Communication

Climate change/global warming/climate emergency versus general climate research: Historical (1910-2020) and bibliometric trends of publications

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Abstract: This article presents and discusses analytical data on the scientific publication record from 1910 to 2020 on two topics: "climate" and "climate change/global warming/climate emergency". The goal is to visualize how the publication record on these two topics has evolved over time, from different classification perspectives (year, country, source and organization). Three hypotheses are tested using data collected from Web of Science and various graphical representations of the data. It is found that research output related to the Earth's contemporary changing climate overtook that of general climate research in 2011, and the publication ratio has been expanding in the last decade. There are significant differences in the publication countries and sources between the two topics, and conversely less significant differences in terms of organizations publishing these works. Differentiation factors that affect the level of research output and engagement on the climate challenge include: island versus landlocked nations, specialized versus general scientific journals, academic versus institutional organizations. The future of the publication records is discussed, such as the emergence of new terms to refer to the climate challenge, such as "climate emergency".

Keywords: bibliometric analysis; scientometrics; human influence on climate; natural control of climate; climatic and non-climatic effects on living organisms; improving climate monitoring; climate variability; climate models; CO_2.

1. Introduction

Climate Change, Global Warming and more recently Climate Emergency (CC/GW/CE) have been, in the past decade and more, terms synonymous with the greatest sustainability challenge of the 21st century [1-4]. In this article we explore, using bibliometric analysis, the publication trends since these terms appeared in the journal records, in the early part of the 20th century, to test the following hypotheses:
1. It is possible to substantially distinguish the scientist literature that pertains to the study of the aforementioned climate challenge (or solutions for mitigating it) from studies that address gaining better understanding of the Earth's climate itself, using topical keyword searches.
2. The scientific literature has become so enriched in works addressing the climate challenge, that it surpassed climate research in terms of number of publications sometime in the late part of the 20th century.
3. The scientific literature that pertains to the climate challenge is at least partly distinct from that on climate research, in terms of venue of publication, country of origin of studies, and organizations that have conducted these works.

Various bibliometric studies have explored different topics related to climate change [5], global warming [6], scientific [7] and technological [8] questions. Studies that merge traditional bibliometrics with scientific topics also term these types of studies scientometrics [8,9]. Such studies often rely on the most comprehensive literature databases available, including Web of Science and Scopus

[8,10,11]. It is also common for such studies to span several decades [7,9], and cover regional [5,6] to global [7,11] topics. The present study is global in scope, and covers over a century of data, as it looks to highlight key moments in the publication record and scientific advancement histories, in addition to the temporal and various categorical trends. It is also unique in its aim to contrast general climate research versus CC/GW/CE research via hypothesis testing, and via various publication ratios and graphical representations of the data.

2. Methodology

Web of Science (WoS) was used to search the scientific literature and collect the relevant publication data for analysis. The searches were conducted on March 6th, 2021 (for 1900 to complete 2020 data); all data were collected within a short time those days, to obtain a snapshot of the publication record. Figure 1 shows the protocol used for this bibliometric study, which is classified into five steps detailed below.

Step one: The search used a timespan of 1900 to 2020 and all indexes within the Web of Science Core Collection, namely: Science Citation Index Expanded: SCI-EXPANDED (1900-2020), Social Sciences Citation Index: SSCI (1900-2020), Arts & Humanities Citation Index: A&HCI (1975-2020), Conference Proceedings Citation Index- Science: CPCI-S (1990-2020), Conference Proceedings Citation Index- Social Science & Humanities: CPCI-SSH (1990-2020), and Emerging Sources Citation Index: ESCI (2015-2020). The two search strings used were: (i) TOPIC: ("climate change" OR "global warming" OR "climate emergency"); and (ii) TOPIC: ("climate" NOT ("climate change" OR "global warming" OR "climate emergency")). The former search string was used to collect papers related to research on the climate challenge (CC/GW/CE), and the latter search string was used to collect papers related to general research on the Earth's climate (CL). That is, these search strings tested Hypothesis 1.

Step two: The searchers were further refined to document type 'Article'. These searches yield 229,084 on the CC/GW/CE topic, and 237,595 papers on the CL topic. The use of the NOR logical operator in the CL search string ensures that the two records are unique; that is, there are no repeating papers.

To verify if the search string used for CC/GW/CE research may have missed a substantial portion of research papers that did not use the three searched keywords, a third search was conducted using the following search string: TOPIC: ((("greenhouse gas*" OR "GHG*") NOT ("climate" OR "climate change" OR "global warming" OR "climate emergency"))). This search yielded 29,943 articles. This represents 11.56% of articles obtained with the combined search strings. In the Discussion and Conclusions section, the omission of these articles from the data analysis is explained.

Step three: The search results were at first analyzed using the Analyze Results feature of WoS. In the analysis page, it is possible to download tab-delimited text files containing a set of publication data according to the WoS category selected. Data files were obtained for the following four categories: publication years; organizations-enhanced; source titles; countries/regions. The data from these text files were then imported into Microsoft Excel for further processing and analysis. These data and analyses enabled testing Hypotheses 2 and 3. More details on the data handling procedure is provided in the Data Analysis section.

One additional procedure used was to recover keywords from the search records. This was done using the Export feature of WoS on the search results page to generate Excel files containing various attributes of each paper, including the keywords. Keywords were compiled from the top 100 cited papers from both topics (CC/GW/CE and CL), as of March 6th, 2021. These keywords were used to generate word clouds using the software Wordle [12].

Step four: A bibliometric analysis including keywords co-occurrence, countries collaboration, most relevant words, beamplots and affiliations was also performed on the full search results, which was exported from WoS as a bibtex or CSV file, using the bibliometrix package in RStudio software (Version 1.2.5001 ©2009-2019 RStudio, Inc [13]. These data and analyses enabled testing Hypotheses 2 and 3, which are shown in the Supplementary Materials. This package uses the meta-data in the

Web of Science citations to calculate and rank country production, journal sources, and country collaborations.

Step five: The previous steps (step one to four) were for all selected databases. In this step, each database was separately selected for analysis. Therefore, steps 2 to 4 were repeated again, and the results from each search were imported to Excel and Rstudio for further analysis.
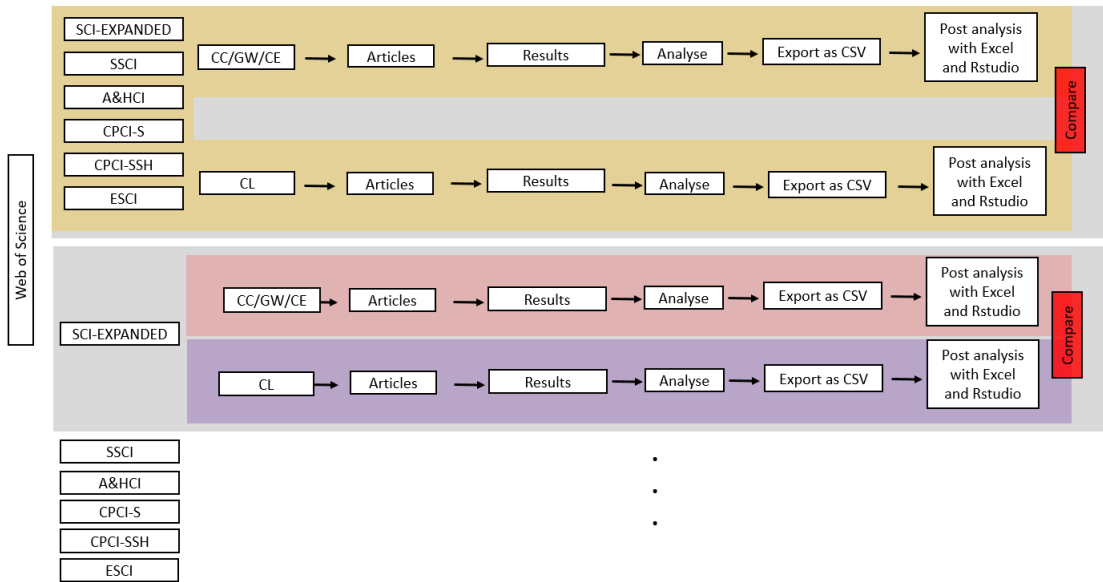

Figure 1. Protocol used for the bibliometric study.

3. Publication Record Highlights

From 1910 to 1970, the publications record for CC/GW/CE shows only eight entries, with 1971 being the first year with multiple (three) records. In fact, a line can be drawn at 1970 with the publication of Berton's paper titled "Carbon dioxide and its role in climate change" [14]. This is the first of the papers on record to specifically address contemporary anthropogenic climate change. It does not mean that only in 1970 the role of humans on climate change was understood; such hypothesis dates to decades earlier. But it may be one of the first papers to consistently use the term "climate change" to describe the observed phenomena (increasing atmospheric concentration of greenhouse gases and increasing global surface temperatures, as discussed in the paper). Another evidence of this shift in terminology is that two of the three 1971 papers, those by Frisken [15] and Kopec [16], address the pressing climate challenge. This is in contrast with the first paper on this record, the 1910 Nature article by Lockyer titled "Does the Indian climate change?" [17], which discusses short term observations of changing frequency of monsoons to conclude that the climate on the sub-continent varies from year to year, with both short- and long-term trends, but the influence of humans on these trends is not addressed, in fact, the opposite (the natural control of climate) is inferred. Notably, both Frisken [15] and Kopec [16] highlight that by the early 1970's it is well accepted that humans can have a significant effect on the climate by air emissions, but that at that time (when CO_2 atmospheric concentration have just surpassed 320 ppm [14]), the role of nature was still deemed stronger than the role of humans.

One way to contrast the publication record of CC/GW/CE versus that of CL is to compare their most cited works.

Table 1 presents the publication history of the authors of five most cited journal articles from each record and their subject classifications.

Briefly reviewing these papers (i.e. reading the paper's aims and conclusions) helps to understand if the two data records contain the required topical selection of CC/GW/CE versus CL. For their first

top cited papers, seven of the ten papers are correctly classified, two are unusually misclassified, and one is an outlier, as follows.

1   Table 1. The first three most cited journal articles of the first 5 authors with the highest citation from the two records (CC/GW/CE and CL).

CL Record			Top three most cited papers									
	Author first	Author	First highest cited-paper			Second highest cited-paper				Third highest cited-paper			
Author name	publication (year)	total citation	Ref	Citation	Subject	Ref	Citation	Document Type	Subject	Ref	Citation	Subject	Document Type
Rayner, Nick	1985	20,006	[18]	6,114	CC	[19]	5,526	Review	CL	[20]	3,096	CL	Article
Parmesan, Camille	1987	29,097	[21]	5,998	CC	[22]	5,875	Review	CC	[23]	4,776	CC	Review
Kottek, Markus	2005	29,747	[24]	4,184	CL	[25]	452	Article	CC	[26]	44	CL	Editorial Material
Thomas, Chris D.	1984	29,747	[27]	4,184	CC	[28]	2,208	Article	CC	[29]	1,554	CC	Article
Allen, Craig D.	1994	17,731	[30]	3,474	CC	[31]	2,009	Review	CC	[32]	1,319	CC	Article
CC/GW/CE Record			**Top three most cited papers**										
	Author first	Author	First highest cited-paper			Second highest cited-paper				Third highest cited-paper			
Author name	publication (year)	total citation	Ref	Citation	Subject	Ref	Citation	Document Type	Subject	Ref	Citation	Subject	Document Type
Kalnay, Eugenia	1976	36,675	[33]	20,774	CL	[34]	3,261	Article	CL	[35]	2,250	CL	Artile
Hijmans, Robert J.	1996	26,275	[36]	12,441	CL	[37]	4,818	Review	CL	[38]	1,856	CL	Article
Taylor, Karl E	1976	25,298	[39]	7,972	CC	[40]	3,179	Article	Out of scope	[41]	2,025	CC	Article
Phillips, Steven J.	1969	24,380	[42]	7,750	CL	[37]	4,818	Article	CL	[43]	3,154	Out of scope	Article
Tenenbaum, Joshua B.	1991	18,292	[44]	7,016	Out of scope	[45]	611	Review	Out of scope	[46]	576	Out of scope	Article

2   [1] Of corresponding author.

3   [2] WoS Core citations as of March 6th 2021.

Rayner et al. [18] present sea ice and sea surface temperature and nighttime marine air temperature data sets, starting from 1871. That is, the study covers parameters pertinent for climate change research and the contemporary post-industrial revolution period attributed to anthropogenic climate change; and he reached to his most cited paper after 18 years from his first publication. Parmesan and Yohe [21] showed that climate change effects on living systems can be discerned from non-climatic effects by looking for systematic trends over diverse species and geographic regions; and he reached to his most cited paper after 16 years from his first publication. Kottek et al. [24] provide a climate classification map update valid for the second half of the 20th century, which was updated from the original 1961 Wladimir Köppen map. One motivation for this update was that climate changes have occurred and thus up-to-date global temperature and precipitation data sets were required to update the geographical distribution of the various climate zones (equatorial, arid, warm temperate, snow, and polar, and the various sub-classifications); and he reached to his most cited paper after one year from his first publication. Thomas et al. [27] showed how climate change leads to species-level extinction. They concluded that 18% to 35% of species will be committed to extinction by 2050 because of climate change, in part because of habit loss due to changes in biome; and he reached to his most cited paper after 20 years from his first publication. Allen et al. [30] studied about the effect of climate change and drought on trees mortality risks. They concluded that there is a direct relationship between tree mortality rates and heat severity and climate change; and he reached to his most cited paper after 16 years from his first publication.

All of these five highly cited papers are thus correctly classified under the CC/GW/CE topic. Also, all of their second and third most cited papers were in the same area and mostly are classified into the CC/GW/CE topic (7 out of 10).

Kalnay et al. [33] investigated how improvements to climate monitoring can avoid misinterpretation of climate variations that are not a result of climate change. The study is not concerned about studying climate change directly, even if the advances can benefit climate change research; and he reached to his most cited paper after 20 years from his first publication.

Hijmans et al. [36] developed a method for very high resolution interpolation of temperature and precipitation climate data, which can be used to generate accurate climate surfaces (i.e. continuous grids); and he reached to his most cited paper after 9 years from his first publication.

This advance can help improve analysis of climate change, since more accurate values are obtained, though this was not the main aim of the study. An example was provided on how for Madagascar, the newly interpolated data set does not how direct evidence of climate change between 1930 and 1990. Another example stated that insufficiently dense station network can lead to erroneous climate change conclusions. Phillips et al. [42] present a model of the distribution of biological species due to geographic distribution, including climatic variables and conditions. The model was posed as being able to predict movement of species due to climate change, such as invasive species, but this was not the study's main aim; and he reached to his most cited paper after 37 years from his first publication. These are the three out of five highly cited papers correctly classified under CL. In addition, 90% of their second and third most cited papers are correctly classified.

Tenenbaum et al. [44] is the outlier. This paper does have relevance for CL research, as it pertains to development of nonlinear algorithms to find trends in complex and large data sets, such as climate data sets, and is certainly not about CC/GW/CE. So while correctly classified, due to the use of the word "climate" in the abstract, the paper's topic is largely mathematical rather than about natural or engineering sciences. Taylor et al. [39] is the paper that was unusually misclassified. This article does not have an abstract registered in WoS, and the article's single keyword registered in WoS is "climate" (the article itself does not have a keywords list). The article is in fact about CC/GW/CE research, thus the unusually incomplete record for this article caused it to be misclassified. These two papers highlight that the CL record is less robust than the CC/GW/CE record, particularly because of the CL record's less specific search string. While a weakness, the more analytical data processing presented in the Data Analysis section will show that this record is

still useful for contrasting against the CC/GW/CE to yield data-set level (as opposed to paper-by-paper) trends and conclusions.
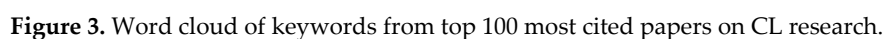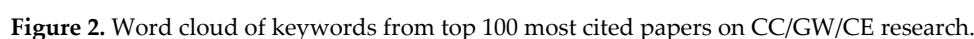
Table S-1 and S-2 in the Supplementary Materials also present the classification of 50 top cited papers for each record. Based on the results from these tables, for CC/GW/CE records, 45 papers are correctly classified, two are unusually misclassified, and three of them are outliers. While for CL records, 41 papers are correctly classified in CL subject, 8 are misclassified, and one is an outlier.

Bornmann and Marx first introduced beamplots in 2014 to better visualize the citation impact and productivity of researchers. In addition, beamplots are used to see performance variation over time to make more informed decisions about research impact and evaluation [47]. The beamplot represents a single frame of an author's output (the citation performance of an author's entire publication list), which reflects how it varies over time. In the beamplot, each dot represents a specific publication and its position is based on its publication year and its normalized citation percentile score (0-100). For example, a score of 90 for an article means that the article is among the top 10% most cited publications of the subject area, document type, and year.

In all correctly classified articles listed in Table 1, the citation percentiles were higher after publishing these articles except in Parmesan and Yohe [21]. Figure S-1 in the Supplementary Materials shows the beamplots of these authors in both records. For example, for Rayner, N. A. who have recorded the highest cited paper in CL subjects, the citation percentile after their highest cited papers [18] was increased from 48% to 78%. Also, for Kalnay, Eugenia who have the highest citation in CC/GW/CE records, the citation percentile was increased from 65% to 69%.

The citation percentile of Parmesan, Camille who have the second highest cited paper [21] in CL subjects, was lower after 2003 when they published their highest cited paper than before 2003. Figure S-6 in the Supplementary Materials shows that their citation percentiles during 2009 and 2010 were zero which were for five book chapters and causes this difference between the citation percentile before and after publishing their highest cited paper in 2003. These book chapters were manually removed from the beamplot and the new results showed that the author's performance was improved after their highest cited paper.

Figures 2 and 3 present the word clouds generated for the keywords extracted from the top 100 most cited papers in each record. In contrast to the aforementioned analysis of the top 5 most cited papers in each record, which showed significant differences in the two records, the word clouds are qualitatively less precise. Table 2 also presents the top 10 words frequency for the top 100 cited papers in each record. It is understandable that research on CC/GW/CE will use many similar keywords to more general research on the Earth's climate, thus several terms are similarly enlarged on both clouds. For example, model, variability, temperature, precipitation and circulation some of the main words on both clouds. In fact, the vast majority of words from Figure 2 also appear in Figure 3, even if in different size. Climate-change and CO_2 are the two terms in Figure 2 that are particularly distinct from Figure 3, which is expected given that these are key topics of CC/GW/CE research. Figure S-2 in the Supplementary Materials also shows the word dynamic of both records over time. Based on the results from this figure, "climate change" and "climate" terms had the highest increase over time in term of occurrence in articles. The conclusion from word clouds is that they are visually interesting, but are not ideal tools to evaluate two unique but topically similar publication records. As aforementioned, the Data Analysis section presents more deeply analytical comparisons between the two records, from which clearer trends can be seen.

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Figure 2. Word cloud of keywords from top 100 most cited papers on CC/GW/CE research.

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Figure 3. Word cloud of keywords from top 100 most cited papers on CL research.

Table 2. Word frequency of top ten used words in Figure 1 and 2.

CC/GW/CE record		CL record	
Word	Frequency	Word	Frequency
climate-change	26	climate	21
variability	11	variability	15
ocean	10	model	11
temperature	10	system	8
model	9	ocean	7
trends	9	parameterization	7
united-states	9	temperature	7
climate	8	sea-surface temperature	6
circulation	6	carbon	4
surface air-temperature	6	part	4

Figure S-3 in the Supplementary Materials shows the co-occurrence analysis of keywords using the
bibliometrix package in Rstudio in order to find research focus [13]. Based on results from this
figure, "climate change", "climate", and "variability" were the most frequent words among all
keywords from 500 top most cited papers which were similar to the key topics from the word clouds
(Figure 2 and 3).

109   **4. Data Analysis**

110   This section is sub-divided into the four categories of data collection and analysis of the
111   publication records: (i) year of publication; (ii) country (corresponding author's) of publication; (iii)
112   source (i.e. journal) of publication; and (iv) organization (corresponding author's) of publication.

113   *4.1. Year of Publication*

114   Figure 4 presents the data analysis for year of publication, ranging from 1910 to 2020. The
115   number of articles published per year in the two publication records (CC/GW/CE and CL) were
116   compiled from WoS. For each year, a ratio of the number of articles in the CC/GW/CE record over
117   the number of articles in the CL record was calculated. This ratio is plotted as a function of time on
118   Figure 3a. The purpose of this ratio is to help visualize when the scientific record became more
119   enriched in CC/GW/CE versus general CL research; that is, when the ratio surpasses a value of 1.
120   This occurred in 2011, and the ratio has since increased to 1.260 in 2019 (full year record) and then
121   to 1.346 in 2020 (record up to October 20th). Notably, before 1989, the ratio was consistently smaller
122   than 0.1, meaning that CC/GW/CE research was scarce for much of the 20th century. The exceptions
123   in 1910, 1939 and 1941 are due to the very small number of CL publications on record for those
124   decades. From 1989 onwards, the ratio increases nearly every year (in fact, it increases 26 out of 31
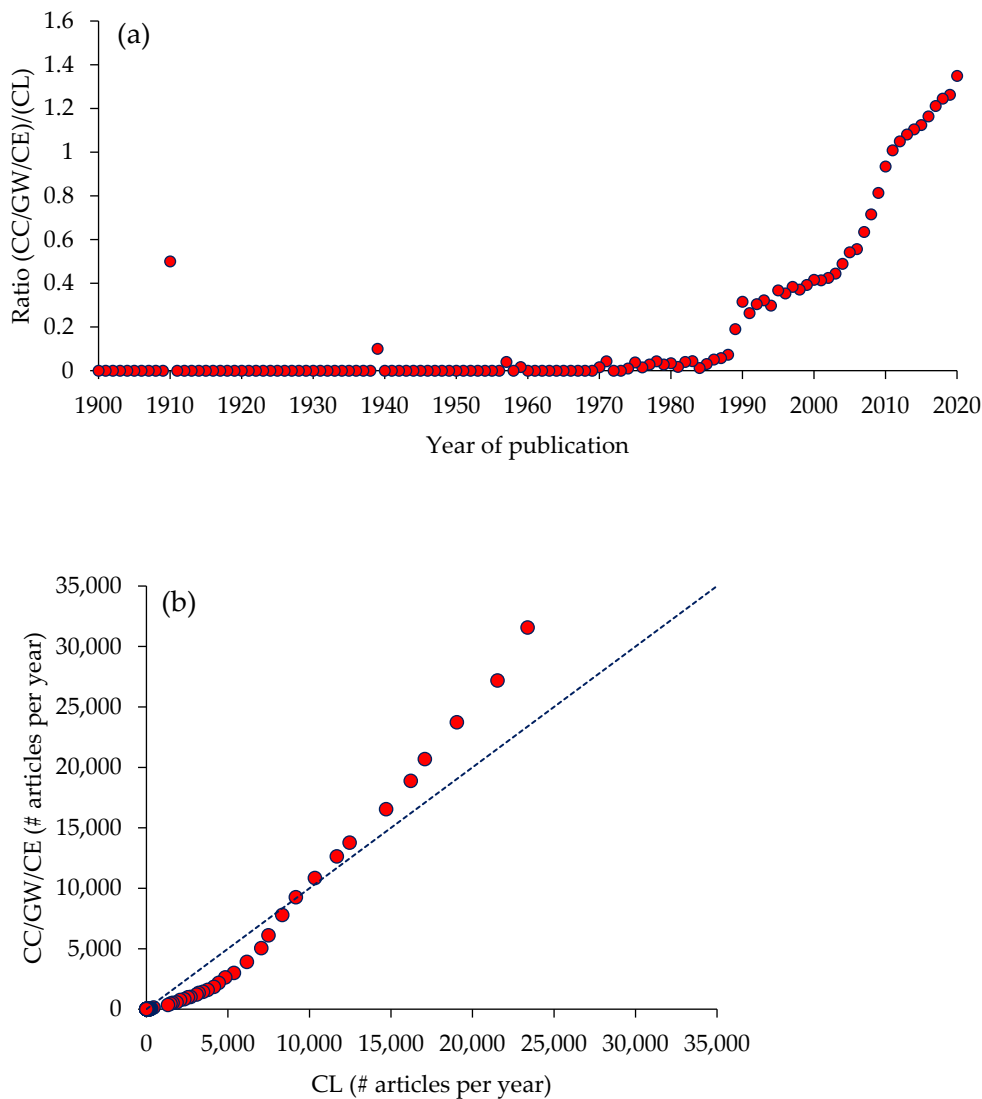125   times, and every year since 2001).

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129 **Figure 4.** Data for CC/GW/CE and CL records for year of publication: (**a**) Publication ratio
130 ((CC/GW/CE)/(CL)) as a function of time (years); (**b**) Number of publications per year in the CC/GW/CE
131 record versus those in the CL record (dashed line illustrates the 1:1 mark).

132   The number of publications in both records rose by orders of magnitude over the last several
133 decades, and Figure 4b helps to visualize this climb. The CL record crossed 100 publications in a
134 year in 1975, versus 1990 for the CC/GW/CE record. The CL record also crossed 1,000 publications
135 is a year first, in 1991, followed by the CC/GW/CE record in 1998. Then both records breached 10,000
136 articles in a year in 2012. This coincides almost exactly with the 2011 threshold, when the CC/GW/CE
137 record overtook the CL in number of publications per year. Points on Figure 3b above the dashed
138 line indicate the records from the last decade, while those below the dashed line correspond to the
139 pre-2011 record.
140   Figure 5 presents the data analysis for the number of articles per year ranging from 1910 to
141 2020 for each database. The number of articles published per year in the two publication records
142 (CC/GW/CE and CL) for each database was compiled from WoS. The number of articles is plotted
143 as a function of time in Figure 5. The goal of this Figure is to show the variation of the number of
144 articles in each database over time. Figure 5 shows that the biggest and oldest database SCI-
145 EXPANDED and SSCI (back from 1900 to present) started in 1910 and 1955, earlier from all other

146 databases, for both records. The smaller databases like CPCI-S, CPCI-SSH, and ESCI are the newer
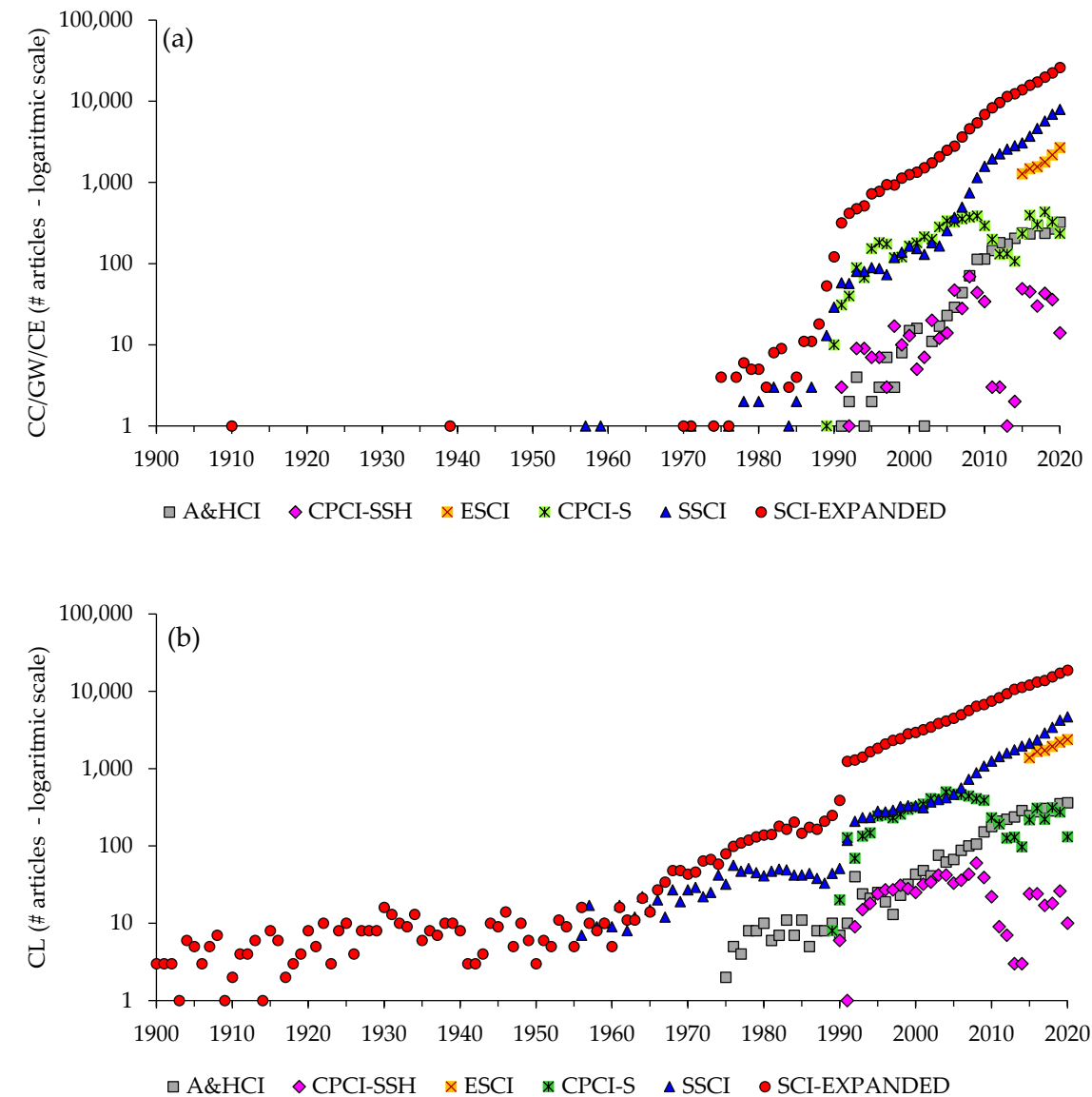147 databases and have started since 1990.
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Figure 5. Data for number of articles per year for all databases in logarithmic scale: (a) CC/GW/CE and
(b) CL.

4.2. Country/Region of Publication

155 Figure 6 and Figure S-4 in the Supplementary Materials presents the data analysis for the
156 country (or region) of publication, for the full records ranging from 1910 to 2020. The number of
157 articles published per country/region in the two publication records (CC/GW/CE and CL), from
158 1910 to 2020, was compiled from WoS. For each country/region, a ratio of the number of articles in
159 the CC/GW/CE record over the number of articles in the CL record was calculated. This ratio is
160 plotted for each country/region on Figure 6a, ordered from largest to smallest ratio.
161 Countries/regions with a ratio greater than one have been more engaged in CC/GW/CE research,
162 while those with ratio smaller than 1 have been more engaged in CL research. The number of
163 countries and regions for which a ratio was calculated in 215. An additional 32 countries of regions
164 did not have a ratio calculated, either due to no CC/GW/CE or CL articles on record (this occurs for
165 small states such as Equatorial Guinea and Turks and Caicos, among others, or for states that no
166 longer exist such as the German Democratic Republic and Rhodesia). Figure 6a shows that slightly

167 more than half of countries/regions have a ratio greater than 1, showing that the climate challenge
168 has become the dominant scientific topic in many places around the world. It is notable that the
169 majority of countries/regions with ratio greater than 2 are island states, such as Tuvalu and Cook
170 Islands (ratio = 3.00), Marshall Islands and Palau (ratio = 5.50), and Kiribati and Falkland Islands
171 (ratio = 11.00). This highlights that small island states are at most risk of the catastrophic effects of
172 climate change, particularly rising sea levels [48-52]. In contrast, countries and regions with ratio
173 lower than 0.50 tend to be those of lower gross domestic product, those in arid regions of the world,
174 or those landlocked nations, such as Albania, Djibouti, Algeria and Turkmenistan. Other countries
175 of interest to view ratios for are those with long publication history (USA (0.90), England (1.16),
176 France (0.86), Germany (0.92)) and the emerging/fast growing economies (China (1.07), India (1.00),
177 Brazil (0.76), South Africa (1.27)). The average ratio of these eight countries is very close to 1 (0.99),
178 showing that such countries contribute with diverse research. On a case-by-case basis it may be
179 possible to claim which countries are more engaged in the climate challenge, but this has to also
180 take into account the fact that rich amount of older literature from some countries, when CL research
181 was dominant, may be holding back their ratio, but that it does not mean that currently these
182 countries are just as engaged as others in CC/GW/CE research.

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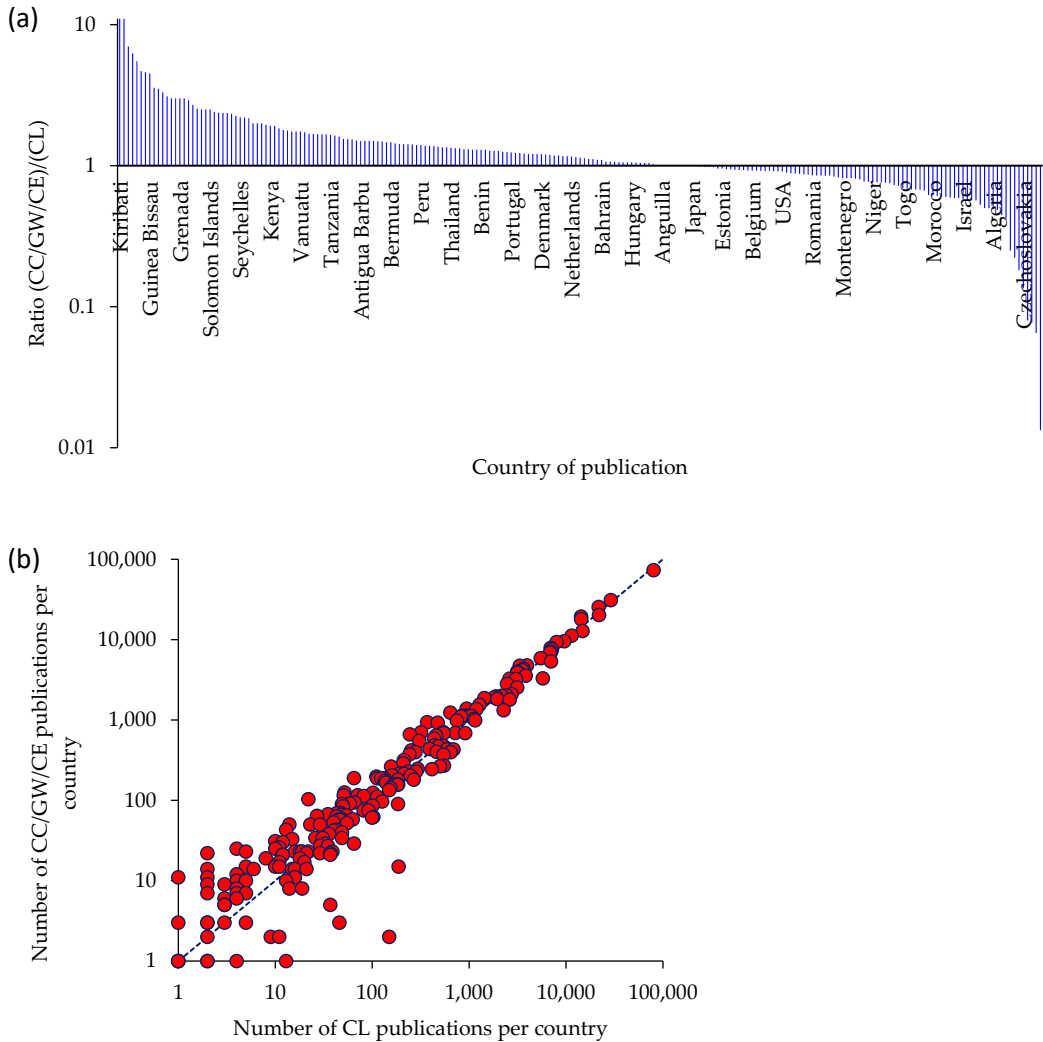186 **Figure 6.** Data for CC/GW/CE and CL records for country/region of publication: (**a**) Publication ratio
187 ((CC/GW/CE)/(CL)) for 215 countries/regions, ordered from highest to lowest ratio (axis labels are
188 provided for a selection of states); (**b**) Number of publications per country/region in the CC/GW/CE
189 record versus those in the CL record (dashed line illustrates the 1:1 mark).

190   Figure 6b provides a different view of the country/region publication records. By plotting the
191   number of CC/GW/CE publications for each country/region versus the number of CL publications
192   in the same country/region, it is possible to see a focusing effect about the 1:1 dashed line. Countries
193   that have published more, have more diverse body of literature, and tend towards the 1:1 line (the
194   USA is the highest point). Countries that have published less are more likely to be more engaged in
195   recent research, and thus have more CC/GW/CE articles than CL articles. Notable outliers with more
196   than 10 CL publications (i.e. farthest from the 1:1 line and with robust body of literature) are Fiji
197   (2.90 ratio) and Monaco (4.68 ratio), both above the line. The outliers below the line are no longer
198   existing states such as the USSR, Czechoslovakia, and the Federal Republic of Germany, which
199   explains their low number of CC/GW/CE publications.

200   4.2.1. Country collaboration

201   Figure S-5 shows the country collaboration of the first 5 top cited authors for CC/GW/CE and
202   CL records. For CL records, the USA and England have the highest collaboration with these authors
203   except Kottek, Markus who have published only 5 papers; they have a strong collaboration with the
204   University of Veterinary Medicine Vienna, Austria, where is their affiliation. For CC/GW/CE record
205   and for all authors, the USA has the highest collaboration. Hijmans, Robert J. also collaborated with
206   Peru and the Philippines, which have serious problems with droughts and floods [37-38]. Therefore,
207   it can be stated that for CC records, the focus of research on climate topics was in the USA and
208   England. On the other hand, for research on CC/GW/CE topics, after the USA which has the highest
209   collaboration, the countries which have been facing serious problems with climate change like
210   droughts and floods (ratio more than 2 for the number of articles in the CC/GW/CE record over the
211   number of articles in the CL record) have the highest collaboration with these authors.

212   Figure S-4, S-6 and S-7 in the Supplementary Materials also show that the countries scientific
213   production and collaboration for CC/GW/CE records are significantly higher than CL records. For
214   CC/GW/CE records, as mentioned earlier, small island states are at most risk of the catastrophic
215   effects of climate change, particularly rising sea levels [48-52], which is obvious in the countries
216   scientific production and collaboration map (Figure S-4 and S-7).

217   *4.3. Source of Publication*

218   Table 3, Figure 5, present the data analysis for the source (i.e. journals indexed in WoS) of
219   publication, for a part of the records, ranging from 1910 to 2020. The sources analyzed are the top
220   20 venues of publications from each record in terms of number of publications in each source. The
221   top 20 were chosen to make the analysis manageable from a reporting and graphing perspective.
222   The top 20 of the CC/GW/CE record represents 18.49% of all articles in this record, and the top 20 of
223   the CL record represents a very similar 18.78% of that record. It is deemed that observations and
224   trends made from the top 20 will be valid as a proxy for the trends of the full record.

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Table 3. Top 20 sources of articles from the two records (CC/GW/CE and CL). Number of articles in each source, and percentage of total number of articles in the full record. Bolded entries are the top 20 of each record.

| CC/GW/CE Sources	Articles	% of 219,830	CL Sources	Articles	% of 231,016
ATMOSPHERIC CHEMISTRY AND PHYSICS	709	0.003	**ATMOSPHERIC CHEMISTRY AND PHYSICS**	**2359**	**1.021**
BUILDING AND ENVIRONMENT	239	0.001	**BUILDING AND ENVIRONMENT**	**1036**	**0.448**
CLIMATE DYNAMICS	**1698**	**0.772**	**CLIMATE DYNAMICS**	**3268**	**1.415**
CLIMATIC CHANGE	**3188**	**1.450**	CLIMATIC CHANGE	915	0.004
EARTH AND PLANETARY SCIENCE LETTERS	547	0.002	**EARTH AND PLANETARY SCIENCE LETTERS**	**1169**	**0.506**
ENERGY AND BUILDINGS	319	0.001	**ENERGY AND BUILDINGS**	**1590**	**0.688**
ENERGY POLICY	**1510**	**0.687**	ENERGY POLICY	623	0.003
ENVIRONMENTAL RESEARCH LETTERS	**1769**	**0.805**	ENVIRONMENTAL RESEARCH LETTERS	811	0.004
FOREST ECOLOGY AND MANAGEMENT	**1317**	**0.599**	FOREST ECOLOGY AND MANAGEMENT	938	0.004
GEOPHYSICAL RESEARCH LETTERS	**2585**	**1.176**	**GEOPHYSICAL RESEARCH LETTERS**	**4842**	**2.096**
GLOBAL CHANGE BIOLOGY	**3266**	**1.486**	GLOBAL CHANGE BIOLOGY	634	0.003
INTERNATIONAL JOURNAL OF CLIMATOLOGY	**1636**	**0.744**	**INTERNATIONAL JOURNAL OF CLIMATOLOGY**	**2329**	**1.008**
JOURNAL OF CLEANER PRODUCTION	**2204**	**1.003**	JOURNAL OF CLEANER PRODUCTION	474	0.002
JOURNAL OF CLIMATE	**2019**	**0.918**	**JOURNAL OF CLIMATE**	**5279**	**2.285**
JOURNAL OF GEOPHYSICAL RESEARCH ATMOSPHERES	**1668**	**0.759**	**JOURNAL OF GEOPHYSICAL RESEARCH ATMOSPHERES**	**5234**	**2.266**
JOURNAL OF GEOPHYSICAL RESEARCH OCEANS	420	0.002	**JOURNAL OF GEOPHYSICAL RESEARCH OCEANS**	**1149**	**0.497**
JOURNAL OF HYDROLOGY	**1637**	**0.745**	**JOURNAL OF HYDROLOGY**	**1395**	**0.604**
JOURNAL OF THE ATMOSPHERIC SCIENCES	146	0.001	**JOURNAL OF THE ATMOSPHERIC SCIENCES**	**1093**	**0.473**
PALAEOGEOGRAPHY PALAEOCLIMATOLOGY PALAEOECOLOGY	1017	0.005	**PALAEOGEOGRAPHY PALAEOCLIMATOLOGY PALAEOECOLOGY**	**2220**	**0.961**
PLOS ONE	**3375**	**1.535**	**PLOS ONE**	**1679**	**0.727**
PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	**1510**	**0.687**	PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA	862	0.004
QUATERNARY SCIENCE REVIEWS	**1167**	**0.531**	**QUATERNARY INTERNATIONAL**	**1692**	**0.732**
QUATERNARY SCIENCE REVIEWS	1167	0.005	**QUATERNARY SCIENCE REVIEWS**	**1761**	**0.762**
REMOTE SENSING	1051	0.005	**REMOTE SENSING**	**1117**	**0.484**
SCIENCE OF THE TOTAL ENVIRONMENT	**3101**	**1.411**	**SCIENCE OF THE TOTAL ENVIRONMENT**	**1419**	**0.614**
SCIENTIFIC REPORTS	**1982**	**0.902**	**SCIENTIFIC REPORTS**	**1326**	**0.574**
SUSTAINABILITY	**2309**	**1.050**	SUSTAINABILITY	845	0.004
THEORETICAL AND APPLIED CLIMATOLOGY	**1113**	**0.506**	**THEORETICAL AND APPLIED CLIMATOLOGY**	**1428**	**0.618**
WATER	**1598**	**0.727**	WATER	650	0.003

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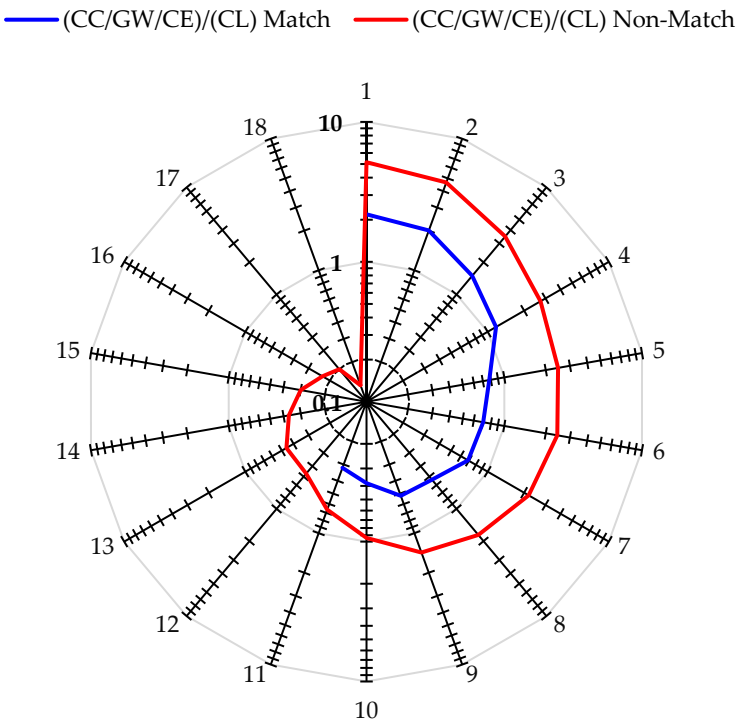
Figure 5. Publication ratio ((CC/GW/CE)/(CL)) for 29 journals, categorized as 'match' or 'non-match' based on appearance or not in both top 20 lists, ordered from highest to lowest ratio (one curve contains 18 entries and the other 11).

Table 3 presents the number of articles from each record that appear in these journals. A total of 29 journals appear in Table 2, organized in alphabetic order, since there is partial overlap of the top 20 from each record; in fact, there 11 journals that are common to both top 20's (these are referred to as 'match' journals), and 9 journals in each top 20 that is not in the other top 20 (these are referred to as 'non-match' journals). The top journal in the CC/GW/CE record is PLOS One, with 3375 articles representing 1.535% of the full record. The top journal in the CL record is the Journal of Climate, with 5279 articles representing 2.285% of the full record. Both of these journals are in both top 20 lists, with PLOS One having a stronger record of CC/GW/CE articles as given by a ratio (as previously calculated to compare records) of 2.01, while the Journal of Climate has a stronger record of general CL research, with a 0.38 ratio. The 'match' journal with the highest ratio (2.19) is Science of the Total Environment, while the Journal of Geophysical Research Atmospheres has the lowest ratio of 0.32. The range of ratios is larger for 'non-match' journals. Here the highest ratio is 5.15 for Global Change Biology, and the smallest ratio is 0.13 for Journal of the Atmospheric Sciences. These ratios agree with the perception that can be taken about each of these journals. Journals like PLOS One, Science of the Total Environment and Global Change Biology appeal to more applied areas of research, including the applied sciences and engineering, and have wider aims and scopes, while journals such as the Journal of Climate, Journal of Geophysical Research Atmosphere and Journal of the Atmospheric Sciences appeal to more fundamental and specialized research.

Figure 5 helps to highlight the different scopes of the 29 journals listed in Table 2. Here, the ratios for each journal are plotted and categorized according to 'match' or 'non-match' journals. The spider plot shows data arranged from largest to smallest ratio for each category (i.e. each line). Had there been no significant difference in the distribution of the articles across the various journals, both of these lines would be very close to the value of 1. It is clear that the 'non-match' line deviates the most from 1, with nearly every value much higher or much lower than 1. Even the 'match' line deviates significantly from 1. The ratio value closest to 1 from both categories is that of the journal Remote Sensing (0.94). This is not surprising as remote sensing is a climate monitoring technique that can be used both for general climate research as well as to track changes in the climate due to

260   anthropogenic effects [53-55]. What can be concluded from this analysis is that journals and authors
261   are able to distinguish the research topics sufficiently to steer more CC/GW/CE research to certain
262   journals and more general CL research to other journals. This helps to confirm that these two topics
263   are distinct in practice.

264   *4.4. Organization of Publication*

265   Table 4, Figure 6, present the data analysis for organization (i.e. universities, research institutes,
266   and other research-intensive organizations, associated with the corresponding author's primary
267   affiliation) of publication, for a part of the records, ranging from 1910 to 2020. As with sources, the
268   organizations analyzed are the top 20 from each record, and identical data analysis procedure was
269   used here. The top 20 of the CC/GW/CE record represents 36.92% of all articles in this record, and
270   the top 20 of the CL record represents a slightly higher 39.07% of that record. A total of 26
271   organizations appear in Table 4, signifying that there are 14 common organizations within the top
272   20 (i.e. 'match' organizations), and 6 'non-match' organizations. Here, the top three organizations
273   are the same on both records, with the Chinese Academy of Sciences (China) being slightly more
274   engaged in CC/GW/CE research, and the University of California System (USA) and the Centre
275   National de la Recherche Scientifique (France) being slightly more productive in general CL
276   research; though their ratios are very close to 1 (1.03, 0.98 and 0.81, respectively). In fact, the ratios
277   of these organizations are much closer to 1, on average, than those of the journals. The highest ratio
278   among the 26 organizations is 1.74 for the United States Forest Service, and the lowest ratio is 0.40
279   for two NASA organizations (the main NASA organization, and the Goddard Space Flight Centre).
280   This suggests that academic organizations may have more varied research, and hence ratios closer
281   to 1, while governmental organizations may be more focused on a particular line of research, and
282   thus rations more different than 1. Though such conclusion would require analysis of a large set of
283   organizations, and is complicated by some countries have organizations that have a dual academic
284   and institutional role.

285 **Table 4.** Top 20 organizations of articles from the two records (CC/GW/CE and CL). Number of articles
286 from each organization, and percentage of total number of articles in the full record. Bolded entries are the
287 top 20 of each record.

CC/GW/CE Organizations	Articles	% of 219,830	CL Organizations	Articles	% of 231,016
CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	**7079**	**3.220**	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	8770	3.796
CHINESE ACADEMY OF SCIENCES	**12132**	**5.519**	**CHINESE ACADEMY OF SCIENCES**	11770	5.095
COLUMBIA UNIVERSITY	2132	0.970	**COLUMBIA UNIVERSITY**	3011	1.303
COMMONWEALTH SCIENTIFIC INDUSTRIAL RESEARCH ORGANIZATION CSIRO	**3195**	**1.453**	COMMONWEALTH SCIENTIFIC INDUSTRIAL RESEARCH ORGANIZATION CSIRO	2499	1.082
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS CSIC	**3028**	**1.377**	**CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS CSIC**	2862	1.239
HELMHOLTZ ASSOCIATION	**4221**	**1.920**	**HELMHOLTZ ASSOCIATION**	5382	2.330
INRAE	**2600**	**1.183**	INRAE	1972	0.854
INSTITUT DE RECHERCHE POUR LE DEVELOPPEMENT IRD	**2770**	**1.260**	**INSTITUT DE RECHERCHE POUR LE DEVELOPPEMENT IRD**	3021	1.308
MAX PLANCK SOCIETY	1814	0.825	**MAX PLANCK SOCIETY**	2731	1.182
NASA GODDARD SPACE FLIGHT CENTER	1282	0.583	**NASA GODDARD SPACE FLIGHT CENTER**	3173	1.373
NATIONAL AERONAUTICS SPACE ADMINISTRATION NASA	**2286**	**1.040**	**NATIONAL AERONAUTICS SPACE ADMINISTRATION NASA**	5674	2.456
NATIONAL CENTER ATMOSPHERIC RESEARCH NCAR USA	1816	0.826	**NATIONAL CENTER ATMOSPHERIC RESEARCH NCAR USA**	3626	1.570
NATIONAL OCEANIC ATMOSPHERIC ADMIN NOAA USA	**3358**	**1.528**	**NATIONAL OCEANIC ATMOSPHERIC ADMIN NOAA USA**	5373	2.326
RUSSIAN ACADEMY OF SCIENCES	1910	0.869	**RUSSIAN ACADEMY OF SCIENCES**	3676	1.591
STATE UNIVERSITY SYSTEM OF FLORIDA	**3154**	**1.435**	**STATE UNIVERSITY SYSTEM OF FLORIDA**	2892	1.252
UNITED STATES DEPARTMENT OF AGRICULTURE USDA	**4149**	**1.887**	**UNITED STATES DEPARTMENT OF AGRICULTURE USDA**	3013	1.304
UNITED STATES DEPARTMENT OF ENERGY DOE	**3130**	**1.424**	**UNITED STATES DEPARTMENT OF ENERGY DOE**	3522	1.525
UNITED STATES DEPARTMENT OF THE INTERIOR	**3951**	**1.797**	**UNITED STATES DEPARTMENT OF THE INTERIOR**	2764	1.196
UNITED STATES FOREST SERVICE	**2389**	**1.087**	UNITED STATES FOREST SERVICE	1371	0.593
UNITED STATES GEOLOGICAL SURVEY	**3413**	**1.553**	UNITED STATES GEOLOGICAL SURVEY	2532	1.096
UNIVERSITY OF CALIFORNIA SYSTEM	**8654**	**3.937**	**UNIVERSITY OF CALIFORNIA SYSTEM**	8838	3.826
UNIVERSITY OF CHINESE ACADEMY OF SCIENCES CAS	**4108**	**1.869**	**UNIVERSITY OF CHINESE ACADEMY OF SCIENCES CAS**	3309	1.432
UNIVERSITY OF COLORADO BOULDER	2179	0.991	**UNIVERSITY OF COLORADO BOULDER**	3337	1.444
UNIVERSITY OF COLORADO SYSTEM	**2335**	**1.062**	**UNIVERSITY OF COLORADO SYSTEM**	3507	1.518
UNIVERSITY OF LONDON	**2766**	**1.258**	UNIVERSITY OF LONDON	2358	1.021
WAGENINGEN UNIVERSITY RESEARCH	**2450**	**1.114**	WAGENINGEN UNIVERSITY RESEARCH	1467	0.635

288
289 Figure 6, in contrast to Figure 5, makes it clear that organizational information is not enough
290 to place a research as belonging to one record or another. Both the 'match' and 'non-match' lines
291 deviated by small extents away from the ratio of 1 level, with the 'non-match' line deviating more,
292 as would be expected. For comparison with the earlier case, the ratio value closest to 1 from both
293 categories is that of the University of California System (0.98). Notable about this organization is

294 that it consists of nine campuses offering comprehensive education, with varying levels of research
295 excellence (e.g. excellent (Berkeley), very good (Davis), less highly ranked (Riverside), emerging
296 (Merced) [56]). This can explain the diversity of research output, covering both CC/GW/CE and CL
297 topics. Of course, this diversity of topic is an average since 1900, and it is possible that in recent
298 years the research in many organizations has shifted towards the climate challenge, as the year and
299 country trends presented earlier suggested.
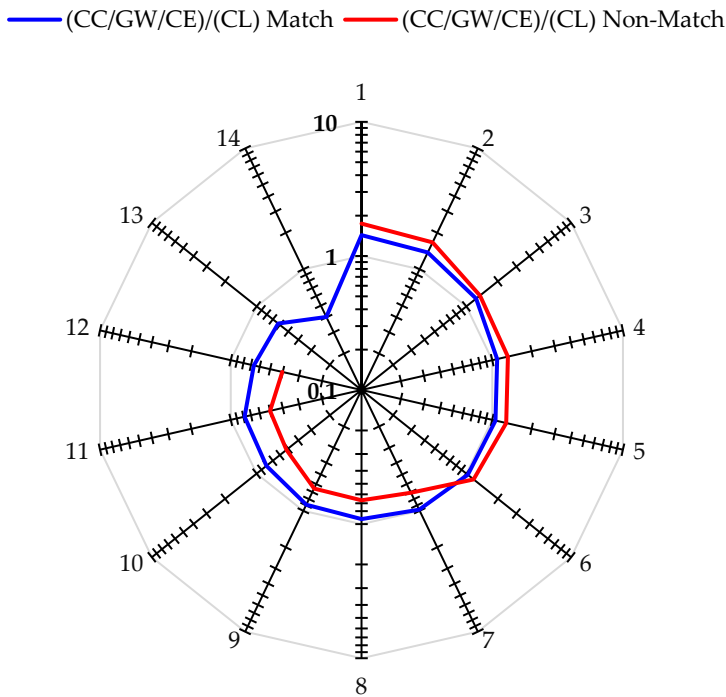
300
301 **Figure 6.** Publication ratio ((CC/GW/CE)/(CL)) for 26 organizations, categorized as 'match' or 'non-match'
302 based on appearance or not in both top 20 lists, ordered from highest to lowest ratio (one curve contains
303 14 entries and the other 12).

304 **5. Discussion and Conclusions**

305 Here we can re-visit the three hypotheses and reach conclusions about their claims. With
306 regards to hypothesis 1, it was possible to distinguish the scientist literature linked to CC/GW/CE
307 research from that pertaining to CL research using the two search strings tested. This was verified
308 by reviewing the scope of a number of highly cited papers in both records, and is further supported
309 by the trends seen with regards to years of publication, country/region of publication, and source of
310 publication. That is, in these three categories, the publication records showed significant numerical
311 and graphical differences, and these could at times be explained rationally, with basis on data
312 interpretation. Evidence was found that the two publication records contained some misinterpreted
313 publications and outliers, but it is deemed that the consistency of trends observed signify that these
314 issues are minor and acceptable given the simplicity of the publication record assemblage method.
315 A third search string, related to the topic of greenhouse gases, was also tested, but its data did not
316 become part of this study's analysis. The reason for this is that such search string finds many articles
317 that discuss the emissions of greenhouse gases (e.g. from flue gas stacks [57] or from livestock
318 farming [58]) and technologies to control or mitigate these emissions (e.g. via carbon sequestration
319 [59] or green energy [60]). As such, these articles fall outside the scope of the two topical records of
320 interest here. This is further evidence that the two search strings used are effective in reaching their
321 intended goal.
322 With hypothesis 1 confirmed, it is also possible to confirm hypothesis 2. The publication year
323 data clearly shows that the scientific literature has become enriched in CC/GW/CE works in relation
324 to CL works. This is despite both of these records experiencing massive growth over the decades

325   (from under 100 articles per year in the first half of the 20th century to over 10,000 articles per year
326   in recent years). It is clear that the more pressing the climate challenge becomes, and its effects
327   actually witnessed [61], the more research is being undertaken to forecast the avoidable or
328   unavoidable impacts [62, 63]. It is difficult to foresee for how much longer the publication ratio
329   devised in this study will continue to rise, globally or country-by-country, as climate research will
330   become increasingly important in the framework of a sustainable society, so it will be worth
331   revisiting this in a decade or more. Perhaps by then another keyword could be added to complement
332   CC/GW/CE. As of December 27th 2020, 84.85% of this record is retrieved using only CC and
333   excluding (via the NOR operator) the other two search terms; this compares to only 9.20% of the
334   record that only contains GW, and a mere 0.019% of the record that only contains CE. A simple
335   search for CE yields 99 articles, 86 of which published since 2019, and the oldest from 2011 [64] being
336   the most cited to date. This shows that this popular term (in the greater public sphere) is not yet
337   commonly used scientifically; will it eventually be?

338   Hypothesis 3 was partly confirmed. The data and its interpretation show that the two
339   publications records have distinct differences in terms of size (i.e. number of publications) when it
340   comes to the originating country/region and venue (journal) of publication. Yet the two records are
341   nearly indistinguishable when the criteria used is the organization responsible for producing the
342   work. As was explained, research organizations have broad research interests, and it is
343   understandable that the same departments and research groups that perform CC/GW/CE research
344   also tend to perform CL research. Of course, this would not be the case at the researcher level, since
345   expertise for these two topics of research is sufficiently different. WoS allows data analysis at the
346   researcher (i.e. corresponding author level). However, in addition to the number of entries being
347   very large (there are over 100,000 corresponding authors listed in the most recent CC/GW/CE and
348   CL records), there is ambiguity with common author names (i.e. same last name and same first letter
349   of first name), making any possible analysis less accurate. Such analysis would thus require close
350   scrutiny at the article level.

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