columbia University, USA	435	6 (1.4)	10 (0.53)	4 (2.0)	7 (0.64)	7 (0.60)	86
National Oceanic and Atmospheric Administration (NOAA), USA	415	7 (1.4)	13 (0.49)	7 (1.9)	13 (0.53)	11 (0.57)	86
Russian Academy of Science, Russia	393	8 (1.3)	2 (1.4)	19 (1.2)	2 (0.75)	2 (0.76)	59
University of Washington, USA	393	8 (1.3)	4 (0.82)	9 (1.6)	4 (0.66)	6 (0.63)	76
University of California Berkeley, USA	377	10 (1.2)	6 (0.72)	10 (1.6)	5 (0.66)	9 (0.59)	78
University of East Anglia, UK	370	11 (1.2)	3 (0.85)	13 (1.4)	6 (0.66)	5 (0.65)	73
Centre National de la Recherché Scientifique (CNRS), France	356	12 (1.2)	32 (0.38)	8 (1.6)	13 (0.53)	15 (0.47)	87
University of Wisconsin, USA	348	13 (1.1)	8 (0.69)	14 (1.4)	9 (0.61)	8 (0.60)	77
University of Oxford, UK	332	14 (1.1)	24 (0.43)	11 (1.5)	12 (0.56)	13 (0.50)	85
University of Minnesota, USA	324	15 (1.1)	28 (0.41)	12 (1.5)	21 (0.43)	15 (0.47)	85
University of Arizona, USA	311	16 (1.0)	28 (0.41)	15 (1.4)	19 (0.44)	21 (0.42)	85
University of Bern, Switzerland	301	17 (1.0)	32 (0.38)	16 (1.4)	16 (0.50)	14 (0.48)	85
Colorado State University, USA	283	18 (0.92)	55 (0.29)	17 (1.3)	26 (0.40)	29 (0.38)	88
Institut de Ciències del Mar (CSIC), Spain	274	19 (0.90)	47 (0.32)	18 (1.3)	22 (0.43)	20 (0.42)	86
University of California, San Diego, USA	269	20 (0.88)	25 (0.42)	22 (1.2)	18 (0.47)	15 (0.47)	82

TA: Total number of articles; SAR, Single country article rank; CAR, Internationally collaborative article rank; FAR, First author article rank; RAR, Corresponding author article rank; % C: percentage of inter-institutionally collaborative articles in total institute articles.

3.2. Distribution of author keywords analysis

Author keywords analysis offers information about research trends that concern researchers. Bibliometric methods concerning author keywords have only been used in recent years (Chiu and Ho, 2007), and their use in analyzing research trends is rare (Xie et al., 2008; Li et al., 2009a; Zhang et al., 2010). Examination of author keywords in this study revealed that altogether 40059 were used, among which, 29435 (73%) appeared only once and 4563 (11%) appeared only twice. The large number of once-only author keywords probably indicates a lack of continuity in research and a wide disparity in research foci (Chuang et al., 2007). Furthermore, these keywords might not be standard or widely accepted by researchers (Ugolini et al., 2001).

Author keywords that appeared in articles referring to climate change from 1992 to 2009 were counted and ranked in 3 six-year periods (Table 2), from which the most frequently used keywords were identified, such as “holocene”, “temperature”, and “global warming”. The analysis of author keywords demonstrated that the most popular and novel research methods were “phenology”, “pollen”, “paleoclimate”, “diatoms”, “stable isotopes”, “modeling”, “biogeography”, “remote sensing”, “palynology”, and “phylogeography”. “Paleoclimate” studies variations in pollen and diatoms to reconstruct past temperatures (Langdon et al., 2004; Clarke et al., 2005). The rank and percentage of “stable isotopes” rose from #60 (0.64%) in 1992–1997 to #13 (1.4%) in 1998–2003, indicating the importance and popularity of isotope technology in climate change research. Stable isotope ratios in the water molecules of ice, relative to that of Standard Mean Ocean Water, reflect the temperature of cloud vapor at the time of snow formation, and hence, to a certain degree, the ambient air temperature (Dansgaard, 1964; Jouzel et al., 1997; Johnsen et al., 2001). “Phylogeography” was introduced by John Avise in 1987 to describe the mitochondrial-DNA bridge between population genetics and systematics (Avise et al., 1987); then it was first applied to examine the effects of historical climate change on vertebrate differentiation in tropical rainforest in 1998 (Schneider et al., 1998), yet its rank rose from #441 with 2 articles during 1992–1997 to #23 with 110 articles during 2004–2009.

Meanwhile, the rank and percentage of articles with “adaptation” and “vulnerability” went up, respectively, from #151 (0.36%) and #441 (0.14%) during 1992–1997 to #7 (1.8%) and #27 (0.80%) during 2004–2009. Research focused on the vulnerability of ecology and living conditions, and besides, governments searched for the best policies to accelerate mitigation and adaptation measures, thereby alleviating the consequences of climate change, such as reducing greenhouse gas emissions, raising river or coastal dikes, and substituting temperature-shock-resistant plants for sensitive ones (Bohringer, 2003; Dessai and Hulme, 2007).

On the other hand, the ranks of words such as “climatic change”, “paleoecology”, “elevated CO_2”, and “greenhouse effect” markedly descended from #2, #11, #12, and #21 during 1992–1997, to #14, #129, #118, and #290 during 2004–2009. Three possible explanations for these decreases are (a) some were general words which were replaced by more specific or definite author keywords (“climatic change” fell into this category and was replaced by “climate change”), (b) some author keywords were gradually disregarded or fell out of the mainstream of climate change research (“elevated CO_2” is a case in point), and (c) the communication revolution, notably the internet, promoted international collaboration, and normalization and standardization of research themes and vocabulary (Marriner et al., 2010). Moreover, the lack of standardization among keywords assigned by authors greatly hampered our analysis since the use of synonymous

Table 2
Top 20 most frequent author keywords used during 1992–2009 and in 3 six-year periods.

Author keywords	TA	92–09 R (%)	92–97 R (%)	98–03 R (%)	04–09 R (%)
Climate change	6124	1 (32)	1 (36)	1 (31)	1 (32)
Holocene	748	2 (3.9)	3 (5.0)	2 (5.8)	4 (3.1)
Temperature	628	3 (3.3)	4 (4.6)	5 (3.1)	3 (3.2)
Global warming	598	4 (3.1)	6 (3.1)	6 (2.7)	2 (3.2)
Climate	578	5 (3.0)	5 (3.3)	3 (3.5)	5 (2.8)
Climatic change	437	6 (2.3)	2 (8.6)	4 (3.3)	14 (1.2)
Drought	337	7 (1.7)	38 (0.86)	13 (1.4)	6 (2.0)
Precipitation	333	8 (1.7)	31 (1.0)	9 (1.9)	9 (1.7)
Phenology	312	9 (1.6)	17 (1.4)	18 (1.2)	8 (1.8)
Carbon dioxide	301	10 (1.6)	7 (2.9)	7 (2.0)	13 (1.3)
Adaptation	294	11 (1.5)	151 (0.36)	27 (1.0)	7 (1.8)
Global change	289	12 (1.5)	9 (2.1)	10 (1.8)	12 (1.3)
Pollen	276	13 (1.4)	17 (1.4)	11 (1.7)	11 (1.4)
Paleoclimate	257	14 (1.3)	31 (1.0)	8 (2.0)	15 (1.1)
Biodiversity	255	15 (1.3)	74 (0.57)	29 (0.94)	10 (1.5)
Diatoms	208	16 (1.1)	52 (0.71)	12 (1.6)	19 (0.95)
Arctic	201	17 (1.0)	17 (1.4)	32 (0.88)	16 (1.1)
Global climate change	199	18 (1.0)	10 (1.9)	15 (1.4)	25 (0.81)
Photosynthesis	190	19 (1.0)	8 (2.6)	19 (1.1)	32 (0.77)
Stable isotopes	190	19 (1.0)	60 (0.64)	13 (1.4)	21 (0.87)

TA: total articles; R (%): rank and percentage of author keywords in total articles.

terms, spelling variations, abbreviations, and more or less specific terms made the exact interpretation of the author's intended meaning difficult (Li et al., 2009a).

3.3. Distribution of paper titles, KeyWords plus, and abstracts analysis

The title of an article always includes the information that the author would most like to express to the readers, therefore analysis of the word distribution in article titles in different periods was recently used to evaluate research trends (Xie et al., 2008; Zhang et al., 2010). The search keys "climate", "climatic", "change", and "changes", "temperature", "global", "carbon", "effects", and "model" had the highest frequencies, indicating that carbon flux and trading, as well as the human effects on increasing temperature were mainstream issues (Jones et al., 1999; Challinor et al., 2007; Hepburn, 2007). Meanwhile, the rank and percentage of "China" increased steeply from #158 (0.75%) during 1992–1997 to #21 (3.1%) during 2004–2009, similar to the results of analysis of author keywords, from #193 (0.29%) during 1992–1997 to #17 (1.0%) during 2004–2009. On the contrary, a decline in the ranking of the keyword "climate-change" was evident, from #6 (7.3%) during 1992–1997 to #750 (0.20%) during 2004–2009.

KeyWords Plus supplies additional search terms extracted from the titles of articles cited by authors in their bibliographies and footnotes in the ISI database, and substantially augment title-word and author-keyword indexing (Garfield, 1990). Other than "climate-change" and "climate", the search keywords in this study, the top five most frequent KeyWords Plus were "variability", "temperature", "model", "vegetation", and "United-States", which indicated hot spots in climate change research world-wide. Through KeyWords Plus analysis, it can be concluded that additional spikes of attention were given to "trends", "precipitation", "growth", "dynamics", "record", and "responses", whose ranks gradually rose during the last 16 years. Long-term changes in precipitation extremes are of great importance to the welfare of human beings as well as the entire ecosystem (Liu et al., 2009), therefore observation, simulation and prediction of precipitation are of great importance (Hulme, 1992; Shiu et al., 2009).

Zhang et al. (2010) first used the analysis of single words in abstracts to make specific inferences about the scientific literature and identify the subjective focus and emphasis specified by authors. As with the distribution of paper titles, author keywords, and KeyWords Plus, "temperature" and "model(s)" were the most frequently used single words during 1992–2009. Moreover, "global", "conditions", "years", "time", "water", "effects", and "species" were also emphasized in abstracts. "Climate change" is a "global" issue and its "effects" on plants, animals and human beings are of most concern (Loehle and LeBlanc, 1996; Briones et al., 1997; Costello et al., 2009).

3.4. Hot issues

In order to overcome the weaknesses of each of the four separate types of keyword analysis, paper titles, author keywords, KeyWords Plus, and abstracts 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 more completely and precisely and, more importantly, to discover new directions that the science is taking. This is a new method named "word cluster analysis", which was applied for the first time to the analysis of research trends in atmospheric simulation (Li et al., 2009a) and risk assessment (Mao et al., 2010). The words listed in Figs. 4 and 5 all include their plural forms, abbreviations, and other transformations, as well as words with similar meanings. For example, "model" included "model", "models", "modeling", "modelling", "simulation", "gcm", "gcms", "general-circulation model", "general-circulation models", "regional climate model", "ocean-atmosphere model", and "coupled model".

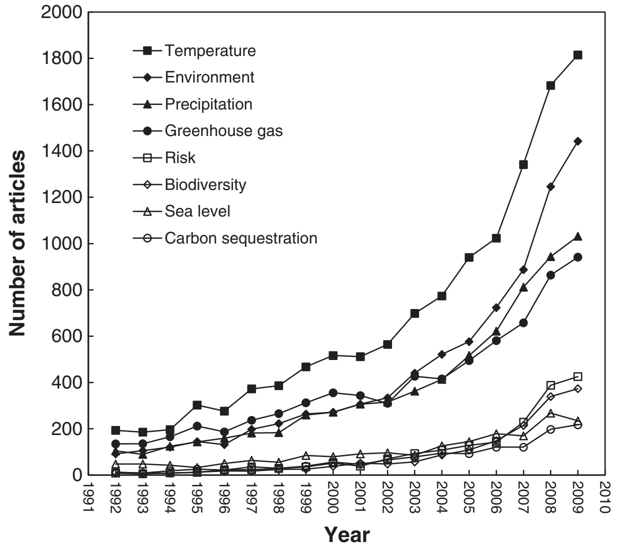

Fig. 4. Comparison of trends of items affected by climate change, temperature, environment, precipitation, greenhouse gas, risk, biodiversity, sea level, and carbon sequestration.

Research trends in climate change were separated into two categories — affected items and research methods. Referring to the items that climate change research affected (Fig. 5), "temperature" had a distinctly higher incidence, being mentioned in 12241 articles at a rate of over 300 articles in 2007 and 2008. Besides, "environment"-related research presented a vigorous growth pattern, indicating researchers' concentration on the relationship between climate change and the environment, as well as the corresponding impact on human beings and species (Langdon et al., 2004; Jacob and Winner, 2009). More attention was paid to the research on "risk", especially after 2006. The number of articles related to "risk" already exceeded that of "greenhouse gas" and "sea level" in 2007. Along with the continual occurrence of natural disasters due to climate change, both governments and academia focused special attention on potential risk (Harte et al., 2004; Thomas et al., 2004; Sonnett, 2010). Thus a risk society emerged with a link to the contemporary climatic fears, which resulted from the unknown climatic futures and would in the end be

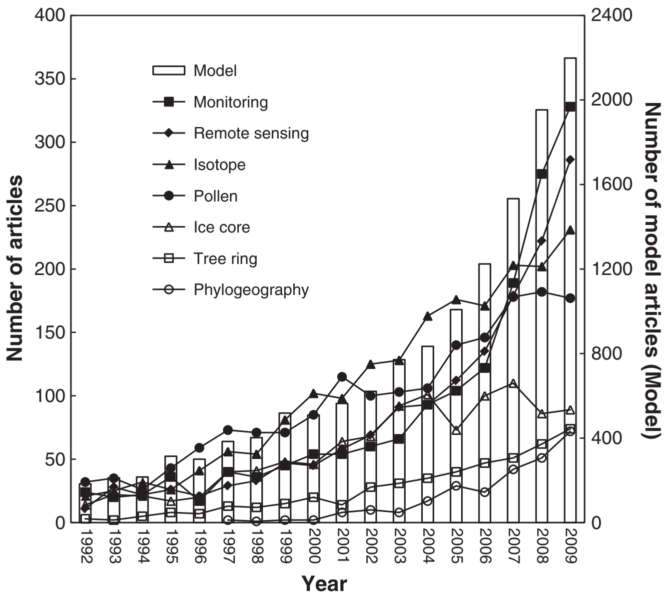

Fig. 5. Comparison of trends of research methods, model, monitoring, remote sensing, isotope, pollen, ice core, tree ring, and phylogeography.

dissipated by the cultural change (Hulme, 2008). This kind of fears directly promoted current climate change research, such as geo-engineering (Crutzen, 2006; Morton, 2007), political engineering (Biermann, 2007) and social engineering (Baron, 2006), all of which connoted global control and mastery of the climate future (Hulme, 2008). Unlike other items, the research on "sea level" decreased in 2009.

Numerous methods have been used to reconstruct past temperatures, among which, modeling was the most predominant (Fig. 5). Various climate models were developed, such as the Atmosphere–Ocean General Circulation Models (Crowley, 2000; Levitus et al., 2001), which are applied as a research tool to study and simulate climate, and for operational purposes, including monthly, seasonal and interannual climate predictions (IPCC, 2007). In addition, "remote sensing" became more widely used after 2004, the number of related articles exceeding that of "isotope" in 2008. Satellites have been measuring the temperature of the troposphere since 1979 (Christy et al., 2007). The Moderate Resolution Imaging Spectroradiometer is one of the five instruments aboard the Terra Earth Observing System platform launched in December 1999, which began earth observations in late February 2000 (Platnick et al., 2003). A comprehensive set of remote sensing algorithms for cloud detection and the retrieval of physical and optical cloud properties have been developed, the archived products of which have applications in climate change studies, climate modeling, numerical weather prediction, and fundamental atmospheric research (Platnick et al., 2003). "Remote sensing" was also used to monitor the thinning or loss of ice shelves in some near-coastal regions of Greenland, the Antarctic Peninsula and West Antarctica (Zwally et al., 2005). Emerging remote sensing techniques such as Synthetic Aperture Radar interferometry, feature tracking, scatterometry, altimetry, and gravimetry provide vital information without which our understanding of ice sheets would be far less advanced (Quincey and Luckman, 2009). Phylogeography is a novel method, and its number of applications has increased rapidly in recent years.

3.5. Most cited articles

Yearly variations in the number of citations can be used to trace the impact of publications (Chiu and Ho, 2007; Li and Ho, 2008). Miscounting citations may occur due to the possibilities of simply spelling errors in titles and DOI in articles, or other similar problems in ISI's data (Adam, 2002; Nature, 2002), but the main patterns remain in the data (Schwartz et al., 2005). Table 3 shows the most frequently cited articles in each year since publication through 2009. Six were published in *Nature* (IF = 31.434 in 2009) and five in *Science* (IF = 28.103 in 2009). Sixteen articles included authors from the USA and seven from the UK. Among the climate change articles, the most frequently cited article was "evidence for general instability of past climate from a 250-kyr ice-core record" (Dansgaard et al., 1993), which was published in *Nature* and had been cited 1718 times through 2009. Ice cores provide the most direct and highly resolved records of atmospheric parameters over these timescales, because they record climate signals as well as forcing factors of global significance such as greenhouse gases and of more regional significance such as atmospheric aerosol content (Augustin et al., 2004). Fig. 6 shows article life with 7 articles which were cited at least 100 times in 2009. The articles in 2003, 2004, 2005, and 2006 had rather vigorous article lives, and their numbers of citations maintained a rapid growth rate, indicating researchers' attention to the impact of climate change on natural systems, tropical cyclones, extinction risk, and the Community Climate System Model version 3 (Parmesan and Yohe, 2003; Thomas et al., 2004; Webster et al., 2005; Collins et al., 2006). In addition, "land clearing and the biofuel carbon debt" (Fargione et al., 2008) published in 2008 had 131 citations in 2009.

4. Conclusions

In this study on climate change publications listed in SCI-EXPANDED, significant findings on worldwide research performance from 1992 to 2009 were obtained. A total of 2023 journals were listed in the 154 SCI subject categories. The greatest number of articles appeared in *Geophysical Research Letters*. The subject category "environmental sciences" has had the most rapid growth since 2002, with a high frequency of "environment", indicating a research emphasis on the interactional relationship between climate change and environmental problems. It was notable that the USA ranked first with respect to all indicators, namely total, single country, internationally collaborative, first author, and corresponding author articles.

Table 3
Most frequently cited articles during 1992–2009.

Year	TC-2009	C/Y	Article/journal	Country
1992	1411	78	Climate forcing by anthropogenic aerosols/*Science*	USA
1993	1718	101	Evidence for general instability of past climate from a 250-kyr ice-core record/*Nature*	Iceland, France, USA, Denmark
1994	956	60	Decadal atmosphere-ocean variations in the Pacific/*Climate Dynamics*	USA
1995	1316	88	A global-model of natural volatile organic-compound emissions/*Journal of Geophysical Research-Atmospheres*	USA, UK, South Africa, Germany, Australia
1996	420	30	Increased activity of northern vegetation inferred from atmospheric CO_2 measurements/*Nature*	USA
1997	379	29	Maximum and minimum temperature trends for the globe/*Science*	UK, New Zealand, Russia, Australia, USA
1998	375	31	Sensitivity of boreal forest carbon balance to soil thaw/*Science*	USA
1999	659	60	Representing twentieth-century space-time climate variability. part I: development of a 1961–90 mean monthly terrestrial climatology/*Journal of Climate*	UK
2000	759	76	Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model/*Nature*	UK
2001	441	49	Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models/*Global Change Biology*	Germany, UK, USA, Sweden
2002	344	43	Interpretation of recent Southern Hemisphere climate change/*Science*	USA
2003	1097	157	A globally coherent fingerprint of climate change impacts across natural systems/*Nature*	USA
2004	857	143	Extinction risk from climate change/*Nature*	UK, Netherlands, Australia, South Africa, Brazil, USA, Mexico
2005	428	86	Changes in tropical cyclone number, duration, and intensity in a warming environment/*Science*	USA
2006	307	77	The Community Climate System Model version 3 (CCSM3)/*Journal of Climate*	USA
2007	132	44	Global and regional drivers of accelerating CO_2 emissions/*Proceedings of the National Academy of Sciences of the United States of America*	Australia, USA, France, UK, Germany
2008	169	85	Land clearing and the biofuel carbon debt/*Science*	USA
2009	25	25	Irreversible climate change due to carbon dioxide emissions/*Proceedings of the National Academy of Sciences of the United States of America*	USA, Switzerland, France

TC-2009: total citations of articles from publication to 2009; C/Y: number of citations/year.

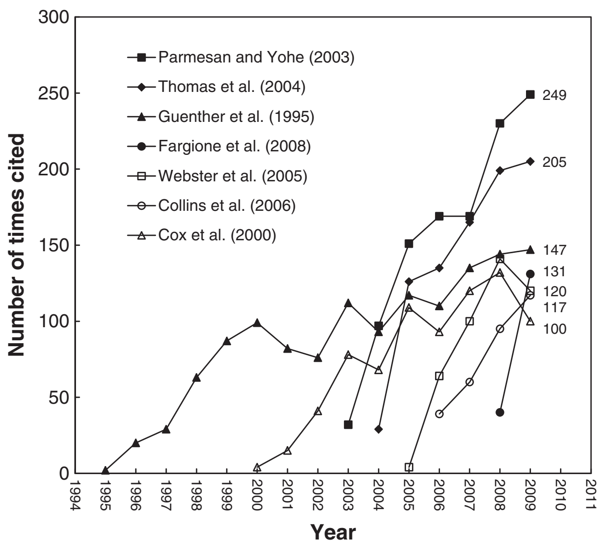

Fig. 6. Citation history of the top 7 most frequently cited articles in 2009 from Table 2.

University of Colorado was the most productive university. Analysis of the most cited articles revealed that the impact of climate change on natural systems, tropical cyclones, and extinction risks continued to be the mainstream research topics. By synthetically and innovatively analyzing the distribution and changes of words in article titles and abstracts, author keywords, KeyWords Plus, and most-cited articles, the development of climate change research during last decade was described, and the future orientation of climate change research was predicted. Analysis by a new bibliometric method – "word cluster analysis" – can help researchers realize the panorama of global climate change research and establish future research directions. It can be concluded that items affected by climate change including "temperature", "environment", "precipitation", "greenhouse gas", "risk", and "biodiversity" will be prominent directions of climate change research in the 21st century, while "model", "monitoring", and "remote sensing" will continue to be the leading research methods. The novel method "phylogeography", first applied in 1997, has a bright application future.

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