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REVIEW

Impact of climate change on land, water and ecosystem quality in polar and mountainous regions: gaps in our knowledge

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ABSTRACT: Nowhere are the effects of climate change more visible than in polar and mountainous regions. To initiate the Interregional Technical Co-operation Project INT/5/153 (2014–2018) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions (funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture), we built a database containing 769 of the most significant journal papers on the effects of climate change in polar and mountainous regions between 2000 and 2014 (up until the Fifth IPCC Assessment). Using the number of paper citations per year (CPY), we derive the top 50 most cited journal papers published in the 15 yr period. Analysis of the focus of these 'top 50' papers is compared to the IPCC Fifth Assessment (AR5) Report (IPCC 2013) and the full database. Five categories emerged, and after combining the number of papers in each category with the average CPY for the category, research on the impacts of climate change on terrestrial ecosystems (E) in polar and mountainous regions dominated, research on the impact on water resources (W) was second, and the impact on people's livelihood (P) third, with ice and snow (I) fourth and landscape (L) fifth. Landscape (L), in our view, appears to be under-researched and is presumably included in the IPCC Terrestrial Ecosystems category. We propose that policy makers should note this under-representation of high-impact research into landscape processes (erosion and deposition processes), which needs to be addressed in future.

KEY WORDS: Climate change impacts · Polar regions · Mountainous regions · Livelihood adaptation · Soil-water-ecosystem quality

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1. INTRODUCTION

Modern climate change has been described as 'the defining human development challenge of the 21st century' (United Nations Intellectual History Project 2011). Model projections suggest that global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 for all Representative Concentration Pathways adopted by the Intergovernmental Panel Climate Change (except RCP2.6) (IPCC 2013). Indeed, average global warming in the period 1990 to 2100 is expected to be between 1.1 and 6.4°C depending on the global release of greenhouse gas emissions (Kohler & Maselli 2009). This warming will not be uniform, but in general will be greater over land and in high latitudes.

Nowhere are its effects more visible than the warming already occurring in polar and mountainous re-

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gions. Climate change is progressing at a rate several times the global average in Western Antarctica, for example. The Antarctic Peninsula region has experienced a rise of ca. 3°C for surface air temperature over the last 50 yr (Bromwich et al. 2013), and 87% of 244 glaciers along the west coast of the Antarctic Peninsula (AP) have retreated in the last 50 yr (Cook & Vaughan 2010). Higher elevation sites in the Rocky Mountains have experienced a 3-fold increase in warming compared to the global average during the last few decades (Kohler & Maselli 2009). In the European Alps, regional climate projections indicate warming of ~1.5-fold the global average, with greater warming in summer (FAO 2015). Precipitation is projected to decrease in summer and as an annual average, and to increase in winter—although Giorgi et al. (2016) used an ensemble of global climate model simulations to conclude that while broad-scale summer precipitation reduction is projected, regional models simulate an increase in precipitation over high Alpine elevations that is not present in global simulations. The latter finding challenges the picture of a ubiquitous decrease of summer precipitation over the Alps found in coarse-scale projections. General warming is predicted to result in an upward shift of the glacier equilibrium line by between 60 to 140 m per degree Celsius temperature increase (Oerlemans 1992), along with a substantial glacier retreat during the 21st century. The duration of snow cover is expected to decrease by several weeks for each degree Celsius of warming at middle elevations in the Alpine region.

The 1992 United Nations Framework Convention on Climate Change recognized that 'developing countries with fragile mountainous ecosystems are particularly vulnerable to the adverse effects of climate change' (United Nations 1992). Agenda 21 (Chapter 13) identified the need to generate and strengthen knowledge about the ecology and sustainable development of mountain ecosystems, and the Rio+20 United Nations Conference on Sustainable Development in 2012 called for long-term vision and a holistic approach to sustainable mountain development.

Examining the impacts of climate change in Antarctic and Arctic landscapes can be particularly useful for a better understanding of the future impacts of climate change on landscape dynamics (including land degradation and resulting changes in land, water and ecosystem quality) in mountainous regions across the world. Mountains cover ~25% of the global land surface, and are home to 10% of the world's population. An estimated 40% of mountain populations are located in developing countries, and nearly 300 million mountain people are food insecure, with half suffering from chronic hunger (Kohler & Maselli 2009). Furthermore, it is estimated that mountains provide freshwater to half of the world's population. Climate change will affect the availability of water, and combined with increasing temperatures can make farming communities in some countries—such as those in the Andes in South America or in the Himalayas—shift to higher altitudes, often in more fragile ecosystems. In such regions, slopes which are no longer supported by glaciers become unstable, leading to landslides, mass movements and related hazards that can result in severe land degradation and undermine food security. Zhang et al. (1997) working on the North Slope, Alaska, reported that the thickness of the active layer (the top layer of soil that thaws during the summer and freezes again during the autumn) increased from the Arctic coast to the foothills of the Brooks Range, and is directly proportional to summer air temperatures and the thawing index. Increasing air temperature is therefore likely to result in continuously or seasonally frozen soils releasing more greenhouse gases into the atmosphere, although the magnitude of this effect remains highly uncertain (UNEP/WGMS 2008).

The United Nations Environment Programme (UNEP) reports indicate the need for existing data to be made more accessible, better assessment of data quality, and the generation of new data in a manner that allows data sharing among researchers.

This study aims to identify and discuss the top 50 most cited (and therefore, arguably the highest impact) journal papers published in the 15 yr period 2000–2014 which relate to the issue of climate change impacts in polar and mountainous regions. Analysis of the focus of these 'Top 50' papers are compared to the IPCC Fifth Assessment (AR5) Report (IPCC 2013) and a wider database of 800 journal articles and key reports. The intention is that this analysis will highlight where we have gaps in our knowledge, and therefore serve to help policy makers and funders of research to plug these knowledge gaps.

This analysis was carried out in the frame of Interregional Technical Co-operation Project INT/5/153 (2014-18) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions, which is organized and funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture. The project involved scientists from 23 countries representing 13 benchmark research sites (Fig. 1) designed to assess the impact of climate change on land-water-ecosystem quality in polar and mountainous regions.

Fig. 1. Benchmark sites of the INT 5153 project

The overall objective of the project is to improve the understanding of the impact of climate change on fragile polar and mountainous ecosystems at the local and global scale for their better management and conservation.

The project expects to have the following outcomes: (1) improved understanding of the impact of climate change on the cryosphere, and its effects on land-water-ecosystem quality at local and global scale in polar and mountainous ecosystems, and (2) recommendations for improvement of regional policies for soil and agricultural water management, conservation and environmental protection in polar and mountainous regions.

2. MATERIALS AND METHODS

2.1. Developing a literature database

It was decided in the planning stage for the INT5153 project that a database should be developed which should:

1. be easily accessible to, and updatable by, all members of the project, project partners and managers;
2. focus on peer-reviewed scientific literature;
3. be searchable by key words, date, journal and benchmark site;
4. focus on research produced in the last two IPCC Assessment Reports (Four and Five), i.e. since the year 2000; and
5. perform a gap analysis that should prepare the ground for the scientific approach and training, and highlight where we have gaps in our knowledge, therefore helping policy makers and funders of research to plug these knowledge gaps.

A core team decided that Microsoft Excel would meet the criteria as a widely available platform in which to build the database. The following stages were completed to populate the database:

1. Google Scholar (http://scholar.google.co.uk/) was used, and search terms were input as follows: 'climate change *King George Island*' etc. with the benchmark site (*italics*) changed for each of 13 searches (1 search for each of the benchmarks sites shown in Fig. 1). Between 10 and 13 key journal papers were then selected from the first 20 search hits and entered into the database. This generated ~150 entries.
2. All project members were invited by email to contribute additional literature relating to their benchmark sites. This generated approximately 200 further entries for the database.
3. Following the first project coordination meeting in Vienna in June 2014, scientists representing benchmark sites forwarded further scientific papers arising from research undertaken at/around their benchmark site/research station, and a further 248 papers were subsequently added to the database bringing the total number of entries to ~550.
4. Next, the top 35 academic journals which most frequently appeared in the database were assigned an impact factor (Garfield 1999, 2006).
5. The journal impact factor was then used to calculate the proportion of the remaining entries to the database which were to come from each of the top 35 journals.
6. Each of the 35 journals was searched in turn, normally using the Science Direct online database (https://www.sciencedirect.com/) or Google Scholar to find references relevant to the project using the terms: 'climate', 'change', 'impact', 'polar', 'mountainous', 'regions'.
7. Uncovering new papers became increasingly difficult and searching stopped at 721 entries.
8. The number of citations for each paper (found from Google Scholar) was entered into a new column in the database. The number of citations the paper

had was then divided by the age (the number of years it had been published prior to 2014) of the publication to derive the average number of citations per year (CPY).

9. The database entries were then ranked from highest to lowest based on the CPY.

10. The top 50 ranked papers were then selected for content analysis and compared with findings from IPCC and the full database.

3. FINDINGS

3.1. General findings from the entire database

The distribution of database entries by year of publication (Fig. 2) shows that all years 2000 to 2014 were represented in the database, though the higher numbers in the second half of the period correspond with the statement made by IPCC (2014): 'The number of scientific publications available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, with especially rapid increases in publications related to adaptation' (IPCC 2014, p. 3).

The 721 database entries included 616 journal papers (from 191 different journals), 31 reports, 31 book chapters, 19 conference/symposium proceedings, 18 web news articles, and 6 books. The titles of journals (with number of entries) used in the database are given in Table A1 in the Appendix.

Science, Nature Geoscience and Nature were the top 3 of the most popular journals with entries of ≥3. The top 35 journals (based on impact factor) and the number of entries in the database for each journal is given in Table 1.

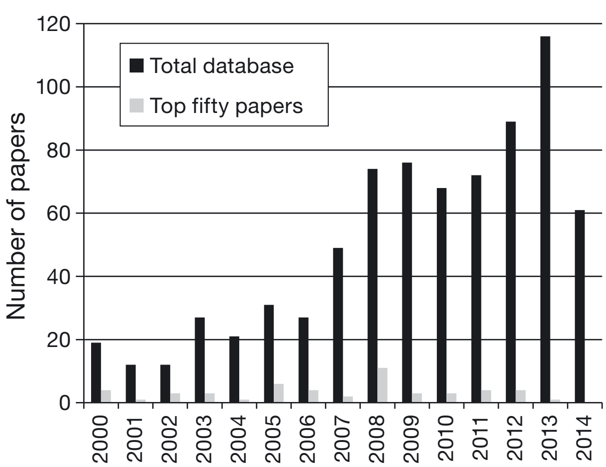

Fig. 2. Distribution of database entries by year of publication

There was a significant relationship between the number of journal references added to the database and the impact factor, i.e. the higher the journal impact factor, the more papers from that journal that were searched and added (Fig. 3). This approach was adopted so that the database contained a significant proportion (n = 164 or 21.3%) of high-impact research papers drawn from the top 35 impact factor journals shown in Table 1 which are not specifically linked to benchmark sites for the INT 5153 project. This, we believe, strengthened the validity of the database and added to the 512 entries which were specifically linked to the benchmark sites or regions chosen for this project.

Up to 3 key words were entered next to each entry in the database (Table 2). In total, 1113 key words were entered next to database entries, and these were assigned to 5 categories based on emerging themes (Maykut & Morehouse 1994) which are colour coded in Table 2. Keywords associated with Glacial lakes/lakes/proglacial lakes had the highest count of 208.

Looking at the years when journal papers in the database were published, there is a tendency towards a normal distribution, but it is skewed towards the second half of the period searched which indicates that the number of research papers concerned with the impacts of climate change on land-water-ecosystem quality was increasing.

Four of the 5 categories which emerged from the analysis of the 1113 key words corresponded to the 4 used by IPCC (2014): Snow and Ice (termed Ice in this study, abbreviated to I); Rivers and Lakes (termed Water in this study, abbreviated to W); Terrestrial Ecosystems (termed Ecosystems in this study, abbreviated to E) and Food Production & Livelihoods (termed People in this study, abbreviated to P) plus a new Landscape category which emerged from our thematic analysis (abbreviated to L). The 5 categories into which the keywords were grouped, the number of keywords associated with each group, and the percentage of the papers in the database which were in each group are given in Table 2.

Using the 5 categories in Table 2, all database entries were assigned to ≥1 of these, leaving 721 entries which had citations assigned. On closer inspection, 58 of the journal paper entries were only concerned with climate change and not the impact of climate change on polar and mountainous regions. These papers were assigned the category C (for Climate) and thereafter removed from the analysis, leaving 663 journal articles. However, sometimes research papers were concerned with >1 category. For example, if the paper was concerned with glacier recession (I) and

Table 1. List of the Top 35 highest impact academic journals used to search for material relevant to climate change impacts in polar and mountainous regions to supplement the papers provided by benchmark site scientists

	Journal title	No. of papers 30 May 2014	Impact factor 13 Aug 2014	% of total impact	Search target No. of papers	No. of papers 02 Sep 2014
1	Science	8	31.477	15	44	44
2	Nature Geoscience	1	11.668	5	16	35
3	Nature	10	42.351	20	60	34
4	Nature Climate Change	3	15.295	7	22	28
5	Global and Planetary Change	16	3.707	2	5	21
6	Geomorphology	6	3.167	1	4	16
7	Remote Sensing of the Environment	5	6.065	3	9	16
8	Earth-Science Reviews	2	8.95	4	13	15
9	Global Change Biology	1	8.22			15
10	Hydrological Processes	7	2.81	1	4	15
11	Journal of Glaciology	9	3.213	2	5	14
12	Advances in Ecological Research	4	3.59	2	5	13
13	Quaternary Science Reviews	5	5.463	3	8	13
14	Arctic, Antarctic, and Alpine Research	8	1.78	1	3	12
15	Cryosphere	2	4.684	2	7	12
16	Journal of Hydrology	3	3.678	2	5	12
17	Climate Change	3	4.622	2	6	11
18	Global Environmental Change	1	8.05			10
19	Journal of Geophysical Research	5	3.174	1	4	9
20	Quaternary International	2	2.446	1	3	9
21	Annals of Glaciology	9	2.524	1	4	8
22	Ambio	7	2.973	1	4	7
23	Geophysical Research Letters	5	4.456	2	6	7
24	Palaeogeography, Palaeoclimatology, Palaeoecology	5	3.035	1	4	7
25	Hydrology and Earth System Sciences	5	3.59	2	5	6
26	Mountain Research and Development	3	0.989	0	1	6
27	Environmental Science and Policy	1	3.948	2	6	5
28	Geografiska Annaler: Series A, Physical Geography	5	0.659	0	1	5
29	Natural Hazards	4	1.958	1	3	5
30	PLOS ONE	1	3.234	1	3	5
31	Polar Biology	2	2.071	1	3	5
32	Environmental Research Letters	3	4.09	2	6	4
33	Journal of Mountain Science	2	0.763	0	1	4
34	Permafrost and Periglacial Processes	1	2.177	1	3	4
35	Science of the Total Environment	2	3.906	2	5	4

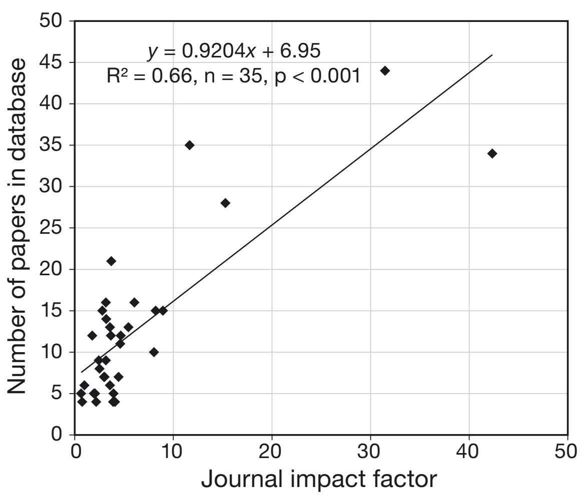

Fig. 3. Relationship between number of papers and journal impact factor

changes in runoff (W), then it was assigned IW (e.g. a study of glacial lake outburst floods). In total, 157 of the journal papers were assigned 2 categories, and 13 were assigned 3 categories. When the total number of papers in each category was calculated, a paper with 2 categories, such as IW, would be assigned 0.5 to I and 0.5 to W. For 3 categories such as IEW, then each category would be assigned 0.33. Table 3 shows the results for all papers in database (columns 2 to 3) and Top 50 only (columns 6 to 7), and the last row shows the ranking of the 5 categories. Columns 4 and 8 in Table 3 show the average number of citations per year (CPY) for each category, and columns 5 and 9 give the product of the number of papers multiplied by the average CPY. This measure, we think, gives the most robust weighting for each category. The final row in Table 3 summarises the ranks for all pa-

Table 2. Keywords (with number of entries) used in database, keyword categories are given by the colour coding key at top of the table

COLOUR KEY

Impacts on snow, glaciers, ice caps and ice sheets Total keywords 366 (36.1 %)	Impacts on livelihoods: agriculture, food, water security and hydropower Total keywords 146 (14.4 %)	Impacts on landscape, geomorphology and slope stability Total keywords 70 (6.9 %)
Impacts on terrestrial ecosystems: soil, biodiversity, greenhouse gases and feedback systems Total keywords 260 (25.1 %)	Impacts on water and water resources Total keywords 173 (17.0 %)	Non-coloured = not assigned

Keywords	Total	Keywords	Total	Keywords	Total
Abrupt climate change	1	**Feedback**	6	Quinoa	6
Acclimatisation capacity	1	**Food security/production**	5	**Rainfall**	3
Adaptation	33	Frost	6	**Range shifts**	3
Afforestation	1	Fungi	1	**Rockfall**	4
African drought	0	**Geomorphology**	1	Remote sensing	7
Aerial photos	3	**Greenhouse gas emissions**	6	Respiration	3
Airborne laser	1	**Glacier/recession/melt/mass balance**	5	Risk	1
Agriculture/crops/biofuels	24	**Glacial lakes/lakes/proglacial lakes**	208	**River discharge/runoff**	20
Agroforestry	1	**GLOF/jokulhaulp**	14	**Rock glacier**	2
Animals/fauna	6	**Governance**	22	**Sea level/rise**	4
Annual production/biomass	2	**Grassland/grazing**	1	Sediment	1
Arctic tundra/fen	8	**Hazard management**	4	**Ski industry**	2
Biodiversity	5	**HEP**	10	**Slope failure**	6
Biogeochemical cycling/response	3	**Human/adaptaton/response**	5	**Snow cover/melt/avalanche/pack**	31
Biomass burning/wildfire	3	**Hydrology/irrigation**	10	**Socio-economic/vulnerability/limits**	34
Black carbon	3	**Ice sheet/mass/core**	46	**Soil carbon/respiration/moisture/sequester**	29
Carbon/cycle/CO_2	49	Isotope	13	Soil erosion	1
Catastrophic soil erosion	1	**Lake/lake ice**	5	**Species**	3
Climate /change/extremes/hazard	78	**Land/land-use/cover**	16	Sub-marine	1

Table 2 (continued)

Keywords	Total	Keywords	Total	Keywords	Total
Crops/yields	8	**Landslide/mass movement/slope failure**	9	**Suspended sediment**	5
Crustal uplift	4	Management	26	**Technology**	1
Cryosphere	5	Mapping	2	**Terrestrial ecosystem/carbon cycle**	4
Cultural dimension	1	**Methane/emissions/flux**	57	**Tropical**	6
Damage costs/disease/disaster	4	**Nutrients/**	13	Thawing	6
Dating	1	**Organic matter/carbon**	4	**Trees/tree-line/tree rings**	13
Dams	1	Organisations	7	**Vegetation**	12
Debris flow	4	Palaeoclimate	7	Villages	1
Dendrochronology	1	**Peat/decomposition**	7	**Vulnerability**	3
Dust	1	**Periglacial/permafrost/active layer**	2	**Water resources/water**	48
Early warning system (landslide)	1	Phosphorus	52	Weathering	1
Ecology/ecosystems	3	Pine beetle	2	Weeds	1
Ecomonics/impacts	25	**Plant/ecology/herbivore interaction**	5	Wetlands	2
Energy/budgets/HEP	8	Planation	1		
Forests	8	**Policy/political**	9	**Total**	**1113**

pers (n) in the database as I > E > W > P > L and for just the Top 50 papers as E > P > W > I > L.

Most papers published in the last 15 yr concerned with the impact of climate change on polar and mountainous regions are classified as I. There are 213 papers in this category, which represents 33.7 % of the total. There were 194 papers in the E category, which represents 30.6 % of the total. The third category, the impact of climate change on W (rivers and lakes), contained 97 papers (15.3 % of the total). The fourth category, climate change impacts on people and livelihoods (P), contained 74 papers (11.6 % of the total). The fifth category, landscape (L), contained 55 papers (8.7 % of the total).

These distributions can be compared with the IPCC (2014) confidence levels of knowledge in each of the first 4 categories (I, E, W and P) (see Fig. 4). The fifth category (L) was created by us through the key word analysis (Table 2). However, IPCC (2014) deals with the levels of confidence that the Fifth Assessment Report has in making statements about the impact of climate change on snow and ice (I), terrestrial ecosystems (E), rivers and lakes (W) and food production/livelihoods (P). Table 4 shows the number of the research papers in these categories, and includes L, which, in our view, appears to be under-researched and is presumably included in the IPCC Terrestrial Ecosystems category. We feel that policy makers should note this under-representation of research, or at least high-impact research, on landscape processes, which we discuss in more detail later.

The Top 50 papers in the database with the highest average CPY are given in Table 3 (column 8). There is a mismatch between the nature of the research coming from the larger database (of 663 papers) in Table 3 (column 4) and those in the Top 50. The rank order for the average CPY for all papers in the database has changed from E > W > P > L > I to E > I > P > W > L for the average CPY of the Top 50 (Table 3). In other words, using this method (CPY), the number of research papers in I reaching the Top 50 has declined greatly, from 33.7 % in the whole database (Table 3, column 3) to just 7.0 % in the Top 50, while research on terrestrial ecosystems (E) has increased from 30.6 % in the whole database to 57.0 % in the Top 50. P has remained in third rank of the 5 categories (though has increased its % of papers from 11.6 % in the whole database to 20.0 % in the top 50), and water (W) has dropped from second to third place (changed from 15.3 % in the whole database to 15.0 % in the top 50). Landscape research (L) remains in fifth place (decreased from 8.7 % in the whole database to just 1.0 % in the Top 50).

Table 3. Comparison of all papers in database vs. top 50 only. I: snow and ice; E: terrestrial ecosystems; W: water; rivers and lakes; P: people's livelihoods; L: landscape; CPY: citations per year. Column numbers are referred to in body text

Category	All papers in database				Top 50 papers			
(1)	(2) No.	(3) %	(4) Average CPY	(5) No. of papers × Ave. CPY	(6) No.	(7) %	(8) Average CPY	(9) No. of papers × Ave. CPY
I	213	33.7	31	6609	3.5	7.0	315.3	1104
E	194	30.6	121	23457	28.5	57.0	376.6	10733
W	97	15.3	103	9968	7.5	15.0	282.6	2120
P	74	11.6	94	6915	10.0	20.0	287.5	2875
L	55	8.7	40	2238	0.5	1.0	49.9	25
Total	633	100.0			50.0	100.0		
Ranks	I > E > W > P > L		E>W>P>L>I	E>W>P>I>L	E > P > W > I > L		E>I>P>W>L	E>P>W>I>L

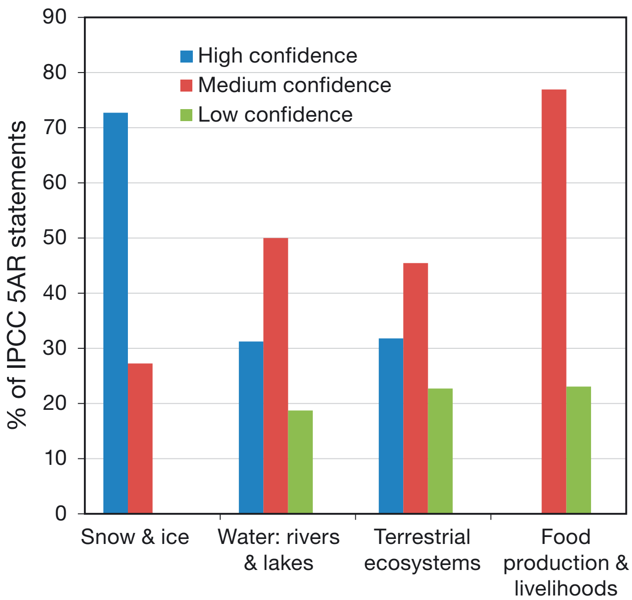

Fig. 4. Confidence levels in statements made by IPCC (2014) in 4 areas which are being impacted by climate change (IPCC 2014)

To summarise, when considering average CPY as a measure of impact or importance to the scientific community, the rank order of categories for the whole database is E > W > P > L > I but becomes E > I > P > W > L for the Top 50 papers. It would therefore seem sensible to combine the number of papers in each category with the average CPY for the category. This results in the rank order for the whole database as E > W > P > I > L (Table 3, column 5), and the rank order for the Top 50 papers is E > P > W > I > L (Table 3, column 9). By this method the rank order for the whole database are almost the same as for the Top 50, except P and W are reversed. However, E remains top ranked, and I and L remain in 4th and 5th places.

In order to assess the changes over the 15 yr (2000–2014) period, the database was split into three 5 yr time periods: 2000–2004; 2005–2009; and 2010–2014 (Fig. 5), which shows how the number of papers (Fig. 5a) and the percentage of papers (Fig. 5b) published in each of the 5 categories changed through the 3 time periods. The number of published papers increased in each category from 2000–2004 to 2005–2009 and again to 2010–2014 (Fig. 5a).

On examining the Top 50 papers (Fig. 5c,d), it is difficult to see any obvious pattern over the 15 yr period.

3.2. Findings concerned with the Top 50 highest impact papers only

3.2.1. Overview of the topics of the Top 50 papers

On a closer examination of these Top 50 papers (Table 4), the most researched topics were concerned with the impact of climate change on species distribution and biodiversity (10 of the papers; 20%). The areas impact of climate change on agriculture and food production, greenhouse gases/feedback mechanisms, and soil and forest carbon/carbon cycle were addressed by 6 papers (12%) each. Human health/social limits/adaptation was the topic of 5 papers (10%), whereas 4 papers (8%) addressed issues related to water resources. Two papers were on the impacts of climate change on Himalayan, Antarctic, and Patagonian glaciers. A further 2 papers were concerned with sea level rise, and the remaining 11 papers were each concerned with a range of topics as outlined in Table 4. Inevitably, there is scope for some overlap, for example, the paper by Searchinger et al. (2008) found that the use of US croplands for biofuels increases greenhouse gases through emis-

Table 4. Most popular research topics in the Top 50 papers

Category	Topic	No. of papers	Reference (impact rank)
E	Species distribution change, biodiversity	10	Parmesan & Yohe 2003 (2), Walther et al. 2002 (3), Sala et al. 2000 (5), Chen et al. 2011 (10), Dawson et al. 2011 (27), Lenoir et al. 2008 (36), Schröter et al. 2005 (40), Stenseth et al. 2002 (41), Davis & Shaw 2001 (44), Post et al. 2009 (48)
EP/P/W	Agriculture and food production, water resources	6	Lal 2004 (24), Lobell et al. 2011 (12), Lobell et al. 2008 (16), Piao et al. 2010 (31), Shindell et al. 2012 (28), Asseng et al. 2013 (46)
E/EP	Greenhouse gases, feedback mechanisms	6	Searchinger et al. 2008 (1), Fargione et al. 2008 (4), Westerling et al. 2006 (6), Cox et al. 2000 (13), Bonan 2008 (9), Cramer et al. 2001 (34)
E/EP	Soil and forest carbon, carbon cycle	6	Davidson & Janssens 2006 (7), Lal 2004 (8), Kurz et al. 2008 (22), Van der Werf et al. 2009 (39), Donato et al. 2011 (42), Bond-Lamberty & Thomson 2010 (45)
P	Human health, social limits, adaptation	5	Adger et al. 2009 (18), McMichael et al. 2006 (23), Patz et al. 2005 (26), Shindell et al. 2012 (28), Adger et al. 2003 (49)
W	Water resources	4	Barnet et al. 2005 (19), Piao et al. 2010 (31), Vörösmarty et al. 2000 (25), Immerzeel et al. 2010 (30)
I	Himalayan, Antarctic, Patagonian glaciers	2	Bolch et al. 2012 (37), Schaefer et al. 2013 (11)
W/IW	Sea level rise	2	Jacob et al. 2012 (33), Nicholls & Cazenave 2010 (29)
E/EP	Land use change, forest management	1	Canadell & Raupach 2008 (50)
E	Primary production	1	Nemani et al. 2003 (21)
E	Disease risk	1	Harvell et al. 2002 (32)
E	Deforestation	1	Malhi et al. 2008 (35)
EW	Soil moisture	1	Seneviratne et al. 2010 (20)
I	Black carbon	1	Ramanathan & Carmichael 2008 (15)
IE	Permafrost thaw	1	Hinzman et al. 2005 (47)
IE	Carbon dioxide sinks	1	Le Quéré et al. 2009 (14)
P	Sustainable development equity	1	Smit & Pilifosova 2003 (43)
P	Economics of climate change	1	Weitzman 2009 (17)
LW	Sediment flux to oceans	1	Syvitski et al. 2006 (38)

sions from land-use change, and so bridges the agriculture and greenhouse gas topics.

Ecosystems. The highest impact paper found in this whole study concerned with ecosystems was by Searchinger et al. (2008) (Table 5), who used a worldwide agricultural model to estimate emissions from land-use change, and found that corn-based ethanol, instead of producing a 20% saving, nearly doubled greenhouse emissions over 30 yr and would increase greenhouse gases for 167 yr. They estimated that biofuels from switchgrass, if grown on US corn lands, would increase emissions by 50%, results that raise concerns about using biofuels in future to produce fuel.

Fargione et al. (2008) pointed out that converting rainforests, peatlands, savannas, or grasslands to produce food crop–based biofuels in Brazil, Southeast Asia, and the United States created a 'biofuel carbon debt' by releasing 17 to 420 times more CO_2 than the annual greenhouse gas (GHG) reductions that these biofuels would provide by displacing fossil fuels. Biofuels made from waste biomass or from biomass grown on degraded and abandoned agricultural lands planted with perennials, on the other hand, incur little or no carbon debt, and could offer immediate and sustained GHG reductions. Parmesan & Yohe (2003) applied diverse analyses to >1700 species, examining phenological changes in woody, herbaceous and mixed plants, birds, insects, amphibians, fish. In addition, the distribution/abundance changes of tree lines, herbs and shrubs, lichens, birds, mammals, insects, reptiles and amphibians, as well as marine invertebrates and zooplankton were also examined by Parmesan & Yohe (2003). The study showed that recent biological trends matched climate change predictions (Parmesan & Yohe 2003). Global

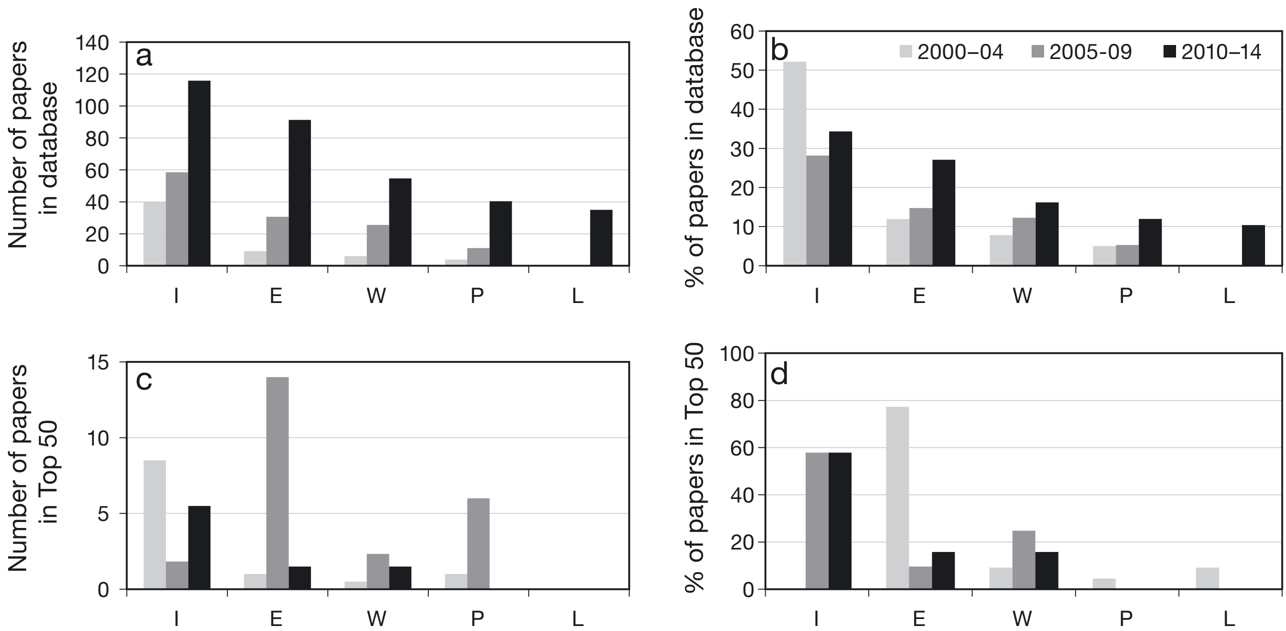

Fig. 5. (a) Number of papers in whole database in the 5 categories (n = 633). I: Snow and Ice; W: Rivers and Lakes (Water); E: Terrestrial Ecosystems; P: Food Production & Livelihoods (termed People); L: Landscape category. (b) Percentages of papers in whole database in the 5 categories. (c) Number of papers in Top 50 (by CPY) in the 5 categories (n = 50). (d) Percentages of papers in Top 50 (by CPY) in the 5 categories

meta-analyses showed horizontal range shifts averaging 6.1 km per decade towards the poles (or 6.1 m per decade upwards), and significant mean advancement of spring events by 2.3 d per decade. Parmesan & Yohe's (2003) diagnostic fingerprint of temporal and spatial 'sign-switching' found for 279 species generated 'very high confidence' (as laid down by the IPCC) that climate change was already affecting living systems that they studied. Walther et al. (2002) found that the responses of both flora and fauna to climate change span an array of ecosystems and organizational hierarchies, from the species to the community levels. Despite continued uncertainty as to community and ecosystem trajectories under global change, their review exposed a coherent pattern of ecological change across systems. Sala et al. (2000) claimed that scenarios of changes in biodiversity for the year 2100 could be developed based on scenarios of changes in atmospheric carbon dioxide, climate, vegetation, and land use and the known sensitivity of biodiversity to these changes. Davidson & Janssens' (2006) key paper pointed out that despite much research, a consensus had not yet emerged on the temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Lal (2004) estimated that the carbon sink capacity of the world's agricultural and degraded soils is 50 to 66 % of the historic carbon loss of 42 to 78 Gt of carbon.

Table 5. Top 10 most cited papers in the Ecosystems (E) category

Rank	Publication	Journal	No. of citations	No. of citations per year by 2015
1	Searchinger et al. (2008)	Science	3255	465.0
2	Parmesan & Yohe (2003)	Nature	5230	435.8
3	Walther et al. (2002)	Nature	5249	403.8
4	Fargione et al. (2008)	Science	2785	397.9
5	Sala et al. (2000)	Science	4657	310.5
6	Westerling et al. (2006)	Science	2338	259.8
7	Davidson & Janssens (2006)	Nature	2228	247.6
8	Lal (2004)	Science	2512	228.4
9	Bonan (2008)	Science	1442	206.0
10	Chen et al. (2011)	Science	781	195.3

A comprehensive database of large wildfires in western United States forests since 1970 was compiled by Westerling et al. (2006) who then compared it with hydroclimatic and land-surface data to show that large wildfire activity increased suddenly and markedly in the mid-1980s, with higher large-wildfire frequency, longer wildfire durations, and longer wildfire seasons. Bonan (2008) reported that forests are under tremendous pressure from global change, and that interdisciplinary science that integrates knowledge of the many interacting climate services of forests with the impacts of global change is necessary to identify and understand as yet unexplored feedbacks in the Earth system and the potential of forests to mitigate climate change Using a meta-analysis, Chen et al. (2011) estimated that the distributions of species had recently shifted to higher elevations at a median rate of 11.0 m per decade, and to higher latitudes at a median rate of 16.9 km per decade, rates that were approximately two and three times faster than previously reported.

People and livelihoods. Investments aimed at improving agricultural adaptation to climate change inevitably favour some crops and regions over others. Lobell et al. (2008), ranked highest in the Top 10 Highest Cited Papers in the P category (Table 6), performed an analysis of climate risks for crops in 12 food-insecure regions to identify adaptation priorities based on statistical crop models and climate projections for 2030 from 20 general circulation models. Results showed South Asia and Southern Africa as two regions that, without sufficient adaptation measures, will likely suffer negative impacts on several crops that are important to large food-insecure human populations. Weitzman (2009) addresses the economics of catastrophic climate change, and asked questions about the extent that catastrophe insurance should be invested in (and what exactly catastrophe insurance is buying with regards to climate change or other applications). Adger et al. (2009) contended that limits to adaptation are endogenous to society, and hence contingent on ethics, knowledge, attitudes to risk, and culture. Writing in the medical journal The Lancet McMichael et al. (2006) summarised the epidemiological evidence of how climate change is affecting various health outcomes. Thermal stress, extreme weather events, and infectious diseases have been mainly researched to date, with some attention to estimates of future regional food yields and hunger prevalence, but an emerging broader approach warns of a wider spectrum of health risks due to the social, demographic, and economic disruptions of climate change. Patz et al. (2005) argued that many prevalent human diseases are linked to climate fluctuations, from cardiovascular mortality and respiratory illnesses due to heatwaves, to altered transmission of infectious diseases and malnutrition from crop failures. How tropospheric ozone and black carbon contribute to both degraded air quality and global warming was examined by Shindell et al. (2012), who considered ~400 emission control measures to reduce pollutants by using current technology and experience. Smit & Pilifosova (2003) examined adaptation to climate change in the context of sustainable development and equity, while by analysing new research across the social sciences Adger et al. (2003) showed that climate change threatened cultural dimensions of lives and livelihoods that include: identity, community cohesion and sense of place, and that there are important cultural dimensions to how societies respond and adapt to climate-related risks. Adger et al. (2003) showed how culture mediates changes in the environment and changes in societies, and highlighted shortcomings in contemporary adaptation policy. That civil conflicts were associated with the global climate was shown by Hsiang et al. (2011) by examining the dominant interannual mode of the El Niño/Southern Oscillation (ENSO). Using data from 1950 to 2004, they showed that the probability of new civil conflicts arising throughout the tropics doubled during El Niño years relative to La Niña years. This result, which indicated that ENSO may have had a role in 21% of all civil conflicts since 1950, was the first demonstration that the stability of modern societies relates strongly to the global climate.

Table 6. Top 10 most cited papers in the People and Livelihoods (P) category

Rank	Publication	Journal	No. of citations	No. of citations per year (CPY) by 2015
1	Lobell et al. (2008)	Science	1195	170.7
2	Weitzman (2009)	The Review of Economics and Statistics	971	161.8
3	Adger et al. (2009)	Climate Change	959	159.8
4	McMichael et al. (2006)	The Lancet	1153	128.1
5	Patz et al. (2005)	Nature	1261	126.1
6	Shindell et al. (2012)	Science	364	121.3
7	Smit & Pilifosova (2003)	Sustainable Development	1051	87.6
8	Adger et al. (2003)	Progress in Development Studies	874	72.8
9	Hsiang et al. (2011)	Nature	243	60.8
10	Adger et al. (2013)	Nature Climate Change	109	54.5

Water. The paper by Barnett et al. (2005) was ranked highest in the Top 10 most cited papers in the W category (Table 7). With more than one-sixth of Earth's population relying on glaciers and seasonal snow packs for water, the consequences of likely hydrological changes for future water availability—predicted with high confidence and already diagnosed in some regions — are likely to be severe.

Numerical experiments combining climate model outputs, water budgets, and socioeconomic information along digitized river networks carried out by Vörösmarty et al. (2000) demonstrated that a large proportion of the world's population is currently experiencing water stress, and that rising water demands greatly outweighed greenhouse warming in defining the state of global water systems to 2025. Nicholls & Cazenave (2010) claimed that global sea level rise through the 20th century will almost certainly accelerate through the 21st century and beyond because of global warming, but its magnitude remains uncertain. Immerzeel et al. (2010) investigated how climate change will affect the Asian water towers: >1.4 billion people depend on water from the Indus, Ganges, Brahmaputra, Yangtze, and Yellow rivers where upstream snow and ice reserves, important in sustaining seasonal water availability in these basins, are likely to be affected substantially by climate change, though the extent is yet unclear. Meltwater is extremely important in the Indus and Brahmaputra basins, which are most susceptible to reductions of flow, threatening the food security of an estimated 60 million people, but plays only a modest role for the Ganges, Yangtze, and Yellow rivers. The impacts of climate change on water resources and agriculture in China were evaluated by Piao et al. (2010). China experienced explosive economic growth in recent decades, but with only 7% of the world's arable land available to feed 22% of the world's population, China's economy may be vulnerable to climate change. Although clear warming has occurred in China in recent decades, current understanding does not allow a clear assessment of the impact of anthropogenic climate change on China's water resources and agriculture and therefore China's ability to feed its people. The strategic importance of ground water for global water and food security was highlighted by Taylor et al. (2013) who stated that it will probably intensify under climate change as more frequent and intense climate extremes (droughts and floods) increase variability in precipitation, soil moisture and surface water. García-Ruiz et al. (2011) reported that Mediterranean areas of both southern Europe and North Africa were subject to dramatic changes that would affect the sustainability, quantity, quality, and management of water resources. Fischer et al. (2007) computed future regional and global irrigation water requirements as a function of both projected irrigated land and climate change with simulations performed from 1990 to 2080. Results suggested that mitigation of climate change could reduce the impacts of climate change on agricultural water requirements by about 40%, or 125–160 billion m^3 compared with unmitigated climate. Simple estimates of future changes in irrigation efficiency and water costs suggested that by 2080 mitigation may translate into annual cost reductions of about 10 billion US$. Based on the 1956–2006 runoff data from the Aksu River Basin, Turkey, Wang et al. (2008) analysed the characteristics and trends of runoff variation, and found that runoff presented an increasingly significant upward trend in the last 50 yr, and glacier water was considered the main contributor. Runoff and high altitude temperatures began to increase eminently from the mid-1990s. The snowlines of the glacier system will readjust if the 0°C level height exceeds the altitude

Table 7. Top 10 most cited papers in the Water (W) category

Rank	Publication	Journal	No. of citations	No. of citations per year (CPY) by 2015
1	Barnett et al. (2005)	Nature	1506	150.6
2	Vörösmarty et al. (2000)	Science	1894	126.3
3	Nicholls & Cazenave (2010)	Science	605	121.0
4	Immerzeel et al. (2010)	Science	586	117.2
5	Piao et al. (2010)	Nature	577	115.4
6	Taylor et al. (2013)	Nature Climate Change	129	64.5
7	García-Ruiz et al. (2011)	Earth-Science Reviews	227	56.8
8	Fischer et al. (2007)	Technological Forecasting and Social Change	255	31.9
9	Wang et al. (2008)	Journal of Glaciology and Geocryology	168	24.0
10	Schmocker-Fackel & Naef (2010)	Journal of Hydrology	73	14.6

of the distribution of the largest glacier areas, which will bring a great deal of glacier meltwater, and then ultimately a possible reversal of the runoff trend from more to less. Over the past 10 yr, climate warming has resulted in significant snow cover and glacier wastage, with increases in flood frequency and magnitude. The increase in runoff mitigates the drought during the spring, to a certain extent, but also brings about flood disasters. Based on changes in flood frequency in Switzerland since 1850, Schmocker-Fackel & Naef (2010) projected flooding to become increasingly frequent during this century.

Ice and snow. Schaefer et al. (2013), ranked highest in the Top 10 Highest Cited Papers in the I category (Table 8), detected an increase in accumulation on the Northern Patagonia Icefield from 1990−2011 as compared to 1975−1990, and using geodetic mass balance data, calving losses from the Northern Patagonia Icefield could be inferred, which doubled in 2000−2009 as compared to 1975−2000. The 21st century projection of future mass balance of the Northern Patagonia Icefield shows a strong increase in ablation from 2050 and a reduction in solid precipitation from 2080, both due to higher temperatures. Ramanathan & Carmichael (2008) claimed that emissions of black carbon are the second strongest contribution to current global warming, after carbon dioxide emissions. In the Himalayan region, solar heating from black carbon at high elevations may be just as important as CO_2 in the melting of snow packs and glaciers. Rabatel et al. (2013) reported that, in terms of changes in surface area and length, glacier retreat in the tropical Andes over the last 3 decades was unprecedented since their maximum extension in the Little Ice Age period (LIA, mid-17th to early 18th century). Based on observations on glacier extent from Ecuador, Peru and Bolivia, Vuille et al. (2008) give a detailed and unequivocal account of rapid shrinkage of tropical Andean glaciers since the LIA. Given the projected changes in climate, based on different IPCC scenarios for 2050 and 2080, simulations with a tropical glacier−climate model indicate that glaciers will continue to retreat. Many smaller, low-lying glaciers are already completely out of equilibrium with current climate and will disappear within a few decades. Even in catchments where glaciers do not completely disappear, the change in streamflow seasonality, due to the reduction of the glacial buffer during the dry season, will significantly affect the water availability downstream. In the short term, as glaciers retreat and lose mass, they add to a temporary increase in runoff to which downstream users will quickly adapt, thereby raising serious sustainability concerns. Widespread acceleration in glacial melt in Greenland was observed by Rignot et al. (2010), which they associated with the thinning of the lower reaches of the glaciers as they terminate in the ocean.

A review of the changing state of European permafrost was presented by Harris et al. (2009), which focused on a spatial zone that included the continuous high-latitude arctic permafrost of Svalbard and the discontinuous high-altitude mountain permafrost of Iceland, Fennoscandia, and the Alps. Data indicated recent warming trends, with greatest warming at higher latitudes. Equally important are the impacts of shorter-term extreme climatic events, most immediately reflected in changes in active layer thickness. A large number of complex variables, including altitude, topography, insolation and snow distribution, determine permafrost temperatures. The potential impacts of climate change on rock weathering, permafrost creep, landslides, rock falls, debris flows and slow mass movements were discussed. Brown & Mote (2009), in a snowpack model sensitivity study, observed changes of snow

Table 8. Top 10 most cited papers in the Ice and Snow (I) category

Rank	Publication	Journal	No. of citations	No. of citations per year (CPY) by 2015
1	Schaefer et al. (2013)	Journal of Geophysical Research	368	184.0
2	Ramanathan & Carmichael (2008)	Nature Geoscience	1222	174.6
3	Rabatel et al. (2013)	Cryosphere	105	52.5
4	Vuille et al. (2008)	Earth-Science Reviews	296	42.3
5	Rignot et al. (2010)	Nature Geoscience	187	37.4
6	Harris et al. (2009)	Earth-Science Reviews	221	36.8
7	Brown & Mote (2009)	International Journal of Climatology	186	31.0
8	Christiansen et al. (2010)	Permafrost and Periglacial Processes	131	26.2
9	Moholdt et al. (2010)	Remote Sensing of Environment	117	23.4
10	Racoviteanu et al. (2008)	Journal of Glaciology	150	21.4

cover in the NOAA satellite dataset. Under conditions of warming and increasing precipitation that characterizes both observed and projected climate change over much of the northern hemisphere land area with seasonal snow cover, the sensitivity analysis indicated that snow cover duration was the snow cover variable exhibiting the strongest climate sensitivity, with sensitivity varying with climate regime and elevation. Christiansen et al. (2010) reported on how the permafrost monitoring network in the polar regions of the Northern Hemisphere was enhanced during the International Polar Year (IPY; 2007-2009), and new information on permafrost thermal state was collected for regions where there was little available. This augmented monitoring network is an important legacy of the IPY, as is the updated baseline of current permafrost conditions against which future changes may be measured. Their results indicated that the permafrost warming which started two to three decades ago had generally continued into the IPY period.

Three methods for estimating 2003–2008 elevation changes of Svalbard glaciers from multi-temporal ICESat laser altimetry (https://earthobservatory.nasa.gov/features/ICESat) were tested by Moholdt et al. (2010). The geodetic mass balance (excluding calving front retreat or advance) of Svalbard's 34600 km^2 glaciers was estimated to be -4.3 ± 1.4 Gt yr^{-1}, corresponding to an area-averaged water equivalent (w.e.) balance of -0.12 ± 0.04 m w.e. yr^{-1}. The largest ice losses had occurred in the west and south, while northeastern Spitsbergen and the Austfonna ice cap had gained mass. Winter and summer elevation changes derived from the same methods indicate that the spatial gradient in mass balance was mainly due to a larger summer season thinning in the west and the south than in the northeast.

Decadal changes in glacier parameters in the Cordillera Blanca, Peru, derived from remote sensing by Racoviteanu et al. (2008) showed an overall loss in glacier area of 22.4% from 1970 to 2003, an average rise in glacier terminus elevations by 113 m and an average rise in the median elevation of glaciers by 66 m, showing a shift of ice to higher elevations, especially on the eastern side of the Cordillera, and an increase in the number of glaciers, which indicates disintegration of ice bodies.

Landscape. Syvitski et al. (2005), ranked highest in the Top 10 Highest Cited Papers in the L category (Table 9), provided global estimates of the seasonal flux of sediment, on a river-by-river basis, under modern and pre-human conditions. Humans have simultaneously increased sediment transport by global rivers through soil erosion (by 2.3 ± 0.6 Gt yr^{-1}), yet reduced the flux of sediment reaching the world's coasts (by 1.4 ± 0.3 Gt yr^{-1}) because of retention within reservoirs. Over 100 Gt of sediment and 1 to 3 Gt of carbon are now sequestered in reservoirs constructed largely within the past 50 yr.

Measurements of African dust made by Prospero & Lamb (2003) showed that it was carried over large areas of the Atlantic and to the Caribbean during much of the year. Between 1965 and 1998, measurements taken in the Barbados trade winds showed large inter-annual changes that were negatively correlated with rainfall in the Soudano-Sahel, a region that has suffered varying degrees of drought since 1970. Regression estimates based on long-term rainfall data suggested that dust concentrations were sharply lower during much of the 20th century before 1970, when rainfall was more normal (Prospero & Lamb 2003). Because of the great sensitivity of dust emissions to climate, future changes in climate could result in large changes in emissions from African and

Table 9. Top 10 most cited papers in the Landscape (L) category

Rank	Publication	Journal	No. of citations	No. of citations per year (CPY) by 2015
1	Syvitski et al. (2005)	Science	998	99.8
2	Guzzetti et al. (2012)	Earth-Science Reviews	195	65.0
3	Prospero & Lamb (2003)	Science	593	49.4
4	Huggel et al. (2012)	Earth Surface Processes and Landforms	58	19.3
5	Stoffel & Huggel (2012)	Progress in Physical Geography	58	19.3
6	Crozier (2010)	Geomorphology	79	15.8
7	Kääb et al. (2007)	Global and Planetary Change	119	8
8	Huggel et al. (2010)	Philosophical Transactions of the Royal Society A	68	13.6
9	Huggel (2009)	Quaternary Science Reviews	74	12.3
10	Mabit et al. (2014)	Earth-Science Reviews	12	12.0

other arid regions that, in turn, could lead to impacts on climate over large areas.

Guzzetti et al. (2012) examined conventional and new techniques for producing landslide maps. Conventional methods relied mainly on the visual interpretation of stereoscopic aerial photography, aided by field surveys – both time consuming and resource intensive. New and emerging techniques based on satellite, airborne, and terrestrial remote sensing technologies can reduce the time and resources required for their compilation and systematic update. They argued that the new tools will help to improve the quality of landslide maps, with positive effects on all derivative products and analyses, including erosion studies and landscape modeling, susceptibility and hazard assessments, and risk evaluations

A series of catastrophic slope failures that occurred in the mountains of Europe, the Americas, and the Caucasus since the end of the 1990s were analysed by Huggel et al. (2012), who distinguished between rock and ice avalanches, debris flows from de-glaciated areas, and landslides that involved dynamic interactions with glacial and river processes. Based on several case studies, they proposed that the following mechanisms can significantly alter landslide magnitude and frequency, and thus hazard, under warming conditions: (1) positive feedbacks acting on mass movement processes that after an initial climatic stimulus may evolve independently of climate change; (2) threshold behaviour and tipping points in geomorphic systems; (3) storage of sediment and ice involving important lag-time effects. With a clear focus on studies from the European Alps, Stoffel & Huggel (2012) reported that changes in mass-movement activity could hardly be detected in observational records. They documented the role of climate variability and change on mass-movement processes in mountains through the description and analysis of selected, recent mass movements where effects of global warming and the occurrence of heavy precipitation are thought to have contributed to, or triggered, events. They then assessed possible effects of future climatic changes on the incidence of mass-movement processes, concentrating on high-mountain systems, including processes such as glacier down-wasting and the formation of new ice-marginal lakes, glacier de-buttressing and the occurrence of rock slope instability, temperature increase and permafrost degradation, as well as on changing sediment reservoirs and sediment supply. Crozier (2010) evaluated several landslide modelling approaches on the basis of their potential to predict landslide response to climate projections. Crozier found that existing hydrological, slope stability and statistical models were capable of yielding useful prognoses on occurrence, reactivation, magnitude and frequency of landslides. Although there is a strong theoretical basis for increased landslide activity as a result of predicted climate change, there is still a high level of uncertainty due to the margins of error associated with scenario-driven global climate predictions, and the lack of sufficient spatial resolution of currently available downscaled projections. Changes resulting from human activity are seen as a factor of equal, if not greater, importance than climate change in affecting the temporal and spatial occurrence of landslides

Using a one-dimensional thermo-mechanically coupled numerical model to simulate the potential response of rock glacier creep to a change in surface temperature, Kääb et al. (2007) found that due to the — in general considerable — ice content of rock glaciers, their dynamics respond sensitively to climate forcing. Other influences such as the occurrence and complex influence of liquid water in the frozen material might be the most important factor for permafrost close to 0°C, though such factors were difficult to model. Huggel et al. (2010) reported on recent and future warm extreme events and high-mountain slope failures, and Huggel (2009) described exceptional slope failures in high-mountain, glacial environments: the 2002 Kolka–Karmadon rock–ice avalanche in the Caucasus; a series of ice–rock avalanches on Iliamna Volcano, Alaska; the 2005 Mt. Steller rock–ice avalanche in Alaska; and ice and rock avalanches at Monte Rosa, Italy in 2005 and 2007.

Increasing anthropogenic pressures coupled with climate change impacts on natural resources have promoted a quest for innovative tracing techniques for understanding soil redistribution processes and assessing soil resources. Mabit et al. (2014) provided a comprehensive evaluation and discussion of the various applications of $^{210}Pb_{ex}$ as a tracer in terrestrial and aquatic environments, with particular emphasis on catchment sediment budget investigations. Their paper summarizes the state-of-the-art related to the use of this tracer, the main assumptions, the requirements (including the need for accurate analytical measurements and for parallel validation), and the limitations which must be recognised when using this fallout radionuclide as a soil and sediment tracer.

Authorship of published papers. Science (14 papers) and Nature (11 papers), followed by Earth-Science Reviews (5 papers) were the journals which published the largest number of Top 10 papers in each category (Table 10). The remaining 20 journals published only one single Top 10 article.

The numbers of authors listed on each manuscript varied widely. While, only 10% (5) of the papers in the Top 50 in each of the 5 categories had a single author, 18% (9) had 2 authors, 14% (7) had 3 authors and 16% (8) had 4 authors. Therefore, 58% of the Top 50 papers had 4 or fewer authors. By contrast, one paper had 28 authors (Fig. 6a). The countries of authorship affiliations also varied widely. Single country authorship was observed in 48% of the papers (24), whereas 20% (10) of the papers had authors from 2 countries and 16% (8) from 3 countries (Fig. 6b). One paper, Taylor et al. (2013), had authors from 13 countries (from a total of 26 authors). Most papers were authored by groups of 2–4 authors (48% of papers) with only 18% of the papers having 10 or more authors. There were no relationships between the number of authors and CPY of the paper or between the number of countries represented by the authors and CPY (data not shown). Therefore, writing papers with more authors or more countries represented does not make for higher CPY as might have been expected.

In total 302 unique authors were listed in the Top 10 papers within the 5 categories (Tables 5–9). The USA was the country with most author affiliations (29% or 88 authors), followed by China with 13% and the UK with 11%. Over half of the authors (53%) were affiliated with these 3 countries. Altogether, authors from 35 countries contributed to the papers in the Top 10 of the 5 categories (Fig. 7). The USA (20), followed by Switzerland (7) and the UK (6) had the highest number of first authorships (Fig. 7).

4. DISCUSSION

4.1. Origin of authorship and language of publication

The approach of attempting to find and list the Top 50 or Top 100 papers in a particular field is not new. Medicine is the field with the largest number of attempts to rank published papers (e.g. Loonen et al. 2007, Ponce & Lozano 2010, Azer 2015). Even in fields such as terrorism studies there have been attempts to evaluate the rankings of top papers published (Silke & Schmidt-Petersen 2017). However, to the best of our knowledge there have been no other attempts like this to evaluate research in the area of climate change, so it is not possible to directly compare our findings with any others in the same field. We found that most of the Top 50 papers in this study

Table 10. Journal frequency in the Top 50 papers

	Table 5 E	Table 6 P	Table 7 W	Table 8 I	Table 9 L	Totals
Nature	3	3	3	2		11
Science	7	2	3		2	14
Earth-Science Reviews			1	2	2	5
The Review of Economics and Statistics		1				1
Climate Change		1				1
The Lancet		1				1
Sustainable Development		1				1
Progress in Development Studies		1				1
Technological Forecasting and Social Change			1			1
Journal of Glaciology and Geocryology			1			1
Journal of Hydrology			1			1
Journal of Geophysical Research				1		1
Cryosphere				1		1
International Journal of Climatology				1		1
Permafrost and Periglacial Processes				1		1
Remote Sensing of Environment				1		1
Journal of Glaciology				1		1
Earth Surface Processes and Landforms					1	1
Progress in Physical Geography					1	1
Geomorphology					1	1
Global and Planetary Change					1	1
Philosophical Transactions of the Royal Society A					1	1
Quaternary Science Reviews					1	1

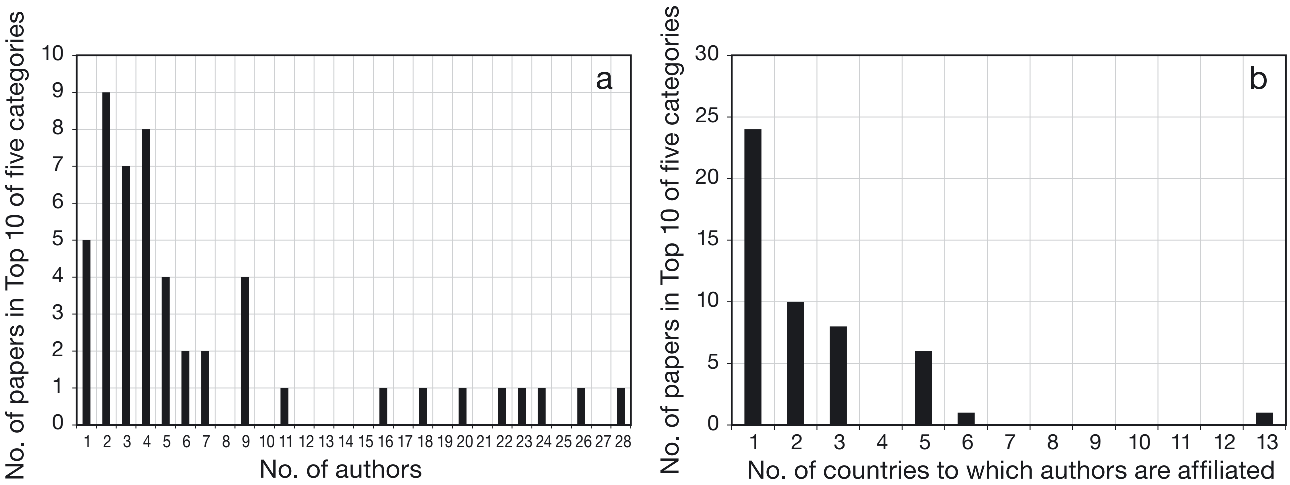

Fig. 6. Top 10 papers of each of the 5 categories. (a) Analysis of the number of authors of papers. (b) Analysis of the countries to which authors of these papers are affiliated

were written by US based authors (Fig. 7), a tendency which is reflected by other studies ranking published papers. For example, Eshraghi et al. (2013) evaluated the 100 top-cited scientific papers in limb prosthetics and found that the majority of authors also originated from the North America and were written in English. Similarly, Kelly et al. (2010) suggested, using the Science Citation Index with data ranging from 1945–2008 in orthopaedic surgery, that of the Top 100 cited papers the majority originated from the USA, followed by the UK. While authors from the UK contributed a considerable number of publications to the Top 50 in this study, Chinese authors contributed the second largest number of papers. It is also interesting to note that in contrast to the 7 journals in which the Top 100 orthopaedic surgery papers were published (Kelly et al. 2010), studies published in the Top 50 in climate change, however, were published in 23 different journals (Table 10). This wide range of journals likely reflects the broad range of climate change research in comparison to the field of orthopaedic surgery.

The ranking of highly cited papers is often limited to English language publications. For example, the Institute for Scientific Information (ISI) has a preference for English language journals as only 2 German social science journals were included. By contrast a German database listed a total of 542 different German language journals (Artus 1996). This language bias will favour English-speaking authors, given the strong tendency of authors to cite selectively articles in their own national language. However, Chinese authors in climate science are now starting to bridge that gap, by publishing in English and citing both Chinese and English language articles. More than half of all citations are by US scientists, who, as Seglan (1998) claims, are particularly prone to cite one another, thereby helping to raise the citation rate of US science to 30% above the world average. Seglan's (1998) claim might hold true for our study, as we only included English language citations. However, the increasing trend in climate science of Chinese authors to also pub-

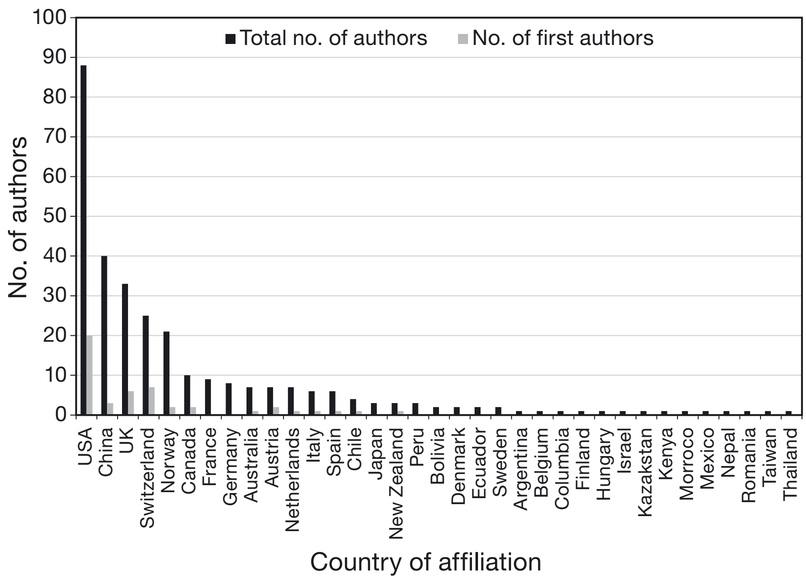

Fig. 7. Frequency distribution to show the country of affiliation of authors in the Top 10 papers of each of the 5 categories

lish in English, as indicated in our study, is potentially an indication that non-English speaking countries are adopting English language publications to increase the reach of their research.

4.2. Importance of impact factor and paper citations

The majority of Top 50 papers published in climate research are located in top ranking, high impact factor journals (Table 10). The principle of journal 'impact factors' goes back to the 1960s to Irving H. Sher and Eugene Garfield (Garfield 1999, 2006). Gradually, the impact factor has evolved to include both journal and author impact, and has become widespread in its use, particularly in science. However, Seglen (1998) argued convincingly that citation rates and journal impact factors are not suitable for evaluation of research. Citation data are assembled by ISI on the basis of reference lists in scientific journals, which are listed by year in the annual Science Citation Index (SCI). The SCI covers about 3200 journals, which is a small proportion of the word's total of ca. 126 000 journals as Seglen (1998) argues. Seglen (1994) claimed that there was a causal relationship between article citation rates and journal impact factors. In addition, different research fields are covered unequally: the coverage for chemistry has been estimated at 90%, as compared to 30% for biology. Of course, climate science, as we have seen in this study, is very multidisciplinary in its nature, making it very difficult to assess it as a distinct research field. However, climate research is a 'hot' topic and therefore likely of increased interest to top journals such as Science and Nature, as well as to Government Agencies, politicians and decision makers.

The frequency of citations within the Top 50 climate research papers varies widely. Broader topics (category E) are generally more frequently cited than more specific research areas (as found in category L). This variation of citations between different topics is not uncommon. Unfortunately, the journal impact factor does not take this variation into account. Leydesdorff (2012) suggests an alternative measure to impact factors: a proportion of the most highly cited papers (the top 10% or top quartile) on the basis of fractional counting of citations may provide an alternative to the current impact factor. Again, this point should be borne in mind when interpreting the results of this study — citation distributions vary among fields of science — and it may be that the papers in the E category of this study are generally in field of research which gains higher citation distributions, than say the L category which did not.

A further point which should be discussed here is that we deemed 33 of the 50 papers (66%) to be dealing with global issues, whereas the other 17 (34%) were more regionally focused (e. g. the Andes or Europe) which might explain their higher average CPY.

This study has identified 5 research areas (categories), whereas the IPCC (2014) identified 4. Our fifth category of Landscape Research (L) has been identified as a knowledge 'gap'. In the Top 50 highest impact journal papers in the period 2000–2014 (Table 5), only one paper (Syvitski et al. 2006) was categorised as being related to Landscape Research. When the Top 10 papers concerned with landscape research were identified (Table 10), it is clear that this type of research is indeed being carried out and does reach high impact journals, but it is not yet finding its way into the Top 50 highest impact journals we list in Table 5. This may be because much of this type of research (e.g. rockfall, landslides, erosion and sediment transport) is necessarily local, or maybe at best regional in its coverage and applicability, whereas some of the highest impact papers we identified are concerned with more global issues like species distribution change and biodiversity (Parmesan & Yohe 2003), agriculture and food production (Lobell et al. 2011), water resources (Barnett et al. 2005), soil and forest carbon (Lal 2004, Davidson & Janssens 2006, Kurz et al. 2008), human health (McMichael et al. 2006), and social limits and adaptation (Nicholls & Cazenave, 2010). This may explain why landscape research does not generally feature in the Top 50 highest cited journals identified in this study, and maybe why IPCC (2014) did not identify this gap specifically but has perhaps included it in their Terrestrial Ecosystems (E) of Ice and Glaciers (I) categories.

As a result of our analysis we think that research on landscape processes and change resulting from climate change in polar and particularly populated mountainous regions should be encouraged and supported in future. The IPPC (2014) Summary for Policy Makers (p. 32–34) states that there is *high confidence* (with a major contribution of climate change) that in future there will be:

- retreat of tropical highland glaciers in East Africa
- retreat of Alpine, Scandinavian and Icelandic glaciers in Europe
- permafrost degradation in Siberia, central Asia, the Tibetan Plateau and the Southern Arctic

- increased flow in rivers due to shrinking glaciers in the Himalayas and central Asia
- reduced flow in river systems in southwestern Australia
- shrinkage of glaciers across western and northern North America
- decreasing amount of water in spring snowpack in western North America (1960–2002)
- shift to earlier peak flow in snow dominated rivers in western North America
- reduction in ice volume in Arctic glaciers
- disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat.

In other words, there is high confidence that there will be glacier retreat and decreases in ice volume in all continents (Vuille et al. 2008), changes (often reductions) in flow in rivers fed by glaciers (Dery et al. 2012) and widespread permafrost degradation in the Arctic (Zhang et al. 1997) all of which illustrate the associated responses in the landscape An important consequence of predicted increases in mean, maximum and minimum temperature and more intense rainstorms may be an increase in landslides in high mountains. Huggel et al. (2012) argued that more research is needed to be able to detect changes in landslide magnitude and frequency related to contemporary climate, particularly in alpine regions hosting glaciers, permafrost, and snow. Based on an analysis of a series of catastrophic slope failures from the mountains of Europe, the Americas, and the Caucasus, Huggleyu et al. (2012) proposed that the following mechanisms can significantly alter landslide magnitude and frequency, and thus hazard, under warming conditions: (1) positive feedbacks acting on mass movement processes that after an initial climatic stimulus may evolve independently of climate change; (2) threshold behavior and tipping points in geomorphic systems; (3) storage of sediment and ice involving important lag-time effects.

5. CONCLUSIONS

In this paper, we describe the building and subsequent analysis of a database of 663 of the most significant journal papers on the effects of climate change in polar and mountainous regions between 2000–2014 (up until the Fifth IPCC Assessment). All papers were assigned up to three key words and a thematic analysis of these key words resulted in the papers being assigned to 5 categories (snow and ice, terrestrial ecosystems, rivers and lakes, food production and livelihoods, landscape: I, E, W, P, L, respectively). By a count of all papers in the database, the ranks were I (34%) > E (31%) > W (15%) > P (11%) > L (9%). When the average citations per year (CPY) was calculated, the ranking changed to E > W > P > L > I and when the number of papers was multiplied by CPY the ranks became E > W > P > I > L.

When just the 50 papers with the highest CPY (Top 50) were analysed, the ranking of the numbers in each of the 5 categories was E (57%) > P (20%) > W (15%) > I (7%) > L (1%). When the average CPY of the Top 50 was calculated, the ranking changed to E > I > P > W > L and when the number of papers was multiplied by CPY the ranks became E > P > W > I > L. Using the number of paper citations per year to derive the Top 50 most cited journal papers published in the 15 yr period, an analysis of the topic of these Top 50 papers is compared to the IPCC Fifth Assessment (AR5) Report (IPCC 2013) and the wider database of 663 entries.

When only considering the Top 50 papers (ranked by highest number of CPY), there is a mismatch between the ranking of the categories in the larger database (of 663 papers) and those in the Top 50. The rank order changed from E > W > P > I > L in the whole database to E > P > W > I > L in the Top 50. Only 10% (5) of the papers in the Top 50 in each of the 5 categories had single authors, Most papers had groups of 2–4 authors (48% of papers) with only 18% of the papers having 10 or more authors. One paper in the Top 50 had 28 authors. 48% of the papers (24) had all the authors from 1 country, 20% (10) had authors from 2 countries and 16% (8) from 3 countries (Fig. 6b). One paper had authors from 13 countries (from a total of 26 authors). There was a total of 302 authors of the Top 10 papers in each of the 5 categories. The country with most authors affiliated (29%) was the USA (with 88 authors), followed by China with 13% and the UK with 11%. This means that these 3 countries had 53% of the total authorship. Authors were affiliated to 35 countries all together.

We feel that policy makers should note the under-representation of high-impact research into landscape processes (erosion and deposition processes), which need to be addressed in future. The Interregional Technical Co-operation Project INT/5/153 (2014-18) on Assessing the Impact of Climate Change on Land-Water-Ecosystem Quality in Polar and Mountainous Regions, organized and funded by the International Atomic Energy Agency and supported by the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, will address this gap to some extent.

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Appendix. Table A1. Titles of journals (with number of entries) used in database

Journal	No.	Journal	No.	Journal	No.
Acta Bot. Boreal.-Occident. Sin	1	Ecological Monographs	1	Journal of African Earth Sciences	1
Acta Ecologica Sinica	1	Ecology	2	Journal of Agronomy and Crop Science	1
Acta Geológica Hispánica	1	Ecology and Society	1	Journal of Arid Environments	2
Acta Pedologica Sinica	1	Ecology Letters	2	Journal of Asian Earth Sciences	1
Acta Societatis Botanicorum Poloniae	2	Ecosystems	1	Journal of Biogeography	2
Advances in Agronomy	1	Emotion, Space & Society	1	Journal of China University of Geosciences	2
Advances in Climate Research	1	Energy Policy	2	Journal of Climate	1
Advances in Ecological Research	13	Engineering Geology	1	Journal of Climatology	1
Advances in Geosciences	3	Environmental and Resource Economics	1	Journal of Food, Agriculture & Environment	1
Agricultural and Forest Meteorology	1	Environmental Conservation	1	Journal of Environmental Management	1
Agriculture, Ecosystems and Environment	1	Environmental Development	1	Journal of Environmental Radioactivity	2
Agricultural Systems	1	Environmental Management	1	Journal of Geophysical Research	9
Agricultural Water Management	1	Environmental Pollution	1	Journal of Glaciology	14
Ambio	7	Environmental Research Letters	4	Journal of Glaciology and Geocryology	2
American Scientist	1	Environmental Science and Policy	5	Journal of Historical Geography	1
Annals of Botany	1	EOS	2	Journal of Hydrology	12
Annals of Glaciology	8	Forest Ecology and Management	3	Journal of Hydrometeorology	1
Annals of the Association of American Geographers	3	Forest Policy and Economics	1	Journal of Integrated Disaster Risk Management	1
Annals of Tourism Research	1	Forestry Studies in China	2	Journal of Mountain Science	4
Antarctic Science	1	Freshwater Biology	1	Journal of Paleolimnology	1
Applied Soil Ecology	2	Fungal Ecology	1	Journal of Plant Nutrition and Soil Science	1
Arctic, Antarctic, and Alpine Research	12	Geochimica et Cosmochimica Acta	1	Journal of Quaternary Science	2
Atmospheric Chemistry & Physics	1	Geoderma	3	Landslides	2
Austrian Journal of Earth Sciences	2	Geografiska Annaler: Series A, Physical Geography	5	Marine Geology	1
Biodiversity	1	Geographica Helvetica	1	Microbes and Infection	1
Biogeochemistry	1	Geology	1	Mountain Research and Development	6
Biogeosciences	2	Geology Today	1	Mycorrhiza	1
Bioscience	3	Geomorphology	16	Natural Hazards	5
Books	5	Geophysical Research Abstracts	2	Natural Hazards and Earth System Sciences	3
Book chapters	31	Geophysical Research Letters	7	Nature	34
Canadian Water Resources Journal	1	Global and Planetary Change	21	Nature Climate Change	28
Catena	2	Global Biogeochemical Cycles	2	Nature Geoscience	35
CECNet	1	Global Change Biology	15	Norsk Geografisk Tidsskrift	1
Central Asia and the Caucasus	1	Global Climate Change and Cold Regions Ecosystems	1	Oceanography-Oceanography Society	1
Chinese Journal of Plant Ecology	1	Global Ecology and Biogeography	2	Organic Geochemistry	1
Climate Change	11	Global Environmental Change	10	PAGES News	1
Climate Dynamics	1	Hydrological Processes	15	Palaeogeography, Palaeoclimatology, Palaeoecology	7
Climate of the Past	1	Hydrological Sciences Journal	2	Permafrost and Periglacial Processes	4
Conference/Symposium Proceedings	18	Hydrology and Earth System Sciences	6	Perspectives in Plant Ecology, Evolution and Systematics	1
Cryosphere	12	IAHS Symposium Proceedings	2	Pesquisa Antártica Brasileira	1
Current Biology	1	Ice and Snow	2	PhD theses	3
Current Opinion in Environmental Sustainability	2	International Journal of Climatology	2	Philosophical Transactions of the Royal Society A	1
Danish Journal of Geography	1	International Journal of Environmental Protection	1		
Discussion papers	2	International Journal of Remote Sensing	1		
Earth and Planetary Science Letters	2	International Journal of Sustainable Society	1		
Earth-Science Reviews	15	International Journal of Water Resources Development	1		
Earth Surface Processes and Landforms	2				
Earth System Science Data	2				
Ecological Applications	1				
Ecological Economics	1				

Appendix. Table A1 (continued)

Journal	No.	Journal	No.	Journal	No.
Photogrammetric Engineering and Remote Sensing	1	Remote Sensing of the Environment	16	State of Antarctic Environment Quarterly Bulletin	2
Plant and Soil	1	Renewable and Sustainable Energy Reviews	1	Surveys in Geophysics	1
PLOS ONE	5	Report	30	Sustainable Development	1
Polar Biology	5	Report in Spanish	1	Technological Forecasting and Social Change	1
Polar Geography	1	Resources Science	1	Tellus	3
Polar Science	1	Resource and Environment in the Yangtse Basin	1	The Holocene	1
Polish Polar Research	1	Reviews of Geophysics	1	The Lancet	1
Polish Journal of Ecology	1	Revista Brasileira de Geomorfologia	3	The Review of Economics and Statistics	2
Problems of Arctic and Antarctic	3	Revista de la Asociación Geológica Argentina	1	Theoretical and Applied Climatology	3
Proceedings of the National Academy of Sciences	1	Scandinavian Journal of Forest Research	2	Tourism Management	1
Progress in Development Studies	1	Science	44	Transactions American Geophysical Union	2
Progress in Physical Geography	1	Science China Earth Sciences	1	Tree Physiology	1
Quaternary International	9	Science of the Total Environment	4	Trees	1
Quaternary Research	1	Silva Fennica	1	Water International	1
Quaternary Science	1	Soil Biology and Biogeochemistry	2	Water Science and Technology	1
Quaternary Science Reviews	13	Soil Science Society of America Journal	1	Zeitschrift für Geomorphologie	1
Regional Environmental Change	1	Soils	1		
Radiation and Environmental Biophysics	1	Spanish Journal of Agricultural Research	1		
Remote Sensing Letters	1				

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