Current trends in scientific research on global warming: a bibliometric analysis

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Abstract: The objective of this paper is to contribute to a better understanding of the scientific knowledge in global warming, as well as to investigate the evolution of the research knowledge through the published papers included in Web of Science database. A bibliometric and social network analyses was performed to obtain indicators of scientific productivity, impact and collaboration between researchers, institutions and countries. A subject analysis was also carried out taking into account the key words assigned to papers and subject areas of journals. A number of 1,672 articles were analysed since 2005 until 2014. The most productive journals were *Journal of Climate* (n = 95) and

the most frequent keyword have been climate change (n = 722). The network of collaboration between countries shows the central position of the USA. Papers on the topic are published in a vast amount of journals from several subject categories.

Keywords: global warming; research trends; scientific collaboration; bibliometric analysis; social network analysis; SNA.

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1 Introduction

The definition of global warming stands for the globalised increase in the worldwide average temperatures. Natural events and human activities are thought to be the main contributors to this increase. Alongside with this, the exponential increase in 'greenhouse' gasses, mainly carbon dioxide (CO_2) has been identified. Weather patterns are also being affected due to the planet warming. Melting of glaciers, more intense tropical storms, snow pack, acidification of the ocean, sea level increase and ice rise are

some of the reported effects caused by the augmented greenhouse gas (GHG) emissions (IPCC, 2013). These effects represent one of the most relevant threats to human being survival as well as to international political stability.

The current political agenda has adopted global warming, GHGs emissions and reductions of CO_2 emissions as top priorities. The international Kyoto Protocol has committed (Bohringer, 2003) to reduce during the 2008–2012 period the GHG emissions by at least 5% below the levels measured in 1990. Through those agreements countries are taking measures to mitigate damages derived from climate change through the reduction of GHG emissions (Zhang and Wei, 2010).

Humans are altering the Earth's climate (Houghton et al., 2001; Stott, 2003; Barnett et al., 2005) and thus the working of living systems (Root et al., 2003, 2005; Lovejoy and Hannah, 2005), including pathogens and their hosts (Epstein, 2001; Harvell et al., 2002; Rodo et al., 2002). One of the identified outcomes of the climate alteration is related with the extinction of many species (Thomas et al., 2004). However, this affirmation needs to be taken with caution as other changes, especially habitat destruction, might also be contributing. As a result, the population of thousands of species have declined and hundreds are almost or already vanished (Stuart et al., 2004).

Additionally, plant pollination alterations have also been observed as global warming side-effects (Memmott et al., 2007). Pollination is not only beneficial for the interaction between plants and animals. It also has a strong influence on several areas, such as in the definition of the production yield of many crops or by its contribution to the behaviour of terrestrial ecosystems (Nabhan and Buchmann, 1997; Klein et al., 2007). Unfortunately, the threat caused by human activities is also increasing the risk of extinction of plant and pollination species (Biesmeijer et al., 2006) as the necessary overlap between flower production and pollination flight activity may be disrupted by global warming (Harrison, 2000; Wall et al., 2003).

Moreover, the existence of several studies concerning global warming and his several effects has been noticed. The global warming benefits on small species in aquatic ecosystems (Daufresne et al., 2009), extinctions of endemics species from biodiversity hotspots (Malcolm et al., 2006), the projection of coral reef evolution under global warming and ocean acidification (Pandolfi et al., 2011), global warming pattern formation and its influence on sea surface temperature and rainfall (Xie et al., 2010) or forecasting the effects of increasing temperatures on biodiversity (Botkin et al., 2007) have been well documented. Even specific reviews on the behaviour of drought under global warming have been reported (Dai, 2011).

Bibliometric studies analysing trends in research through published studies have recently gained importance because they provide indicators of scientific research and its progression (Vain, 2007). Despite the increasing public importance of research on global warming, there are no scientometric studies on this topic available in the literature. This paper was written with the aim to contribute to a better understanding of the scientific knowledge in global warming as well as to investigate the evolution of the research knowledge of the topic through the published papers included in Web of Science database. The main goal of this study was to evaluate the research structure on the global warming topic through the assessment of the indicators of scientific productivity, impact and collaboration between researchers, institutions and countries.

2 Methods

Papers included in the study were collected from the Web of Science Core Collection (WOS) platform from Clarivate Analytics. The search strategy included the term 'global warming'. In order to ensure greater accuracy in the results, the search was only conducted in the 'Title' field of the registries in the WOS. Despite restricting the search strategy to the title filed may exclude publications that do not have this word in the title, it avoids obtaining non-relevant records that may have 'global warming' in the abstract but contain a different topic as main subject. The term was included into quotation marks to guaranty more accuracy in the obtained records, e.g., all records containing one term after the other. The search was also limited to the 2005–2014 period. The study was restricted to articles and reviews and, therefore, abstract of conferences, bibliographical articles, book reviews, editorials, letters, reprints and news were excluded.

As indicators of scientific production we considered: annual evolution of published papers and distribution of papers per journals and institutions and countries that developed the research. As indicators of impact we extracted: number of citations and ratio citations per article of institutions and countries; impact factor and quartile of journals in Journal Citation Reports and most cited papers. The number of citations was obtained from WOS database and we took into account those received by the analysed papers during the period of study. Impact factors were obtained from the 2014 Journal Citation Reports edition. To investigate and sketch the collaboration patterns, a social network analysis (SNA) was performed, identifying the number of co-occurrences between authors, institutions and countries. Co-occurrences refer to all combinations of pairs of authors, institutions or countries in each paper, which also appear in other papers.

A subject analysis was also performed taking into account three different strategies: the most frequent keywords assigned to papers; the subject areas of journals publishing the analysed papers according to its classification in the Journal Citation Reports in combination with the three most frequently reported keywords assigned to papers and to three most productive journals in each identified area and finally the network of co-words through a SNA analysis. Co-words refer to all combinations of pairs of keywords that are repeated in the set of papers revised. SNA applied to co-word analysis provides graphs that show the strongest associations between the concepts included in papers and represented by keywords (Lanza and Svendsen, 2007). To map the knowledge in other fields, similar approaches have been constructed, such as environmental science (Ho, 2007), tsunamis (Chiu and Ho, 2007) and wine and health (Aleixandre et al., 2013), among others.

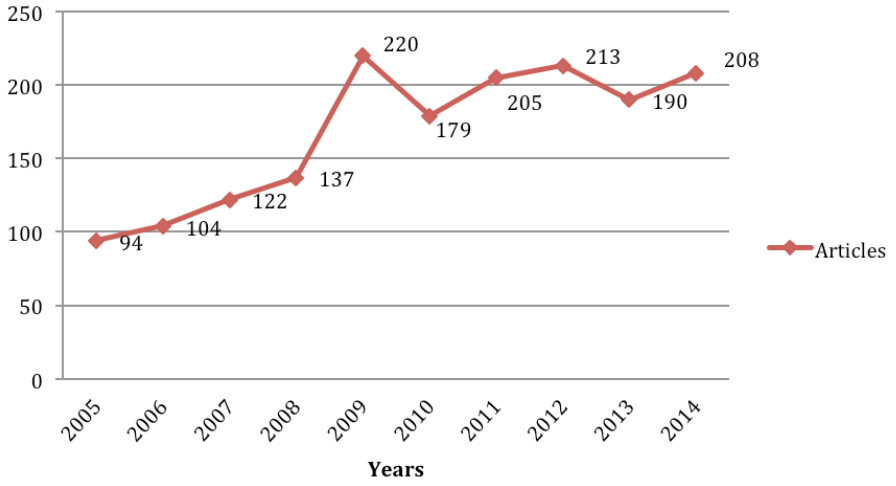
To visualise the networks of authors, institutions and co-words the software's Pajek and VOSviewer (Batagelj and Mrvar, 2002) were used. A threshold or minimum of relations was applied in order to visualise correctly the networks. This threshold is specified in each figure.

3 Results

3.1 Authors, institutions and countries scientific production and impact

During the period of analysis, 1,672 articles on global warming were included in WOS. As shown in Figure 1, the number of published articles has grown since 2005, when 94 articles were published (2.78%), until 2014, with 208 (18.22%) articles. Most papers (n = 995; 60%) were published during the second five-year period.

Figure 1 Annual evolution of published papers (see online version for colours)



The obtained records have been published in 686 different journals. The 23 journals publishing 10 or more papers are shown in Table 1, along with the evolution of impact factor as reported in Journal Citation Reports, quartile and the ranking in the subject category. The most productive journals which published more than 30 articles were *Journal of Climate* (n = 95), *Geophysical Research Letters* (n = 78), *Climate Dynamics* (n = 38) and *Climatic Change* (n = 38). If journals publishing more 15 or papers are considered, *Proceedings of The National Academy of Sciences of The United States of America* appeared as the journal with the higher impact factor (IF = 10.235 in 2005), followed by *Global Change Biology* (IF = 8.224 in 2013), *Renewable & Sustainable Energy Reviews* (IF = 6.018 in 2011) and *Environmental Science & Technology* (IF = 5.481 in 2013). Most of the mentioned journals rank in first quartile in the Journal Citation Reports subject categories (n = 15).

Table 2 lists the most productive institutions (n > 10), citations and ratio citations per article. The Chinese Academy of Sciences is the most productive (n = 62), followed by National Oceanic and Atmospheric Administration (NOAA) from the USA (n = 43) and Centre National de la Recherche Scientiphique-CNRS (France) (n = 37). National Oceanic and Atmospheric Administration (NOAA) is the institution with most citations (n = 3,715), followed by National Center for Atmospheric Research, also from the USA (n = 2,714) and University of Miami (USA) (n = 1,955). Eleven institutions received more than 1,000 citations, including: Columbia University (New York, USA), University of California (San Diego, USA), Princeton University (New Jersey, USA); Met Office Hadley Centre for Climate Science and Services and University of Oxford (UK).

Table 1 Most productive journals, citations and impact factor

JOURNAL	*COUNTRY*	*ARTICLES*											*CITES*	*CITES/ ARTICLE*	*FI 2014*	*WOS CATEGORY*	*QUARTILE*	*JOURNAL RANK*
		2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*TOTAL*						
Journal of Climate	USA	4	5	4	9	15	12	8	14	10	14	95	5,027	52.92	4.435	Meteorology and atmospheric sciences	Q1	6/77
Geophysical Research Letters	USA	9	10	8	4	14	11	3	7	9	3	78	2,331	29.88	4.196	Geosciences, multidisciplinary	Q1	9/175
Climate Dynamics	USA	-	4	1	2	1	4	5	5	8	8	38	1,007	26.50	4.673	Meteorology and atmospheric sciences	Q1	5/77
Climatic Change	Netherlands	1	6	1	2	3	4	8	8	5	-	38	667	17.55	3.43	Meteorology and atmospheric sciences	Q1	11/77
																Environmental sciences	Q1	35/223
Journal of Geophysical Research – Atmospheres	USA	-	1	2	2	4	2	3	5	1	5	25	604	24.16	3.426	Geosciences, multidisciplinary	Q1	19/175
Global Change Biology	England	-	3	5		3	2	4	2	3	3	25	1,050	42.00	8.708	Biodiversity conservation	Q1	1/44
Environmental Research Letters	England	-	-	-	1	5	1	3	4	3	7	24	364	15.17	3.906	Environmental sciences	Q1	23/223
																Meteorology and atmospheric sciences	Q1	8/77
Proceedings of The National Academy of Sciences of The United States of America	USA	1	1	2	-	3	3	2	3	2	2	19	1,355	71.32	10.563	Multidisciplinary sciences	Q1	4/57
SOLA	Japan	10	3	1		1	1	1	1	1	-	19	324	17.05	1.53	Meteorology and atmospheric sciences	Q4	64/77
Journal of the Meteorological Society of Japan	Japan	1	4	2	1	3	-	1	5	-	-	17	489	28.76	1.44	Meteorology and atmospheric sciences	Q3	55/77
Renewable & Sustainable Energy Reviews	USA	-	-	-	1		2	3	4	4	2	16	297	18.56	7.445	Energy and fuels	Q1	8/89

Table 1 Most productive journals, citations and impact factor (continued)

JOURNAL	*COUNTRY*	*ARTICLES*											*CITES*	*CITES/ ARTICLE*	*FI 2014*	*WOS CATEGORY*	*QUARTILE*	*JOURNAL RANK*
		2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*TOTAL*						
Waste Management & Research	England	-	-	-	-	15	-	1	-	-	-	16	561	35.06	1.526	Environmental sciences	Q3	140/223
																Engineering, environmental	Q3	30/47
Energy Policy	England	1	1	2	2	1	3	2	1	1	1	15	486	32.40	3.394	Environmental sciences	Q2	68/223
Environmental Science & Technology	USA	1	2	-	1	4	2	1	1	-	3	15	236	15.73	6.326	Engineering, environmental	Q1	3/47
																Environmental sciences	Q1	10/223
Nature Climate Change	England	-	-	-	-	-	-	-	3	6	5	14	681	48.64	15.462	Meteorology and atmospheric sciences	Q1	1/77
																Environmental sciences	Q1	2/223
																Environmental studies	Q1	1/100
Theoretical and Applied Climatology	Germany	-	-	-	-	1	4	3	2	1	2	13	34	2.62	2.287	Meteorology and atmospheric sciences	Q2	32/77
PLoS One	USA	-	-	-	-	1		4	2	4	2	13	120	9.23	3.702	Multidisciplinary sciences	Q1	9/57
International Journal of Global Warming	England	-	-	-	-	4	1	4	2	1	1	13	150	11.54	0.601	Environmental sciences	Q4	196/223
Journal of Cleaner Production	USA	1	-	-	-	1	1	-	3	1	6	13	128	9.85	4.167	Engineering, environmental	Q1	10/47
																Environmental sciences	Q1	24/223
Energy & Environment	England	-	-	-	-	4	2	4	1	-	1	12	2,525	210.42	0.438	Environmental studies	Q4	87/100
Nature	England	2	3	1	-	2		1	2	1		12	19	1.58	41.296	Multidisciplinary sciences	Q1	1/57
Science	USA	3	-	1	1	-	2	1	-	-	2	10	178	17.80	35.263	Multidisciplinary sciences	Q1	2/57
Journal of Physical Chemistry A	USA	2	-	-	1	2	-	1	1	1	2	10	1,975	197.50	2.713	Chemistry, physical	Q2	52/139
																Physics, atomic, molecular and chemical	Q2	10/34

Table 2 Most productive institutions, citations and impact factor

INSTITUTION	*COUNTRY*	*ARTICLES*	*CITES*	*CITES/ARTICLE*
Chinese Academy of Sciences	China	62	606	9.77
NOAA – National Oceanic and Atmospheric Administration	USA	43	3,715	86.40
Centre national de la recherche scientifique (CNRS)	France	37	1,167	31.54
Yale University	USA	34	1,087	31.97
National Center for Atmospheric Research	USA	31	2,714	87.55
University of Hawaii	USA	30	1,232	41.07
Columbia University	USA	27	1,773	65.67
Meteorological Research Institute (MRI)	Japan	27	860	31.85
University of Tokyo	Japan	26	1,158	44.54
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Japan	25	393	15.72
Russian Academy of Sciences	Russia	24	154	6.42
University of Reading	UK	23	914	39.74
University of Washington	USA	23	688	29.91
Potsdam Institute for Climate Impact Research	Germany	22	1,011	45.95
University of California, Berkeley	USA	22	726	33.00
University California, San Diego	USA	21	1,628	77.52
Princeton University	USA	21	1,433	68.24
Met Office Hadley Centre for Climate Science and Services	UK	20	1,342	67.10
United States Department of Agriculture (USDA)	USA	20	866	43.30
University of Wisconsin	USA	19	718	37.79
University of Oxford	UK	19	1,244	65.47
University of Tsukuba	Japan	19	508	26.74
Université Pierre et Marie Curie – UPMC	France	18	694	38.56
Ocean University of China	China	17	406	23.88
Technical University of Denmark	Denmark	17	606	35.65
Commonwealth Scientific and Industrial Research Organisation (CSIRO)	Australia	16	881	55.06
NASA – National Aeronautics and Space Administration	USA	16	420	26.25
University of Toronto	Canada	15	408	27.20

Table 2 Most productive institutions, citations and impact factor (continued)

INSTITUTION	*COUNTRY*	*ARTICLES*	*CITES*	*CITES/ARTICLE*
University of London – UCL	UK	15	158	10.53
University of Colorado	USA	15	772	51.47
Texas A&M University	USA	14	298	21.29
University of California, Los Angeles	USA	14	869	62.07
George Mason University	USA	14	327	23.36
Centre for Australian Weather and Climate Research	Australia	14	443	31.64
Seoul National University	South Korea	13	122	9.38
MIT - Massachusetts Institute of Technology	USA	13	591	45.46
University of Copenhagen	Denmark	13	184	14.15
University of Miami	USA	13	1,955	150.38
Swiss Federal Institute of Technology in Zurich (ETHZ)	Switzerland	13	1,027	79.00
Academia Sinica	Taiwan	12	304	25.33
Nanjing University of Information Science & Technology	China	12	97	8.08
Max-Planck-Institut für Meteorologie	Germany	12	207	17.25
Ford Motor Co	USA	12	197	16.42
University of Oslo	Norway	12	498	41.50
Nanjing Agricultural University	China	12	184	15.33
Western Sydney University	Australia	12	309	25.75
National Research Council of Italy (CNR)	Italy	12	248	20.67
Natural Environment Research Council (NERC)	UK	12	317	26.42
University of East Anglia	UK	11	390	35.45
California Institute of Technology (CALTECH)	USA	11	282	25.64
Beijing Climate Center	China	11	193	17.55
Hokkaido University	Japan	11	70	6.36
University California, Davis	USA	11	163	14.82
Cornell University	USA	11	169	15.36
University of Melbourne	Australia	11	317	28.82
National Taiwan University	Taiwan	11	284	25.82

In the ratio citations per article, three institutions stood out: University of Miami (Florida, USA) (C/A = 150.38), National Centre for Atmospheric Research (C/A = 87.55) and National Oceanic and Atmospheric Administration (C/A = 86.40).

Regarding the distribution of papers per country (Table 3), the country publishing the higher number of papers is the USA (n = 587), followed by the UK (n = 165) and China (n = 159). Other countries with more than 100 papers were: Japan (n = 137), Germany (n = 121), France (n = 103) and Australia (n = 102). When considering citations, the USA appeared in first position (n = 21,678), followed by the UK (n = 6,124), Germany (n = 4,319) and France (n = 3,174). The ratio citations per article highlights Switzerland (C/A = 66.57) and seven countries with ratios around 30 C/A: the Netherlands, the UK, the USA, Germany, Austria, Canada and France.

Table 3 Most productive countries and citations

COUNTRY	*ARTICLES*	*CITES*	*CITES/ARTICLE*
USA	587	21,678	36.93
UK	165	6,124	37.12
China	159	2,124	13.36
Japan	137	2,723	19.88
Germany	121	4,319	35.69
France	103	3,174	30.82
Australia	102	2,754	27
Canada	78	2,563	32.86
Spain	63	1,596	25.33
South Korea	55	794	14.44
India	48	831	17.31
Denmark	48	1,385	28.85
Norway	46	1,033	22.46
Italy	45	1,138	25.29
Russia	43	245	5.7
The Netherlands	38	1,431	37.66
Brazil	29	397	13.69
Switzerland	28	1,864	66.57
Sweden	28	640	22.86
Turkey	22	294	13.36
Austria	19	672	35.37
Taiwan	18	323	17.94
New Zealand	17	435	25.59
Belgium	15	376	25.07
Malaysia	13	61	4.69
South Africa	12	261	21.75
Israel	11	157	14.27

Table 4 Annual evolution of most frequent keywords

KEYWORD	*ARTICLES*										
	2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*TOTAL*
Climate-change	30	42	47	54	85	80	91	94	94	105	722
Model	8	18	13	18	28	29	21	28	31	22	216
Temperature	11	12	19	15	23	17	26	24	28	21	196
Climate	8	13	14	13	21	21	18	25	17	20	170
Variability	5	14	13	14	17	17	14	17	20	17	148
Impact	5	5	13	13	17	10	20	19	19	25	146
Carbon dioxide	10	4	6	9	26	15	16	10	22	16	134
Greenhouse gas emissions	8	7	6	5	25	5	15	17	19	19	126
Simulations	5	10	5	10	11	14	10	16	16	6	103
Precipitation	5	5	6	7	10	4	8	14	15	16	90
El Niño-southern oscillation	4	8	7	7	12	8	9	8	9	15	87
Trends	8	5	7	7	11	8	8	11	12	6	83
Emissions	6	3	1	3	8	11	11	15	11	9	78
Circulation	2	4	6	3	6	4	9	13	13	12	72
Ocean	3	2	5	5	13	4	10	12	9	6	69
Life-cycle assessment	2	2	1	2	12	4	6	13	8	13	63
Systems	4	5	1	6	8	3	4	8	9	13	61
United-States	2	4	5	5	5	5	8	14	4	9	61

Table 4 Annual evolution of most frequent keywords (continued)

KEYWORD	*ARTICLES*										
	2005	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*TOTAL*
Forests	1	2	4	6	9	2	8	10	10	4	56
Responses	3	5	3	4	7	8	5	9	3	6	53
Sensitivity	5	3	6	8	1	8	7	8	4	1	51
Cycle	1	1	1	5	7	4	5	5	12	5	46
Sea-surface temperature	2	1	2	2	10	4	6	3	8	8	46
Hydrological cycle	2	3	4	2	3	6	6	8	2	7	43
Science			2	7	6	6	11	4	2	5	43
Surface air-temperature	3	4	3	6	2	3	3	9	5	5	43
Uncertainty	3	4	1	7	5	9	1	7	2	4	43
Atmosphere	2	6	4	3	6	8	2	4	5	1	41
China	1	1	3	3	4	2	5	3	9	10	41
Coupled climate models	2	2	5	2	4	5	7	7	5	2	41
Climate models	1	1	5	2	6	4	6	4	6	3	38
Evolution	1		6		8	3	5	4	6	5	38
Ecosystems	1	4	2	6	4	3	4	4	3	6	37
Energy	2		1		7	3	7	2	7	7	36
Management	2	3	2	1	8	3	7	3	2	5	36
Policies		1	3	8	4	1	3	5	4	7	36

Table 5 Subject categories, most frequent keywords and most productive journals

Subject area	*Articles*	*Main keywords*						*Most productive journals*	*n*
		KW 1	*n*	*KW 2*	*n*	*KW 3*	*n*		
Meteorology and atmospheric sciences	384	Climate-change	162	Model	89	Variability	86	*Journal of Climate*	95
								Climatic Change	38
								Climate Dynamics	38
Environmental sciences	253	Climate-change	174	Model	49	Temperature	39	*Climatic Change*	38
								Global Change Biology	25
								Environmental Research Letters	24
Geosciences, multidisciplinary	176	Climate-change	53	CLIMATE	36	Model	28	*Geophysical Research Letters*	78
								Global and Planetary Change	8
								Biogeoscience	8
Ecology	144	Climate-change	108	Temperature	38	Model	17	*Global Change Biology*	25
								Ecological Modelling	9
								Biogeoscience	8
Environmental studies	120	Climate-change	64	Model	17	Policy	10	*Energy Policy*	15
								Nature Climate Change	14
								Energy & Environment	12
Multidisciplinary sciences	99	Climate-change	49	Temperature	15	Model	14	*Proceedings of the National Academy of Sciences of the United States of America*	19
								Plos One	13
								Nature	12
Energy and fuels	74	Climate-change	16	Renewable energy	13	Energy	7	*Renewable & Sustainable Energy Reviews*	16
								Energy Policy	15
								Applied Energy	8
Engineering, environmental	70	Climate-change	17	Life-cycle assessment	14	Greenhouse gases	12	*Waste Management & Research*	16
								Environmental Science & Technology	15
								Journal of Cleaner Production	13

Table 5 Subject categories, most frequent keywords and most productive journals (continued)

Subject area	*Articles*	*Main keywords*						*Most productive journals*	*n*
		KW 1	*n*	*KW 2*	*n*	*KW 3*	*n*		
Economics	53	Climate-change	20	Model	10	Economics	6	*Ecological Economics*	4
								Journal of Environmental Economics And Management	4
								Energy Economics	4
Biodiversity conservation	50	Climate-change	49	Temperature	10	Model	7	*Global Change Biology*	25
								Biological Conservation	6
								Conservation Biology	5
Oceanography	49	Climate-change	17	Variability	11	Model	6	*Tellus Series A-Dynamic Meteorology and Oceanography*	6
								Journal of Geophysical Research	5
								Marine Ecology Progress Series	4
								ICES Journal of Marine Science	4
								Izvestiya Atmospheric and Oceanic Physics	4
Plant sciences	37	Climate-change	18	Responses	8	Temperature	7	*Phyton-Annales Rei Botanicae*	4
								American Journal of Botany	3
								Journal of Integrative Plant Biology	2
								Plant and Soil	2
								Plant Physiology	2
								Soil Science and Plant Nutrition	2
Marine and freshwater biology	37	Climate-change	22	Temperature	9	Biodiversity	6	*Hydrobiologia*	6
								Marine Ecology Progress Series	4
								ICES Journal of Marine Science	4

Table 5 Subject categories, most frequent keywords and most productive journals (continued)

Subject area	*Articles*	*Main keywords*						*Most productive journals*	*n*
		KW 1	*n*	*KW 2*	*n*	*KW 3*	*n*		
Water resources	35	Climate-change	21	Temperature	8	Trends	7	*Natural Hazards*	3
								Water Resources	2
								Journal of Water Resources Planning and Management- Asce	2
								Hydrological Processes	2
								Journal of Hydrology	2
								Environmental Geology	2
								Ocean & Coastal Management	2
								Hydrology and Earth System Sciences	2
								Physics and Chemistry of the Earth	2
								Environmental Earth Sciences	2
Geography, physical	31	Climate-change	16	Temperature	5	Climate	5	*Global and Planetary Change*	8
								Journal of Biogeography	4
								Palaeogeography Palaeoclimatology Palaeoecology	3
Engineering, chemical	29	Climate-change	5	Impact	3	CO2	3	*Applied Energy*	8
								Energy Sources Part A-Recovery Utilization and Environmental Effects	3
								Chemical & Engineering News	2
								TCE	2
								Energy & Fuels	2
								Environmental Progress	2

3.2 Keywords, subject areas of research and network of co-words

Table 4 lists the most common keywords, as well as the annual evolution. Excluding global warming, the most frequent keyword was climate change (n = 722), followed distantly by two keywords included in near 200 papers: model (n = 216) and temperature (n = 196). Other four keywords reported in more than one hundred papers were: climate (n = 170), variability (n = 148), impact (n = 146), carbon dioxide (n = 134), greenhouse gas emissions (n = 126) and simulations (n=103). Most of the keywords were observed to increase in frequency, especially in the second five-year period: 65% of papers related with climate change and with El Niño-southern oscillation (ENSO), respectively; near 63% of papers related with impact; 64% related with greenhouse-gas emissions.

The most productive subject categories, the three most common assigned keywords to the articles, and three journals publishing more articles in each subject categories are detailed in Table 5. In first place, the subject category meteorology and atmospheric sciences (n = 384) stood out, where the most common keywords were climate change (n = 162), model (n = 89) and variability (n = 86). Journals belonging to this subject category that published more articles were *Journal of Climate* (n = 95), *Climatic Change* (n=38) and *Climate Dynamics* (n=38). Climate change was the most frequent keyword in all subject categories. The second most productive subject category was environmental sciences (n = 253), which most frequent keywords was climate change (n = 174), model (n = 49) and temperature (n = 39). Journals belonging to this subject category with the highest number of publications were *Climatic Change* (n = 38), *Global Change Biology* (n = 25) and *Environmental Research Letters* (n = 24). Other three subject categories including more than 100 articles were: geosciences multidisciplinary (n = 176), with the most frequent keywords excluding climate change were climate and model; ecology (n = 144), with the keywords temperature and model; and environmental studies (n = 120), with the keywords model and food policy.

Figure 2 Network of co-words (see online version for colours)

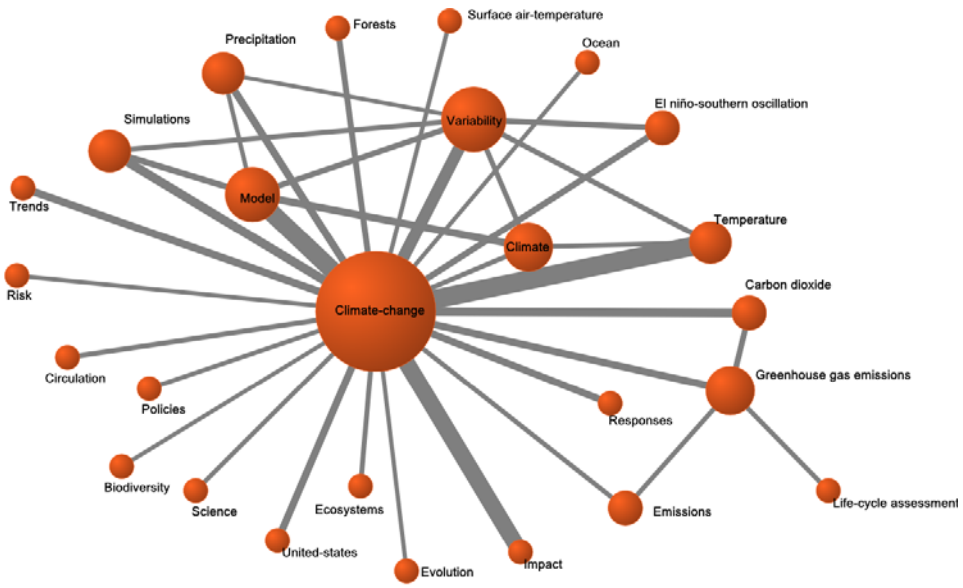


Table 6 Most cited papers

AUTHORS	*TITLE*	*SOURCE*	*TIMES CITED*
Held, IM; Soden, BJ	Robust responses of the hydrological cycle to global warming	*Journal of Climate* 2006; 19(21): 5686–5699	1,080
Pounds, JA; Bustamante, MR; Coloma, LA; Consuegra, JA; Fogden, MPL; Foster, PN; La Marca, E; Masters, KL; Merino-Viteri, A; Puschendorf, R; Ron, SR; Sanchez-Azofeifa, GA; Still, CJ; Young, BE	Widespread amphibian extinctions from epidemic disease driven by global warming	*Nature* 2006; 439(7073): 161–167	698
Meinshausen, M; Meinshausen, N; Hare, W; Raper, SCB; Frieler, K; Knutti, R; Frame, DJ; Allen, MR	Greenhouse-gas emission targets for limiting global warming to 2 degrees C	*Nature* 2009; 458(7242): 1158-U96	567
Vecchi, GA; Soden, BJ	Global warming and the weakening of the tropical circulation	*Journal of Climate* 2007; 20(17): 4316–4340	430
Crutzen, PJ; Mosier, AR; Smith, KA; Winiwarter, W	N2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels	*Atmospheric Chemistry and Physics* 2008; 8(2): 389–395	398
Parmesan, C	Influences of species, latitudes and methodologies on estimates of phenological response to global warming	*Global Change Biology* 2007; 13(9): 1860–1872	360
Dai, AG	Drought under global warming: a review	*Wiley Interdisciplinary Reviews-Climate Change* 2011; 2(1): 45–65	345
Wentz, FJ; Ricciardulli, L; Hilburn, K; Mears, C	How much more rain will global warming bring?	*Science* 2007; 317(5835): 233–235	340
Colwell, RK; Brehm, G; Cardelus, CL; Gilman, AC; Longino, JT	Global warming, elevational range shifts, and lowland biotic attrition in the wet tropics	*Science* 2008; 322(5899): 258–261	335
Jacobson, MZ	Review of solutions to global warming, air pollution, and energy security	*Energy & Environmental Science* 2009; 2(2): 148-173	334
Collins, M; An, SI; Cai, WJ; Ganachaud, A; Guilyardi, E; Jin, FF; Jochum, M; Lengaigne, M; Power, S; Timmermann, A; Vecchi, G; Wittenberg, A	The impact of global warming on the tropical Pacific ocean and El Nino	*Nature Geoscience* 2010; 3(6): 391–397	314
Memmott, J; Craze, PG; Waser, NM; Price, MV	Global warming and the disruption of plant-pollinator interactions	*Ecology Letters* 2007; 10(8): 710–717	302
Solomon, S; Rosenlof, KH; Portmann, RW; Daniel, JS; Davis, SM; Sanford, TJ; Plattner, GK	Contributions of stratospheric water vapor to decadal changes in the rate of global warming	*Science* 2010; 327(5970): 1219–1223	297
Lu, J; Vecchi, GA; Reichler, T	Expansion of the Hadley cell under global warming	*Geophysical Research Letters* 2007; 34(6): 0–0	279
Pandolfi, JM; Connolly, SR; Marshall, DJ; Cohen, AL	Projecting coral reef futures under global warming and ocean acidification	*Science* 2011; 333(6041): 418–422	274

Table 6 Most cited papers (continued)

AUTHORS	*TITLE*	*SOURCE*	*TIMES CITED*
Vicente-Serrano, SM; Begueria, S; Lopez-Moreno, JI	A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index	*Journal of Climate* 2010; 23(7): 1696–1718	270
Meehl, GA; Washington, WM; Collins, WD; Arblaster, JM; Hu, AX; Buja, LE; Strand, WG; Teng, HY	How much more global warming and sea level rise?	*Science* 2005; 307(5716): 1769–1772	266
Daufresne, M; Lengfellner, K; Sommer, U	Global warming benefits the small in aquatic ecosystems	*Proceedings of the National Academy of Sciences of the United States of America* 2009; 106(31): 12788–12793	254
Emanuel, K; Sundararajan, R; Williams, J	Hurricanes and global warming – results from downscaling IPCC AR4 simulations	*Bulletin of the American Meteorological Society* 2008; 89(3): 347	250
Malcolm, JR; Liu, CR; Neilson, RP; Hansen, L; Hannah, L	Global warming and extinctions of endemic species from biodiversity hotspots	*Conservation Biology* 2006; 20(2): 538–548	247
Oouchi, K; Yoshimura, J; Yoshimura, H; Mizuta, R; Kusunoki, S; Noda, A	Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: frequency and wind intensity analyses	*Journal of the Meteorological Society of Japan* 2006; 84(2): 259–276	241
Botkin, DB; Saxe, H; Araujo, MB; Betts, R; Bradshaw, RHW; Cedhagen, T; Chesson, P; Dawson, TP; Etterson, JR; Faith, DP; Ferrier, S; Guisan, A; Hansen, AS; Hilbert, DW; Loehle, C; Margules, C; New, M; Sobe	Forecasting the effects of global warming on biodiversity	*Bioscience* 2007; 57(3): 227–236	239
Sheffield, J; Wood, EF	Projected changes in drought occurrence under future global warming from multi-model, multi-scenario, IPCC AR4 simulations	*Climate Dynamics* 2008; 31(1): 79–105	233
Xie, SP; Deser, C; Vecchi, GA; Ma, J; Teng, HY; Wittenberg, AT	Global Warming Pattern Formation: Sea Surface Temperature and Rainfall	*Journal of Climate* 2010; 23(4): 966–986	233
Wing, SL; Harrington, GJ; Smith, FA; Bloch, JI; Boyer, DM; Freeman, KH	Transient floral change and rapid global warming at the Paleocene-Eocene boundary	*Science* 2005; 310(5750): 993–996	226
Lourens, LJ; Sluijs, A; Kroon, D; Zachos, JC; Thomas, E; Rohl, U; Bowles, J; Raffi, I	Astronomical pacing of late Palaeocene to early Eocene global warming events	Nature 2005; 435(7045): 1083–1087	222
Weber, EU	Experience-based and description-based perceptions of long-term risk: why global warming does not scare us (yet)	Climate Change 2006; 77(1–2): 103–120	212

Figure 2 shows the network of co-words. The size of the spheres and the number of connections having each keyword with others are proportional, and the thickness of lines connecting the spheres also behaves proportionally to the number of papers including simultaneously two keywords. A threshold of 15 co-occurrences has been applied; the network consisted of 26 keywords. Remarkably, the keyword climate change occupies a more central position, as it is strongly associated with the following keywords: temperature (n = 113 co-occurrences), model (n = 106), impact (n = 99), variability (n = 71), simulation (n = 53) and carbon dioxide (n = 51). Other words that act as intermediaries with less intensity are model, variability, climate and greenhouse gas emission.

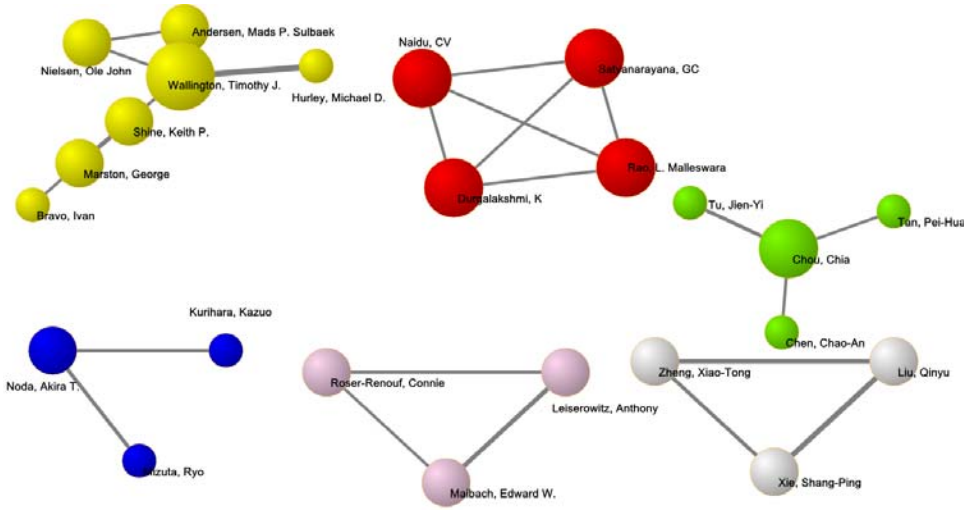
3.3 Most cited papers

Twenty-seven papers receiving more than 200 citations are showed in Table 6. The most cited article (n = 1,080) was entitled 'Robust responses of the hydrological cycle to global warming' and was published by *Journal of Climate* in 2006 by Held and Sodden, two researchers from Rosenstein School of Marine and Atmospheric Science (University of Miami, USA) and The Geophysical Fluid Dynamics Laboratory of National Oceanic and Atmospheric Administration (University of Princeton, USA), respectively. The second most cited paper (n = 698) was 'Widespread amphibian extinctions from epidemic disease driven by global warming', which was also published in 2006 in *Nature* by a research team from six countries (Costa Rica, Ecuador, USA, Japan, Venezuela and Canada). The authors highlighted a shift towards the optimal temperature conditions for *Batrachochytrium* in many highland localities. The urgency of reducing GHG concentrations was identified as top necessity to avoid promotion of increased infection disease activity and biodiversity loss. The third most cited paper, with 567 citations, was also published in *Nature* in 2009, by Meinshausen et al. from a collaboration of several institutions from the UK, Germany and Switzerland. A comprehensive probabilistic analysis was developed with the aim of quantifying the GHG emission budgets for the 2000–2050 period. Based on climate system properties distribution and observational constraints, these adjustments would theoretically limit global warming throughout the 21st century to below 2°C.

3.4 Collaboration network between authors, institutions and countries

Figure 3 shows the six main groups integrating the network of collaboration between authors. A threshold of almost four papers written in collaboration was applied. The size of the spheres is proportional to the number of connections having collaboration with others, and the size of the lines connecting two authors is proportional to the number of papers published in collaboration. A team of seven researchers integrate the first group with researchers belonging to five different institutions from four countries: University of Copenhagen (Denmark); California State University (USA); University of Reading (UK); University of Castilla-La Mancha (Spain) and Ford Motors Corporation (Miami, USA). Two groups of four components integrate researchers from Andhra University (India) and National Taiwan University (Taiwan), respectively. Finally, other three groups include researchers from Meteorology Research Institute (Ibarnki, Japan), George Mason University and Yale University (USA), and Tsinghua University (Beijing, China), respectively.

Figure 3 Network of collaboration between authors (see online version for colours)



Regarding the network of collaboration between institutions (Figure 4), with a threshold of two papers in cooperation, the main network includes eight non-connected groups and 25 institutions. Here, the size of the spheres is again proportional to the number of connections having one institution in collaboration, and the size of the lines connecting two institutions is proportional to the number of papers published in collaboration. The main group integrates eight institutions, seven from the USA and one from China. The most central institution in this group is the National Oceanic and Atmospheric Administration – NOAA, which connects with Ocean University of China trough the University of Hawaii. Other institutions in this group are Princeton University, University of Miami, University of California and University of Colorado. Other three groups of institutions included in this network belong to the following countries: Australia (University of Melbourne) and Germany (Potsdam University and Potsdam Institute for Climate Research); Japan (Japan Agency for Marine-Earth Science and Technology, University of Tokyo and National Institute for Environmental Studies); and France (Centre National de la Recherche Scientifique-CNRS, Université Pierre et Marie Curie and Institute Pierre Simon Laplace.

The network of collaboration between countries (Figure 5) shows, first, the most central position of four countries: USA, Germany, UK and France; second, the strongest cooperation between USA and China (n = 46), USA and UK (n = 39), USA and Australia (n = 22), UK and Germany (n = 21) and USA and France (n = 20); third, the cooperation between these countries and other more 'peripheral', including European (as Denmark, Spain, The Netherlands and Switzerland), American (as Canada) and Asian (as Japan and South Korea).

Figure 4 Network of collaboration between institutions (see online version for colours)

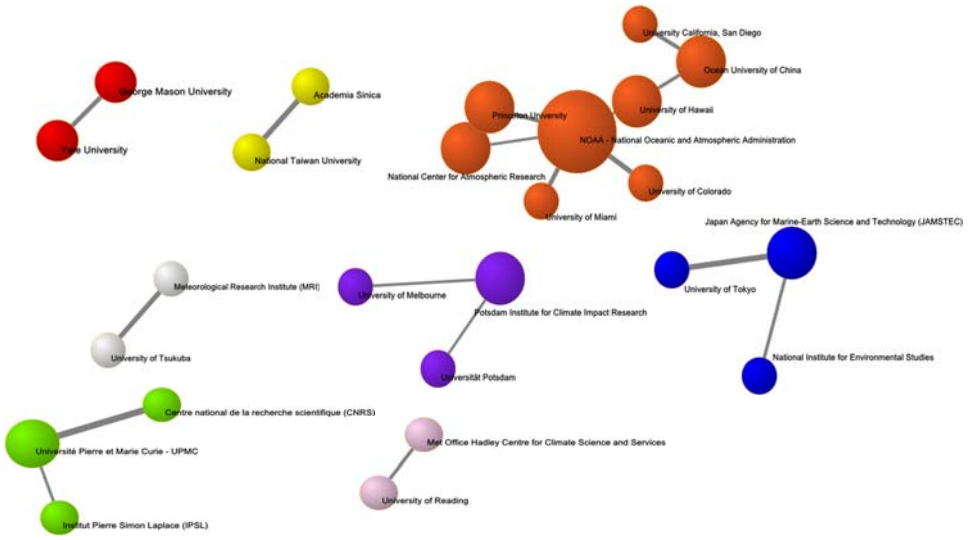
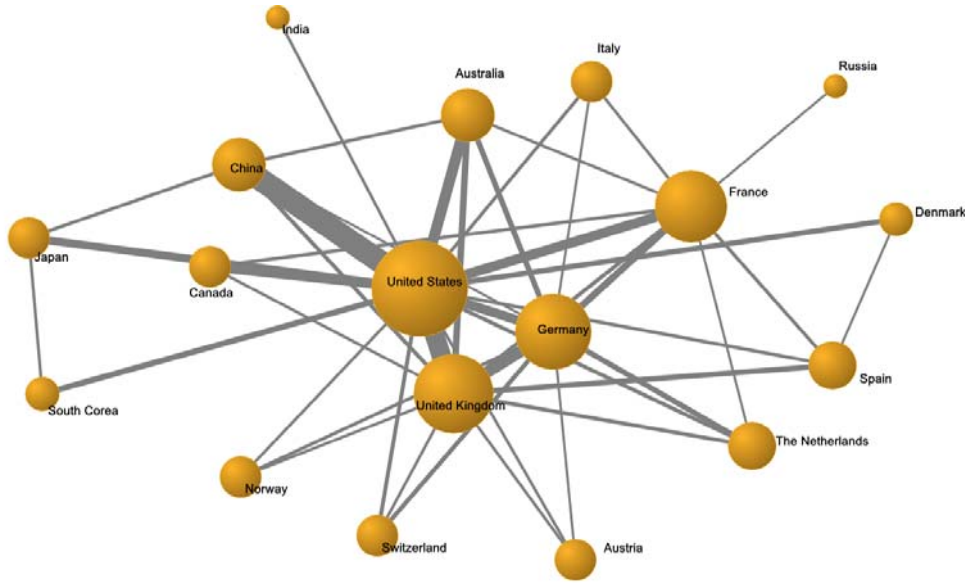


Figure 5 Network of collaboration between countries (see online version for colours)



4 Discussion

This work provides an approximation to the scientific trends on global warming research from articles published during a decade. This bibliometric study comprises the analyses of most productive and cited papers and journals, subject categories, research groups,

institutions and their international collaboration. It has also been shown the main topics discussed on this subject through the most assigned keywords and the SNAs of co-words.

The mitigation of global warming effects has become a top priority worldwide. A large number of publications have focused on reducing GHGs emissions in energy related scenarios at an engineering scale (Cortés-Borda et al., 2015). As an environmental issue global warming is becoming increasingly important for stakeholders and Media, global leaders, customers, environmentalists and investors which are taking this issue seriously. The inclusion of global warming related issues are nowadays part of the annual reports of many companies throughout the world (Ahmad and Hossain, 2015). Despite this fact, it is perceived that a substantial minority of citizens may understand and are vaguely aware of the consequences that climate change has on human health (Maybach et al., 2015).

An increasing number of local governments that have taken on initiatives can be nowadays identified; although it is unclear to what extent they can accumulate support for major shifts in global trends without strong actions at national and international levels (Ross et al., 2016). The recent Paris Climate Summit from 30 November to 12 December 2015, officially referred to as the 21st Conference of Parties (COP 21) under the United Nations Framework Convention on Climate Change (UNFCCC), was an important part of the international efforts to tackle climate change (Li, 2016)

The European Union has also targeted the mitigation of climate change effect as key priority. Europe is making a big effort to reduce its GHG emissions substantially while it is also encouraging other nations and regions to do likewise. A reduction in the emissions by 80–95% of the levels measured in 1990 is the aim intended to be achieved in 2050. At least 20% of the EU's budget for the 2014–2020 period (€180 billion) is assigned to climate change mitigation activities. This was included as extra funding from individual EU countries (European Commission, 2016). The US Government, through the US Environmental Protection Agency (EPA) is currently working on a number of steps to address the challenge of climate change. The promotion of clean energy economy and the reduction of GHGs emissions is intended to be achieved by promoting strong partnerships and common-sense regulatory initiatives, *Partnering with the Private Sector and Reducing EPA's Carbon Footprint* (EPA, 2016).

Haze pollution is one of the main concerns for the Chinese Government in recent years. Since 2007, the Chinese Government has implemented a national policy framework to include climate change adaptation in both urban and rural areas. With this strong campaign by a determined central government, local institutions are nominated as key actors to fight climate change effects. By 2010, all provinces had a strategic climate change adaptation plan (Li, 2013). On the other hand, and as part of the 12th Five-Year Plan for the Solar PV Industry the Chinese Government is determined to decrease the average total electricity consumption to 120 kW h/kg according to the (MIIT, 2012). The Action Plan for Air Pollution Prevention and Control (2013–2017) initiated in 2013 has targeted the three developed regions: the Beijing-Tianjin-Hebei region, the Yangtze River Delta (YRD) region and the Pearl River Delta (PRD), which all consist of megacities and city clusters (Sheehan et al., 2014) with strict obligations. The results of these Chinese Government policies may be the reason why the Chinese Academy of Science is the most productive institution, followed by NOAA with Similar results found by Li et al. (2011), where the most productive institution was also the Chinese Academy of Sciences while the National Oceanic and Atmospheric Administration appeared in the sixth place.

The number of published articles has grown since 2005 with most of papers (n = 995; 60%) published during the second five-year period. The increase in the research publications may be associated to an increased international attention to climate change effects especially after the entry into force of the Kyoto Protocol, which has been cited as the first step to globally reduce the influence of human activities on the climate system (Lorenzoni and Pidgeon, 2006). In the same way, the noticeable effects of climate change have induced an urgent and pervasive preoccupation worldwide, which calls for international strategies and ambitious global responses (Alex and Preedip Balaji, 2010).

In other similar studies, scientific production also increased in recent years, for example in the bibliometric analysis of solid waste research (Fu et al., 2010); organic farming (Aleixandre et al., 2015) and in carbon market research (Du et al., 2015). The increasing trend in the number of research publications observed during the past years may be thus due to the general increasing awareness on the environmental issues and specifically on global warming (in this study).

This work has identified the groups of authors and institutions that currently make up the research front in this area and its main research topics. This information would be useful worthwhile both to intensify the ties of collaboration between the teams investigating on similar or related subjects, or those beginners that may become active members of the established teams. Multinational and multidisciplinary teams are essential for the advancement of research, and it is imperative that the current research community recognises this fact and encourage interdisciplinary research (Bullock et al., 2007).

Author keywords showed relevant information about the main issues addressed and research trends that are important for researchers (Zhang et al., 2010). Excluding global warming, the most frequent keyword was climate change, followed by model and temperature, coinciding with similar bibliometric studies related with climate change where temperature and global warming were the most frequently used (Wang et al., 2014). A previous scientometric analysis revealed that research on climate change had grown rapidly, especially since the 1970s (Stanhill, 2001). Li et al. (2011) in a report that analysed research trends on global climate change also found an increase in the number of published papers.

Looking at the subject areas of research, as expected, global warming is dominated by natural sciences. In accordance with the previous rationale about keywords, it was observed that the articles were published in a vast variety of areas, including meteorology and atmospheric sciences, environmental sciences, geosciences, ecology, energy and fuels, economics and oceanography, among others. This fact is an evidence of the significance of global warming and its multidisciplinary nature, and also suggests that global warming is an area that needs the contributions of other research areas for its optimum development. Another characteristic that stood out was that climate change is the main research topic in almost all areas, which is a sign of its importance and impact on global warming regardless of the research area.

Encouraging the establishment of research networks, with research groups including scientists from different countries, would thus be a top priority strategy for cooperation. The research carried out by these international groups has many advantages such as: enhanced knowledge, quality improvement, and an increased innovation and competitiveness (Aleixandre et al., 2015). Regarding collaboration between institutions, the fact that WOS collects all the institutional addresses of the authors allows to know precisely the collaboration between centres. The USA appeared as the country in the centre of those collaborations.

From the content analysis of most cited papers, several considerations should be emphasised. First, most of them deal with several aspects of global warming (changes in the hydrological cycle, animal extinctions, predictions on increase of earth temperature, effects on drought, possible solutions to global warming, impact on oceans, including coral reef and sea level rise, relation with hurricanes and plant pollinator interactions, among others). Secondly, the scope of the identified journals denotes the multidisciplinary nature of the subject, contributing journals on climate, meteorology, environment, ecology, geophysics and of general purpose. Third, 9 out of 27 highly cited papers have been published in high impact factor journals of general scope such as *Nature* (three papers) and *Science* (six papers).

As in the study of Zhi et al. (2015) about carbon cycling research, China is one of the countries with more intense publication in global warming. This marked increase is probably due to China's efforts to mitigate air pollution by investing in relevant research and with the final goal of implementing large-scale air-cleaning actions (Chen et al., 2013; Wang et al., 2010). This result is in agreement with that found in other studies, such as, in the scientific analysis of the low carbon energy research during 2007-2016 period reported by Ossa et al. (2018), where the UK heads the ranking, followed by China, USA, Germany and Japan or in the study about urban heat island research from 1991 to 2015 reported by Huang and Lu (2018) where the five most productive countries were USA, China, UK, Japan and Italy.

5 Conclusions

This paper has provided a broad understanding on the global warming research topic during the 2005–2014 period. Many aspects embracing the most publishing and cited journals, institutions, countries, subject areas and topics of research, have been discussed, along with the identification of collaboration between researchers, institutions and countries. The results highlighted the significant increase in the number of research papers reported from 2005 (3%) to 2014 (18%). This growth indicates that global warming is a hot topic of increasing concern to more agents, becoming important in our society. A vast amount of journals from several subject areas, including high impact factor journals of general purpose such as *Nature* and *Science*, published the papers on the topic, being *Journal of Climate*, *Geophysical Research Letters* and *Climate Dynamics* the most productive journals. The countries with the highest number of publications were the USA, the UK and China. The most productive subject categories were meteorology and atmospheric sciences, environmental sciences and geosciences multidisciplinary. Almost all the countries in the study have the USA as the connecting country to which collaborate with. The analysis of keywords shows that topics related with climate change, impact, temperature, models and variability are the most important issues in the studies on global warming. The topics of most cited papers denotes the multidisciplinary nature of the global warming problem, with the inclusion of journals on climate, meteorology, environment, ecology, geophysics and of general purpose.

6 Limitations

The database used to collect the research papers, Web of Science Core Collection, does not include the totality of the published scientific research on global warming, so other available bibliographic databases could have complemented the research records. Nevertheless, the reason of selecting this database is because it is usually used in bibliometric studies analysing scientific research and includes the most significant journals in the world, which includes the most relevant papers. On the other hand, it supplies data about citations and journals impact factor, as well as the institutional affiliations of the authors, which allowed us to investigate the indicators of collaboration between institutions and countries.

7 Future research

Future directions in this line could follow the evolution of the networks of collaboration between researchers and institutions. Another line of research would investigate the development of main topics identified and the emergence of new research groups and new issues. It would be also interesting to look into other kind of information related with scientific research on global warming, as current research projects, doctoral thesis and conference proceedings, among others.

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