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Greater than 99% consensus on human caused climate change in the peer-reviewed scientific literature

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Abstract

While controls over the Earth's climate system have undergone rigorous hypothesis-testing since the 1800s, questions over the scientific consensus of the role of human activities in modern climate change continue to arise in public settings. We update previous efforts to quantify the scientific consensus on climate change by searching the recent literature for papers sceptical of anthropogenic-caused global warming. From a dataset of 88125 climate-related papers published since 2012, when this question was last addressed comprehensively, we examine a randomized subset of 3000 such publications. We also use a second sample-weighted approach that was specifically biased with keywords to help identify any sceptical peer-reviewed papers in the whole dataset. We identify four sceptical papers out of the sub-set of 3000, as evidenced by abstracts that were rated as implicitly or explicitly sceptical of human-caused global warming. In our sample utilizing pre-identified sceptical keywords we found 28 papers that were implicitly or explicitly sceptical. We conclude with high statistical confidence that the scientific consensus on human-caused contemporary climate change—expressed as a proportion of the total publications—exceeds 99% in the peer reviewed scientific literature.

1. Introduction

The extent of the scientific consensus on human-caused climate change is of great interest to society. If there remains substantial genuine scientific doubt about whether modern climate change is human-caused, then the case for mitigation of greenhouse gas emissions is weakened. By contrast, a widely-held consensus view in the peer-reviewed literature invalidates alternative arguments which claim that there is still significant debate in the scientific community about the reality of anthropogenic climate change (ACC).

The question of the cause of observed and predicted global warming and precipitation change is still highly politically salient. A Gallup poll published in April 2021 found that there has been a deepening of the partisan divide in American politics on whether observed increases in the planet's temperature since the Industrial Revolution are primarily caused by humans [1]. Among elected U.S. politicians the divide is similarly stark: according to the Center for American Progress there were 139 elected officials in the 117th Congress (sitting in 2021), including 109 representatives and 30 senators, 'who refuse to acknowledge the scientific evidence of human-caused climate change' [2]. In 2016 Pew Research found that only 27% of U.S. adults believed that 'almost all' scientists agreed that climate change is due to human activity [3].

Many efforts have been made over the years to quantify the extent of the scientific consensus on ACC [4, 5]. These are comprehensively reviewed in a paper published in 2016 entitled 'Consensus on consensus'

[6]. It has additionally been argued that perception of scientific consensus is a 'gateway belief' motivating wider public support for mitigation of climate change [7]. While scientific consensus does not *sensu stricto* prove a statement about the physical world, science-based anlaysis and hypothesis testing is capable of disproving alternative constructs, which could explain a given observation, either absolutely or relatively [8]. Hence, quantifying the scientific consensus clarifies the extent of any dissent in the scientific community in the process of disproval, and the plausible validity of alternative hypotheses in the face of scientific scrutiny, observations, and testing over time.

The most recent well-known effort to quantify the consensus was published in 2013, encompassing papers appearing in the peer-reviewed literature between 1991 and 2012, and sparked the famous headline that 97% of the world's science supported the climate change consensus [9]. The '97% consensus' view (published by Cook *et al* 2013, referred to hereafter as C13) had a big impact on global awareness of the scientific consensus on the role of greenhouse gases in causing climate change and was extensively covered in the media. Our primary motivation for this current study was to re-examine the literature published since 2012 to ascertain whether any change in the scientific consensus on climate change is discernible.

2. Method

Previous attempts to quantify the consensus on climate change have employed many different methodologies, varying from expert elicitation to examination of abstracts returned by a keyword search. We base our methodology on C13 with some important refinements. We searched the Web of Science for English language 'articles' added between the dates of 2012 and November 2020 with the keywords 'climate change', 'global climate change' and 'global warming'. C13 used the latter two phrases but not 'climate change' without the preceding 'global'. (As discussed below, this was justified post-facto in our study because the majority of sceptical papers we found would not have been returned had we used the same search phrases as C13.) This wider set of search terms yielded a total of 88125 papers, whereas C13 identified a total of 11944 abstracts from papers published over the years 1991 and 2011. (Using our expanded search terms over the same 1991–2011 time period as C13 would have yielded 30627 results.)

Given the large number of papers found using our approach we randomly sub-sampled 3000 abstracts out of the 88125 total papers identified in our search, and subsequently categorized them in accordance with C13 (See table 1).

As per C13 we rated the abstracts of papers, assigning them numbers according to their level of implicit or explicit endorsement or rejection of ACC (table 2). Abstracts were rated with only the title and abstract visible; information about authors, date and journal were hidden at this stage.

To further extend our approach for identifying as many sceptical papers as possible within the full dataset, we created an algorithm to identify keywords within the papers rated by C13 as sceptical that had appeared more often in sceptical papers than consensus papers. The software counted the appearance of every word in the title, author list and abstract of every sceptical paper. For each word that appeared in at least two papers, the algorithm counted the number of sceptical and consensus papers it appeared in to calculate its predictive power. We took the 150 most predictive words, then manually reviewed them to remove words that appeared to be there by chance (e.g. 'walk' and 'nearest') leaving those we believed could be predictively useful (e.g. 'cosmic' and 'rays'). A second algorithm then scored all 88125 papers (including the 3000 sampled separately earlier) based on the appearance of the predictive words. (See supplementary info for precise details of this exercise (available online at stacks.iop.org/ERL/16/114005/mmedia)). We then rated and categorized the 1000 papers with the highest score using the same approaches from C13 as detailed in tables 1 and 2. As stated earlier, this approach was taken in order to increase the chances of us finding sceptical papers in the full dataset, allowing for a robust assessment and inclusion of any dissent.

In contrast to C13, we did not perform an author elicitation survey asking authors to carry out a self-rating of their papers.

3. Results

3.1. Results of random sampling

Our random sample of 3000 papers revealed a total of 282 papers that were categorized as 'not climate-related'. These false-positives occurred because, even though the climate keywords occurred in their title/abstracts, the published articles dealt with social science, education or research about people's views on climate change rather than original scientific work. Hence, we excluded these papers in accordance with C13's approach. We then assessed the remaining total of 2718 papers in the data set and found four that argued against the scientific consensus of ACC.

The ratings and categorizations for the 3000 randomly sampled papers are shown in table 3. Note that 'not climate-related' papers are displayed in table 3 for completeness. Figure 1 shows the same data, but with 'not climate-related' papers excluded.

Our estimate of the proportion of consensus papers was $1 - (4/2718) = 99.85\%$. The 95% confidence limits for this proportion are 99.62%–99.96%

Table 1. Categorization of climate papers, as per C13.

Category	Description	Example
(1) Impacts	Effects and impacts of climate change on the environment, ecosystems or humanity	'… global climate change together with increasing direct impacts of human activities, such as fisheries, are affecting the population dynamics of marine top predators'
(2) Methods	Focus on measurements and modelling methods, or basic climate science not included in the other categories	'This paper focuses on automating the task of estimating Polar ice thickness from airborne radar data…'
(3) Mitigation	Research into lowering CO_2 emissions or atmospheric CO_2 levels	'This paper presents a new approach for a nationally appropriate mitigation actions framework that can unlock the huge potential for greenhouse gas mitigation in dispersed energy end-use sectors in developing countries'
(4) Not climate-related	Social science, education, research about people's views on climate	'This paper discusses the use of multi-media techniques and augmented reality tools to bring across the risks of global climate change'
(5) Opinion	Not peer-reviewed articles	'While the world argues about reducing global warming, chemical engineers are getting on with the technology. Charles Butcher has been finding out how to remove carbon dioxide from flue gas'
(6) Paleoclimate	Examining climate during pre-industrial times	'Here, we present a pollen-based quant-itative temperature reconstruction from the midlatitudes of Australia that spans the last 135 000 years…'

Table 2. Rating of climate papers, as per C13.

Level of endorsement	Description	Example
(1) Explicit endorsement with quantification	Explicitly states that humans are the primary cause of recent global warm-ing	'The global warming during the 20th century is caused mainly by increasing greenhouse gas concentration especially since the late 1980s'
(2) Explicit endorsement without quantification	Explicitly states humans are causing global warming or refers to anthropo-genic global warming/climate change as a known fact	'Emissions of a broad range of green-house gases of varying lifetimes contrib-ute to global climate change'
(3) Implicit endorsement	Implies humans are causing global warming. e.g. research assumes green-house gas emissions cause warming without explicitly stating humans are the cause	'…carbon sequestration in soil is import-ant for mitigating global climate change'
(4a) No position	Does not address or mention the cause of global warming	—
(4b) Uncertain	Expresses position that humans' role in recent global warming is uncertain/un-defined	'While the extent of human-induced global warming is inconclusive…'
(5) Implicit rejection	Implies humans have had a minimal impact on global warming without say-ing so explicitly. e.g. proposing a natural mechanism is the main cause of global warming	'…anywhere from a major portion to all of the warming of the 20th century could plausibly result from natural causes according to these results'
(6) Explicit rejection without quantification	Explicitly minimizes or rejects that humans are causing global warming	'…the global temperature record provides little support for the cata-strophic view of the greenhouse effect'
(7) Explicit rejection with quantification	Explicitly states that humans are causing less than half of global warming	'The human contribution to the CO_2 content in the atmosphere and the increase in temperature is negligible in comparison with other sources of carbon dioxide emission'

Table 3. Results of rating and categorization of 3000 abstracts.

Rating/categorization	# of abstracts
1—Explicit endorsement with quantification	**19**
Impacts	7
Methods	9
Mitigation	3
2—Explicit endorsement without quantification	**413**
Impacts	204
Methods	78
Mitigation	124
Not climate-related	4
Opinion	1
Paleoclimate	2
3—Implicit endorsement	**460**
Impacts	95
Methods	119
Mitigation	199
Not climate-related	43
Paleoclimate	4
4a—No position	**2104**
Impacts	915
Methods	790
Mitigation	60
Not climate-related	235
Opinion	3
Paleoclimate	101
5—Implicit rejection	**2**
Methods	2
6—Explicit rejection without quantification	**1**
Paleoclimate	1
7—Explicit rejection with quantification	**1**
Methods	1
Grand Total	**3000**

(see R code in supplementary info), therefore it is likely that the proportion of climate papers that favour the consensus is at least 99.62%.

Recalculating at the 99.999% confidence level gives us the interval 99.212%–99.996%, therefore it is virtually certain that the proportion of climate papers that do not dispute that the consensus is above 99.212%.

If we repeat the methods of C13 and further exclude papers that take no position on AGW (i.e. those rated 4a), we estimate the proportion of consensus papers to be 99.53% with the 95% confidence interval being 98.80%–99.87%.

3.2. Keywords indicating scepticism

We reviewed the 1000 studies that our keyword matching software identified as most likely to be sceptical out of the entire 88125 dataset. After manual review, 28 sceptical papers within the most likely 1000 papers were identified, with the majority being in the top rows of the dataset. The first paper was sceptical, as were 12 out of the first 50, and 16 out of the first 100. (See supplementary data for the full list.) Table 4 shows how the 1000 studies that the keywords found to be most likely to be sceptical were rated.

In other words, the predictive keywords successfully allowed us to identify a total of 28 papers from the full dataset of 88125 which appeared implicitly or explicitly sceptical of ACC. Only one of these papers had already appeared in the first 3000 randomized sample. While we are aware that this approach does not reveal all sceptical papers that exist in the full dataset, it provides an absolute upper bound to the percentage of papers that agree with the consensus. Knowing that at least 31 (including the 3 additional papers found in the random sample) out of the full 88125 dataset are sceptical, we can say the consensus on ACC is *at most* 99.966%.

4. Discussion

Our analysis demonstrates >99% agreement in the peer-reviewed scientific literature on the principal role of greenhouse gas (GHG) emissions from human activities in driving modern climate change (i.e. since the Industrial Revolution). This result further advances our understanding of the scientific consensus view on climate change as evidenced by the peer reviewed scientific literature, and provides additional evidence that the statements made by the Intergovernmental Panel on Climate Change (see below) accurately reflect the overwhelming view of the international scientific community. We conclude that alternative explanations for the dominant cause of modern (i.e., post-industrial) climate change beyond the role of rising GHG emissions from human activities are exceedingly rare in the peer-reviewed scientific literature.

Previous researchers have debated how to define and therefore quantify 'consensus' in the scientific literature on an array of issues. While C13 define consensus rather narrowly as explicit or implicit agreement, a broader definition can be employed which defines consensus as lack of objection to a prevailing position or worldview. In 2015 James Powell argued for this broader definition, pointing out that the C13 methodology, if applied to other scientific research areas such as plate tectonics or evolution, would fail to find consensus because few authors of papers in the expert literature feel the need to re-state their adherence in both cases to what has long been universally-accepted theory [10].

In a rejoinder to this critique, several C13 authors argued that their narrower definition of consensus was still relevant in other well-established fields if both implicit and explicit agreement was included [11]. Therefore in plate tectonics, for example, seafloor spreading, mountain-building by means of continental collision, subduction etc, could be *implicitly* supportive of a consensus on the reality of the theory of plate tectonics without this necessarily being *explicitly* stated.

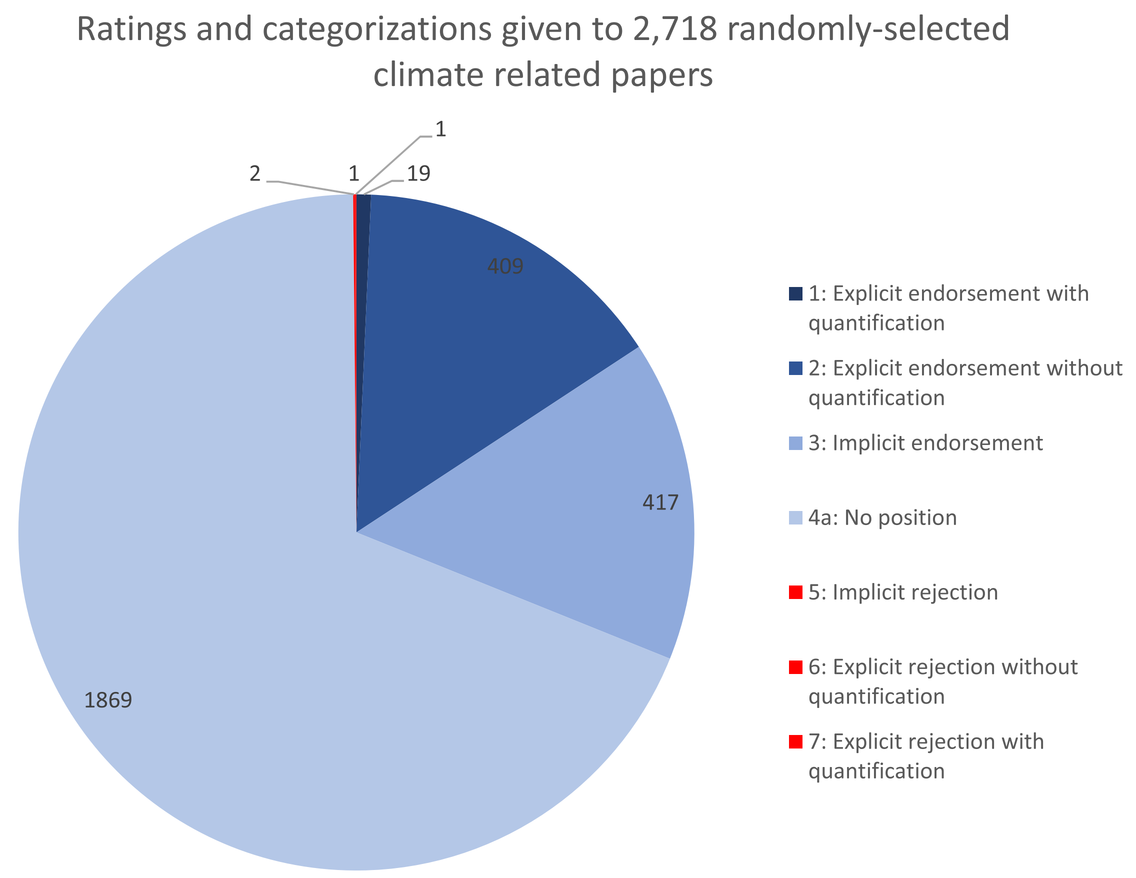

Figure 1. Ratings and categorizations given to 2718 randomly-sampled climate abstracts.

In our paper, for the sake of clarity and comparability with previous literature, we present results using both approaches. However, having reviewed, rated and categorized several thousand papers we believe that there is now a stronger case for the broader approach given how widely accepted ACC has become in the peer-reviewed literature. For example, a majority of the papers we categorized as being about 'impacts' of climate change did not state a position on whether the phenomenon they were studying—the changing climate—was human-caused. It seems highly unlikely that if researchers felt sceptical about the reality of ACC they would publish numerous studies of its impacts without ever raising the question of attribution.

In other words, given that most 4a ('no position') ratings do not either explicitly or implicitly differ from the consensus view of GHG emissions as the principal driver of climate change it does not follow in our view that these analyses should be *a priori* excluded from the consensus. In another example, we gave rating '2' ('explicit endorsement without quantification') to all papers referencing future emissions scenarios in their abstracts, because emissions scenarios by definition imply an evaluation of humanity's role in GHG emissions and their subsequent impact on climate. Thus the authors choice of wording on emissions scenarios or other issues implying human causation to climate change in the abstracts of their climate impact studies might lead to arbitrariness if these were taken as the sole indicators of the authors' adherence to the consensus on ACC.

In addition, decisions about whether to give rating '3' ('implicit endorsement') are subjective in that the rating of a position on ACC is considered to be implied by the authors without this being explicitly stated in the abstract of a paper. Thus subjective judgements by those doing the ratings about the implicit meanings communicated by abstract wording choices of paper authors are critical to the numerical consensus result obtained using C13's method, potentially introducing a source of bias. It is unclear to us why this is preferable to defining consensus in a clearer and more objectively transparent way as simply the absence of clearly-stated rejection or disagreement.

We also note that our keyword choices, in particular not requiring the word 'global' in front of 'climate change' led to our discovery of many sceptical papers that would not have been identified by searches only of 'global warming' and 'global climate change'. This suggests—but does not prove—that a number of

Table 4. Ratings and categorizations for the 1000 abstracts most likely to be sceptical.

Rating/categorization	# of abstracts
1—Explicit endorsement with quantification	**7**
Impacts	4
Methods	3
2—Explicit endorsement without quantification	**69**
Impacts	24
Methods	35
Mitigation	7
Not climate related	1
Paleoclimate	2
3—Implicit endorsement	**134**
Impacts	32
Methods	55
Mitigation	33
Not climate related	9
Paleoclimate	5
4a—No position	**760**
Impacts	156
Methods	276
Mitigation	61
Not climate related	70
Paleoclimate	197
4b—Uncertain	**2**
Methods	2
5—Implicit rejection	**18**
Methods	17
Paleoclimate	1
6—Explicit rejection without quantification	**6**
Methods	5
Paleoclimate	1
7—Explicit rejection with quantification	**4**
Methods	4
Grand Total	**1000**

sceptical papers may have been missed in the original C13 study. However, these minor disagreements aside, we are indebted to C13 for the rigor of their methodology, much of which we re-employ directly here.

4.1. Review of sceptical papers

In supplementary table 1 we present the full list of all 31 sceptical papers we found in our dataset. An in-depth evaluation of their merits is outside the scope of this paper, and could be an interesting area for further work. We note some recurring themes however, such as the hypothesis that changes in cosmic rays are significantly influencing the Earth's changes in climate, that the Sun is driving modern climate change, or that natural fluctuations are somehow involved. An additional area of research might investigate how far these themes in the published literature are reflected in popular discourse outside of the scientific community.

5. Conclusion

Our results confirm, as has been found in numerous other previous studies of this question, that there is no significant scientific debate among experts about whether or not climate change is human-caused. This issue has been comprehensively settled, and the reality of ACC is no more in contention among scientists than is plate tectonics or evolution. The tiny number of papers that have been published during our time period which disagree with this overwhelming scientific consensus have had no discernible impact, presumably because they do not provide any convincing evidence to refute the hypothesis that—in the words of IPCC AR5—'it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century' [12], and, most recently in IPCC AR6—'it is unequivocal that human influence has warmed the atmosphere, ocean and land' [13].

Our finding is that the broadly-defined scientific consensus likely far exceeds 99% regarding the role of anthropogenic GHG emissions in modern climate change, and may even be as high as 99.9%. Of course, the prevalence of mis/disinformation about the role of GHG emissions in modern climate change is unlikely to be driven purely by genuine scientific illiteracy or lack of understanding [14]. Even so, in our view it remains important to continue to inform society on the state of the evidence. According to the IPCC AR6 summary and many other previous studies, mitigating future warming requires urgent efforts to eliminate fossil fuels combustion and other major sources of anthropogenic greenhouse gas emissions. Our study helps confirm that there is no remaining scientific uncertainty about the urgency and gravity of this task.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

M L conceived the paper. S P wrote software and algorithms for data extraction and performed data analysis. M L performed ratings and categorizations. B H, S P and M L wrote the paper.

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