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A bibliometric study of earthquake research: 1900–2010

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Abstract We evaluated earthquake research performance based on a bibliometric analysis of 84,051 documents published in journals and other outlets contained in the Scientific Citation Index (SCI) and Social Science Citation Index (SSCI) bibliographic databases for the period of 1900–2010. We summarized significant publication indicators in earthquake research, evaluated national and institutional research performance, and presented earthquake research development from a supplementary perspective. Research output descriptors suggested a solid development in earthquake research, in terms of increasing scientific production and research collaboration. We identified leading authors, institutions, and nations in earthquake research, and there was an uneven distribution of publications at authorial, institutional, and national levels. The most commonly used keywords appeared in the articles were evolution, California, deformation, model, inversion, seismicity, tectonics, crustal structure, fault, zone, lithosphere, and attenuation.

Keywords Bibliometrics · Evaluation · Earthquake · Research performance

Introduction

An earthquake is a sudden and usually violent shock of the earth resulting from sudden displacements of earth's crust. Large earthquakes can cause significant loss of life and damage of property. Great efforts have been made around the world to better understand earthquake processes, help the public to more adequately prepare for earthquakes and

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associated hazards, and mitigate damages resulting from earthquakes (Geller 1997; Lindell 2000; Okada et al. 2004). In this article, we evaluate earthquake research performance based on a bibliometric analysis of 84,051 documents published in journals and other outlets contained in the Scientific Citation Index (SCI) and Social Science Citation Index (SSCI) bibliographic databases for the period of 1900–2010. This bibliometric analysis could help evaluate the performance of global earthquake research and provide a supplementary perspective on research frontiers (Chen 2004). In the meantime, bibliometric studies that evaluate research progresses based on publication records (Pritchard 1969; Andres 2009) have a long research strand and have been applied to evaluate research progress in a variety of fields (Nederhof et al. 2005; Chiu and Ho 2007; Liu et al. 2011; Tsay 2011).

This paper aims to fill voids in previous bibliometric studies of earthquake research, which have often been limited in scope, analytical methods and substantive discussions. For example, Li et al. (2009) and Taskin (2010) restricted their analysis to a subset of earthquake literature and thus utilized a comparatively small bibliometric dataset, by focusing on earthquake studies in medical journals (2,227 papers) and those published by Turkish scholars (1,098 papers), respectively. In the meantime, Sheeba and Nithyanandam (2011) provided an analysis of global trends in earthquake research, however their analysis was limited to basic bibliometrics of individual, institutional and national performances, and did not attempt to explain the development of this field behind observed patterns. Chiu and Ho (2007) performed a rather comprehensive analysis of world's tsunami research with similar perspectives employed in this paper, and we extend their analysis in terms of both method and scope: methodologically, we incorporate more advanced bibliometric measures (e.g., field citation scores) and analytical procedures (e.g., network analysis and author clustering); and we incorporate a larger sheer of earthquake literatures and provide substantive discussions for observed bibliometric patterns. In addition, earth science as a whole has been studied with bibliometric techniques, however specific patterns in the field of earthquake studies have been largely neglected (Gokceoglu et al. 2008; Mikki 2010).

Therefore, we would provide a comprehensive bibliometric analysis and substantive discussion of research progress in earthquake research. More specifically, we aim at (1) summarizing significant publication patterns in earthquake research with basic statistics as well as advanced analytics, (2) evaluating research performance from multiple perspectives, such as author, institution, nation, journal, and keywords (Slyder et al. 2011), and (3) presenting a supplementary evaluation of research development, which is complimentary to conventional reviews of research fields.

Data and methods

We amassed publications on earthquake using the Scientific Citation Index (SCI) and Social Science Citation Index (SSCI) bibliographic databases. Despite the emergence of other bibliometric databases in recent years, these two databases remain as the de facto standard sources in the analysis of scientific output (Kostoff 2000). We performed bibliographic searches using the following searching words: "earthquake", "seismology", "seismic", and "quake", and located publications that contained these searching words in their titles, abstracts, or keywords, and retrieved author name(s), author affiliation(s), subject category(ies), journal name(s), publication title(s), and publication year(s) of each publication. Based on this searching strategy, a total of 84,051 publications were identified in the SCI and SSCI databases for the period 1900–2010 (Our bibliometric database far exceeds previous datasets for bibliometric analysis of earthquake literature, the largest among which has around 15,000 entries). Still, we grouped research conducted in England, North Ireland, Scotland, and Wales into publications from the United Kingdom (UK). In determining collaborated works among authors, institutions, or countries, each signatory on publications was treated equally.

We then performed a bibliometric analysis to demonstrate trends in earthquake studies from the following perspectives: document types and languages, publication outputs, subject categories and major journals, author productivity, geographic and institutional distribution of publications, as well as keywords analysis.

Results and discussions

Document types and languages

Nineteen document types[1] were found among the total 84,051 publications, and the most frequent document type was peer-reviewed journal articles (67,932), which accounted for 81.0% of the total publications. Proceeding papers (6,150; 7.3%), meeting abstracts (3,515; 4.2%), editorial materials (1,807; 2.2%), reviews (1,715; 2%) and letters (928; 1.1%) are document types with a significant portion of the total. Other less significant document types included note (762), news item (409), discussion (318), correction (212), book review (195), correction/addition (50), reprint (19), biographical item (18), abstract of a published item (14), software review (4), chronology (1), hardware review (1), and bibliography (1) (Numbers in parentheses represent quantities of individual document types). Following the conventions used in other bibliometric studies, we restricted our further analysis to articles, which are peer-reviewed and represent original scientific development. Publications of all other types were thus removed from the analysis for the rest of this article.

As for publishing language, 64,363 or 94.7% of the 67,932 journal articles were written in English. This observation was consistent with the fact that English is the prevalent academic language and that most SCI and SSCI indexed journals are published in English. Other publication languages included Russian (1,351), Chinese (1,086), French (481), German (225), Japanese (115), Spanish (94), Ukrainian (72), Italian (45), Turkish (27), Croatian (24), Polish (18), Czech (6), Slovak (5), Portuguese (4), Dutch (4), Romanian (2), Serbian (2), Malay (2), Serbo-Croatian (1), Arabic (1), Hungarian (1), Welsh (1), Korean (1), and Lithuanian (1).

Publication outputs

Research output descriptors suggested a solid development in earthquake research, in terms of both increasing scientific production and research collaboration. There was a significant increase in earthquake research since the 1990s (Fig. 1), even after controlling for the increasing number of journals and publications indexed in the SCI and SSCI databases. Along with the common explanations such as technological development and social awareness of hazards, we conjectured that this increasing number of publications on earthquakes co-occurred with earthquake disasters. For example, we observed a significant leap in the number of published articles in the US around 1990 after the Loma Prieta earthquake in 1989. The 1989 Loma Prieta earthquake was the second largest earthquake in

[1] Records in the SCI/SSCI databases were categorized as one of the thirty-two (32) ISI document types. A list of all document types can be found on ISI websites.

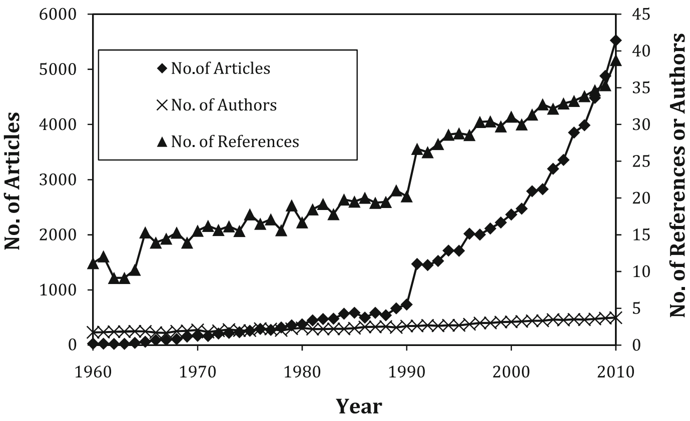

Fig. 1 Scientific outputs descriptors during 1960–2010

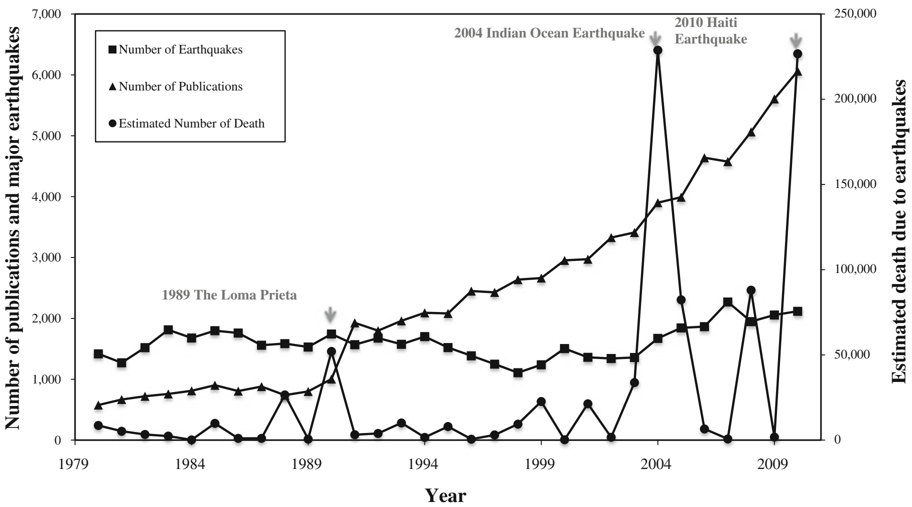

Fig. 2 Number of major earthquakes, estimated death, and publications

the contiguous US—the country which produced most earthquake studies. Moreover, the increasing number of estimated death from earthquakes, as represented by those in Chile, Indonesia, and Japan, was consistent with the growing number of earthquake publications in the last 5 years (Fig. 2). The propelling effect of major earthquakes on scientific productions in earthquake research has also been observed in Li et al. (2009) and Taskin (2010) for Wenchuan earthquake in China and Marmara earthquake in Turkey, respectively. We also perceived a continuously increasing number of major earthquakes in the last decade. Annual production of publications on earthquake increased from 306 in 1970 to 1,004 in 1990, and then to 6,063 in 2010. The number of authors per article, which is usually called the collaboration index, was 1.7, 2.5, and 3.7 in 1960, 1990 and 2010, respectively. This increasing number of authors per article suggested that earthquake studies had been becoming more collaborative in recent years, which was consistent with collaboration patterns in other research fields (Liu et al. 2011) and previous observations

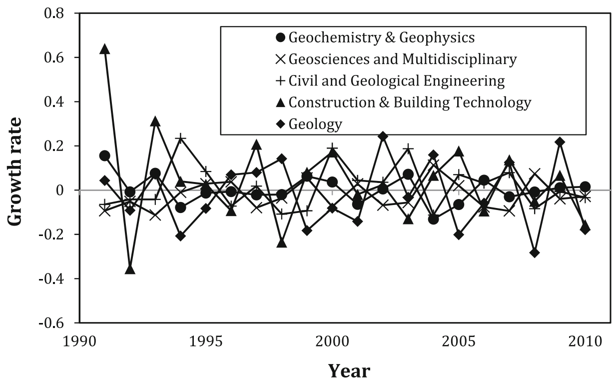

Fig. 3 Annual growth rates of articles in most active subject categories

for the field of earthquake research (Li et al. 2009). The expansion of this field could also be reflected by the increasing number of references per article, which grew from 20.2 in 1990 to 38.7 in 2010. On average, publications on earthquake received 12.9 citations and had 12.7 pages during our study period.

Subject categories and major journals

Earthquake research spanned over 223 ISI identified subject categories in our database. The four most common categories were geochemistry and geophysics (26,608 articles; 28.3% of the total), multidisciplinary geosciences (18,493; 19.7%), civil engineering (7,735; 8.2%), and geological engineering (5,339; 5.7%), followed by construction and building technology (3,049; 3.2%), multidisciplinary sciences (3,035; 3.2%), geology (2,369; 2.5%), oceanography (1,974; 2.1%), mechanical engineering (1,513; 1.6%), and petroleum engineering (1,452; 1.5%). As engineering subjects top this ranking, there implied an applied tradition in earthquake studies. We also demonstrated annual growth rates of top subject categories in Fig. 3. Despite that these subject categories enjoyed a continuous growth in the last two decades, their annual growth rates fluctuated in a volatile fashion, suggesting that the research focus in earthquake shifted frequently.

To assess performance of papers across fields, we summed all of the corresponding FCS (Field Citation Score) values for each paper and calculated a field normalized measured impact ratio (CPP/FCSm) (Van Raan 2000). CPP represents the average number of citations per publication within respectively fields, and FCS represents the number of citations one would expect for a paper published in all journals within a specific field, then FCSm is average expected citations across different fields. Figure 4 demonstrates a spectral analysis of the research outputs of earthquake across those fields with at least 1,000 publications. The darkness of the bar chart corresponds to the average normalized score for the set of papers published in the corresponding field. The largest impact (CPP/FCSm = 3.18) was for multidisciplinary sciences, where lower, but still substantial impact levels (CPP/FCSm above 1.5) were also observed for the fields of geochemistry and geophysics, geology, and multidisciplinary geosciences. The field normalized citation scores indicate that publications in these fields were highly influential and visible, far exceeding the number of citations expected for publications in similar fields for the same time period (Rosas et al. 2011).

Earthquake research appeared in 2,884 SCI and SSCI indexed journals. We presented the 25 journals that published most earthquake studies in Table 1, along with the number of

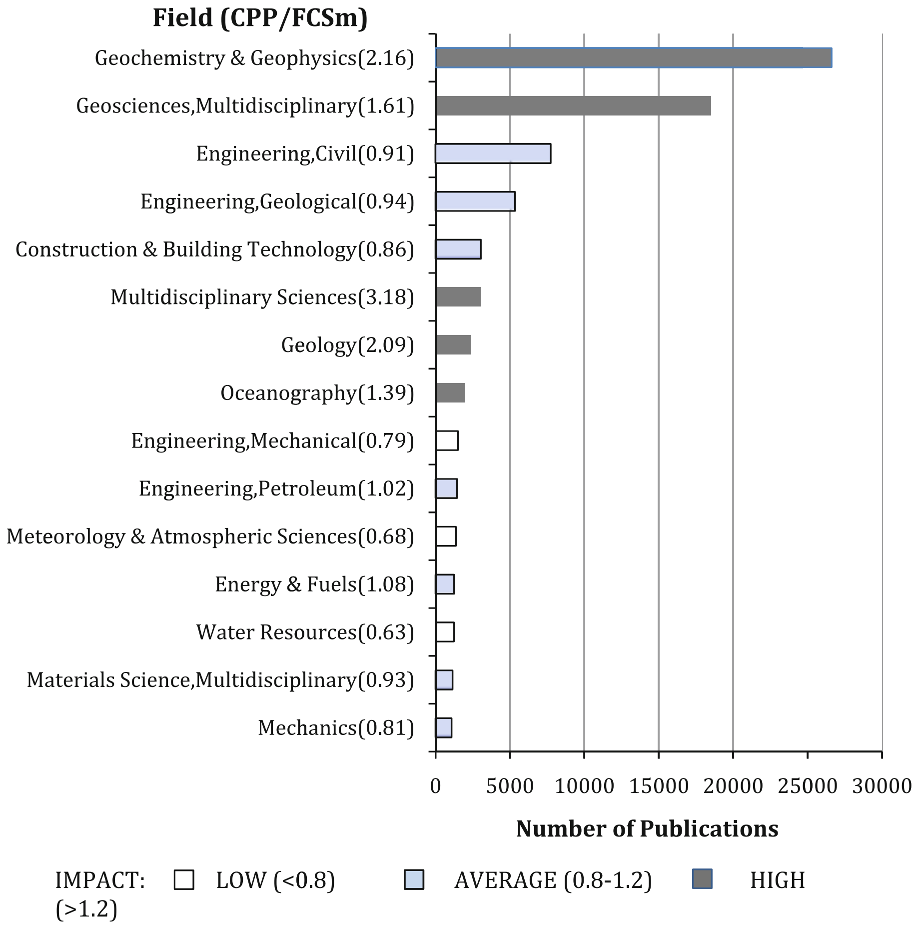

Fig. 4 Research output profile of earthquake across the top 15 fields, 1900–2010

papers, the number of citations received, and the impact factors of each journal. There was a high concentration of earthquake publications in these top journals, which follows the Zipf's law and is consistent with observation in other fields. These 25, or 0.86% out of the 2,884 journals, had published 33,121 or 48.8% of the total 67,932 articles and received 589,569 or 67.53% of the total 873,089 citations. Major publication outlets of earthquake research included *Bulletin of the Seismological Society of America* (4,158 articles), *Journal of Geophysical Research-Solid Earth* (3,630), *Geophysical Journal International* (3,309), *Geophysical Research Letters* (2,844), and *Geophysics* (2,390). These were also journals with most citations, as *Journal of Geophysical Research-Solid Earth* and *Bulletin of the Seismological Society of America* accounted for 20% of the total citations of all retrieved earthquake research articles. Earthquake articles had on average drawn more citations than Journals' ISI impact factors, despite the fact that the latter are computed within a 2-year window. Still, this could suggest that earthquake researches have performed well in boosting journals' reception.

Six articles were cited more than 1,000 times in the SCI/SSCI databases, including *The Composition of The Earth* (McDonough and Sun 1995), *Tectonic Stress and Spectra of*

Table 1 The 25 most active journals in earthquake research

Journal	TP	TP%	TC	TC%	TC/TP	IF
Bulletin of the Seismological Society of America	4,158	6.12	83,610	9.58	20.11	2.027
Journal of Geophysical Research-Solid Earth	3,630	5.34	96,124	11.01	26.48	3.082
Geophysical Journal International	3,309	4.87	51,770	5.93	15.65	2.411
Geophysical Research Letters	2,844	4.19	44,926	5.15	15.80	3.505
Geophysics	2,390	3.52	30,077	3.44	12.58	1.404
Tectonophysics	1,961	2.89	30,036	3.44	15.32	2.509
Earthquake Engineering & Structural Dynamics	1,566	2.31	17,727	2.03	11.32	1.403
Pure and Applied Geophysics	1,250	1.84	12,288	1.41	9.83	1.091
Earth and Planetary Science Letters	1,226	1.80	26,344	3.02	21.49	4.279
Journal of Structural Engineering-ASCE	1,132	1.67	11,769	1.35	10.40	0.834
Engineering Structures	998	1.47	5,760	0.66	5.77	1.363
Chinese Journal of Geophysics-Chinese Edition	919	1.35	2,710	0.31	2.95	0.832
Physics of the Earth and Planetary Interiors	850	1.25	12,004	1.37	14.12	2.640
Geology	793	1.17	21,932	2.51	27.66	4.026
Soil Dynamics and Earthquake Engineering	769	1.13	4,144	0.47	5.39	1.010
Marine Geology	733	1.08	12,107	1.39	16.52	2.517
Nature	684	1.01	34,261	3.92	50.09	36.101
Geophysical Prospecting	641	0.94	4,782	0.55	7.46	1.493
Earth Planets and Space	501	0.74	3,107	0.36	6.20	1.112
Journal of Geophysical Research	500	0.74	31,617	3.62	63.23	3.303
Journal of Volcanology and Geothermal Research	475	0.70	6,265	0.72	13.19	1.941
Science	473	0.70	29,069	3.33	61.46	31.364
Journal of Seismology	464	0.68	3,446	0.39	7.43	1.274
Tectonics	431	0.63	11,327	1.30	26.28	3.147
Earthquake Spectra	424	0.62	2,367	0.27	5.58	3.744

TP number of publication, *TC* total citation count, *TC/TP* average of citations in a paper, *IF* 2010 ISI Impact factor

Seismic Shear Waves From Earthquakes (Brune 1970), and *New Emprical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement* (Wells and Coppersmith 1994), with 2,284, 1,638, and 1,412 citations from ISI Web of Sciences, respectively. We acknowledged that citations may well come from other non-SCI/SSCI publications, and thus focused on the general trend and pattern rather than the exact citation counts in the analysis.

Author productivity

As consistent with observations in other fields, a small group of prolific authors contributed to a significant share of publications in earthquake research. For example, 62,638 or 88.9% of the 70,465 authors who contributed to earthquake research had signed on less than five papers, while the top 200 or 0.28% authors produced 12,646 or 6.1% of the total signatories. The most productive authors in earthquake research were Kanamori H with 169 articles, followed by Panza GF with 127 papers, McMechan GA with 126, Kennett BLN with 123, Hasegawa A with 122. We also listed 30 most productive and cited authors in Table 2.

Table 2 The 30 most productive and most cited authors

Most prolific author					Most cited author			
Name	TP	CP	TC	TC/TP	Name	TP	TC	TC/TP
Kanamori, H	169	157	9,168	54.25	Kanamori, H	169	9,168	54.25
Panza, GF	127	126	1,502	11.83	Aki, K	93	6,075	65.32
McMechan, GA	126	122	1,482	11.76	Dziewonski, AM	49	4,860	99.18
Kennett, BLN	123	98	4,041	32.85	Engdahl, ER	46	4,854	105.52
Hasegawa, A	122	122	3,206	26.28	Brune, JN	82	4,398	53.63
Zhao, DP	120	119	3,203	26.69	Kennett, BLN	123	4,041	32.85
Hayakawa, M	117	115	1,588	13.57	Anderson, DL	42	4,030	95.95
Sato, T	113	109	1,330	11.77	Sykes, LR	40	3,596	89.90
Trifunac, MD	111	86	2,302	20.74	Wyss, M	97	3,468	35.75
Lay, T	107	105	2,543	23.77	Stein, RS	41	3,390	82.68
Toksoz, MN	107	107	3,213	30.03	Scholz, CH	48	3,310	68.96
Wang, CY	105	101	1,142	10.88	Silver, PG	62	3,308	53.35
Singh, SK	97	97	1,957	20.18	Ellsworth, WL	43	3,242	75.40
Wyss, M	97	79	3,468	35.75	Ekstrom, G	94	3,237	34.44
Burgmann, R	95	94	2,577	27.13	Toksoz, MN	107	3,213	30.03
Giardini, D	95	93	1,837	19.34	Detrick, RS	58	3,207	55.29
Ekstrom, G	94	88	3,237	34.44	Hasegawa, A	122	3,206	26.28
Aki, K	93	78	6,075	65.32	Zhao, DP	120	3,203	26.69
Helmberger, DV	93	93	2,890	31.08	Mooney, WD	69	3,129	45.35
Okal, EA	93	77	1,566	16.84	Christensen, NI	57	3,031	53.18
Chopra, AK	92	88	1,710	18.59	Jackson, J	56	2,967	52.98
Campillo, M	88	87	2,727	30.99	Hyndamn, RD	71	2,956	41.63
Sato, H	88	74	1,262	14.34	Helmberger, DV	93	2,890	31.08
White, RS	88	83	2,371	26.94	Smith, RB	50	2,883	57.66
Shearer, PM	86	78	2,820	32.79	Shearer, PM	86	2,820	32.79
Kanazawa, T	83	83	1,075	12.95	Rice, JR	51	2,817	55.24
Boschi, E	82	74	1,849	22.55	King, GCP	39	2,796	71.69
Brune, JN	82	68	4,398	53.63	Campillo, M	88	2,727	30.99
Kaneda, Y	80	80	1,030	12.88	Heaton, TH	34	2,648	77.88
Kodaira, S	80	80	1,348	16.85	Burgmann, R	95	2,577	27.13

TP total publications, *CP* collaborated publications, *TC* total citation count, *TC/TP* average of citations in a paper; Scholars underlined are among top 30 in both rankings

Twelve authors (Kanamori H, Kennett BLN, Hasegawa A, Zhao DP, Toksoz MN, Wyss M, Burgmann R, Ekstrom G, Aki K, Helmberger DV, Shearer PM, Brune JN) were listed in both rankings. This ranking of authors was in general consistent with Web of Sciences' list of top 20 seismologists (Thomson Reuters 2010). There was a high proportion of Japanese researchers (9 out of 30) in the top 30 list, suggesting that there were many active researchers conducting earthquake studies in Japan-an earthquake prone country.

We analyze the collaboration pattern for the 100 most productive author with VOSview (Waltman et al. 2010), and collaboration map is presented as Fig. 5. The size of circles represents the amount of publications, and the distance between two circles is inversely proportional to the number of collaboration between individual authors, i.e., shorter

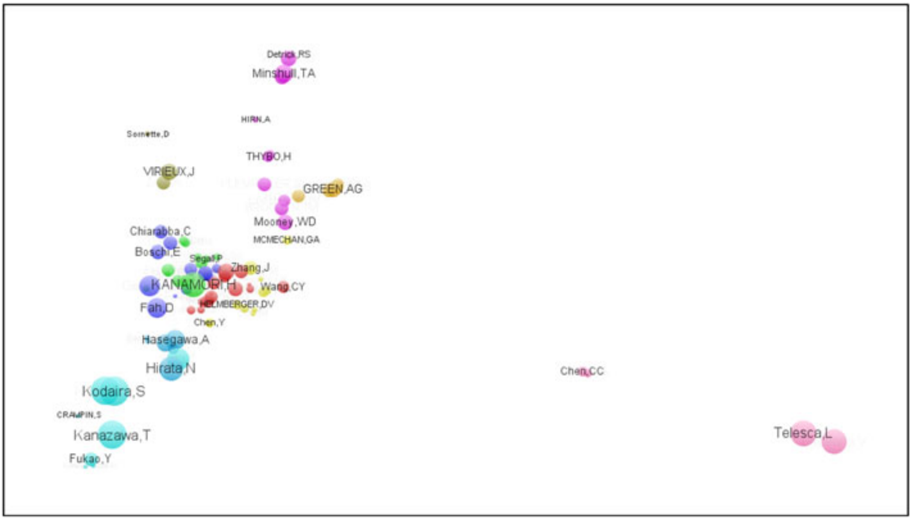

Fig. 5 Combined mapping and clustering of the 100 most productive authors in earthquake research during 1900–2010

distances suggest more collaboration. We noticed that several authors tended to cooperate with a small group of collaborators, generating 10 major clusters of authors, each of which usually have one or two core authors. Author productivity analysis could be biased due to the fact that two or more authors may have the same name initials (e.g., Wang, CY), or authors may use different names in their publications (e.g., names changed due to marriage). So an "international identity number (IIN)" which is offered to an individual when he/she first publishes in an ISI-listed journal is exigently in need. We believe assigning and tracing IIN offers a method that wouldassess authorship more appropriately.

Geographic and institutional distribution of publications

We present publication indicators for the 30 most productive countries/territories in earthquake research were presented in Table 3, suggesting a geographic inequality in earthquake research: out of these 30 countries, 17 were from Europe, 8 from Asia, 3 from North America, and none from South America, Oceania or Africa. We conjecture that this uneven geographic distribution was correlated with individual countries' proneness to earthquakes, as countries like Japan, and Iran usually did not have such high publication ranks in other scientific fields. Economic development and thus scientific investment also contributed to this distribution, as some major industrialized countries (G7 group: Canada, France, Germany, Italy, Japan, the UK, and the USA) and developing countries (Russia, India, and China) were all among countries on the list.

The U.S. topped the productivity ranking of countries, with the highest number of single-country (15,922) and internationally collaborative articles (7,363). Japan published the second highest number of articles (5,682), followed by France (4,801), the UK (4,659), Italy (4,351), and Germany (3,932). As also observed in other fields, internationally collaborated articles tended to draw more citations than those single-country publications. The U.S.'s central position in earthquake research could also be observed by its pivotal role in the national collaboration network in earthquake research (Fig. 4), where the nodal size

Table 3 The 30 most productive countries/territories in earthquake research

Country	TP	Single-country				Internationally collaborated			
		SP	TC	TC/SP	SP%	CP	TC	TC/CP	CP%
USA	23,285	316,350	282,987	19.87	68.38	7,363	135,575	18.41	31.62
Japan	5,682	41,260	40,614	11.09	65.51	1,960	28,127	14.35	34.49
France	4,801	28,621	31,410	15.58	38.26	2,964	54,803	18.49	61.74
UK	4,659	34,775	38,414	16.23	45.98	2,517	43,179	17.15	54.02
Italy	4,351	26,626	11,873	9.77	62.61	1,627	21,884	13.45	37.39
China	3,932	8,567	36,486	3.30	66.10	1,333	12,638	9.48	33.90
Canada	3,696	27,482	26,168	12.68	58.66	1,528	23,304	15.25	41.34
Germany	3,066	15,204	20,120	12.73	38.94	1,872	27,175	14.52	61.06
Russia	2,555	3,306	5,606	2.08	62.27	964	12,892	13.37	37.73
India	2,218	9,956	8,578	5.59	80.30	437	4,744	10.86	19.70
Taiwan	1,776	6,664	8,772	6.07	61.77	679	7,844	11.55	38.23
Australia	1,569	10,458	6,152	14.11	47.23	828	13,848	16.72	52.77
Turkey	1,374	4,431	10,589	5.33	60.55	542	7,601	14.02	39.45
Greece	1,343	6,522	6,519	7.77	62.47	504	6,252	12.40	37.53
Norway	1,247	7,203	6,914	12.17	47.47	655	8,768	13.39	52.53
Spain	1,241	4,738	7,535	9.57	39.89	746	9,584	12.85	60.11
New Zealand	1,129	7,601	8,137	13.77	48.89	577	7,962	13.80	51.11
USSR	1,036	4,446	2,858	4.73	90.73	96	2,163	22.53	9.27
Switzerland	1,010	5,540	5,346	18.34	29.90	708	11,352	16.03	70.10
Netherlands	954	5,224	7,685	13.60	40.25	570	9,874	17.32	59.75
Mexico	930	3,567	6,164	7.91	48.49	479	6,665	13.91	51.51
South Korea	781	1,964	1,303	4.18	60.18	311	2,258	7.26	39.82
Iran	697	814	3,173	1.88	62.27	263	1,972	7.50	37.73
Israel	537	2,689	2,211	9.47	52.89	253	3,534	13.97	47.11
Denmark	501	1,877	2,209	10.15	36.93	316	5,854	18.53	63.07
Sweden	443	2,114	1,853	11.43	41.76	258	4,049	15.69	58.24
Belgium	400	769	2,023	9.61	20.00	320	4,686	14.64	80.00
Czech Republic	371	1,269	1,433	6.64	51.48	180	1,822	10.12	48.52
Poland	363	1,114	1,315	5.77	53.17	170	2,728	16.05	46.83
Hong Kong	335	944	1,550	7.67	36.72	212	1,611	7.60	63.28

TP total publication, *SP* single-country publication, *CP* internationally collaborated publication, *TC* citations

corresponds to eigenvalue centrality in the collaboration network and tie strengthen represents amount of papers co-signed by a pair of nations/territories. The eigenvalue centrality does not only measure the "quantity" of research collaborations, but also reveal nations/territories that were pivotal in forming global research communities (Fig. 6).

There was also an uneven institutional distribution of earthquake publications among 17,255 institutions that contributed to the publications. The US Geological Survey (USGS) led institutional productivity ranking with 2,536 papers, followed by the Russian Academy of Sciences with 1,600, University of Tokyo with 1,374, University of California-Berkeley with 1,129, and Caltech with 1,076. These institutions are also central participants in the institutional collaboration network. The institutional productivity values could be biased by

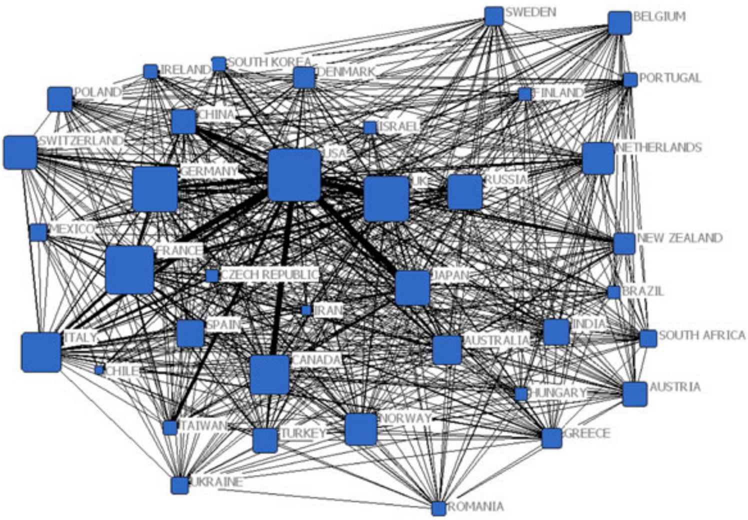

Fig. 6 National/Territorial collaboration network of 30 most central countries in earthquake research (the nodal size corresponds to network eigenvalue centrality in the collaboration network and tie strengthen represents amount of papers co-signed by a pair of nations/territories)

the fact that organizations such as the Chinese Academy of Sciences and the Russian Academy of Sciences are in fact organizations that consist of hundreds of branch institutions. Inter-institutional collaboration was more prevalent than international collaboration, as individual articles were collaborated by 1.8 institutions and 1.3 countries on average. Moreover, more than 60% of papers produced by the 30 most productive institutions in earthquake research were inter-institutionally collaborated. Similar to internationally collaborated articles, inter-institutionally collaborative articles were cited more often than those produced by single institutions (Table 4; Fig. 7).

Temporal evolution of keyword frequencies

We performed a keywords analysis to gain insights about earthquake research trends and frontiers (Chiu and Ho 2007). The keywords analysis provided an overview of research trends, as keywords reflect the focuses of individual articles (Table 5). We used two types of keywords: author keywords and keywords plus (Garfield 1990). The former were provided by authors as parts of the articles, and the latter were generated by ISI based on an article's references. Author keywords and keywords plus were grouped and referred as keywords for simplicity.

There were 76,892 unique keywords in the database used in this analysis, with a total of 435,899 occurrences. However, 49,051 or 63.7% out of these 76,892 keywords appeared only once, and 71,452 (92.9%) keywords appeared less than ten times. We presented the 50 most frequently used keywords within each of the 5-year intervals during 1991–2010 in Table 5. These 50 or 0.06% of the 76,892 keywords appeared 62,712 times and, thus, were responsible for 14.6% of the total keyword occurrences.

Over the 20 years, the most commonly used keywords appeared in the articles were earthquake, evolution, California, deformation, model, inversion, seismicity, tectonics, crustal structure, fault, zone, lithosphere, and attenuation. Although it was not surprising to

Table 4 The 30 most productive research institutions in earthquake research

Institution	TP	Single-institution				Inter-institutional			
		SI	TC	TC/SI	SI%	CI	TC	TC/CI	CI%
USGS, USA	2,536	945	27,353	28.94	37.26	1,591	49,909	31.37	62.74
Russian Academy of Sciences, Russia	1,600	917	1,751	1.91	57.31	683	7,057	10.33	42.69
University of Tokyo, Japan	1,374	415	5,628	13.56	30.20	959	14,015	14.61	69.80
University of California-Berkeley, USA	1,129	371	7,263	19.58	32.86	758	13,713	18.09	67.14
Caltech, USA	1,076	379	16,238	42.84	35.22	697	21,119	30.30	64.78
Chinese Academy of Sciences, China	965	294	1,213	4.13	30.47	671	3,421	5.10	69.53
Stanford University, USA	932	288	8,373	29.07	30.90	644	16,790	26.07	69.10
University of California-San Diego, USA	871	263	6,761	25.71	30.20	608	13,334	21.93	69.80
Kyoto University, Japan	841	243	2,308	9.50	28.89	598	6,144	10.27	71.11
University of Texas, USA	779	282	4,975	17.64	36.20	497	11,277	22.69	63.80
INGV, Italy	770	215	2,248	10.46	27.92	555	5,235	9.43	72.08
University of Southern California, USA	748	202	3,821	18.92	27.01	546	12,049	22.07	72.99
Columbia University, USA	735	236	7,390	31.31	32.11	499	12,075	24.20	67.89
MIT,USA	716	225	8,166	36.29	31.42	491	15,592	31.76	68.58
IPGP, France	710	113	2,846	25.19	15.92	597	13,933	23.34	84.08
Geological Survey, Canada	670	169	3,695	21.86	25.22	501	12,154	24.26	74.78
University of California-Los Angeles, USA	588	177	4,487	25.35	30.10	411	11,353	27.62	69.90
University of Colorado, USA	583	143	3,149	22.02	24.53	440	10,542	23.96	75.47
University of Cambridge, UK	563	155	3,658	23.60	27.53	408	10,385	25.45	72.47
National Geophysics Research Institute, India	557	386	2,903	7.52	69.30	171	1,774	10.37	30.70
Tohoku University, Japan	516	149	2,878	19.32	28.88	367	4,575	12.47	71.12
China Earthquake Administration, China	507	141	425	3.01	27.81	366	1,633	4.46	72.19
National Taiwan University, Taiwan	496	95	473	4.98	19.15	401	4,084	10.18	80.85
CNR, Italy	480	83	932	11.23	17.29	397	5,014	12.63	82.71

Table 4 continued

Institution	TP	Single-institution				Inter-institutional			
		SI	TC	TC/SI	SI%	CI	TC	TC/CI	CI%
University of Washington, USA	462	112	3,197	28.54	24.24	350	6,707	19.16	75.76
Geoforschungszentrum Potsdam, Germany	460	58	897	15.47	12.61	402	7,080	17.61	87.39
Indian Institute of Technology, India	458	260	1,167	4.49	56.77	198	962	4.86	43.23
CNRS, France	453	33	390	11.82	7.28	420	7,419	17.66	92.72
University of British Columbia, Canada	442	150	2,383	15.89	33.94	292	4,313	14.77	66.06
University Nacional Autonoma Mexico, Mexico	442	118	1,082	9.17	26.70	324	3,660	11.30	73.30

TP total publication, *SI* single-institution publication, *CI* inter-institutionally collaborated articles, *TC* total citations

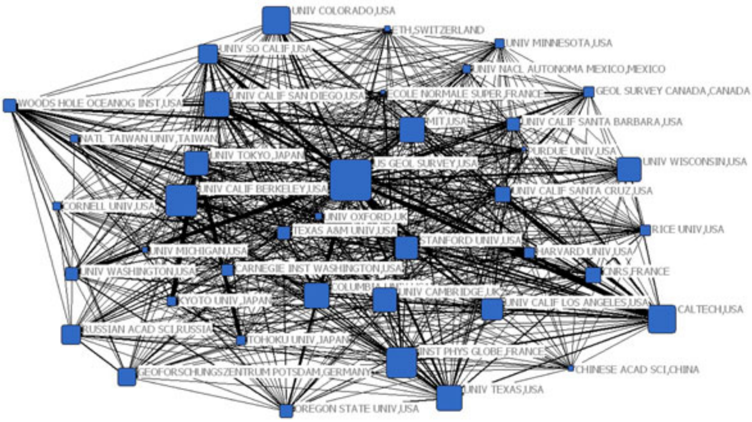

Fig. 7 Institutional collaboration network of 30 most central institutions in earthquake research (the nodal size corresponds to network eigenvalue centrality in the collaboration network and tie strengthen represents amount of papers co-signed by a pair of institutions)

have our searching terms in the data retrieval process as top keywords, such as "earthquakes" and "earthquake", we noted that topics related to other top keywords remained the core of research activities in earthquake studies. Research interests related to rock dynamics, crust deformation analysis, and earthquake source parameters received relatively less attention in the period from 2006 to 2010 compared to each of the three 5-year periods from 1991 to 2005. The number of articles discussing issues related to stress, seismic wave propagation, seismic response, the lithosphere, and the mantle fluctuated over the period from 1991 to 2010. There were clearly increasing research interests in earthquakes near subduction zones as well as in topics related to tomography, anisotropy, and the upper-mantle judging by the relatively higher ranking of these keywords in the years from 2005 to 2010. The reason for active research in subduction zone was likely that some of the most powerful earthquakes appeared in subduction zones. We had quite a few such earthquakes in recent years, including the 2004 Sumatra Earthquake and the Chilean earthquake. Tomography technology was originally used for medical studies, and was introduced to earthquake research in the early 1980s during the 1984 Society of Exploration Geophysicists (SEG) annual meeting. Since then seismic tomography gradually became a research hotspot and a main technique in the exploration of seismicity.

In terms of geographic regions, many articles covered California and Japan, and there was a clear trend indicating that more and more studies covered earthquakes in these two regions in recent years. More specifically, California and Japan were the only two place names appeared in our ranking, and ranked 4th and 28th, respectively.

"Prediction" had a relatively low rank in the keywords list. Earthquake prediction received significant attention in the earthquake research community in the 1970s through the 1990s, but research interests in earthquake prediction declined significantly in recent years. This trend was reflected in the low ranking for the word "prediction". Some researchers believed it was impossible to predict an earthquake (Geller 1997; Geller et al. 1997; Hough 2009), but others advocated that research about 'earthquake prediction' should continue (Wyss 1997). Recent examples from China seemed to suggest that it might be possible to make medium-term forecasts of large earthquakes (Zhu et al. 2010; Zhan et al. 2011).

Table 5 The temporal evolution of most frequently used keywords

Keywords	1991–1995		1996–2000		2001–2005		2006–2010		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Earthquake	385	2	774	1	1,373	1	2,443	1	4,975	1	1	53,016	10.66
Earthquakes	381	3	652	2	892	2	1,171	3	3,096	2	2	41,087	13.27
Evolution	414	1	608	3	785	5	1,075	5	2,882	3	4	49,823	17.29
California	353	4	507	4	855	3	1,062	6	2,777	4	4	45,282	16.31
Deformation	258	8	480	5	799	4	1,197	2	2,734	5	6	48,404	17.70
Model	261	7	449	7	685	6	1,143	4	2,538	6	3	38,281	15.08
Inversion	299	5	456	6	588	8	802	7	2,145	7	4	34,858	16.25
Seismicity	234	10	424	8	605	7	731	8	1,994	8	4	30,708	15.40
Tectonics	289	6	386	9	527	9	536	14	1,738	9	8	29,612	17.04
Crustal structure	193	13	277	13	481	10	681	9	1,632	10	4	25,803	15.81
Fault	161	18	267	14	443	11	635	10	1,506	11	8	24,081	15.99
Zone	199	12	278	12	385	12	524	15	1,386	12	3	23,505	16.96
Lithosphere	247	9	324	10	369	14	354	34	1,294	13	25	27,487	21.24
Attenuation	203	11	308	11	333	18	449	25	1,293	14	14	17,374	13.44
Beneath	169	17	241	18	354	15	504	17	1,268	15	6	24,660	19.45
Basin	170	16	259	15	343	17	477	21	1,249	16	7	18,419	14.75
Stress	176	15	243	17	379	13	447	27	1,245	17	20	20,195	16.22
Velocity	140	19	214	19	320	20	504	17	1,178	18	4	18,556	15.75
Waves	186	14	250	16	290	23	446	28	1,172	19	14	16,288	13.90
Propagation	109	27	154	29	316	21	568	12	1,147	20	19	13,068	11.39
Tomography	57	56	153	30	346	16	575	11	1,131	21	45	19,696	17.41
Region	97	34	187	21	321	19	493	20	1,098	22	16	15,972	14.55
Models	129	22	171	24	245	32	495	19	1,040	23	23	16,924	16.27
Slip	104	30	162	26	298	22	454	23	1,018	24	9	18,608	18.28

Table 5 continued

Keywords	1991–1995		1996–2000		2001–2005		2006–2010		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Subduction	120	25	189	20	274	25	380	32	963	25	17	18,520	19.23
System	96	36	143	34	266	27	458	22	963	26	14	15,327	15.92
Behavior	53	60	100	66	253	31	548	13	954	27	59	9,735	10.20
Japan	67	50	136	37	269	26	451	24	923	28	26	11,600	12.57
Seismic anisotropy	39	74	111	50	230	34	520	16	900	29	58	15,247	16.94
Anisotropy	110	26	176	23	289	24	305	44	880	30	24	15,127	17.19
Constraints	70	46	162	26	261	29	386	31	879	31	25	15,646	17.80
Mantle	103	32	180	22	262	28	318	39	863	32	27	18,933	21.94
Velocity structure	93	38	153	30	244	33	366	33	856	33	11	16,134	18.85
Systems	69	47	142	36	215	35	407	29	833	34	18	8,638	10.37
San-andreas fault	128	23	150	33	213	36	295	47	786	35	24	19,055	24.24
Rocks	135	20	161	28	207	37	279	49	782	36	29	13,914	17.79
Seismic response	68	49	130	40	256	30	320	37	774	37	26	5,474	7.07
Design	46	69	71	109	194	40	449	25	760	38	124	4,927	6.48
Crust	128	23	167	25	200	38	255	60	750	39	37	10,809	14.41
Seismic tomography	40	73	93	73	193	41	391	30	717	40	43	11,078	15.45
Source parameters	130	21	135	38	177	54	270	53	712	41	34	11,661	16.38
Motion	95	37	123	42	182	47	256	59	656	42	22	10,483	15.98
Sea	104	30	143	34	164	58	243	64	654	43	34	10,228	15.64
Subduction zone	38	76	99	68	191	42	322	36	650	44	40	11,353	17.47
Upper-mantle	28	83	117	46	187	44	317	40	649	45	43	12,051	18.57
Rupture	58	54	106	57	180	50	300	46	644	46	14	10,485	16.28
Magnitude	39	74	94	72	195	39	310	42	638	47	38	7,265	11.39
Scattering	106	28	152	32	160	62	216	76	634	48	48	8,213	12.95

Table 5 continued

Keywords	1991–1995		1996–2000		2001–2005		2006–2010		Total		RC	TC	TC/TP
	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank	Cnt	Rank			
Plate	97	34	131	39	179	52	225	72	632	49	38	10,909	17.26
Prediction	51	63	108	55	151	66	311	41	621	50	44	8,384	13.50

Cnt count of occurrences, *R* rank, *RC* absolute cumulated changes in rank, *TC* total citations of papers that have the corresponding keywords, *TP* total number of papers that have the corresponding keywords

Conclusions

In this paper, we provided a supplement evaluation on the global research trends in earthquake studies, by summarizing the patterns of authorship, journal and subject categories, geographic and institutional distributions, and temporal evolutions of keyword frequencies. Our analysis suggested that there has been steady growth in the scientific outputs in earthquake research and confirms the dynamic collaborations in this field. This paper could also be useful to informed decisions on curriculum development, library subscription, and/or research performance evaluation. Because bibliometric findings depended on selected bibliographic materials, our analysis and associated interpretations only aim at evaluating research progress based on the selected ISI databases.

Here is a summary of major findings from our bibliometric analysis:

- Research output descriptors suggested a solid development in earthquake research, in terms of increasing scientific production and research collaboration.
- The four most common categories were geochemistry and geophysics, multidisciplinary geosciences, civil engineering, and geological engineering, implying an applied tradition in earthquake studies. Multidisciplinary sciences has the largest field normalized measured impact ratios (CPP/FCSm = 3.18), showing its substantial influence in earthquake researches.
- A small group of prolific authors contributed to a significant share of publications in earthquake research, and 12 authors made the top cited and most published lists simultaneously. Several collaborative clusters of authors were also visualized.
- The uneven geographic distribution of earthquake publications is correlated with individual countries' proneness to earthquakes.
- The US attained a leading position in earthquake research by contributing the largest share of single-country and internationally collaborated articles.
- USGS (USA), Russian Academy of Sciences (Russia), University of Tokyo (Japan), University of California-Berkeley (USA), and Caltech (USA) topped the list of productive institutions in earthquake research.
- The most commonly used keywords appeared in the articles were evolution, California, deformation, model, inversion, seismicity, tectonics, crustal structure, fault, zone, lithosphere, and attenuation, all of which remained the core of research activities in earthquake studies. Topics related to subduction zone, tomography, and seismic anisotropy have received clearly increasing interests.

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