

Scientists' Views about Attribution of Global Warming

Bart Verheggen,^{*,†,‡,§,||} Bart Strengers,[†] John Cook,^{§,||} Rob van Dorland,[⊥] Kees Vringer,[†] Jeroen Peters,[†] Hans Visser,[†] and Leo Meyer[†]

[†]PBL Netherlands Environmental Assessment Agency, PO Box 303, 3720 AH Bilthoven, The Netherlands

[‡]Energy Research Centre of The Netherlands ECN, PO Box 1, 1755 ZG Petten, The Netherlands

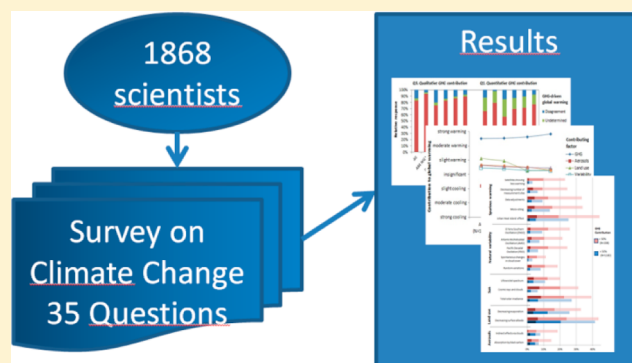
[§]University of Queensland, 4072 Brisbane QLD 4072, Australia

^{||}University of Western Australia, Crawley Washington 6009, Australia

[⊥]Royal Netherlands Meteorological Institute (KNMI), PO Box 201, 3730 AE De Bilt, The Netherlands

Supporting Information

ABSTRACT: Results are presented from a survey held among 1868 scientists studying various aspects of climate change, including physical climate, climate impacts, and mitigation. The survey was unique in its size, broadness and level of detail. Consistent with other research, we found that, as the level of expertise in climate science grew, so too did the level of agreement on anthropogenic causation. 90% of respondents with more than 10 climate-related peer-reviewed publications (about half of all respondents), explicitly agreed with anthropogenic greenhouse gases (GHGs) being the dominant driver of recent global warming. The respondents' quantitative estimate of the GHG contribution appeared to strongly depend on their judgment or knowledge of the cooling effect of aerosols. The phrasing of the IPCC attribution statement in its fourth assessment report (AR4)—providing a lower limit for the isolated GHG contribution—may have led to an underestimation of the GHG influence on recent warming. The phrasing was improved in AR5. We also report on the respondents' views on other factors contributing to global warming; of these Land Use and Land Cover Change (LULCC) was considered the most important. Respondents who characterized human influence on climate as insignificant, reported having had the most frequent media coverage regarding their views on climate change.



■ INTRODUCTION

The general public is strongly divided over the question of human causation of climate change.¹ Many believe that climate scientists are equally divided with respect to the same question, in contrast to what several studies^{2–5} have found. Perceptions about the level of agreement or disagreement among scientists influence people's acceptance of scientific conclusions and their support for related policies.^{6,7} Public perception of climate change and of the scientific consensus on the subject, in turn, is influenced by ethical, social, and political values and attitudes.^{8,9}

Scientists are considered a trusted source of climate information;¹⁰ hence, public commentators frequently use the purported existence of either strong agreement or strong disagreement as an argument pro or contra the validity of assessments by the Intergovernmental Panel on Climate Change (IPCC). Leviston and Walker¹¹ showed that the general public has a tendency to overestimate the prevalence of contrarian opinions in climate science and to underestimate the level of agreement.

Science is an evidence-based process, but the evidence has to be interpreted (research) and weighed (assessment). These interpretations and assessments are influenced by personal

knowledge of the evidence, but also by weighing the competing credibility of different experts and of different explanations.^{12,13} Thus, the “networks of trust” of survey respondents and their views on the “consilience of evidence” will impact any survey results. As the available evidence converges over time, scientists' aggregate opinion can be expected to reflect this convergence, resulting in a broadly—though not necessarily unanimously—shared consensus.

We performed a detailed survey under a large group of scientists studying various aspects of global warming and climate change (including impacts and mitigation) and who have published in peer-reviewed or, in a few cases, gray literature. We explored the distribution of scientific opinion on the causes of recent global warming, using the latest two IPCC assessment reports, AR4¹⁴ and AR5,¹⁵ as a benchmark. An attempt has been made to elucidate, in precise terms, the points of both agreement and disagreement regarding the influence of

Received: April 25, 2014

Revised: July 14, 2014

Accepted: July 22, 2014

Published: July 22, 2014

anthropogenic GHGs. We investigated how the interplay between climate warming by GHGs and cooling by aerosols complicates the issue of attribution to GHGs only, as phrased by the IPCC in 2007 in AR4. The relation between the respondents' views on attribution and their self-reported frequency of media coverage is briefly explored, as this is relevant to the public perception of consensus.¹⁶

Several studies have investigated levels of consensus among scientists in the discourse on climate change, using different questions, approaches, and sample sizes. However, scientific consensus usually is characterized in imprecise ways. This is one of the reasons, in addition to the pivotal role it plays in public perception and policy support, that the debate about the existence of consensus among scientists continues. Our study distinguishes itself from earlier work, in the large size and broad makeup of its survey sample and in the level of detail with which we explored the distribution of scientific opinion; thus, providing a more detailed description of what exactly is agreed upon. Our survey, conducted in 2012, covered a wide range of the physical science issues that are at the center of the public debate on climate change.

In this article, we focus on the level of agreement or disagreement regarding attribution of global warming to various anthropogenic and natural causes. One of our survey questions (Q1) was designed to be directly comparable with the well-known statement of AR4: "Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic GHG concentrations". The comparable AR5 statement reads as follows: "It is extremely likely that human activities caused more than half of the observed increase in global average surface temperature from 1951 to 2010." The equivalent AR5 statement differs from AR4 in two important aspects: the likelihood level is increased in the AR5 statement, and it is written in terms of "human activities", whereas the AR4 statement specifies "anthropogenic GHG concentrations". This last distinction is very relevant to our analysis and we argue that the AR5 statement is clearer and less open to misinterpretation than its AR4 equiv.

■ MATERIALS AND METHODS

Survey Sample. Participation in our survey was sought from scientists having authored or coauthored peer-reviewed articles or assessment reports related to climate change. Approximately 6000 names were assembled from articles with the keywords "global warming" and/or "global climate change", covering the 1991–2011 period via the Web of Science. Around 2000 names were collected from a public database assembled by Jim Prall, based on scientific literature up to 2009,¹⁷ supplemented by an additional ~500 authors of recent (2009–2011) climate science peer-reviewed literature. Prall's database also includes signatories of public statements disapproving of mainstream climate science. They were included in our survey to ascertain that the main criticisms of climate science would be captured. This last group amounts to less than 5% of the total number of respondents, about half of whom had only published in the gray literature on climate change.

There was some overlap between these sources, with the unique total number of names amounting to ~8000. Based on email address availability, 7555 of them were contacted. Of these emails, ~1000 were returned undelivered or unread, leaving a total of 6550 people that were successfully

approached. 1868 questionnaires were returned, although not all of these were fully completed. This amounts to a response rate of 29%. Each respondent could only respond to the survey once. Survey results were analyzed anonymously.

Sample Representation. It is important to consider the extent to which the group of people contacted was representative of "climate scientists". Having applied the above-mentioned sources and criteria, we are confident that most of the main players in climate science were invited. The key word searches "global warming" and "global climate change" ensured that we also sampled the wider scientific field, including those studying impacts and mitigation of global warming. By also soliciting responses from signatories of public statements who are not necessarily publishing scientists, it is likely that viewpoints that run counter to the prevailing consensus are somewhat magnified in our results. This is further exacerbated by this group exhibiting a relatively higher response rate (see below). With the exception of this group, the criteria used for selecting our survey sample are similar to those used in other surveys studying the distribution of scientific opinion on climate change, as discussed, for example, by Bray.¹⁸

Survey invitees were tagged with certain characteristics, which allowed us to check the level of representation of the response group. These characteristics included information regarding expertise in the form of one or more keywords, see Supporting Information (SI). These were subsequently grouped into Working Groups (WG) 1, 2, or 3, or according to certain field of expertise that refer to IPCC nomenclature: WG1 (the physical science basis), WG2 (impacts, adaptation, and vulnerability) and WG3 (mitigation of climate change). Some people were tagged with multiple fields of expertise; therefore, the total of these fields exceeds 100%. 619 invitees were tagged as having been IPCC AR4 WG1 coordinating, lead or contributing authors, and 218 were tagged as being "unconvinced" of the evidence, based on their published articles or signed public declarations critical of mainstream climate science as embodied by the IPCC. The latter information was extracted from Jim Prall's public database. Invitees were also tagged according to their country of employment, based on their email addresses.

The relative prevalence of respondents with certain tags was compared to their prevalence in the total group of invitees (see Figure S1 in SI). The absence of a strong systematic bias led us to conclude that the group of respondents overall could be considered representative of the total group invited, with some minor differences. WG1 and "other" fields of expertise were slightly overrepresented among the respondents, as were invitees tagged as "unconvinced" (3% of invitees against 5% of respondents) and IPCC AR4 WG1 authors (8% and 9%, respectively). Around 80% of both invitees and respondents were from either North America or Europe, with the remainder being predominantly based in Asia or Oceania.

Survey Questions. The survey focused on important topics in the public debate on climate science, while also covering a wide range of scientific topics related to the scientific basis of climate change, not all of which are discussed in this article. Answer options reflected a variety of viewpoints, all of which were phrased as specific and neutral as possible. Questions and answers were previewed by physical and social scientists and climate change public commentators with a wide range of opinions, to minimize the chance of bias. The main questions investigated in this article are listed below, with a brief

description of associated answer options. The complete set of survey questions and answer options is freely available.¹⁹

Q1. What fraction of global warming since the mid-20th century can be attributed to human-induced increases in atmospheric GHG concentrations? Quantitative answer options in percentage ranges of GHG contribution. Answer options included >100% (i.e., GHG warming has been partly offset by aerosol cooling) and <0% (i.e., GHG caused cooling).

Q1b. What confidence level would you ascribe to the anthropogenic GHG contribution being more/less than 50%? Answer options according to the IPCC likelihood scale.^{19,20}

Q3. How would you characterize the contribution of the following factors to the reported global warming of $\sim 0.8^\circ\text{C}$ since preindustrial times: GHGs, aerosols, land use, sun, internal variability, spurious warming? Qualitative answer options ranged from “strong cooling” to “strong warming”. “Spurious warming” refers to global mean surface temperature change being overestimated due to artifacts in the data, such as Urban Heat Island (UHI) effects.

Q3b. How would you describe the level of scientific understanding for each of these factors? Answer options ranged from very low to high.

Q3c. An explanatory question was asked regarding all factors other than GHGs (which were assigned a warming influence), each with specific multiple choice answers.

Q4. What is your estimate of equilibrium (Charney) climate sensitivity, i.e. the temperature response (degrees C) to a doubling of CO_2 ? Open, numeric answer.

Q6. Please indicate your field(s) of expertise in climate science. Multiple choice answer options.

Q7. Please indicate the approximate number of climate-related articles you have published in peer-reviewed scientific journals, including as coauthor. Open, numeric answer.

Q11. How frequently have you featured in the media regarding your views on climate change? Answer options ranging from “very frequently” to “never”.

RESULTS

Aggregation of Results. Given the large sample size (1868) and the diversity in scientific backgrounds of our respondents, results were segregated according to fields of expertise and publication metrics, as indicated by the respondents in their respective answers to questions 6 and 7. The self-declared fields of expertise were categorized as WG1, 2, 3, or other fields of expertise, analogous to the tagged expertise fields (see SI). Around 65% of those with self-declared WG1 fields of expertise also were tagged with WG1 fields of expertise. Respondents who were labeled as “unconvinced” indicated more often than other respondents that they had expertise in one or more of the WG1 fields and they indicated more expertise fields in general. For a subgroup of invitees, Google Scholar metrics regarding number of publications were also available as tagged information. For fields of expertise as well as publication metrics, aggregated results did not strongly depend on tagged or self-declared numbers. More details can be found in the SI.

Attribution. The responses to Q3, on the qualitative GHG contribution to global warming since preindustrial times, are shown in Figure 1. Responses were segregated according to the self-declared number of climate-related peer-reviewed publications, in four ranges of approximately equal size. About half the respondents stated that they had authored or coauthored more than 10 peer-reviewed climate-related publications. Responses

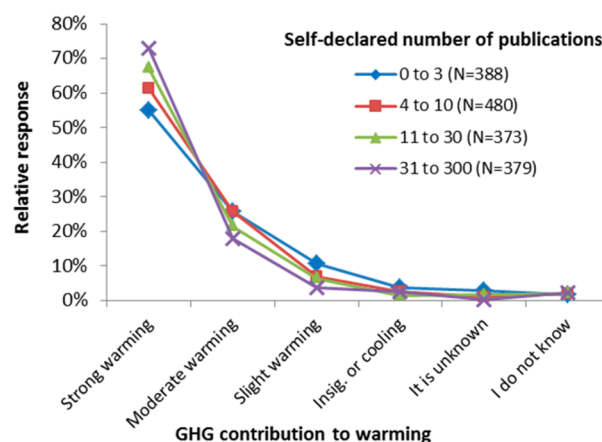


Figure 1. Qualitative contribution of anthropogenic GHGs to global warming since preindustrial times (Q3). Responses are shown as a percentage of the number of respondents (N) in each subgroup, segregated according to self-declared (SD) number of peer-reviewed climate-related publications.

indicating a cooling influence of GHGs (11 responses or less than 1% of the total) were grouped under the category “insignificant”, for graphing purposes. The majority of respondents selected the highest score (“strong warming”) for the GHG contribution. This majority was even stronger for respondents with the highest number of self-declared publications. A similar, though less pronounced trend was found for respondents with increasingly relevant fields of expertise (see SI). Furthermore, 82% of AR4 WG1 authors selected the “strong warming” option for this question (not shown).

Q1 also concerned the contribution of GHGs, but then as a percentage of observed warming since the mid-20th century. This enabled a direct comparison with the well-known AR4 statement on attribution, which states that this contribution is *very likely* (probability >90%) to be more than 50%. Less well-known is the fact that IPCC in AR4 also states that GHG forcing alone was *likely* (probability >66%) to have resulted in greater than observed warming if there had not been an offsetting, cooling effect from aerosol and other forcings. In AR5 this was further clarified. The net cooling effect of aerosols means that the sum of all warming contributions exceeds 100%.^{21–23} This is the reason for including the answer option “>100%”, which, even if counterintuitive, would be consistent with both AR4 and AR5 and with recent research.^{21–23}

Their awareness of or judgment about the offsetting effect of aerosols appears important in how respondents answered Q1, as is discussed in more detail below. The proportion of respondents who chose GHG > 100% was higher among respondents with expertise in “attribution” or “aerosols and clouds” (see Figure 2).

AR4 WG1 authors (not shown) responded similarly to those with (self-declared) expertise in attribution or aerosols, also preferentially selecting “>100%”. As the self-declared number of publications increased, so did the proportion of respondents selecting “>100%”, although still below the answer option of “76–100%” (see SI).

Four respondents tagged as AR4 WG1 authors chose the “26–50%” option and, as such, disagreed with AR4’s attribution statement. Those who were tagged as “unconvinced” (N = 88, not shown) consisted of two main subgroups: one claiming only a minor effect of anthropogenic GHGs (GHG < 25%),

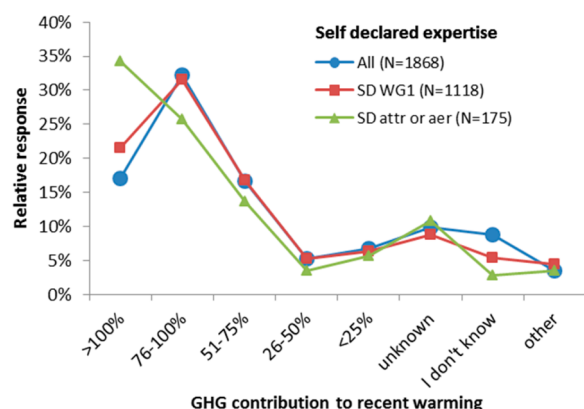


Figure 2. Percentages for the contribution of anthropogenic GHG to global warming since the mid-20th century (Q1). Responses are shown as a percentage of respondents (N) in each subgroup, segregated according to self-declared (SD) fields of expertise “WG1” (categorized as Working Group 1) and “attr or aer” (expertise in attribution or aerosols and clouds).

and the other claiming the answer was “unknown due to lack of knowledge”. Six of the “unconvinced” respondents selected the option GHG > 50%, thus agreeing with AR4’s attribution statement.

Consensus. Responses to Q1 and Q3 were both condensed into three categories: (1) agreement; (2) disagreement; and (3) undetermined (“unknown”, “I do not know”, and “other”). Those who selected any of the options of GHG > 50% in answer to Q1 were included in the “agreement” category. The answer “no warming” was included in the “disagreement” category. For Q3, responses were interpreted as “agreement” if GHGs were accredited with strong warming or with moderate warming if none of the other natural or anthropogenic factors were deemed to have caused strong warming. So, according to these respondents, GHGs were either the strongest or tied for the strongest contributor to global warming.

In Figure 3 the distribution of respondents over the categories “agreement”, “undetermined”, and “disagreement” is shown for all respondents and for five different subgroups: the group of AR4 WG1 authors ($N = 174$) and four quartiles of approximately equal size ($N = \sim 400$), based on their self-reported number of publications. Results are shown separately for the questions of qualitative (Q3) and quantitative (Q1) attribution.

Undetermined responses (unknown, I do not know, other) were much more prevalent for Q1 (22%) than for Q3 (4%); presumably because the quantitative question (Q1) was considered more difficult to answer. This explanation was confirmed by the open comments under Q1 given by those with an undetermined answer: 100 out of 129 comments (78%) mentioned that this was a difficult question.

There are two ways of expressing the level of consensus, based on these data: as a fraction of the total number of respondents (including undetermined responses), or as a fraction of the number of respondents who gave a quantitative or qualitative judgment (excluding undetermined answers). The former estimate cannot exceed 78% based on Q1, since 22% of respondents gave an undetermined answer. A ratio expressed this way gives the appearance of a lower level of agreement. However, this is a consequence of the question being difficult to answer, due to the level of precision in the answer options, rather than it being a sign of less agreement.

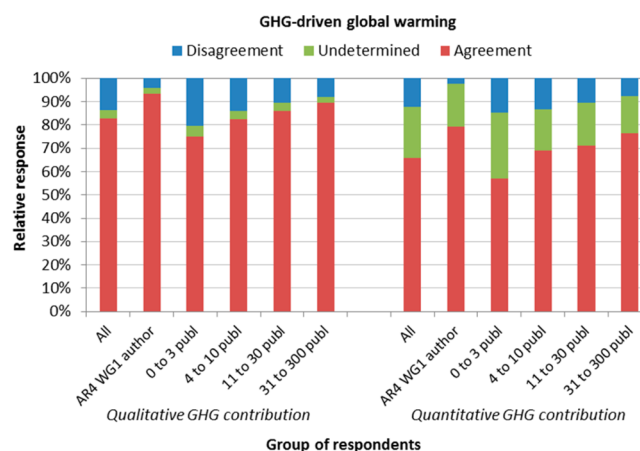


Figure 3. Responses shown as percentages of agreement and disagreement about the dominant influence of GHGs on global warming, based on responses to Q3 (qualitative GHG contribution) and Q1 (quantitative GHG contribution). Also shown are the percentages of responses for the answer options “unknown”, “I do not know”, and “other”, combined and labeled as “undetermined”. These answer options were much more prevalent for the quantitative question (Q1). The level of agreement increases for respondents with increased self-declared number of peer-reviewed climate-related publications and is highest for AR4 WG1 authors.

As a fraction of the total, the level of agreement based on Q1 and Q3 was 66% and 83%, respectively, for all respondents, and 77% and 89%, respectively, for the quartile with the highest number of self-declared publications. As a fraction of those who expressed an opinion (i.e., excluding the undetermined answers), the level of agreement based on Q1 and Q3 was 84% and 86%, respectively, for all respondents, and 91% and 92%, respectively, for the quartile with the highest number of self-declared publications.

The similarity between the fractions as derived from Q1 and Q3 (excluding the undetermined responses) suggests that it is reasonable to interpret the answer option “moderate warming” (provided no other factor was deemed to have caused “strong warming”) as agreeing with the IPCC. The fraction of respondents that disagreed with a dominant human influence on climate was 12% and 14%, based on the answers to Q1 and Q3, respectively. This group becomes smaller, 8% in both cases, for the quartile with the highest number of publications. A table with consensus estimates for the different subgroups and expressed in the above-mentioned two different ways can be found in the SI (Table S3). Excluding undetermined answers, 90% of respondents, with more than 10 self-declared climate-related peer-reviewed publications, agreed with dominant anthropogenic causation for recent global warming. This amounts to just under half of all respondents.

Different surveys are not directly comparable, due to different groups of people being asked different questions. However, since climate science surveys typically drew from the same overall pool of climate-related scientists, Bray¹⁸ suggests that these can be meaningfully compared, to study the net change in aggregate opinions. He concluded that the level of consensus has grown over time. This is consistent with the analysis of the peer-reviewed literature that shows a similar increase in consensus.

Our results for the level of consensus are similar to those found in other surveys.^{3,24–26} Doran and Kendall-Zimmermann³ reported an 82% consensus among 3146 earth scientists,

which rose to 88% for those who identified themselves as climatologists, which is very similar to our findings. However, Oreskes,² Anderegg et al.,⁴ and Cook et al.⁵ reported a 97% agreement about human-induced warming, from the peer-reviewed literature and their sample of actively publishing climate scientists, as did Doran and Kendall-Zimmermann³ for the most published climatologists. Literature surveys, generally, find a stronger consensus than opinion surveys. This is related to the stronger consensus among often-published—and arguably the most expert—climate scientists. The strength of literature surveys lies in the fact that they sample the primary fora where the evidence is laid out, whereas the strength of opinion surveys such as ours relates to the fact that much more detail can be achieved about the exact opinions of scientists. As such, these two methods for describing scientific consensus are complementary. Different surveys typically use slightly different criteria to determine their survey sample and to define the consensus position, hampering a direct comparison. It is possible that our definition of “agreement” sets a higher standard than, for example, Anderegg’s definition (e.g., AR4 WG1 author or having signed a public declaration) and Doran and Kendall-Zimmermann’s survey question about whether human activity is “a significant contributing factor”.

As indicated, contrarian viewpoints are likely overrepresented in our sample (amounting to ~5% of respondents), about half of whom have published peer-reviewed articles in the area of climate. However, this does not fully explain the difference with the abovementioned studies. Excluding those tagged as “unconvinced” more closely approximates the methodologies of earlier studies and increases the level of agreement, for example, from 84% to 87% based on Q1, excluding undetermined responses. Moreover, we solicited responses from a wide group of scientists. A larger proportion of those not specializing in climate science research may be unconvinced by or unaware of the scientific evidence for anthropogenic causation, as was also found by Doran and Kendall-Zimmermann.³ Our results agree with Anderegg’s and Doran and Kendall-Zimmermann’s findings that the level of consensus is strongest for actively publishing climate scientists. For example, the level of agreement—excluding undetermined responses—among AR4 WG1 authors, usually highly published domain experts, for Q1 and Q3, was 97% and 96%, respectively.

Likelihood of a Dominant Human Influence. Responses of the confidence level of the anthropogenic GHG contribution being larger or smaller than 50% are shown in Figure 4. Respondents who estimated this contribution to be more than 50% (GHG > 50%) did so in combination with a higher level of likelihood, than respondents who estimated this contribution to be smaller than 50% (GHG < 50%). Of the group GHG > 50%, 89% assigned at least the same likelihood as the AR4 (“very likely”) to GHGs contributing more than 50% to recent warming; 65% chose a likelihood at least as high as that in AR5 for net anthropogenic activities (“extremely likely”). In fact, “virtually certain” was selected most often by these respondents (Figure 4). Those with more relevant self-declared fields of expertise assigned a higher likelihood to their particular choice than those with less relevant expertise. Only 39% of the group GHG < 50% assigned a likelihood of “very likely” or stronger to their choice.

Contribution of Other Factors to Warming. Besides asking for the qualitative contribution of GHGs to the warming of ~0.8 °C since preindustrial times, Q3 also asked about the influence of other factors (see Figure 5). To allow averages to

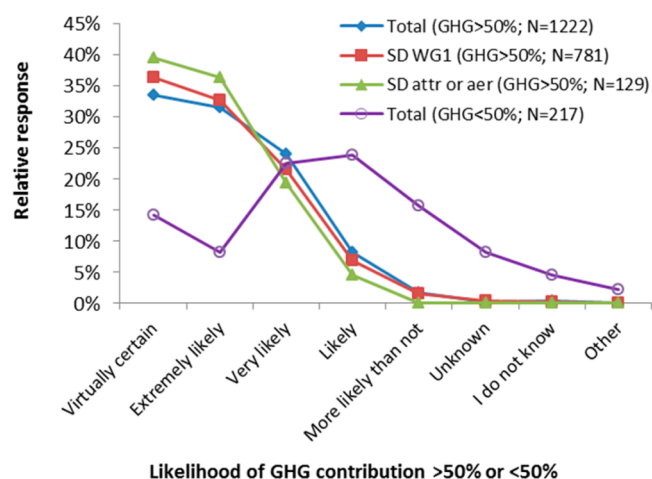


Figure 4. Likelihood of anthropogenic GHG contribution being larger (GHG > 50%) or smaller (GHG < 50%) than 50% (Q1b). Responses are shown as a percentage of the respondents (N) in each subgroup. The sample size is given in the legend. For respondents who selected the GHG > 50% option, the assigned level of likelihood is segregated according to self-declared (SD) fields of expertise “WG1” (categorized as Working Group 1) and “attr or aer” (expertise in attribution or aerosols and clouds).

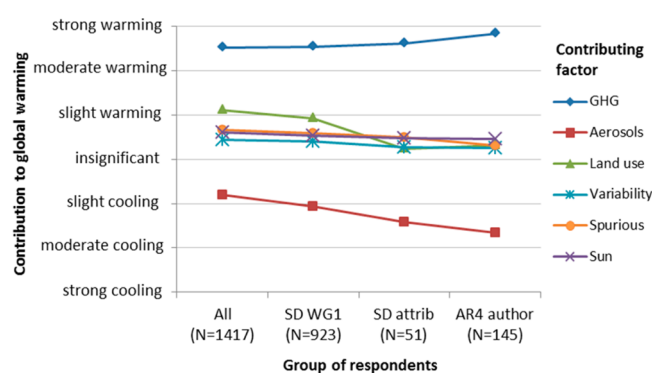


Figure 5. Contribution of different factors to the reported ~0.8 °C warming since preindustrial times, for different groups of respondents (Q3). Qualitative responses for each group were averaged under the assumption of being equidistant. Average sample sizes (N) are shown in brackets, for each group of respondents.

be computed, the qualitative answer scale was transcribed numerically, assuming the scale to be equidistant, meaning that the distance between the different answer options is assumed to be identical. Average sample sizes are given in brackets; they are not constant as they vary slightly according to the proportion of undetermined responses (“unknown” and “I do not know”). Consistent with AR4 and AR5, anthropogenic GHGs were estimated to have had by far the strongest contribution to global warming.

There are however some differences with the IPCC assessments in how some of the other factors were estimated. Land Use and Land Cover Change (LULCC) is estimated by IPCC to have exerted a small negative forcing (cooling) of -0.15 (-0.25 to -0.05) W/m^2 due to an increase in surface albedo. LULCC can also cause surface warming due to reduced evaporation during the summer and in the tropics; this leads to a vertical redistribution of heat and is thus not captured in the reported radiative forcing in AR5 due to LULCC. However, in our survey, on average, LULCC was deemed to have caused

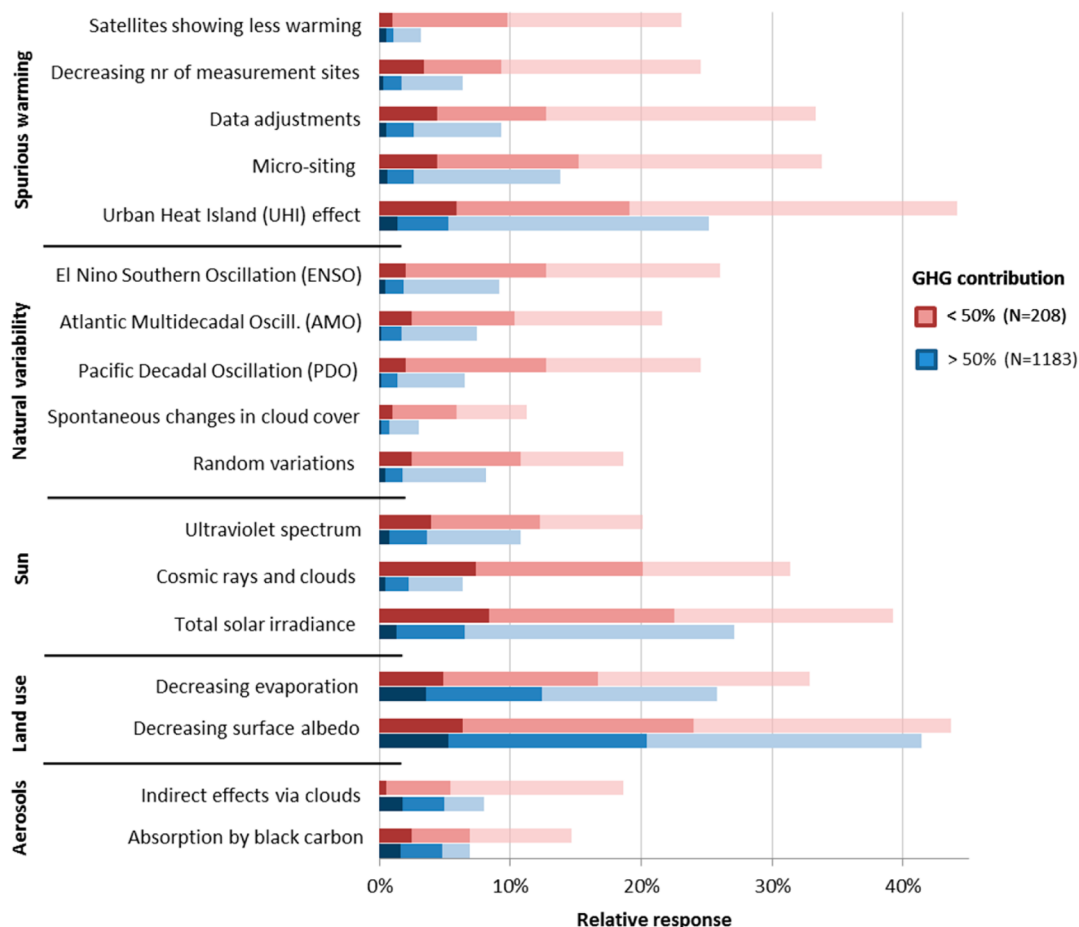


Figure 6. Reasons for, or indications of other factors than anthropogenic GHGs having had a slight (light colored), moderate (medium colored) or strong (dark colored) warming influence on global average temperatures since preindustrial times, in response to Q3c. Responses are shown as a percentage of respondents, who selected either <50% or >50% GHG contribution under question Q1 (in red and blue, respectively).

slight warming. This estimate was substantially lower (insignificant, on average) for both self-declared attribution experts and AR4 WG1 authors. Other potential sources of warming (from the sun, from natural variability, or warming being partly spurious), on average, were estimated from insignificant (4) to slight warming (5), without being strongly dependent on the fields of expertise or AR4 WG1 authorship. Aerosols were estimated by most respondents to have had a cooling influence on climate, in line with the IPCC assessments. However, 16% of all respondents selected (slight, moderate or strong) warming for the net effect of aerosols (see also Figure 6).

The spread in results (see SI Table S4) is smaller for the contribution of GHGs (standard deviation of 0.83 for all respondents together and 0.78 for those with self-declared WG1 fields of expertise) than for the contribution of most other factors. This is also reflected in the higher level of scientific understanding (Q3b) that was reported for GHGs compared to the other factors (see SI Figure S9). The contribution of aerosols shows a wide spread: highest standard deviation of 1.44 for all respondents together and 1.26 for those with self-declared WG1 fields of expertise.

When a factor, other than GHGs, was estimated to have had a slight, moderate or strong warming effect, a clarifying question was asked in Q3c about the reasons for, or indications of this influence. These were phrased as multiple choice questions, for which more than one option per question could

be selected. Figure 6 shows the prevalence of responses, segregated according to their choice of >50% or <50% GHG contribution.

This reveals the similarities and differences between these two groups in how certain issues are perceived. Overall, the UHI effect, changes in solar irradiance, and both options within the category “LULCC” were chosen as the most prevalent contributors to global warming. As mentioned above, according to the IPCC assessments LULCC has probably led to an increase rather than a decrease in surface albedo.

The group GHG < 50% indicated twice as often alternative factors to have contributed to the observed warming than the group GHG > 50%, as expressed by the longer red bars in Figure 6. For the categories “strong” and “moderate” warming influence, the difference becomes even more pronounced: a factor of 3.

Warming due to “spurious warming” and “natural variability” was judged most differently between the two groups. In the category “spurious warming”, referring to a warming bias in the temperature record, the UHI effect was the option chosen most often by both groups. For the group GHG > 50%, the relative popularity of this option, compared to other options, was more pronounced. For the category “Natural Variability”, no large differences were found between the indicated causes, except that ‘spontaneous changes in cloud cover’ was selected the least. Even though the question concerned centennial scale warming,

the short-term El Niño Southern Oscillation (ENSO) was considered by both groups as the most important.

In the category “Sun”, most respondents chose total solar irradiance as the most probable cause. The relative popularity of this option, in comparison with others, was most pronounced among the group GHG > 50%. Only a small fraction of this group believed the influence of the sun to be magnified through, for instance, the ultraviolet part of its spectrum or the cloud-forming potential of cosmic rays. In terms of what was thought to have had a “strong” warming influence, among the group GHG < 50%, “cosmic rays and clouds” were considered as the second strongest contributing factor to global warming, after changes in solar irradiance.

In the category “Aerosol”, the option of indirect effects via clouds was selected somewhat more often than absorption by black carbon. The former option is a direct contradiction to the IPCC, which states that although the magnitude of indirect aerosol effects is highly uncertain, its sign—a negative radiative forcing, and thus a cooling influence—is not. Note that the majority of respondents indicated a slight to moderate cooling due to aerosols (Figure 5).

Aerosol Cooling Versus GHG Warming. Recent studies concluded that it is very likely²³ (90% probability) or extremely likely²¹ (95% probability) that GHG-induced warming since the mid-20th century has been larger than the observed warming. This is not surprising, considering that the radiative forcing from GHGs (in 2005 compared to 1750) amounts to about 140% of the total forcing.¹⁵ AR4 was more conservative regarding attribution, stating that GHG forcing alone would likely (>66%) have resulted in greater than the observed warming if there had not been an offsetting cooling effect from aerosols and other forcings.

Most responses to Q1, thus, indicated a smaller GHG contribution than what could be inferred from AR4 (Figure 2), although most responses claim a higher level of confidence than in the AR4 about GHG contribution exceeding 50% (Figure 4). According to Allen,²⁷ the quintessential AR4 attribution statement, quoted toward the end of the introduction, focused on GHGs rather than on the net anthropogenic effect, in order to have a more quantitative conclusion and a more justifiable statement.

The relative prevalence in our survey of GHG contribution estimations of between 50% and 100%, relative to >100%, suggests that this AR4 statement leads people to underestimate the GHG contribution. Potential reasons for this are the following: (1) the AR4 statement only provides a lower limit (“most”) for the GHG contribution; (2) this lower limit (>50%) is far removed from an inferred best estimate which exceeds 100%; (3) the inferred best estimate is counterintuitive (because how could an isolated contribution exceed 100%?); and (4) there is less awareness of the cooling effect of aerosols than of the warming effect of GHGs and, thus, readers may interpret this statement as referring to the net anthropogenic effect.

The statement taken in isolation, without mentioning offsetting aerosol cooling, could very well be misinterpreted. For example, Curry and Webster,²⁸ in their critique of this statement, appeared to interpret “most” as meaning between 51 and 99% implying a nonexistent plateau at 100%. They deemed the “very likely” designation to be an overstatement of the probability in light of the highly uncertain amplitude of natural variability. This in contrast to most respondents of our survey, who assigned higher levels of likelihood to GHG contribution

exceeding 50%. Hegerl et al.²⁹ responded to Curry and Webster by noting that the IPCC attribution statement assigns a lower probability to this being correct than is implied in individual studies, because structural uncertainty is taken into account. Figure 5 shows that the higher the estimated GHG contribution, the larger the estimated aerosol cooling. This effect was relatively strongest between the two highest GHG categories (“76–100%” and “>100%”; see SI Figure S10).

Q4 asked the respondents’ estimate of the equilibrium climate sensitivity (ECS), that is, the global average temperature increase due to a doubling of the atmospheric CO₂ concentration. Figure 7 shows how the response to Q4 relates

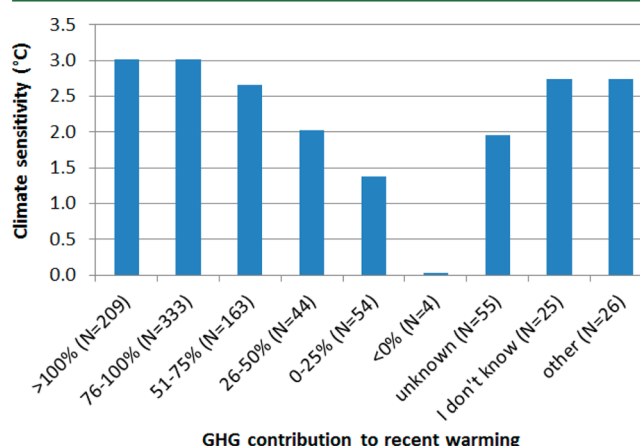


Figure 7. Average estimates of equilibrium climate sensitivity (ECS, in °C per doubling of the atmospheric CO₂ concentration), versus estimates of the quantitative GHG contribution. Sample sizes for each GHG category are noted on the x-axis (total N = 913). The two categories with the highest GHG contribution are not distinguished by the estimates of concomitant ECS, whereas the other categories are.

to the estimated GHG contribution to recent warming. Estimates for ECS exceeding 10 °C were excluded under the assumption that these were made in error. Note that the total sample size for Figure 7 is 913, as there were fewer responses to Q4 than to Q1 and Q3. The higher the estimated GHG contribution, the higher the average estimated ECS, except for the highest two GHG categories, who both estimated 3.0 °C. Between all other categories there is a significant difference in average ECS (*t* test, $\alpha = 0.05$). We pose that many respondents did not distinguish the highest two GHG categories on the basis of having a different opinion about the GHG influence, but rather because they had a different opinion or different level of awareness about the contribution of aerosols.

This conclusion is also supported by the fact that the option with the highest GHG contribution (GHG > 100%) actually becomes relatively less prevalent for sensitivity estimates of more than 3.5 °C, whereas the second highest GHG category (GHG 76–100%) becomes relatively more prevalent (see SI Figure S11). Also note that even for lower sensitivity ranges a significant proportion of the respondents (up to 75% in the range from 1.5 to 2.5 °C) considers the GHG contribution to be greater than 50%.

In AR5, the principal attribution statement was changed to include “the anthropogenic increase in GHG concentrations and other anthropogenic forcings together”, which remedies some of the issues identified above with the equivalent AR4 statement.

Climate Sensitivity. Figure 8 shows the distribution of the respondents' ECS estimates, shown in ranges for graphing

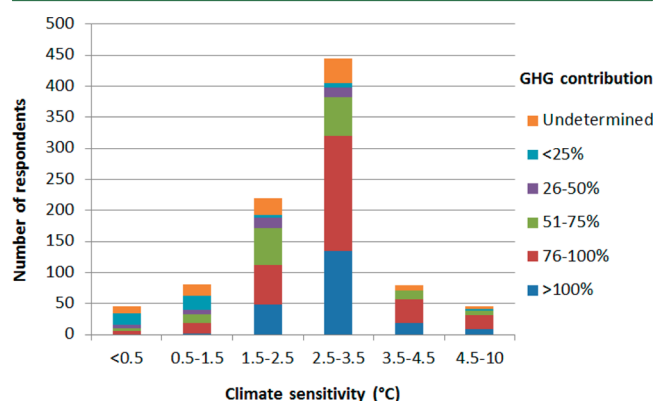


Figure 8. Number of respondents per range of estimated ECS, segregated according to the respondents' answers regarding the quantitative GHG contribution (total sample size $N = 913$).

purposes. The peak for the ECS range (2.5–3.5 °C) is in the middle of the “likely” range as assessed in AR5 (1.5–4.5 °C). On the other hand, the skewed distribution shown in Figure 8, with more responses for lower rather than higher values of ECS, is different from the distribution as inferred from theory and as assessed by the IPCC, which has a fat tail toward higher values.

Media Exposure. Figure 9 shows the self-reported frequency of media coverage (Q11) and how this relates to the responses to the two above-mentioned questions on GHG contribution (Q1 and Q3), as well as to their estimates of ECS (Q4). For ease of presentation, the options “very frequently” and “frequently” were combined, as were “rarely” and “never” (see SI Figure S13 for more details). Those who estimated ECS to be lower than 1.75 °C reported more “frequent” or “very frequent” media coverage than those who estimated it to be higher, although not all of these differences are statistically significant (see SI). Responses to the quantitative attribution question (Q1) showed that respondents on either side of the spectrum reported more frequent media coverage than the

group in the middle. The relative highest frequency of media coverage was reported by those who attributed less than 25% of global warming to GHGs, and those who attributed >100% to GHGs, analogous to what can be inferred from the IPCC, reported only slightly less frequent media coverage. Those who estimated the qualitative greenhouse contribution (Q3) to be insignificant or negative (i.e., cooling) reported significantly more frequent or very frequent media exposure than those who estimate GHGs to have exerted either slight, moderate or strong warming. Relative to their total number, 30% of the group that selected “insignificant or cooling” reported being featured frequently or very frequently in the media, as opposed to 15% of the majority of respondents, who selected a strong warming contribution of GHGs. When only taking the “very frequently” responses into account, the difference between those who regard GHG to cause warming versus those who do not is even stronger (12% versus 4%). These differences are statistically significant ($p = 0.01$ and $p = 0.04$, respectively, using the “Fisher’s exact test”) and indicate that those who most strongly disagree with a discernible influence of anthropogenic GHGs on climate are overrepresented in the media, relative to the prevalence of these opinions in the scientific community.³⁰

■ ASSOCIATED CONTENT

§ Supporting Information

The Supporting Information contains background information on the following topics: Aggregating fields of expertise, comparison between tagged and self-declared fields of expertise, attribution, consensus, contribution of other factors to warming, aerosol cooling versus GHG warming, climate sensitivity, and media exposure. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +31 20 525 8271; e-mail: Verheggen.Bart@gmail.com.

Present Address

#Amsterdam University College AUC, PO Box 94160, 1090 GD Amsterdam, The Netherlands

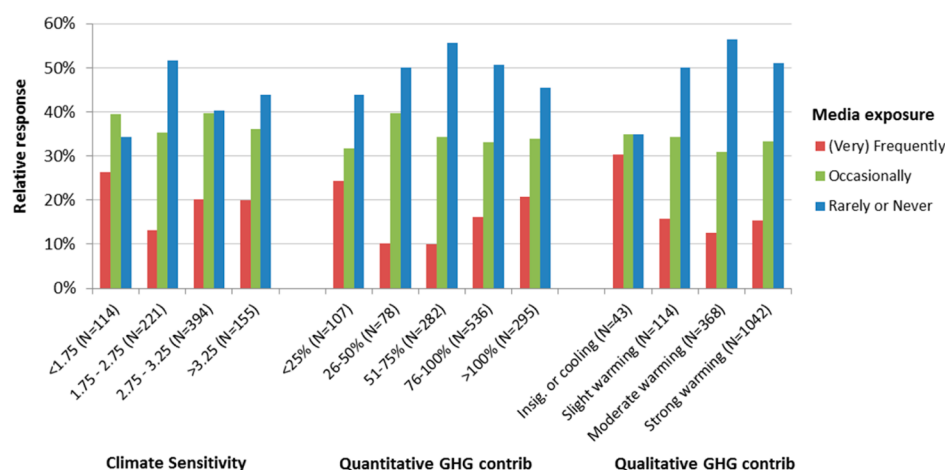


Figure 9. Self-reported frequency of media coverage, segregated according to responses to the questions on quantitative (Q1) and qualitative (Q3) GHG contribution, as well as to the question on ECS. Responses are shown as a percentage of the number of people (N) per response category (as denoted on the x -axis). The most frequent media coverage is reported by respondents who deemed the effect of GHGs to be the smallest and ECS to be the lowest.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank the following people for their contributions to this work: Collection of email addresses: Sanne Boersma, Bärbel Winkler, Rob Painting, Rob Honeycutt, Sarah Green, John Cook, Wendy Cook, Ari Jokimäki, Phil Scadden, Glenn Tamblyn, Anne-Marie Blackburn, John Hartz, Steve Brown, George W. Morrison, Alexander C. Coulter, and many unnamed researchers. Survey preview: Marcel Crok, Gavin Schmidt, Gerbrand Komen, Hans Labohm, Roger Pielke Sr, Rasmus Benestad, Sybren Drijfhout, James Annan, Mike Hulme, Ronald Flippi, Jan Paul van Soest, Gert Spaargaren, Marjolein de Best-Walldober, Tom Fuller, Ernst Schrama, Alex Vermeulen, Iina Hellsten, Arjan Hensen, Remko Kampen, Paul Baer. Funding: Netherlands Ministry of Infrastructure and the Environment

■ REFERENCES

- (1) Center, P. R. *Little Change in Opinions about Global Warming*; Pew Research Centre, Washington, D.C., 2010.
- (2) Oreskes, N. Beyond the ivory tower. The scientific consensus on climate change. *Science* **2004**, *306*, 1686.
- (3) Doran, P. T.; Zimmerman, M. K. Examining the scientific consensus on climate change. *EOS, Trans., Am. Geophys. Union* **2009**, *90*, 22.
- (4) Anderegg, W. R.; Prall, J. W.; Harold, J.; Schneider, S. H. Expert credibility in climate change. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 12107–12109.
- (5) Cook, J.; Nuccitelli, D.; Green, S. A.; Richardson, M.; Winkler, B.; Painting, R.; Way, R.; Jacobs, P.; Skuce, A. Quantifying the consensus on anthropogenic global warming in the scientific literature. *Environ. Res. Lett.* **2013**, *8*, 024024.
- (6) Ding, D.; Maibach, E. W.; Zhao, X.; Roser-Renouf, C.; Leiserowitz, A. Support for climate policy and societal action are linked to perceptions about scientific agreement. *Nat. Clim. Change* **2011**, DOI: 10.1038/nclimate1295.
- (7) McCright, A. M.; Dunlap, R. E.; Xiao, C. Perceived scientific agreement and support for government action on climate change in the USA. *Clim. Change* **2013**, *119*, 511–518.
- (8) Heath, Y.; Gifford, R. Free-market ideology and environmental degradation. The case of belief in global climate change. *Environ. Behav.* **2006**, *38*, 48–71.
- (9) Kahan, D. M.; Jenkins-Smith, H.; Braman, D. Cultural cognition of scientific consensus. *SSRN Electronic J.* **2010**.
- (10) Leiserowitz, A.; Maibach, E.; Roser-Renouf, C.; Smith, N. Climate change in the American mind: Americans' global warming beliefs and attitudes in May 2011. In *Yale Project on Climate Change Communication*; Yale University, George Mason University, 2011.
- (11) Leviston, Z., and Walker, I. Second Annual Survey of Australian Attitudes to Climate Change: Interim report CSIRO, 2011.
- (12) Collins, H. M.; Evans, R. The third wave of science studies: Studies of expertise and experience. *Soc. Stud. Sci.* **2002**, *32*, 235–296.
- (13) Petersen, A. *Simulating Nature: A Philosophical Study of Computer-Simulation Uncertainties and Their Role in Climate Science and Policy Advice*, 2nd ed.; CRC Press: Boca Raton, FL, 2006.
- (14) IPCC The physical science basis. In *Contribution of WG1 to the Fourth Assessment Report of the IPCC*; Cambridge University Press: Cambridge, UK, 2007.
- (15) IPCC *Climate Change 2013: The Physical Science Basis. Contribution of WG1 to the Fifth Assessment Report of the IPCC*; Cambridge University Press, Cambridge, UK, 2013.
- (16) Malka, A.; Krosnick, J. A.; Debell, M.; Pasek, J.; Schneider, D. Featuring skeptics in news media stories about global warming reduces public beliefs in the seriousness of global warming (Woods Institute for the Environment, Stanford University, Technical Paper), 2009. <http://woods.stanford.edu/research/global-warming-skeptics.htm>.
- (17) Prall, J. W. Most-Cited Authors on Climate Science, 2011. <http://www.eecg.utoronto.ca/~prall/climate/index.html>.
- (18) Bray, D. The scientific consensus of climate change revisited. *Environ. Sci. Policy* **2010**, *13*, 340–350.
- (19) PBL Netherlands Environmental Assessment Agency. Climate Science Survey, 2012. http://www.pbl.nl/sites/default/files/cms/nieuwsberichten/Climate_Science_Survey_Questions_PBL_2012.pdf.
- (20) IPCC. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, Table 1, 2010.
- (21) Huber, M.; Knutti, R. Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nat. Geosci.* **2011**, *5*, 31–36.
- (22) Jones, G. S.; Stott, P. A.; Christidis, N. Attribution of observed historical near-surface temperature variations to anthropogenic and natural causes using CMIP5 simulations. *J. Geophys. Res.: Atmos.* **2013**, *118*, 4001–4024.
- (23) Wigley, T. M. L.; Santer, B. D. A probabilistic quantification of the anthropogenic component of twentieth century global warming. *Clim. Dyn.* **2012**, *40*, 1087–1102.
- (24) Bray, D., and von Storch, H. The Perspectives of Climate Scientists on Global Climate Change. A Survey of Opinions, Germany, 2008.
- (25) Lichter, S. R. *Climate Scientists Agree on Warming, Disagree on Dangers, and Don't Trust Media's Coverage of Climate Change*; Service, S. A., Ed.; George Mason University, 2008.
- (26) Rosenberg, S.; Vedlitz, A.; Cowman, D. F.; Zahran, S. Climate change: a profile of US climate scientists' perspectives. *Clim. Change* **2009**, *101*, 311–329.
- (27) Allen, M. In defense of the traditional null hypothesis: Remarks on the Trenberth and CurryWIREsopinion articles. IN *Wiley Interdisciplinary Reviews: Climate Change*, 2011; Vol. 2, pp 931–934.
- (28) Curry, J. A.; Webster, P. J. Climate science and the uncertainty monster. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 1667–1682.
- (29) Hegerl, G.; Stott, P.; Solomon, S.; Zwiers, F. Comment on "Climate Science and the Uncertainty Monster" J. A. Curry and P. J. Webster. *Bull. Am. Meteorol. Soc.* **2011**, *92*, 1683–1685.
- (30) Boykoff, M. *Who Speaks for Climate? Making Sense of Media Reporting on Climate Change*; Cambridge University Press, 2011.