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Quantifying the consensus on anthropogenic global warming in the scientific literature

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Abstract
We analyze the evolution of the scientific consensus on anthropogenic global warming (AGW) in the peer-reviewed scientific literature, examining 11 944 climate abstracts from 1991–2011 matching the topics 'global climate change' or 'global warming'. We find that 66.4% of abstracts expressed no position on AGW, 32.6% endorsed AGW, 0.7% rejected AGW and 0.3% were uncertain about the cause of global warming. Among abstracts expressing a position on AGW, 97.1% endorsed the consensus position that humans are causing global warming. In a second phase of this study, we invited authors to rate their own papers. Compared to abstract ratings, a smaller percentage of self-rated papers expressed no position on AGW (35.5%). Among self-rated papers expressing a position on AGW, 97.2% endorsed the consensus. For both abstract ratings and authors' self-ratings, the percentage of endorsements among papers expressing a position on AGW marginally increased over time. Our analysis indicates that the number of papers rejecting the consensus on AGW is a vanishingly small proportion of the published research.

Keywords: scientific consensus, anthropogenic global warming, peer-review, global climate change, Intergovernmental Panel on Climate Change
S Online supplementary data available from stacks.iop.org/ERL/8/024024/mmedia

1. Introduction

An accurate perception of the degree of scientific consensus is an essential element to public support for climate policy (Ding *et al* 2011). Communicating the scientific consensus also increases people's acceptance that climate change (CC) is happening (Lewandowsky *et al* 2012). Despite numerous indicators of a consensus, there is wide public perception that climate scientists disagree over the fundamental cause of global warming (GW; Leiserowitz *et al* 2012, Pew 2012). In the most comprehensive analysis performed to date, we have extended the analysis of peer-reviewed climate papers in Oreskes (2004). We examined a large sample of the scientific

Table 1. Definitions of each type of research category.

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 modeling 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 multimedia 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 quantitative temperature reconstruction from the midlatitudes of Australia that spans the last 135 000 years...'

literature on global CC, published over a 21 year period, in order to determine the level of scientific consensus that human activity is very likely causing most of the current GW (anthropogenic global warming, or AGW).

Surveys of climate scientists have found strong agreement (97–98%) regarding AGW amongst publishing climate experts (Doran and Zimmerman 2009, Anderegg *et al* 2010). Repeated surveys of scientists found that scientific agreement about AGW steadily increased from 1996 to 2009 (Bray 2010). This is reflected in the increasingly definitive statements issued by the Intergovernmental Panel on Climate Change on the attribution of recent GW (Houghton *et al* 1996, 2001, Solomon *et al* 2007).

The peer-reviewed scientific literature provides a ground-level assessment of the degree of consensus among publishing scientists. An analysis of abstracts published from 1993–2003 matching the search 'global climate change' found that none of 928 papers disagreed with the consensus position on AGW (Oreskes 2004). This is consistent with an analysis of citation networks that found a consensus on AGW forming in the early 1990s (Shwed and Bearman 2010).

Despite these independent indicators of a scientific consensus, the perception of the US public is that the scientific community still disagrees over the fundamental cause of GW. From 1997 to 2007, public opinion polls have indicated around 60% of the US public believes there is significant disagreement among scientists about whether GW was happening (Nisbet and Myers 2007). Similarly, 57% of the US public either disagreed or were unaware that scientists agree that the earth is very likely warming due to human activity (Pew 2012).

Through analysis of climate-related papers published from 1991 to 2011, this study provides the most comprehensive analysis of its kind to date in order to quantify and evaluate the level and evolution of consensus over the last two decades.

2. Methodology

This letter was conceived as a 'citizen science' project by volunteers contributing to the Skeptical Science website (www.skepticalscience.com). In March 2012, we searched the ISI Web of Science for papers published from 1991–2011 using topic searches for 'global warming' or 'global climate change'. Article type was restricted to 'article', excluding books, discussions, proceedings papers and other document types. The search was updated in May 2012 with papers added to the Web of Science up to that date.

We classified each abstract according to the type of research (category) and degree of endorsement. Written criteria were provided to raters for category (table 1) and level of endorsement of AGW (table 2). Explicit endorsements were divided into non-quantified (e.g., humans are contributing to global warming without quantifying the contribution) and quantified (e.g., humans are contributing more than 50% of global warming, consistent with the 2007 IPCC statement that most of the global warming since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations).

Abstracts were randomly distributed via a web-based system to raters with only the title and abstract visible. All other information such as author names and affiliations, journal and publishing date were hidden. Each abstract was categorized by two independent, anonymized raters. A team of 12 individuals completed 97.4% (23 061) of the ratings; an

Table 2. Definitions of each level of endorsement of AGW.

Level of endorsement	Description	Example
(1) Explicit endorsement with quantification	Explicitly states that humans are the primary cause of recent global warming	'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 anthropogenic global warming/climate change as a known fact	'Emissions of a broad range of greenhouse gases of varying lifetimes contribute to global climate change'
(3) Implicit endorsement	Implies humans are causing global warming. E.g., research assumes greenhouse gas emissions cause warming without explicitly stating humans are the cause	'...carbon sequestration in soil is important for mitigating global climate change'
(4a) No position	Does not address or mention the cause of global warming	
(4b) Uncertain	Expresses position that human's role on recent global warming is uncertain/undefined	'While the extent of human-induced global warming is inconclusive...'
(5) Implicit rejection	Implies humans have had a minimal impact on global warming without saying 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 catastrophic 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'

additional 12 contributed the remaining 2.6% (607). Initially, 27% of category ratings and 33% of endorsement ratings disagreed. Raters were then allowed to compare and justify or update their rating through the web system, while maintaining anonymity. Following this, 11% of category ratings and 16% of endorsement ratings disagreed; these were then resolved by a third party.

Upon completion of the final ratings, a random sample of 1000 'No Position' category abstracts were re-examined to differentiate those that did not express an opinion from those that take the position that the cause of GW is uncertain. An 'Uncertain' abstract explicitly states that the cause of global warming is not yet determined (e.g., '...the extent of human-induced global warming is inconclusive...') while a 'No Position' abstract makes no statement on AGW.

To complement the abstract analysis, email addresses for 8547 authors were collected, typically from the corresponding author and/or first author. For each year, email addresses were obtained for at least 60% of papers. Authors were emailed an invitation to participate in a survey in which they rated their own published papers (the entire content of the article, not just the abstract) with the same criteria as used by the independent rating team. Details of the survey text are provided in the supplementary information (available at stacks.iop.org/ERL/8/024024/mmedia).

3. Results

The ISI search generated 12 465 papers. Eliminating papers that were not peer-reviewed (186), not climate-related (288) or without an abstract (47) reduced the analysis to 11 944 papers written by 29 083 authors and published in 1980 journals. To simplify the analysis, ratings were consolidated into three groups: endorsements (including implicit and explicit; categories 1–3 in table 2), no position (category 4) and rejections (including implicit and explicit; categories 5–7).

We examined four metrics to quantify the level of endorsement:

(1) The percentage of endorsements/rejections/undecideds among all abstracts.
(2) The percentage of endorsements/rejections/undecideds among only those abstracts expressing a position on AGW.
(3) The percentage of scientists authoring endorsement/rejection abstracts among all scientists.
(4) The same percentage among only those scientists who expressed a position on AGW (table 3).

3.1. Endorsement percentages from abstract ratings

Among abstracts that expressed a position on AGW, 97.1% endorsed the scientific consensus. Among scientists who expressed a position on AGW in their abstract, 98.4% endorsed the consensus.

The time series of each level of endorsement of the consensus on AGW was analyzed in terms of the number of abstracts (figure 1(a)) and the percentage of abstracts (figure 1(b)). Over time, the no position

Table 3. Abstract ratings for each level of endorsement, shown as percentage and total number of papers.

Position	% of all abstracts	% among abstracts with AGW position (%)	% of all authors	% among authors with AGW position (%)
Endorse AGW	32.6% (3896)	97.1	34.8% (10 188)	98.4
No AGW position	66.4% (7930)	—	64.6% (18 930)	—
Reject AGW	0.7% (78)	1.9	0.4% (124)	1.2
Uncertain on AGW	0.3% (40)	1.0	0.2% (44)	0.4

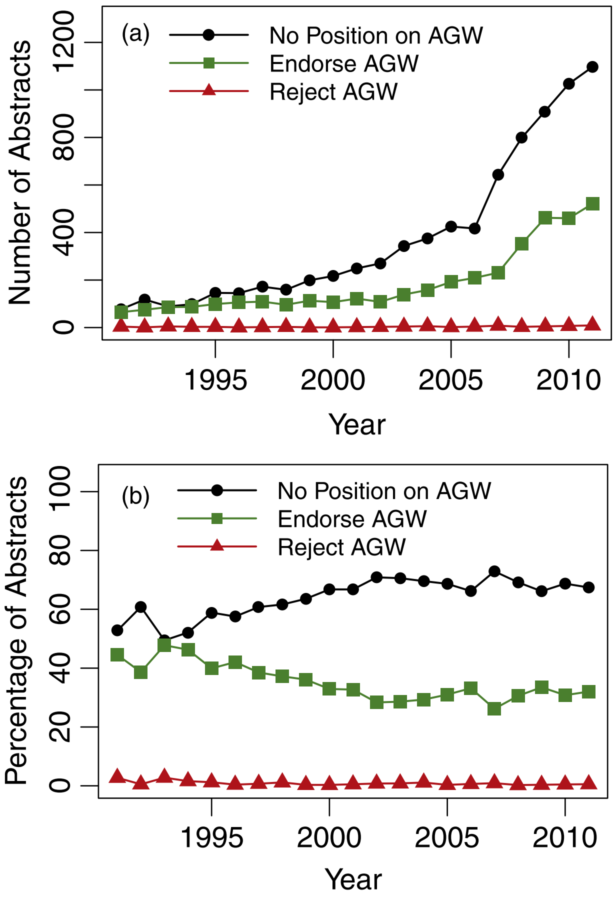

Figure 1. (a) Total number of abstracts categorized into endorsement, rejection and no position. (b) Percentage of endorsement, rejection and no position/undecided abstracts. Uncertain comprise 0.5% of no position abstracts.

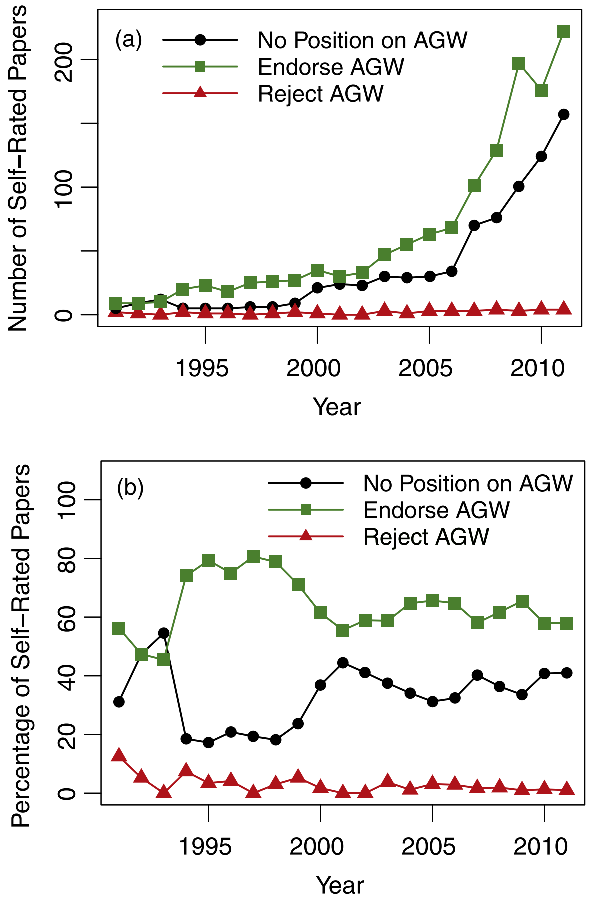

Figure 2. (a) Total number of endorsement, rejection and no position papers as self-rated by authors. Year is the published year of each self-rated paper. (b) Percentage of self-rated endorsement, rejection and no position papers.

percentage has increased (simple linear regression trend $0.87\% \pm 0.28\%\ \mathrm{yr}^{-1}$, 95% CI, $R^2 = 0.66$, $p < 0.001$) and the percentage of papers taking a position on AGW has equally decreased.

The average numbers of authors per endorsement abstract (3.4) and per no position abstract (3.6) are both significantly larger than the average number of authors per rejection abstract (2.0). The scientists originated from 91 countries (identified by email address) with the highest representation from the USA ($N = 2548$) followed by the United Kingdom ($N = 546$), Germany ($N = 404$) and Japan ($N = 379$) (see supplementary table S1 for full list, available at stacks.iop.org/ERL/8/024024/mmedia).

3.2. Endorsement percentages from self-ratings

We emailed 8547 authors an invitation to rate their own papers and received 1200 responses (a 14% response rate). After excluding papers that were not peer-reviewed, not climate-related or had no abstract, 2142 papers received self-ratings from 1189 authors. The self-rated levels of endorsement are shown in table 4. Among self-rated papers that stated a position on AGW, 97.2% endorsed the consensus. Among self-rated papers not expressing a position on AGW in the abstract, 53.8% were self-rated as endorsing the consensus. Among respondents who authored a paper expressing a view on AGW, 96.4% endorsed the consensus.

Table 4. Self-ratings for each level of endorsement, shown as percentage and total number of papers.

Position	% of all papers	% among papers with AGW position (%)	% of respondents	% among respondents with AGW position (%)
Endorse AGW[a]	62.7% (1342)	97.2	62.7% (746)	96.4
No AGW position[b]	35.5% (761)	—	34.9% (415)	—
Reject AGW[c]	1.8% (39)	2.8	2.4% (28)	3.6

[a] Self-rated papers that endorse AGW have an average endorsement rating less than 4 (1 = explicit endorsement with quantification, 7 = explicit rejection with quantification).

[b] Undecided self-rated papers have an average rating equal to 4.

[c] Rejection self-rated papers have an average rating greater than 4.

Table 5. Comparison of our abstract rating to self-rating for papers that received self-ratings.

Position	Abstract rating	Self-rating
Endorse AGW	791 (36.9%)	1342 (62.7%)
No AGW position or undecided	1339 (62.5%)	761 (35.5%)
Reject AGW	12 (0.6%)	39 (1.8%)

Figure 2(a) shows the level of self-rated endorsement in terms of number of abstracts (the corollary to figure 1(a)) and figure 2(b) shows the percentage of abstracts (the corollary to figure 1(b)). The percentage of self-rated rejection papers decreased (simple linear regression trend $-0.25\% \pm 0.18\%\ \mathrm{yr}^{-1}$, 95% CI, $R^2 = 0.28, p = 0.01$, figure 2(b)). The time series of self-rated no position and consensus endorsement papers both show no clear trend over time.

A direct comparison of abstract rating versus self-rating endorsement levels for the 2142 papers that received a self-rating is shown in table 5. More than half of the abstracts that we rated as 'No Position' or 'Undecided' were rated 'Endorse AGW' by the paper's authors.

Figure 3 compares the percentage of papers endorsing the scientific consensus among all papers that express a position endorsing or rejecting the consensus. The year-to-year variability is larger in the self-ratings than in the abstract ratings due to the smaller sample sizes in the early 1990s. The percentage of AGW endorsements for both self-rating and abstract-rated papers increase marginally over time (simple linear regression trends $0.10 \pm 0.09\%\ \mathrm{yr}^{-1}$, 95% CI, $R^2 = 0.20, p = 0.04$ for abstracts, $0.35 \pm 0.26\%\ \mathrm{yr}^{-1}$, 95% CI, $R^2 = 0.26, p = 0.02$ for self-ratings), with both series approaching approximately 98% endorsements in 2011.

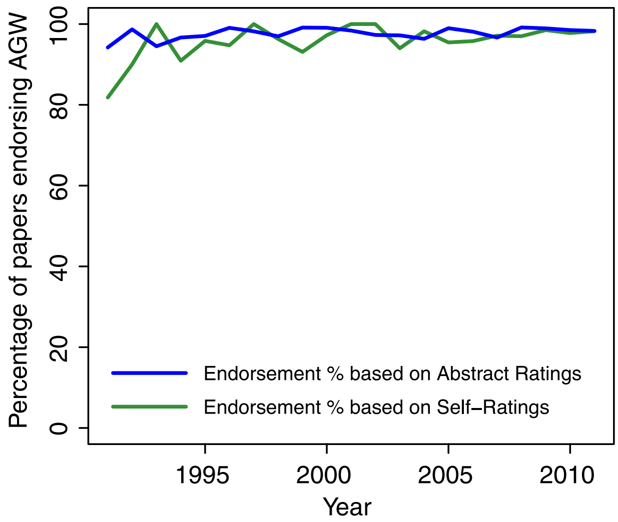

Figure 3. Percentage of papers endorsing the consensus among only papers that express a position endorsing or rejecting the consensus.

4. Discussion

Of note is the large proportion of abstracts that state no position on AGW. This result is expected in consensus situations where scientists '*...generally focus their discussions on questions that are still disputed or unanswered rather than on matters about which everyone agrees*' (Oreskes 2007, p 72). This explanation is also consistent with a description of consensus as a 'spiral trajectory' in which '*initially intense contestation generates rapid settlement and induces a spiral of new questions*' (Shwed and Bearman 2010); the fundamental science of AGW is no longer controversial among the publishing science community and the remaining debate in the field has moved to other topics. This is supported by the fact that more than half of the self-rated endorsement papers did not express a position on AGW in their abstracts.

The self-ratings by the papers' authors provide insight into the nature of the scientific consensus amongst publishing scientists. For both self-ratings and our abstract ratings, the percentage of endorsements among papers expressing a position on AGW marginally increased over time, consistent with Bray (2010) in finding a strengthening consensus.

4.1. Sources of uncertainty

The process of determining the level of consensus in the peer-reviewed literature contains several sources of uncertainty, including the representativeness of the sample, lack of clarity in the abstracts and subjectivity in rating the abstracts.

We address the issue of representativeness by selecting the largest sample to date for this type of literature analysis. Nevertheless, 11 944 papers is only a fraction of the climate literature. A Web of Science search for 'climate change' over the same period yields 43 548 papers, while a search for 'climate' yields 128 440 papers. The crowd-sourcing techniques employed in this analysis could be expanded to include more papers. This could facilitate an approach approximating the methods of Doran and Zimmerman (2009), which measured the level of scientific consensus for varying degrees of expertise in climate science. A similar approach could analyze the level of consensus among climate papers depending on their relevance to the attribution of GW.

Another potential area of uncertainty involved the text of the abstracts themselves. In some cases, ambiguous language made it difficult to ascertain the intended meaning of the authors. Naturally, a short abstract could not be expected to communicate all the details of the full paper. The implementation of the author self-rating process allowed us to look beyond the abstract. A comparison between self-ratings and abstract ratings revealed that categorization based on the abstract alone underestimates the percentage of papers taking a position on AGW.

Lastly, some subjectivity is inherent in the abstract rating process. While criteria for determining ratings were defined prior to the rating period, some clarifications and amendments were required as specific situations presented themselves. Two sources of rating bias can be cited: first, given that the raters themselves endorsed the scientific consensus on AGW, they may have been more likely to classify papers as sharing that endorsement. Second, scientific reticence (Hansen 2007) or 'erring on the side of least drama' (ESLD; Brysse *et al* 2012) may have exerted an opposite effect by biasing raters towards a 'no position' classification. These sources of bias were partially addressed by the use of multiple independent raters and by comparing abstract rating results to author self-ratings. A comparison of author ratings of the full papers and abstract ratings reveals a bias toward an under-counting of endorsement papers in the abstract ratings (mean difference 0.6 in units of endorsement level). This mitigated concerns about rater subjectivity, but suggests that scientific reticence and ESLD remain possible biases in the abstract ratings process. The potential impact of initial rating disagreements was also calculated and found to have minimal impact on the level of consensus (see supplemental information, section S1 available at stacks.iop.org/ERL/8/024024/mmedia).

4.2. Comparisons with previous studies

Our sample encompasses those surveyed by Oreskes (2004) and Schulte (2008) and we can therefore directly compare the results. Oreskes (2004) analyzed 928 papers from 1993 to 2003. Over the same period, we found 932 papers matching the search phrase 'global climate change' (papers continue to be added to the ISI database). From that subset we eliminated 38 papers that were not peer-reviewed, climate-related or had no abstract. Of the remaining 894, none rejected the consensus, consistent with Oreskes' result. Oreskes determined that 75% of papers endorsed the consensus, based on the assumption that mitigation and impact papers implicitly endorse the consensus. By comparison, we found that 28% of the 894 abstracts endorsed AGW while 72% expressed no position. Among the 71 papers that received self-ratings from authors, 69% endorse AGW, comparable to Oreskes' estimate of 75% endorsements.

An analysis of 539 'global climate change' abstracts from the Web of Science database over January 2004 to mid-February 2007 found 45% endorsement and 6% rejection (Schulte 2008). Our analysis over a similar period (including all of February 2007) produced 529 papers—the reason for this discrepancy is unclear as Schulte's exact methodology is not provided. Schulte estimated a higher percentage of endorsements and rejections, possibly because the strict methodology we adopted led to a greater number of 'No Position' abstracts. Schulte also found a significantly greater number of rejection papers, including 6 explicit rejections compared to our 0 explicit rejections. See the supplementary information (available at stacks.iop.org/ERL/8/024024/mmedia) for a tabulated comparison of results. Among 58 self-rated papers, only one (1.7%) rejected AGW in this sample. Over the period of January 2004 to February 2007, among 'global climate change' papers that state a position on AGW, we found 97% endorsements.

5. Conclusion

The public perception of a scientific consensus on AGW is a necessary element in public support for climate policy (Ding *et al* 2011). However, there is a significant gap between public perception and reality, with 57% of the US public either disagreeing or unaware that scientists overwhelmingly agree that the earth is warming due to human activity (Pew 2012).

Contributing to this 'consensus gap' are campaigns designed to confuse the public about the level of agreement among climate scientists. In 1991, Western Fuels Association conducted a $510 000 campaign whose primary goal was to '*reposition global warming as theory (not fact)*'. A key strategy involved constructing the impression of active scientific debate using dissenting scientists as spokesmen (Oreskes 2010). The situation is exacerbated by media treatment of the climate issue, where the normative practice of providing opposing sides with equal attention has allowed a vocal minority to have their views amplified (Boykoff and Boykoff 2004). While there are indications that the situation has improved in the UK and USA prestige press (Boykoff 2007), the UK tabloid press showed no indication of improvement from 2000 to 2006 (Boykoff and Mansfield 2008).

The narrative presented by some dissenters is that the scientific consensus is '*...on the point of collapse*' (Oddie 2012) while '*...the number of scientific "heretics" is growing with each passing year*' (Allègre *et al* 2012). A systematic, comprehensive review of the literature provides quantitative evidence countering this assertion. The number of papers rejecting AGW is a miniscule proportion of the published research, with the percentage slightly decreasing over time. Among papers expressing a position on AGW, an overwhelming percentage (97.2% based on self-ratings, 97.1% based on abstract ratings) endorses the scientific consensus on AGW.

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