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TOPICAL REVIEW

Communications about uncertainty in scientific climate-related findings: a qualitative systematic review

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Abstract

We undertake a systematic review of peer-reviewed literature to arrive at recommendations for shaping communications about uncertainty in scientific climate-related findings. Climate communications often report on scientific findings that contain different sources of uncertainty. Potential users of these communications are members of the general public, as well as decision makers and climate advisors from government, business and non-governmental institutions worldwide. Many of these users may lack formal training in climate science or related disciplines. We systematically review the English-language peer-reviewed empirical literature from cognitive and behavioral sciences and related fields, which examines how users perceive communications about uncertainty in scientific climate-related findings. We aim to summarize how users' responses to communications about uncertainty in scientific climate-related findings are associated with characteristics of the decision context, including climate change consequences and types of uncertainty as well as user characteristics, such as climate change beliefs, environmental worldviews, political ideology, numerical skills, and others. We also aimed to identify what general recommendations for communications about uncertainty in scientific climate-related findings can be delineated. We find that studies of communications about uncertainty in scientific climate-related findings substantially varied in how they operationalized uncertainty, as well as how they measured responses. Studies mostly focused on uncertainty stemming from conflicting information, such as diverging model estimates or experts, or from expressions of imprecision such as ranges. Among other things, users' understanding was improved when climate communications about uncertainty in scientific climate-related findings were presented with explanations about why climate information was uncertain, and when ranges were presented with lower and upper numerical bounds. Users' understanding also improved if they expressed stronger beliefs about climate change, or had better numerical skills. Based on these findings, we provide emerging recommendations on how to best present communications about uncertainty in scientific climate-related findings; and we identify research gaps.

1. Introduction

International organizations such as the Intergovernmental Panel on Climate Change (IPCC) [1] and the European Union's Climate Action Program [2] have warned that members of the general public, as well as decision makers and climate advisors from government, business and non-governmental institutions, need to prepare for future climate change. To promote these users' understanding and inform their

decisions, climate experts provide climate projections about long-term future changes in, for example, rainfall, or temperatures [3, 4], including associated uncertainties.

However, communicating uncertainty in such scientific climate-related findings poses potential challenges. Uncertainty about climate change can delay public climate action [5, 6], and increase public polarization about climate change [7]. To be effective, climate policies that aim to promote mitigation or adaptation behaviors should supplement communications about uncertainty in scientific climate-related findings to help users understand them and make informed decisions [8].

To evaluate whether such supplementary communications are effective, they need to be empirically tested [9, 10]. Studies from cognitive and behavioral sciences [11, 12], or disciplines such as economics [13] or geography [14], identify what kinds of communications help to clarify uncertainty for different users (e.g. [15–19]). These studies may reflect a multitude of goals related to communications about uncertainty in scientific climate-related findings, such as making uncertainty easier to understand for users, or reducing doubt and mistrust [20], and encouraging adaptive behaviors. Here, we review studies from cognitive and behavioral sciences and related disciplines, to better understand users' responses to uncertainty in scientific climate-related findings [9, 10]. Understanding these responses will help to better design recommendations for improving communications about uncertainty in scientific climate-related findings.

To organize our review, we use the 'sampling framework for uncertainty in individual environmental decisions' [21] from cognitive and behavioral sciences, which suggests that responses to communications about uncertainty may depend on characteristics of the decision context as well as the users' [21].

1.1. Characteristics of the decision context
The decision context includes what information is communicated by policy makers or media outlets to users of climate information, and how (figure 1). Communications may report about climate change consequences such as temperature, precipitation, sea level rise or others. They may use numerical, verbal, or visual presentation formats. Additionally, communications about the decision context tend to include three sources of uncertainty [21]. The first source pertains to climate science's deep uncertainty, including ignorance [22] about climate due to 'not knowing what we do not know' [23]. For example, deep uncertainty includes how the climate system will respond to increasing levels of greenhouse gas emissions and associated changes in radiative forcing in the more distant future [24]. Such deep uncertainty may also reflect extremely rare events [25], which bring further uncertainty regarding what losses they cause, and

which specific regions they will impact [24]. A second source of uncertainty can occur when not all climate variables that are potentially observable for individuals are known, or when those are in conflict with each other. For example, users of climate information may face conflicting climate variables, resulting from revised climate projections, or weak consensus among climate experts [21, 26]. Uncertainty may also be expressed in ranges around climate variables, reflecting incomplete or biased measures, or random variation. A third source of uncertainty pertains to how well climate models describe observed climate variables. For example, models may be imperfect in how they predict new observations of climate-related variables, or may include wrong relationships between them.
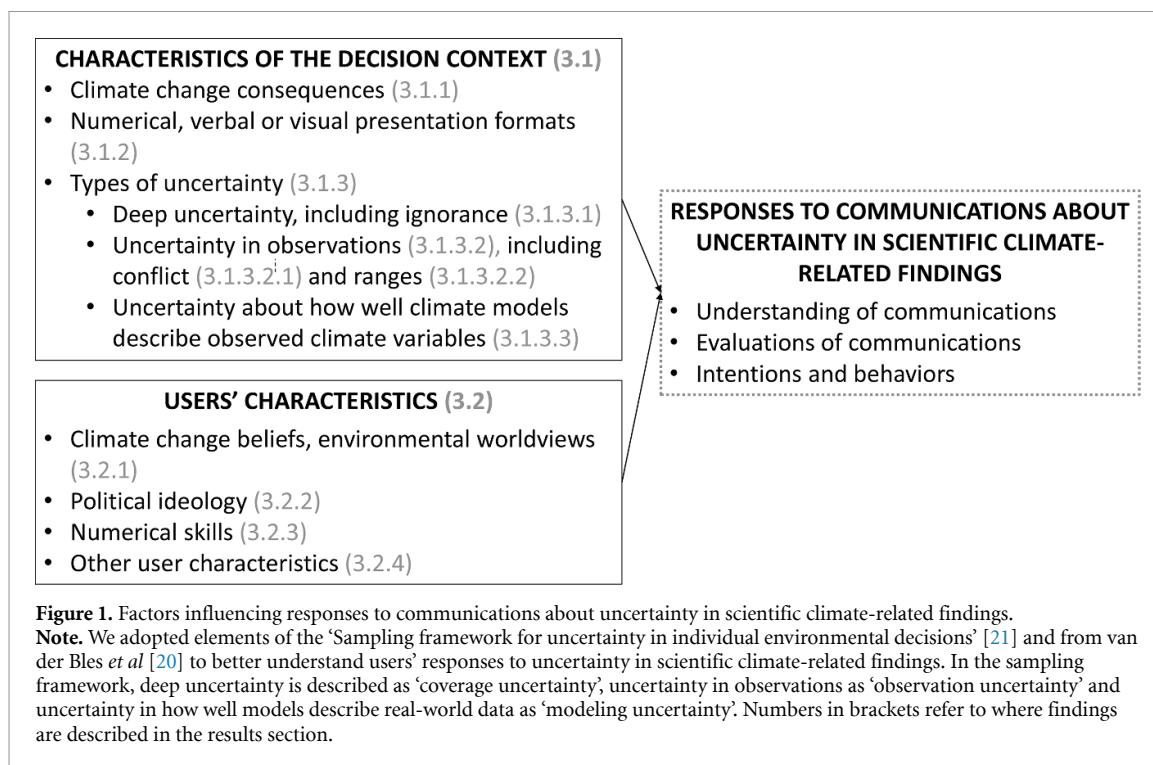
1.2. Users' characteristics
Users' characteristics [8], may affect how users respond to communications about uncertainty in scientific climate-related findings (figure 1). First, users may vary in their climate change beliefs [27], including the extent to which they consider climate change to be a human-caused risk with harmful consequences or requiring individual and collective action [28], or in their environmental worldviews, which refer to the relationship between humans and the environment [29]. Second, users' political ideology may inform their responses to communications about uncertainty in scientific climate-related findings [29–31]. Third, numerical skills reflect how well users are able to process numerical information [32–37]. Other user characteristics that may affect responses to communications include climate literacy [38], or general beliefs about science [39].

1.3. Responses to communications about uncertainty in scientific climate-related findings
Users' responses to communications may in part reflect characteristics of the decision context and the users themselves (figure 1). Users' responses may include their understanding of communications about uncertainty in scientific climate-related findings [17], how they evaluate such communications [40], including for example how trustworthy, credible, or certain they perceive communications to be. Also, communications can inform their subsequent pro-environmental intentions and behaviors [41] (figure 1).

1.4. The current study
We report on a systematic review [42] of the interdisciplinary empirical literature about communicating uncertainty in scientific climate-related findings. We include studies from cognitive and behavioral sciences [11, 12], or disciplines such as economics [13] or geography [14]. Those studies assess responses to uncertainty (e.g. [15–19],) for users from various backgrounds, such as members of the general

Figure 1. Factors influencing responses to communications about uncertainty in scientific climate-related findings.
Note. We adopted elements of the 'Sampling framework for uncertainty in individual environmental decisions' [21] and from van der Bles *et al* [20] to better understand users' responses to uncertainty in scientific climate-related findings. In the sampling framework, deep uncertainty is described as 'coverage uncertainty', uncertainty in observations as 'observation uncertainty' and uncertainty in how well models describe real-world data as 'modeling uncertainty'. Numbers in brackets refer to where findings are described in the results section.

public, as well as decision makers and climate advisors from government, business and non-governmental institutions. Studies also examine how users' characteristics affect responses [18]. We discuss how findings and emerging communication recommendations map onto the framework in figure 1, how generalizable recommendations are, and identify gaps in the literature. Specifically, we address the three following research questions:

(a) How do characteristics of the decision context affect users' responses to communications about uncertainty in scientific climate-related findings, according to studies from cognitive and behavioral sciences and related disciplines?

(b) How do users' characteristics affect users' responses to communications about uncertainty in scientific climate-related findings, according to studies from cognitive and behavioral sciences and related disciplines?

(c) How do findings feed into recommendations for communications about uncertainty in scientific climate-related findings?

2. Methods

All steps in this systematic review followed the ROSES systematic review protocol [43], using the software CADIMA [44]. These steps are described in section S1 of the supplemental material.
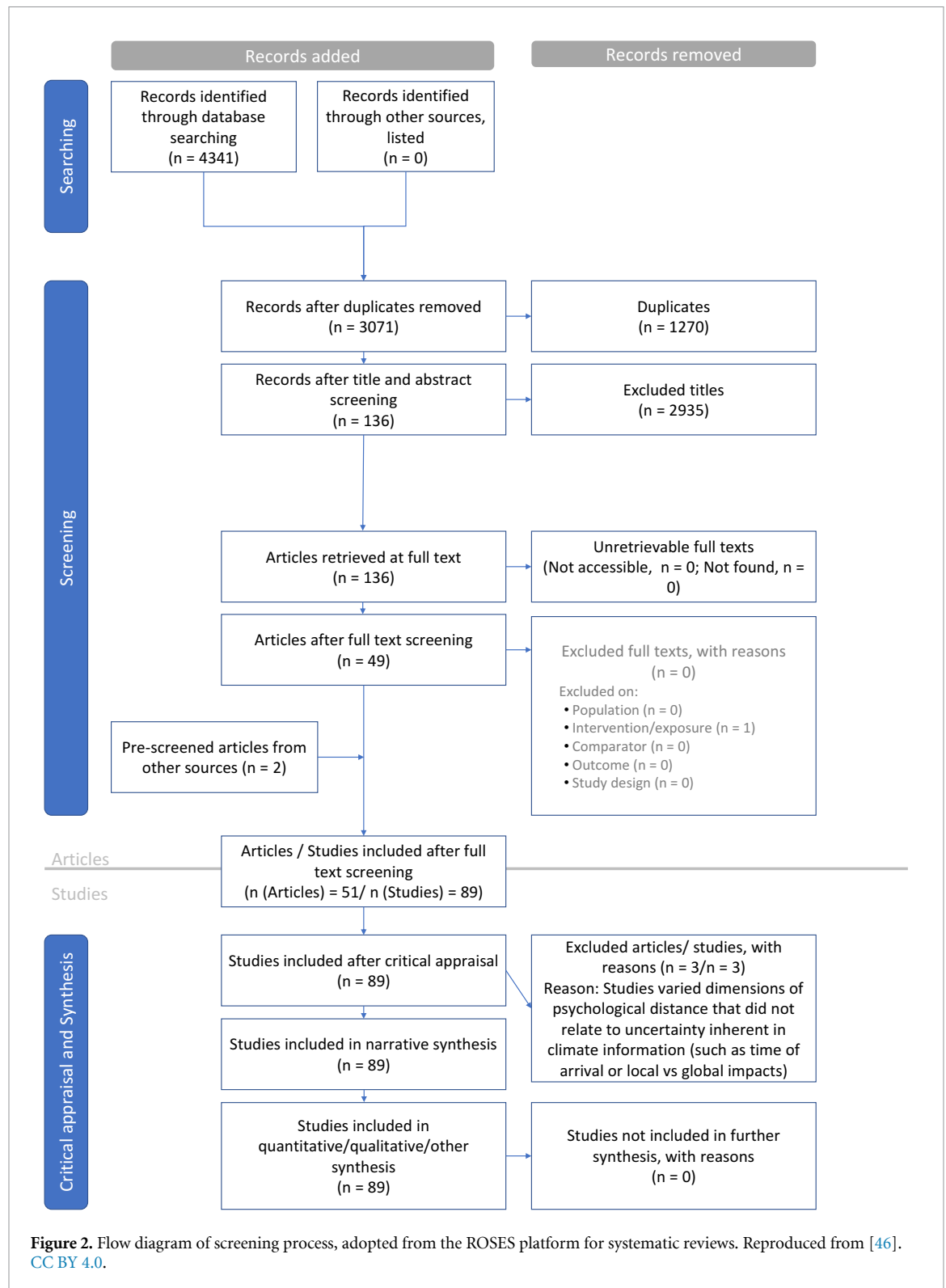
2.1. Search strategy

We adopted a PICO (Population, Intervention, Comparator, Outcome) structure for designing the

search string. We identified the words representing each of the PICO elements by conducting a frequency analysis of words used in the titles and abstracts in our benchmark list of 24 articles (table S1 in supplemental Information (available online at   stacks.iop.org/ERL/16/053005/mmedia)). This benchmark list was obtained through an initial screening of empirical studies, as well as a consultation of team members from different disciplines. We added several substrings to the original string, to specify that articles should focus on communications about uncertainty in scientific climate-related findings and on users' responses to such uncertainty (figure 1), as well as on English peer-reviewed articles published after 1998. These specifications reflected characteristics of articles from the benchmark list (table S2). To ensure that all of the articles in the benchmark list were found by the resulting search string, we iteratively tested and revised it based on searches in the database SCOPUS. Section S1 describes the search string design.

We also searched in the databases Web of Science, and PsychINFO. These were identified at the library database website of the University of Leeds in the fields of Environment, Psychology, Policy, Politics and International Studies, Sociology and Social Policy. The string and respective filters were adapted to the formatting requirements of each of the three databases (see table S3 in supplemental information).

The literature search was performed between July 4 and 16 2019. After removal of duplicates, the number of identified articles was 3071 (figure 2). Before screening the search results, we specified the following inclusion criteria for articles: (1) Any

Figure 2. Flow diagram of screening process, adopted from the ROSES platform for systematic reviews. Reproduced from [46]. CC BY 4.0.

reported studies should involve samples consisting of members of the general public, or decision makers and climate advisors from government, business and non-governmental institutions worldwide; (2) Articles should report on one or more empirical studies or reviews of empirical studies, in which users received communications about climate change consequences in numerical, verbal or visual presentation formats, and including some form of uncertainty in scientific climate-related findings, rather than a precise value or a probabilistic point estimate [21, 45] (figure 1); (3) Any reported studies should randomly assign participants to different versions of communications so as to examine the effects of specific communication characteristics on users' responses. Such experiments may include comparisons of communications with us. without uncertainty; (4) Although analyses of differences in users' characteristics such as

for example climate change beliefs or environmental worldviews, political ideology, numerical skills or other user characteristics (figure 1) were required for answering research question 2, articles were included even if these characteristics were not examined. Table S3 lists all inclusion and exclusion criteria applied.

2.2. Study selection
Two team members (AK and SD) coded the articles that met the selection criteria, in two rounds. In the first round, they screened the titles and abstracts of the 3071 identified articles, after which 136 articles were retained. In the second round, they screened the full texts, after which 49 articles were retained. A consistency check on 10% of the screened titles and abstracts [44] indicated sufficient agreement between the two coders (Cohen's κ = .89). We added two relevant articles published after our initial database search. One reported two replications of a previously included study [47]. Another one [48] presented a re-analysis of a previously included study [17]. Table S5 lists the final set of 51 articles, which reported on 89 studies (figure 2).

2.3. Coding of selected studies
To answer the three research questions, the two coders coded the content of each study. This included characteristics of the decision context, namely the presented climate change consequence, the presentation format, and the source of uncertainty. This also included characteristics of the users and how they were measured, if at all, such as for example climate change beliefs and environmental worldviews, political ideology, numerical skills and other user characteristics (table S6 in supplementary information). They took note of emerging recommendations for communicating uncertainty in scientific climate-related findings (table 1), regarding the presentation of uncertainty in discussions about climate change or reducing perceived uncertainty in users who may be skeptical about climate [20, 27], as well as sample descriptions. To evaluate potential limitations of studies, the coders recorded 'critical appraisal criteria' such as the type of study, the recruitment strategy, the location of the sample, and the external validity of the study materials used (table S4) [49]. No studies were excluded based on these critical appraisal criteria, because all studies were published in peer-reviewed journals and had to adhere to reviewers' methodological standards.

2.4. Analysis
Where possible, the two coders assessed how often variables relevant for answering the three research questions occurred. To answer research question 1, the two coders assessed characteristics of the decision context, including climate change consequences, presentation formats, and the source of uncertainty. For answering research question 2, the

two coders assessed users' characteristics, including climate change beliefs and environmental worldviews, political ideology, numerical skills and others. To answer research question 3, the two coders extracted any recommendations provided by study authors regarding how to present communications about uncertainty in scientific climate-related findings. They also recorded responses that were measured, including users' understanding of communications (such as numerical estimates about climate consequences), users' evaluations of communications (such as perceived trust or perceived uncertainty), and users' intentions and behaviors (such as intentions to behave pro-environmentally or to implement adaptation actions). Because studies varied substantially in terms of how variables were operationalized, a quantitative synthesis of findings was not possible. We therefore present a qualitative narrative synthesis [7].

3. Results

The qualitative narrative synthesis of our systematic review describes findings associated with the presented climate change consequences, presentation formats, sources of uncertainty, any assessments of participants' characteristics and their responses. It also provides emerging recommendations for designing communications about uncertainty in scientific climate-related findings. The synthesis is based on data extracted from 89 included studies (table S6 in supplemental material), and maps these onto the framework shown in figure 1 [21].

Overall, of the 51 articles included in the systematic review, 41 (80%) report empirical studies that were conducted online or in the lab, nine (18%) review empirical evidence on communicating uncertainty in scientific climate-related findings, and one (2%) presents interviews (table S5). A majority of articles that report empirical studies focus on participants recruited in the Global North, mostly Europe and the US. Exceptions include one describing results from samples across 25 different countries [17], one article that presents a study with African participants [58], one article that presents a study with Chinese participants [11], and two articles that do not describe sample locations [59, 60] (figure 3).

Only seven of the reviewed studies (8%) included nationally representative samples of the general public. All other studies were conducted with convenience samples of either policy makers or scientists (6; 7%), of participants recruited online, or of students (65; 83%). Recruiting small non-representative convenience samples is unfortunately a common practice in psychology [61–63], which compromises the generalizability of findings [64]. We also noted that the studie reflected different goals: Most (85%) aimed to make uncertainty in scientific findings

Table 1. Emerging recommendations for communications of different sources of uncertainty in scientific climate-related findings.

	Recommendations addressing uncertainty in observations	Goal
	Conflicting information	
1	To reduce users' feelings of uncertainty, describe the broader context of data variation and consensus within the discipline [50].	Decrease perceived uncertainty
2	To make users less susceptible to implicit political messages in communications about uncertainty in scientific findings about climate, share a warning about the potential implicit politicization of climate messages [51].	Decrease perceived uncertainty
	Ranges	
3	Language used for describing ranges around climate projections affect how those ranges are perceived. • Describing ranges as 'more likely to be correct' helps users to focus on how *accurately* ranges describe projected change. Wide ranges are perceived as more, narrow ranges as less likely. • Describing ranges as 'more certain' helps users to focus on how *informative* ranges are regarding the amount of change [52]. Wide ranges are perceived as less, narrow ranges as more certain.	Decrease perceived uncertainty
4	To increase users' understanding about normally distributed climate projections, include a central estimate as well as a range, rather than only a range [53].	Improve understanding about uncertainty
5	At the same time, be aware that negative climate change consequences described as gains ('it is 10%–30% likely that an event will NOT occur') may motivate users to behave in a more environmentally friendly way compared to climate change consequences described as losses ('it is 70%–90% likely that an event will occur') [41].	Improve understanding about uncertainty; motivate behavior change
6	To facilitate users' understanding of verbal probability expressions: • present verbal probability expressions (such as 'likely') together with their intended numerical interpretation (such as 66%–100%') [7, 17, 18, 54–56] • explicitly state the lower and upper numerical bound of ranges associated with verbal probability expressions ('66%–100%' rather than >66%) [18] • where possible, use positive verbal probability expressions ('likely') rather than negative verbal probability expressions ('unlikely') and especially avoid double negations [57].	Improve understanding about uncertainty
7	To increase users' understanding about ranges in a climate projection, use visual presentation formats as follows: • present density plots [53] to show the nature of the underlying distribution (rather than numerical ranges or boxplots) • present boxplots which show different individual model estimates [7]. • present maps [13] in order to decrease perceived uncertainty; those may show temperature change in colors, and uncertainty in patterns [7].	Improve understanding about uncertainty; decrease perceived uncertainty
	Recommendations addressing users' characteristics	
8	To reduce opposition, doubt and skepticism about climate change in users with a conservative political ideology, or climate skepticism • avoid emphasizing the strong scientific consensus [7] (such as that '97% of scientists agree that climate change is happening'; however see van der Linden *et al* [7, 31]). • illustrate scientific findings about climate with anecdotes (such as 'I can experience the climate change right now where I live') rather than more scientific evidence about climate change consequences (such as 'the evidence shows that climate change is affecting things like skin cancer') [7].	Reduce doubt about climate evidence

(Continued.)

Table 1. (Continued.)

Recommendations addressing uncertainty in observations	Goal
9 Analogies from other disciplines can help users to better understand the nature of uncertainty in findings about climate. For example, a medical analogy comparing uncertainty in evidence about global temperature rise with uncertainty in a medical diagnosis can help conservatives to better understand uncertainty in scientific findings about climate [38].	Reduce doubt about climate evidence

Note. We did not identify any recommendations for communicating other sources of uncertainty specified in figure 1, such as deep uncertainty, including ignorance or uncertainty about how well models describe observed climate variables. Also, recommendations are often based on only one or a few studies and need to be interpreted with care. Specific examples appear in table 2.

Figure 3. Number of studies included in this systematic review, by country.
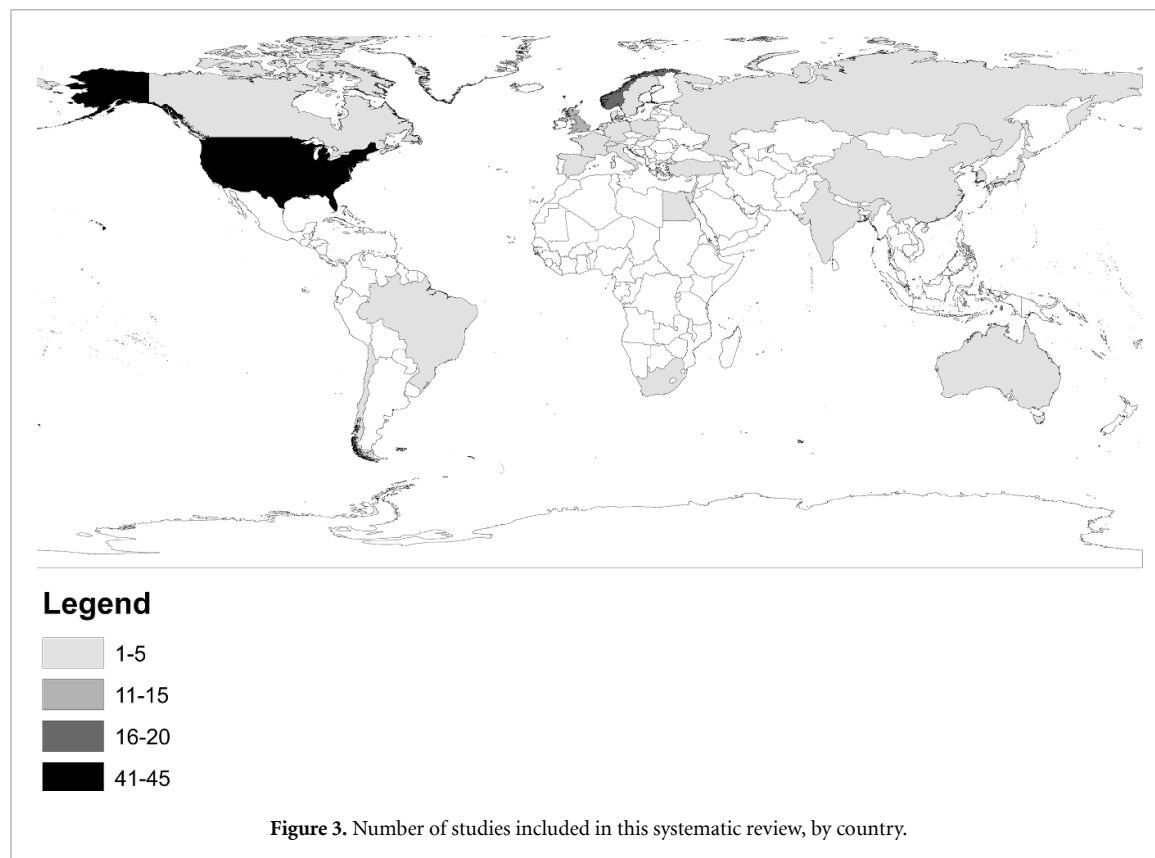
about climate more transparent, so as to include uncertainty into public discussions about climate, or to understand what shapes responses to uncertainty. Others aimed to reduce perceived uncertainty in communications about scientific, climate-related findings, so as to increase credibility and trust, in particular from initially skeptical participants (12%).

3.1. Characteristics of the decision context
In response to research question 1, we find that the majority of studies focused on sea level rise and temperature, and fewer on precipitation, ice melt and various other climate change consequences (figure 4(a)). Numerical presentation formats were most commonly used (figure 4(b)). Regarding types of uncertainty, none focused on deep uncertainty, including ignorance. Most studies assessed responses to uncertainty from observations which,

according to the framework in figure 1, relate to conflict in climate information, presented as revisions of climate projections, differences between greenhouse gas emission trajectories, or weak consensus among climate experts. Studies also examined responses to ranges, for example ranges around central probabilistic estimates of projected climate change consequences. None focused on modeling uncertainty (figure 4(c)). Furthermore, some studies referred to climate information as being generally uncertain, without specifying the source of uncertainty [8, 13, 38, 65, 66–68].

Most articles described how users' responses vary between communication designs and strategies, without giving a clear indication of which variation is better. If articles indicated that one communication design or strategy helps participants better understanding uncertainty in scientific
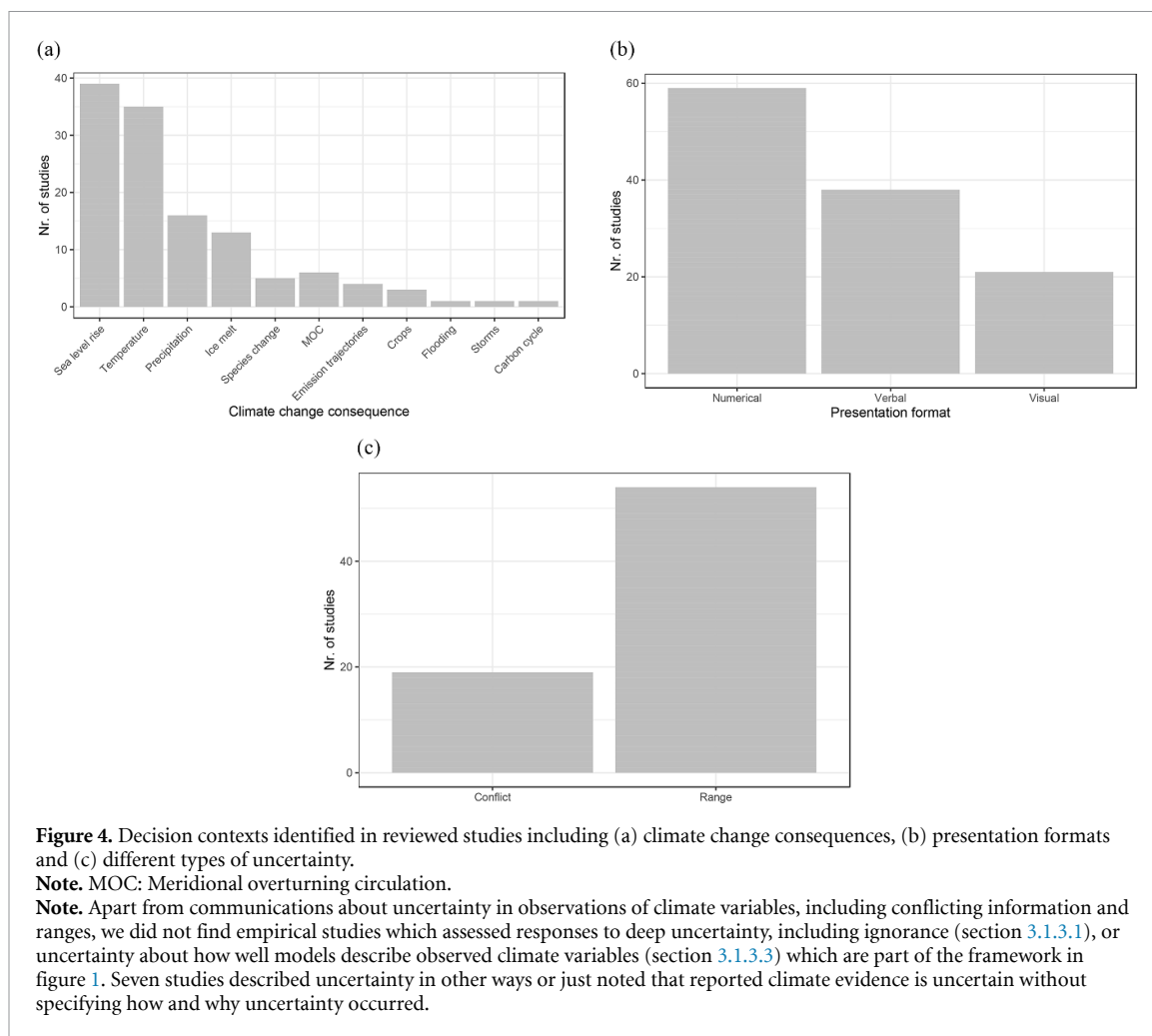
Figure 4. Decision contexts identified in reviewed studies including (a) climate change consequences, (b) presentation formats and (c) different types of uncertainty.
Note. MOC: Meridional overturning circulation.
Note. Apart from communications about uncertainty in observations of climate variables, including conflicting information and ranges, we did not find empirical studies which assessed responses to deep uncertainty, including ignorance (section 3.1.3.1), or uncertainty about how well models describe observed climate variables (section 3.1.3.3) which are part of the framework in figure 1. Seven studies described uncertainty in other ways or just noted that reported climate evidence is uncertain without specifying how and why uncertainty occurred.

climate-related findings, we mention any associated recommendations (table 1) and associated examples (table 2).

3.1.1. Climate change consequences
Studies covered various climate change consequences, including sea level rise [72], temperature rise [53], precipitation [17], ice melt [12], or species change [66] (figure 4(a); table 3).

3.1.2. Numerical, verbal and visual presentation formats
Sources of uncertainty were communicated in three different presentation formats (figure 1, table S5) [20]. Numerical presentation formats provided users with a number, such as, for example, the magnitude of change in climate change consequences including rainfall or sea-level rise, or a probability [11, 12, 17]. Verbal presentation formats used expressions such as 'likely' to describe probabilities, or presented a brief description of uncertainty in scientific, climate-related findings [17]. Visual presentation formats included graphs or pictographs for communicating information such as different climate projections [58], or ranges around projections [59].

3.1.3. Types of uncertainty
3.1.3.1. Communications about deep uncertainty, including ignorance
We did not identify any empirical studies assessing users' responses to communications about deep uncertainty in scientific climate-related findings [74] or ignorance, in either numerical, visual or verbal presentation formats.

3.1.3.2. Communications about uncertainty in observations
In the reviewed studies, conflicting evidence was mostly described in numerical or verbal presentation formats, and focused either on conflicting climate projections, or on conflicts in media reports. Studies about ranges assessed perceptions of ranges in numerical, verbal and visual presentation formats. Some of these studies systematically compared how those different presentation formats improved users' understanding.

3.1.3.2.1. Conflict
Some studies examined how participants responded to revisions of scientific evidence, such as numerical climate projections, using online convenience samples with students from Norway and US residents.

Table 2. Examples of emerging recommendations for communicating uncertainty in scientific, climate-related findings. (Note: Numbering refers to list in table 1)

Examples of recommendations addressing uncertainty in observations

Conflict

1   *Describe the broader context of data variation and consensus within the discipline* 'The ice sheet has been retreating for the last few 1000 years, but we think the end of this retreat has come,' said Tulland. Although the world's scientists agree that the Earth's surface has warmed significantly, especially over the last several decades, there is a far more complicated picture of Antarctica's weather and how global warming will materialize here. A 1991 study indicated that ice was thickening in parts of the continent, and another study found a cooling trend since the mid-1980s in Antarctica's harsh desert valleys. However, other recent studies have noted a dramatic shrinkage in the continent's three largest glaciers, losing as much as 150 feet of thickness in the last decade. While such individual research results seem contradictory, they cast doubt only on where and how soon global climate effects might be evident. At a major international meeting last fall, scientists agreed that global warming is occurring and that human actions are contributing to the warming [50].

2   *Share a warning about the potential implicit politicization of climate messages* 'Political issues can often be complex, contentious, and difficult to understand. One way of making sense of these issues, and the different positions that one can take on an issue, is to think about the frames that structure debate about the issue. Frames help organize facts and information. They help define what counts as a problem, diagnose the problem's causes, and suggest remedies for solving the problem. These ways of thinking have lots of different parts, including stereotypes, metaphors, images, catchphrases, and other elements.
Different framings are often associated with a particular way of talking about or communicating about an issue. In the following questions, words or phrases that might indicate different framings have been highlighted' [51].

Ranges

3   *Describe an interval as 'most likely to be correct' rather than 'conveying more uncertainty'*
'Two teams of climate scientists have made the following predictions regarding the temperature rise by 2099. Please select the prediction that is the most likely to be correct. Team A: The temperature will increase between 1.1 °C and 6.4 °C. Team B: The temperature will increase between 2.2 °C and 5.4 °C' [52].

4   *Describe the underlying distribution, using best estimate and range boundaries*
'If human activities are unchanged, our best estimate is a 4 degree increase in global temperature in 50 years and we are 90% confident that the increase will be between 1 and 8 degrees' [53, 69].

6   *Jointly present verbal probability expressions and numerical probability ranges, explicitly specifying upper and lower bounds.*
'The Greenland ice sheet and other Arctic ice fields likely (60%–100% probability) contributed no more than 4 m of the observed sea-level rise' [7, 17, 18, 54–56, 70].

6   *Use positive rather than negative verbal probability expressions*
'It is very likely that hot extremes, heatwaves, and heavy precipitation events will continue to become more frequent' [71].

Examples of recommendations addressing users' characteristics

9   *Use a medical analogy to idescribe causes and effects of climate change, including uncertainty*
'Imagine that Earth is a patient who has been diagnosed with a serious disease and that you are the patient's (Earth's) legal guardian. Climate experts say that, as with heart disease or cancer, the symptoms of climate change are not obvious in the early stages, but the disease is just as serious. They say that they have run thousands of diagnostic tests over the past 50 years that show that the patient has a disease: climate change. They know that as the disease progresses, we can expect to see increased numbers of severe symptoms (temperature and sea-level rise, damaged ecosystems, etc.). They cannot be sure that each particular symptom is due to climate change rather than some other cause, but they are very confident that the disease is present and getting worse. They are also confident that the main causes are human activities: fossil fuel use, the way people use land, and some other activities.
What will happen next? The scientists are certain that the disease is very hard to reverse. However, they are not certain about how fast it will progress or where and when to expect the most serious symptoms. There could be catastrophic results, especially in some places, but scientists are not yet confident about which very serious outcomes to expect, or how soon.
What should be done? There are several treatments that get at the causes and can even reverse the disease, like reducing use of fossil fuels. Other treatments do not treat causes, but they make it easier to live with symptoms, like building sea walls to reduce flood damage. But all the options have costs and risks. You want treatments that improve the patient's chances at low cost and with limited side effects. You could take a wait-and-see approach and hope that nothing serious happens, but the longer treatment is postponed, the worse the disease will become' [38].

Table 3. Examples of climate change consequences included in the reviewed studies.

Climate change consequence	Example
Sea level rise	*The Greenland ice sheet and other Arctic ice fields **likely** contributed no more than 4 m of the observed sea-level rise* [17].
Temperature rise	*In 2000, Heidi Knutsen concluded that it is 60% likely that the global mean temperature in year 2100 will be about 3 °C higher than in 2000. In her most recent report (2013), she concludes that this temperature increase is 70% likely* [72].
Precipitation	*It is **very likely** that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent* [17].
Ice melt	*Global warming is melting the ice at both the North Pole and the South Pole. The melting of ice leads to a rise in global sea level. Experts from the Intergovernmental Panel on Climate Change (IPCC) conducted 100 projections of the sea rise that will be observed by the year 2100. The projections showed that by 2100, the sea level will rise from 10 to 20 in* [56].

Verbal probability expressions such as 'likely' which were frequently used in reviewed studies to represent numerical probability ranges (such as '66%–100%') following the uncertainty guidance note issued by the IPCC [73].

Participants were shown revised probabilities in sea-level and temperature rise projections. They perceived these revisions as upward or downward trends [72]. Participants also displayed a 'strength-certainty matching' pattern, in which strong certainty was associated with more rather than less powerful effects. Participants from convenience samples in Norway and the US received projections about population change in animal species, indicating 'a 70% probability of observing decline by at least 20%, and at most 40% compared to the present' [75]. When a subsequent revision of that projection was described as more (vs. less) certain, participants estimated not only a higher probability of the revised projection, but a larger decline—plus a smaller range around projected decline. This 'strength-certainty-matching' pattern generalized to positive climate events as well, such as the power production of a new wind farm [75]. Also, revisions towards higher probabilities (from, for example, '60% likely' to '70% likely') made participants from Norway and the US feel more certain and strengthened their beliefs about climate change, including when revisions stemmed from different experts at different time points, and when experts revised divergent probabilities into the same direction [76]. In another study, which did not frame conflicting expert estimates explicitly as revision, an online convenience sample of students recruited in the US tended to report the mean between two presented estimates [77], perhaps because these two probabilistic estimates may have been perceived as random data points, rather than a non-random revision of climate forecasts [72]. Another study conducted with a convenience sample of found that economists and statisticians perceived climate contrarians' statements about actual climate data trends ('Arctic ice is recovering') as misleading, compared to mainstream statements ('Arctic ice is shrinking') [78]. This also held when the climate data trends and statements were presented as if they were about rural population change rather than arctic ice change. Scientists tend to deem climate contrarians' views inaccurate

and misleading, including those that tend to appear in online media [72].

Several studies also presented verbal descriptions about conflict, such as often found in media statements. Media statements about climate change are often created with one of two goals: to inform readers about opposing views [78], or to convince readers of a certain view about climate change. Several studies thus examined responses to conflicting media reports of climate change consequences. One study [50] found that a convenience sample of American students was more certain about climate change after reading a news article about Antarctic ice sheet thickening that elaborated on the nature of the conflict and on past controversies in the research field, as compared to a news article that only described conflict between experts. The findings imply that users may feel less uncertain, if conflict is described in the broader context of data variation and consensus within the discipline [50] (Recommendation 1; table 1). Another study with an online convenience sample of US adults found that warning participants about implicit political messages in communications about general uncertainty in scientific findings reduced their susceptibility to such messages [51] (Recommendation 2; table 1).

3.1.3.2.2. Ranges
Several studies assessed how numerical descriptions of ranges affected climate perceptions, including a variety of measures such as trust, credibility, perceived uncertainty or behavior change. Convenience samples of US students and US residents recruited through a professional online survey panel, evaluated numerical ranges as more credible and accurate, compared to precise estimates [77]. Also, when projections of climate events such as sea-level rise were expressed as numerical ranges rather than as point estimates, US residents recruited online via Amazon Mechanical Turk, and a Pacific Northwest United States weather blog site, trusted these projections

more [79]. Students recruited in Norway and the UK, and US residents recruited online, tended to perceive wider ranges about temperature and sea-level rise as more likely but also as less certain when compared to narrow ranges, leading to a preference for narrower ranges in communications of uncertainty [33, 52] Describing ranges as 'more likely to be correct' helps users to focus on how *accurately* they describe projected change, describing ranges as 'more cetain' helps users to focus on how *informative* they are (Recommendation 3; table 1). Only one study investigated how a range accompanied by different statistical estimates shaped responses to the communicated data. Here, US participants recruited from a university research panel were more likely to perceive data as normally distributed if a provided range about temperature change included a central estimate [53] (Recommendation 4; table 1).

Several studies assessed how verbal presentation formats for ranges shape how participants perceived communicated climate information. Slight variations in verbal descriptions implicitly shape listeners' preferences, and are chosen by speakers to express their point of reference [80]. For example, in three experiments conducted with Norwegian students and online convenience samples of US residents, describing the likelihood of La Niña as being 'less than 70%' rather than 'more than 30%' guided participants' attention more towards the non-occurrence than the occurrence of La Niña [81]. In another convenience sample of US residents recruited online, participants perceived climate projections about precipitation as more severe when those were described as 'as high as 32%' rather than 'unlikely to be higher than 32%' [54]. When receiving a graph of a probabilistic distribution of climate variables, US residents and Norwegian students gave much higher estimates when asked to indicate what values the variables 'can' take rather than 'will' take [82]. In a convenience sample of UK students, projections of negative climate events described as being '70%–90% likely' (vs. '80% likely') led to perceptions that the students' own actions towards reducing emissions would be relatively less efficient. When these same projections indicated events to be '10%–30% likely' (vs. '20% likely') to *not* happen' participants perceived their own actions as relatively more efficient [41]. This implies that describing uncertain climate projections about potential damages as gains ('it is 10%–30% likely that an event will NOT occur') rather than as losses ('it is 70%–90% likely that an event will occur') can motivate behavior change [41] (Recommendation 5; table 1).

Several studies systematically compared numerical with verbal presentation formats for ranges. Guidance notes for communicating uncertainty, such as the one by the IPCC [73], suggest that climate experts use so-called 'verbal probability expressions' to communicate ranges of quantitative probability estimates. For example, the IPCC guidance note specifies that the verbal probability expression 'likely' should be used to reflect the range '66%–100%'. Because verbal probability expressions are used in global reports such as those of the IPCC, as well as the Intergovernmental Panel on Biodiversity, it is important that users understand what these mean.

However, verbal presentation formats may leave room for disagreement [83], because their semantic structure may convey more information than just a numerical probability [84]. Users' interpretations of verbal probability expressions tended to vary more than users' interpretations of the equivalent numerical probability ranges (as suggested by the IPCC guidance note), or a combination of both, when these were presented within projections of increasing sea-level rise and temperatures. This finding held across samples (for which recruitment strategies were unspecified) in Australia, the US, Asia, Europe and South Africa [17, 48], representative samples recruited in the US [7, 55], undergraduate students from the US [85], South African residents [17] and people living in China and the UK [11]. A similar study found that this variation was stronger for Chinese than for UK samples [11]. Moreover, UK and US students, as well as participants of the 2009 Ninth Conference of the Parties of the United Nations Framework Convention on Climate Change [60], reported higher numerical interpretations of verbal probability expressions when those expressions described relatively more severe climate projections about temperature, precipitation and ice melt [12, 85].

Another study gave a graph of a probabilistic distribution for projected amount of sea-level rise to a convenience sample of US residents. The participants expected more extreme sea-level rise if they were asked to complete the sentence with the verbal expression 'it is "unlikely" that sea level will rise … inches' than if they were asked to complete the sentence with either the numerical range that the IPCC guidance deems equivalent such as 'There is a probability between 10% and 33% that the sea level will rise … inches', or a sentence that combined both ('It is unlikely (probability between 10% and 33%) that the sea level will rise … inches.') [56]. In a study with an online convenience sample of US residents, estimated ranges around the probability of sea-level and temperature rise projections were more accurate when verbal probability expressions were presented with lower and upper bounds of the associated numerical range ('0%–33%'), rather than only one bound ('<33%') [18]. Also, a re-analysis of answers from samples recruited in 25 countries worldwide [17] revealed that positive verbal probability expressions (such as 'likely') led to more accurate and less dispersed numerical estimates than negative verbal probability expressions (such as 'unlikely'). Confusion about the latter was exacerbated when

using double negatives (referring to it being unlikely for an event to not occur) [57]. Findings from this series of studies suggest that communications that involve the IPCC's suggested verbal probability expressions can be improved by presenting the intended numerical range [17], including the lower and upper bound of the range [18], by using positive rather than negative verbal probability expressions, and by avoiding double negations [57] (Recommendation 6; table 1).

Finally, visual presentation formats can help users to better understand proportions, or the magnitude of communicated differences in scientific findings [86]. They can also help them to understand uncertainty in scientific climate-related findings, or make them more certain about climate change [13]. Several studies examined participants' responses to a wide array of visual presentation formats about ranges. Studies presented either probabilistic ranges around individual model estimates, or estimates from different climate models [59]. These studies substantially varied in how they measured participants' responses.

Several studies assessed whether and how visual presentation formats improved actual or perceived understanding. Participants recruited via a US university research panel understood the shape of an underlying statistical distribution better when it was displayed in a density plot, as compared to numerical ranges or box plots [53] (figure 5(a)). Climate policy makers who participated in the Conference of the Parties 2009 [69] estimated future temperature change more accurately when they received boxplots that included individual model estimates instead of simple boxplots (figure 5(b)). However, this finding did not replicate in a convenience sample of European students [69]. Maps that used colors to display temperature change, and used patterns to display associated uncertainty (figure 5(c)), helped an online convenience sample of US residents to understand how climate change will affect temperature [65]. In an interview study [59], policy makers who represented the target audience of IPCC reports, were shown an IPCC line graph showing projected temperature increases under different greenhouse gas emission scenarios, including ranges around model projections. Novice participants in particular struggled to understand uncertainty from different greenhouse gas emission scenarios, and often conflated it with uncertainty around model estimates.

Several studies assessed how participants evaluated different visual presentation formats for communicating uncertainty in scientific findings about climate. Climate practitioners seemed to prefer formats that show the underlying distribution of data over those which do not do so. This was shown with users of a UK-based greenhouse gas inventory [87], UK and German climate adaptation practitioners [40, 88] and African climate decision makers (figure 5(d)) [58]. Together, these findings suggest that users'

understanding and use of climate data may be improved through visual presentation formats such as density plots, boxplots, and maps (Recommendation 7; table 1).

3.1.3.3. *Communications about uncertainty how well models describe observed climate variables*

We did not identify studies assessing responses to uncertainty stemming from differences between climate models and observations of climate variables, in either numerical, verbal or visual presentation formats. One review did identify general approaches for communicating uncertainty about how well models describe observed climate variables [89].
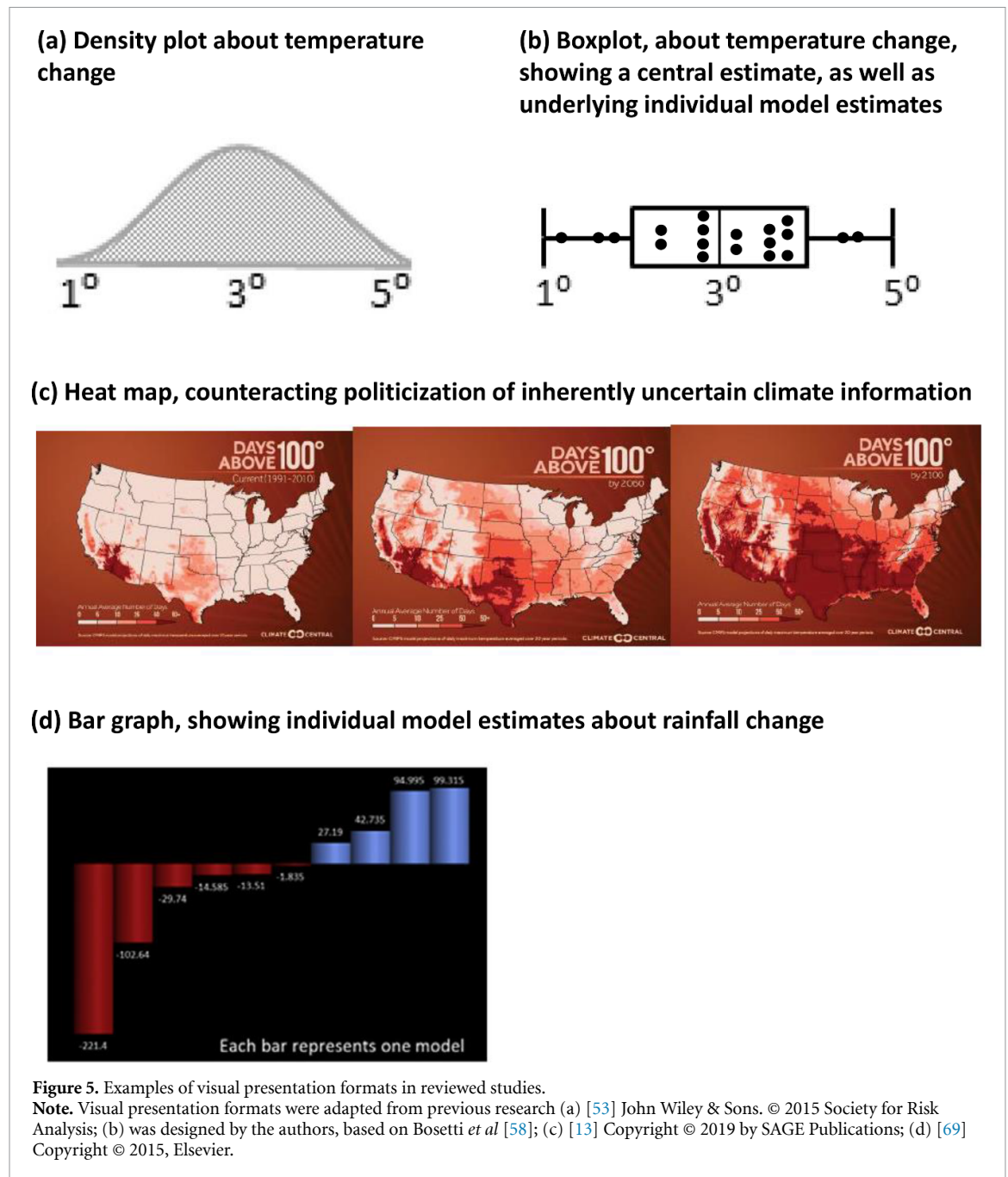
3.2. Users' characteristics

In response to research question 2, we find that studies tended to focus on climate change beliefs, as well as environmental worldviews, political ideology, and numerical skills (figure 6). Other user characteristics were also included, such as climate literacy, or general perceptions of science.

3.2.1. *Climate change beliefs and environmental worldviews*

Climate change beliefs may act as 'filters' that affect how users interpret climate information (figure 1); and that encourage them to search for information that confirms their existing beliefs—which is also called 'motivated reasoning' [90]. One commonly used scale of climate change beliefs [28] measures, among other things, how much participants agree that climate change is actually happening, whether this change has human causes and serious consequences, and whether participants have the self-efficacy and intentions to change their behaviors. Across 25 different countries, participants with stronger climate change beliefs as assessed on this scale gave more accurate probabilistic interpretations of verbal probability expressions such as 'likely' or 'unlikely' when presented as part of climate projections about sea-level and temperature rise [7, 17]. However, no such relationship between perceptions of probability ranges and climate change beliefs was shown in other studies with convenience samples of US and European students and residents [33, 52, 55, 56, 77, 82].

A related scale of climate change beliefs asks participants how much they agree with more general statements such as 'I am certain that climate changes occur', or 'Claims about human activity causing climate change are exaggerated' [82]. Among an online convenience sample of Norwegian students, responses on this scale were positively associated with probabilistic estimates about, for example, future grain yields impacted by climate change [72, 76]. This was, however, not the case for an online convenience sample of US residents presented with temperature

(a) Density plot about temperature change

(b) Boxplot, about temperature change, showing a central estimate, as well as underlying individual model estimates

(c) Heat map, counteracting politicization of inherently uncertain climate information

(d) Bar graph, showing individual model estimates about rainfall change

Figure 5. Examples of visual presentation formats in reviewed studies.
Note. Visual presentation formats were adapted from previous research (a) [53] John Wiley & Sons. © 2015 Society for Risk Analysis; (b) was designed by the authors, based on Bosetti *et al* [58]; (c) [13] Copyright © 2019 by SAGE Publications; (d) [69] Copyright © 2015, Elsevier.

change projections [82]. In some studies with similar samples, climate change beliefs were positively associated with how experts providing such uncertain estimates were evaluated [75]. However, that finding has not been consistent [76].

Another scale [91] asks participants to rate their agreement with statements such as, 'Claims that human activities are changing the climate are exaggerated'. One study [92] presented newspaper editorials about conflicting information to a convenience sample of UK students. Self-identified climate skeptics reported greater skepticism if the editorial described political conflict (e.g. 'US politicians are committing treason against the planet', and 'Why are environmentalists exaggerating claims about climate

change?') instead of scientific conflict (e.g. 'We are as certain about climate change as we are about anything', and 'If we cannot predict the weather, how can we predict the climate?'). Thus, communications which align messages with users' preconceptions about science [92] may reduce climate change skepticism.

Other studies included measures of environmental worldviews such as the 'New Ecological Paradigm' scale [29]. An example item on this scale asks participants how much they agree with statements such as, 'When humans interfere with nature it often produces disastrous consequences' [29]. Among participants recruited from a US university community, stronger environmental worldviews

Figure 6. User characteristics identified in reviewed studies.
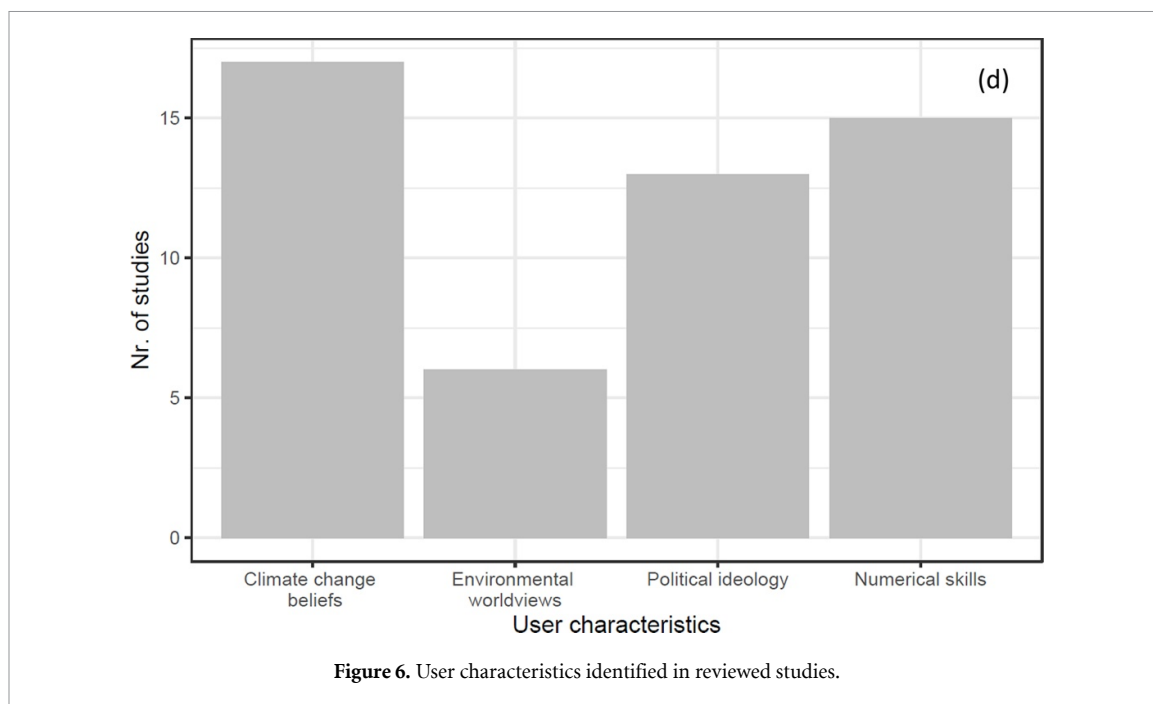
were associated with reporting somewhat higher probability estimates of climate events such as heat waves, sea-level rise or ocean currents [55]. Studies with US students found that environmental worldviews were associated with perceiving greater certainty in scientific findings about sea-level rise [50], as well as with perceiving experts as more trustworthy and competent, and expressing more worry about climate change [75]. Overall, convenience samples of US residents who expressed environmental worldviews perceived the potential financial and health consequences of climate change as more severe [54]. UK students with environmental worldviews were less skeptical about climate change, and more willing to support mitigation behaviors [92]. Except for one study including samples of US residents and UK students [56], findings thus suggest that users' climate change beliefs and environmental worldviews shape how communications about uncertainty in scientific climate-related findings are perceived [20].

3.2.2. Political ideology
Political ideology or party affiliation is typically assessed by asking questions such as 'How politically conservative are you?' [93, 94]. Studies that examined the role of political ideology tended to involve US participants, who were asked whether they identified as 'Democrat' or 'Republican' [54, 93]. Political ideology is a characteristic that affects users' responses to communications about uncertainty in scientific climate-related findings [30] (figure 1). In US convenience online samples, Republicans tended to perceive climate change as less severe than Democrats [13]. They also expressed less trust and less concern about uncertain temperature and sea-level rise forecasts 79]. In UK undergraduate students, political

ideology was unrelated to skepticism about climate change [92].

When receiving communications about uncertainty in scientific climate-related findings, US Republicans who were more likely to question climate change showed 'reactance' to statements about the strong scientific consensus regarding human-made climate change (such as '97% of climate scientists have concluded that human-caused climate change is happening')—that is, they felt more pressured, manipulated and forced to adopt a certain opinion (Recommendation 8, table 1), In its psychological usage, 'reactance' refers to individuals rejecting communicated information, often because they feel pressured or threatened by it [95]) [93]. Polssibly, US Republicans question the scientific consensus [96]. This stands in contrast to previous studies showing that across participants with different political views, perceived scientific consensus drives acceptance of science [31, 96]. Several studies with convenience samples including US residents also explored how to overcome political ideology by varying message content. US conservatives responded more strongly to newspaper articles about health impacts of climate change when those were accompanied by reader comments sharing anecdotal evidence rather than scientific evidence about climate change [94]. Also, highlighting how language (or 'verbal frames') shapes views onto complex issues such as climate in a very subtle way, made US conservatives less susceptible to such frames [51]. If added to verbal communications about generally uncertain climate to US residents, maps (such as figure 5(c)) reduced doubt about whether climate change is happening [13]. Thus, with conservative audiences, reactance and doubt may be reduced by avoiding references to the

scientific consensus, and perceived uncertainty may be reduced by presenting anecdotal evidence rather than scientific evidence (Recommendation 8; table 1). Some studies controlled for political ideology by including it as a covariate in the reported statistical analysis [17, 18].

A climate communication augmented with an analogy that described the earth as a patient who was getting worse but for whom the timing and seriousness of symptoms was unclear, helped a US convenience sample (and especially self-described conservatives) to understand communications about general uncertainty in scientific climate-related findings, and strengthened their beliefs that climate change is happening. Analogies comparing climate change to disaster preparedness or a court trial were less effective [38]. Thus, to capture users' attention, analogies need to be chosen with care—and medical analogies may help conservatives to better understand communications about uncertainty in scientific climate-related findings [38] (Recommendation 9; table 1). Because these studies were conducted with US convenience samples, less is known about how political ideology influences responses outside the US.

3.2.3. Numerical skills

'Numeracy' is the ability to process basic probability and numerical concepts [97]. Numerical skills can help users to better understand financial and health risks [32]. An example question used to determine numerical skills asks, 'Imagine we are throwing a five-sided die 50 times. On average, out of these 50 throws how many times would this five-sided die show an odd number (1, 3 or 5)?', with the correct answer being 30 out of 50 throws [32]. Several studies included numerical skills as a covariate when analyzing responses to communications about uncertainty in scientific climate-related findings by users located in the US [7, 17, 18, 77] and 25 different countries worldwide [17]. Overall, more numerate participants who also had stronger environmental worldviews tended to perceive climate change consequences as more severe [54].

Studies with online samples of US residents found that participants with higher numeracy were more likely to interpret ranges in line with the numbers the IPCC intends to communicate with those expressions. This included verbal probability expressions about ranges around climate projections pertaining to, for example, temperature and sea-level rise [7]. Convenience samples of UK students and US residents were also more likely to accurately interpret wider intervals around climate variables as more likely to be correct and less precise [52]. More numerate US residents were also confident in wider rather than narrower intervals [33]. Participants drawn from a university research panel who were relatively more numerate were more likely to assume that ranges reflected a uniform distribution [53].

3.2.4. Other user characteristics

Studies also assessed climate literacy, perceptions of science, the motivation to think hard about complex problems, and professional background of participants. One study found that UK students who were told that scientific questions may sometimes have more than one true answer perceived uncertainty expressed as probabilistic ranges or conflict between experts more persuasive, compared to their peers who were told that science is a search for the true answer [39]. Achieving alignment between (a) users' beliefs about the nature of science and (b) the style of the scientific messages, may thus prevent negative effects of uncertain communications on users' confidence in climate communications [39]. We acknowledge, however, that this study may not have reflected variation among aims and underlying goals of scientific research across disciplines.

Two articles [47, 94] reported on measures of 'Need for Cognition', or participants' motivation to think hard about complex problems. Example items ask participants to identify how much they agree with statements such as 'Thinking about complex problems is not my idea of fun' [98]. Among conservatives (but not liberals) in a US online convenience sample, lower need for cognition was associated with reporting less certainty about anecdotal evidence regarding, for example, the health consequences of heat waves [94].

Users' expertise and professional background inform their responses to uncertainty in scientific findings about climate [8, 68, 99]. Their responses may reflect the types of climate-related decisions they make, and how familiar they are with specific climate projections. Practitioners who focus on climate change adaptation in Africa expected a stronger decline in rainfall in Africa, and were more confident about their interpretations of graphs displaying rainfall projections, compared to practitioners whose work does not focus on Africa [58]. Furthermore, African practitioners working for governmental institutions trusted scientific information more, compared to practitioners from other continents [58]. A review including studies with various samples suggests that participants with less expertise in map use and floodplain mapping were more likely to underestimate risks associated with sea-level rise [14]. Overall, preferences for seeing how data within a range are distributed was more common among scientists than among decision makers from industry, as well as among individuals who were more knowledgeable about statistics [87, 88].

4. Discussion

Projections about future climate change are often uncertain, which may pose potential communication challenges. To identify how to develop effective communications, we systematically reviewed an

emerging field of research, namely studies published in the peer-reviewed English-language literature in cognitive and behavioral sciences and related disciplines. Those studies assessed how potential users, such as members of the general public, decision makers and climate advisors from government, business and non-governmental institutions worldwide respond to communications about uncertainty in scientific climate-related findings. We mapped studies onto the sampling framework for uncertainty in individual environmental decisions [21] which posits that users' responses to climate communications will depend on the characteristics of the decision context as well as the users themselves (figure 1). We also identified emerging evidence-based recommendations that result from this literature (table 1).

Our systematic review uncovers that research about communicating uncertainty in scientific climate-related findings is in its early stages. Studies lacked consistency in terms of how they operationalized the characteristics of the decision context, including climate change consequences studied, presentation formats, how sources of uncertainty were conceptualized, as well as the users' characteristics including their climate change beliefs and environmental worldviews, political ideology, numerical skills and others. They also varied in terms of how they measured the users' responses, including their understanding of communications, how they evaluated communications, and what their intentions and behaviors were. Future studies need to draw on established frameworks for communicating uncertainty in scientific, climate-related findings. This would facilitate a more systematic understanding of how users respond to communications about different sources of uncertainty [21]. This would also help to improve the social science needed to make evidence-based recommendations about how to effectively communicate uncertainty in scientific, climate-related findings. Our literature review identified several avenues for future research.

First, studies presented communications about a large range of climate change consequences, presented in different numerical [17, 55, 70, 82], visual [5, 13, 40, 47, 53, 58, 69, 83] or verbal [11, 12, 17, 18, 55, 57, 70] formats.

Second, studies mainly focused on communicating uncertainty in observations, namely conflict and ranges. We did not find studies that examined other sources of uncertainty described in the sampling framework for uncertainty in individual environmental decisions and in other classifications of uncertainty [21]. For example, studies have not focused on how to best communicate deep uncertainty [22] due to poorly known processes [21, 100], a lack of information [101], 'known unknowns' or 'unknown unknowns' [23], or variables for which the direction of change but not the magnitude is known [73].

They also did not cover uncertainty which may result from imperfect models for describing real-world observations [21]. Adopting frameworks such as the sampling framework for uncertainty in individual environmental decisions [21] will help to understand which sources of uncertainty have, and which ones have not, been studied to date.

Third, we found that studies conceptualized conflict and ranges differently. Conflict was conceptualized as resulting from revised forecasts from different sources [76], a lack of scientific consensus [27], or disagreements between different greenhouse gas emissions trajectories [59], or different media statements [92]. Ranges were presented as occurring around projected change in climate change consequences such as temperature or sea-level rise, or as probability ranges indicating likelihood of such change. Several studies presented ranges around a central estimate, representing e.g. a confidence interval [53], or a range of model estimates [58].

Fourth, studies substantially varied regarding how they measured users' characteristics. As a result, any variations in findings were difficult to compare, because they may have been due to methodological differences. Most of the studies focused on samples in the Global North, which may have precluded generalizations to users in the Global South. Also, being 'conservative', may affect responses to scientific findings in users from the US, but it is less clear how political ideology is associated with perceptions of users in other countries. Also, while studies often controlled for gender, we did not find any studies that examined how gender affects responses to communications about uncertainty in scientific climate-related findings. Those perceptions may also vary per country, or with differences in ethnic background [102], culture [27], language [11], or political ideology. Studies looking at these characteristics need to include samples that are large enough and representative in terms of demographics and other user characteristics. Ideally, studies are also pre-registered so as to avoid publication bias or omitted reporting of non-significant results [63].

Fifth, studies used a wide range of different measures to assess users' responses to communications, including understanding [17], trust [58], perceived credibility and certainty [94], and intentions [41] (table S5). Remarkably, we did not identify studies that assessed whether communications motivated actual behavior change. Because it is important to understand when and how individuals adapt to a rapidly changing climate, we suggest that future studies also include measures of relevant behaviors [103]. These need to reflect the types of decisions climate communications seek to inform [8].

Finally, we summarized reviewed findings into emerging recommendations on how to design communications about uncertainty in scientific climate-related findings. Recommendations aim at

improving users' understanding and increasing their engagement when presented with communications about uncertainty in scientific climate-related findings. These recommendations may represent a step towards evidence-based communications of uncertainty in scientific findings about climate. They reflect, however, the variability across reviewed studies and thus need to be interpreted with care. Also, they are often based on single studies recruited with convenience samples that are not representative of the intended populations, and may have limited data quality [62, 104]. These recommendations thus need to be empirically tested with representative samples and across countries in order to ensure replicability and generalizability. To our knowledge, one author team tried to (unsuccessfully) replicate previous findings about responses to uncertainty in scientific findings about climate [47]. Another team did rigorously test communications of probabilistic ranges, including different presentation formats, and a broad range of samples (Recommendation 6, table 1). We suggestthat future studies test other emerging recommendations identified in this systematic review in similarly rigorous ways. This will help in identifying what works and what does not for communicating different sources of uncertainty in scientific, climate-related findings. Recommendations will then potentially complement more general guidelines for communications about uncertainty in scientific climate-related findings [15].

Our literature review also uncovered implications for policy-making regarding uncertainty in scientific findings about climate. Authors suggested first that uncertainty should be communicated within a 'deliberative democratic dialogue' [27, 99] rather than merely 'educating' public audiences about climate change. Such a dialogue potentially prevents scientists from being seen as politicians engaging in persuasion [27]. Authors also stated that communicating uncertainty should involve acknowledging diversity in the audience's viewpoints [27]. Second, authors pointed to the importance of developing communications that address users' informational needs [14, 27, 38, 40, 88], while considering how users understand and interpret the presented information [27]. Developing effective messages therefore involves actively seeking feedback from users by assessing how communications are best understood [40, 45, 46, 58, 59, 73]. Also, climate communications should be adjusted to users' personal contexts, including the climate-related costs, consequences, and solutions that will be relevant for them [68, 83]. Third, the effectiveness of communicating uncertainty in scientific findings about climate on users' understanding and subsequent behavior needs to be tested. Such testing needs to involve rigorous experimental methods from social sciences, to identify the most effective communication strategies and designs, and to determine what works well

for different users [8, 40, 48, 53, 69, 74, 88]. Given that behavioral responses to climate communications may require informed decisions that depend on decision contexts and users' characteristics, transparent communications are likely more important than 'nudging' [105]. Empirical testing of messages will facilitate mutual learning about what is known with confidence, regarding uncertainty in scientific findings about climate and users' responses.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5518/811.

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References

[1] Intergovernmental Panel on Climate Change 2014 Summary for Policymakers*Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (https://doi.org/10.1017/CBO9781107415324)

[2] European Commission EU Climate Action (https://ec.europa.eu/clima/citizens/eu_en)

[3] Mitchell C L, Burch S L and Driscoll P A 2016 (Mis)communicating climate change? Why online adaptation databases may fail to catalyze adaptation action *Wiley Interdiscip. Rev. Clim. Change* **7** 600–13

[4] Okan Y, Janssen E, Galesic M and Waters E A 2019 Using the short graph literacy scale to predict precursors of health behavior change *Med. Decis. Mak.* **39** 183–95

[5] Ballard T and Lewandowsky S 2015 When, not if: the inescapability of an uncertain climate future *Philos. Trans. R. Soc. A* **373** 20140464

[6] Dutt V and Gonzales C 2012 Why do we want to delay actions on climate change? Effects of probability and timing of climate consequences *J. Behav. Decis.* **25** 154–64

[7] Budescu D V, Por H-H and Broomell S B 2012 Effective communication of uncertainty in the IPCC reports *Clim. Change* **113** 181–200

[8] Pidgeon N and Fischhoff B 2011 The role of social and decision sciences in communicating uncertain climate risks *Nat. Clim. Change* **1** 35–41

[9] Gigerenzer G, Gaissmaier W, Kurz-Milcke E, Schwartz L M and Woloshin S 2010 Helping doctors and patients make sense of health statistics *Psychol. Sci. Public Interest* **8** 53–96

[10] Bruine de Bruin W and Bostrom A 2013 Assessing what to address in science communication *Proc. Natl Acad. Sci.* **110** 14062–8

[11] Harris A J L, Corner A, Xu J and Du X 2013 Lost in translation? Interpretations of the probability phrases used by the Intergovernmental Panel on Climate Change in China and the UK *Clim. Change* **121** 415–25

[12] Harris A J L and Corner A 2011 Communicating environmental risks: clarifying the severity effect in interpretations of verbal probability expressions *J. Exp. Psychol. Mem. Cogn.* **37** 1571–8

[13] Bolsen T, Palm R and Kingsland J T 2019 Counteracting climate science politicization with effective frames and imagery *Sci. Commun.* **41** 147–71

[14] Retchless D P 2014 Sea level rise maps: how individual differences complicate the cartographic communication of an uncertain climate change hazard *Cartogr. Perspect.* **77** 5–20

[15] Corner A, Lewandowsky S, Phillips M and Roberts O 2015 *The Uncertainty Handbook: A Practical Guide For Climate Change Communicators* (Bristol: University of Bristol) (https://climateoutreach.org/reports/uncertainty-handbook/)

[16] Swart R, Bernstein L, Ha-Duong M and Petersen A 2009 Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC *Clim. Change* **92** 1–29

[17] Budescu D V, Por H-H, Broomell S B and Smithson M 2014 The interpretation of IPCC probabilistic statements around the world *Nat. Clim. Change* **4** 508–12

[18] Harris A J L, Por H H and Broomell S B 2017 Anchoring climate change communications *Clim. Change* **140** 387–98

[19] Harold J, Lorenzoni I, Shipley T F and Coventry K R 2017 Cognitive and psychological science insights to improve climate change data visualization *Nat. Clim. Change* **6** 1080–9

[20] van der Bles A M *et al* 2019 Communicating uncertainty about facts, numbers and science *R. Soc. Open Sci.* **6** 181870

[21] Galesic M, Kause A and Gaissmaier W 2016 A sampling framework for uncertainty in individual environmental decisions *Top. Cogn. Sci.* **8** 242–58

[22] Kandlikar M, Risbey J and Dessai S 2005 Representing and communicating deep uncertainty in climate-change assessments *C. R. Geosci.* **337** 443–55

[23] Spiegelhalter D J and Riesch H 2011 Don't know, can't know: embracing deeper uncertainties when analysing risks *Philo. Trans. R. Soc. A* **369** 4730–50

[24] Weitzman M L 2011 Fat-tailed uncertainty in the economics of catastrophic climate change *Rev. Environ. Econ. Policy* **5** 275–92

[25] Lewandowsky S, Risbey J S, Smithson M, Newell B R and Hunter J 2014 Scientific uncertainty and climate change: part I. Uncertainty and unabated emissions *Clim. Change* **124** 39–52

[26] Hawkins E and Sutton R 2009 The potential to narrow uncertainty in regional climate predictions *Bull. Am. Meteorol. Soc.* **90** 1095–107

[27] Pearce W, Brown B, Nerlich B and Koteyko N 2015 Communicating climate change: conduits, content, and consensus *Wiley Interdiscip. Rev. Clim. Change* **6** 613–26

[28] Heath Y and Gifford R 2006 Free-market ideology and environmental degradation: the case of belief in global climate change *Environ. Behav.* **38** 48–71

[29] Dunlap R E, Liere K D, Van, Mertig A G and Jones R E 2000 Measuring endorsement of the new ecological paradigm: a revised NEP scale *J. Soc. Issues* **56** 425–42

[30] Kahan D M *et al* 2012 The polarizing impact of science literacy and numeracy on perceived climate change risks *Nat. Clim. Change* **2** 732–5

[31] van der Linden S, Leiserowitz A and Maibach E 2019 The gateway belief model: a large-scale replication *J. Environ. Psychol.* **62** 49–58

[32] Cokely E, Galesic M, Schulz E, Ghazal S and Garcia-Retamero R 2012 Measuring risk literacy: the Berlin numeracy test *Judgement Decis. Mak.* **7** 25–47 (https://psycnet.apa.org/record/2012-03055-003)

[33] Lohre E and Teigen K H 2017 Probabilities associated with precise and vague forecasts *J. Behav. Decis. Mak.* **30** 1014–26

[34] Gigerenzer G, Gaissmaier W, Kurz-Milcke E, Schwartz L M and Woloshin S 2007 Helping doctors and patients making sense of health statistics *Psychol. Sci. Public Interest* **8** 53–96

[35] Bruine De Bruin W, Wallin A, Parker A M, Strough J and Hanmer J 2017 Effects of anti- versus pro-vaccine narratives on responses by recipients varying in numeracy: a cross-sectional survey-based experiment *Med. Decis. Mak.* **37** 860–70

[36] Dieckmann N F, Slovic P and Peters E M 2009 The use of narrative evidence and explicit likelihood by decisionmakers varying in numeracy *Risk Anal.* **29** 1473–88

[37] McDowell M, Rebitschek F G, Gigerenzer G and Wegwarth O 2016 A simple tool for communicating the benefits and harms of health interventions: a guide for creating a fact box *MDM Policy Pract.* **1** 1–10

[38] Raimi K T, Stern P C and Maki A 2017 The promise and limitations of using analogies to improve decision-relevant understanding of climate change *PLoS One* **12** 1–20

[39] Rabinovich A and Morton T A 2012 Unquestioned answers or unanswered questions: beliefs about science guide responses to uncertainty in climate change risk communication *Risk Anal.* **32** 992–1002

[40] Lorenz S, Dessai S, Forster P M and Paavola J 2016 Tailoring the visual communication of climate projections for local adaptation practitioners in Germany and the UK *Phil Trans R Soc A* **373** 1–17

[41] Morton T A, Rabinovich A, Marshall D and Bretschneider P 2011 The future that may (or may not) come: how framing changes responses to uncertainty in climate change communications *Glob. Environ. Change* **21** 103–9

[42] Berrang-Ford L, Pearce T and Ford J D 2015 Systematic review approaches for climate change adaptation research *Reg. Environ. Change* **15** 755–69

[43] Haddaway N R, Macura B, Whaley P and Pullin A S 2018 ROSES for Systematic Review ProtocolsROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps *Environ Evid* **7** 1–8

[44] Kohl C *et al* 2018 Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools *Environ. Evid.* **7** 1–17

[45] Knight F H 1921 *Risk, Uncertainty and Profit* (Boston MA: Houghton Mifflin) (https://doi.org/10.1017/CBO97805 11817410.005)

[46] Haddaway N R, Macura B, Whaley B and Pullin A S 2017 ROSES flow diagram for systematic reviews. Version 1.0. (https://doi.org/10.6084/m9.figshare.5897389)

[47] Sleeth-Keppler D *et al* 2019 Does 'When' really feel more certain than 'If'? Two failures to replicate Ballard and Lewandowsky (2015) *R. Soc. Open Sci.* **6** 1–12

[48] Ho E, Budescu D, Dhami M and Mandel D R 2015 Improving the communication of uncertainty in climate science and intelligence analysis *Behav. Sci. Policy* **1** 43–55

[49] Valentine J C and Cooper H 2008 A systematic and transparent approach for assessing the methodological quality of intervention effectiveness research: the study design and implementation assessment device (Study DIAD) *Psychol. Methods* **13** 130–49

[50] Corbett J B and Durfee J L 2004 Testing public (Un) certainty of science - Media representations of global warming *Sci. Commun.* **26** 129–51

[51] Baumer E P S, Polletta F, Pierski N and Gay G K 2017 A simple intervention to reduce framing effects in perceptions of global climate change *Environ. Commun. J. Nat. Cult.* **11** 289–310

[52] Løhre E, Juanchich M, Sirota M, Teigen K H and Shepherd T G 2019 Climate scientists' wide prediction intervals may be more likely but are perceived to be less certain *Weather. Clim. Soc.* **11** 565–75

[53] Dieckmann N F, Peters E and Gregory R 2015 At home on the range? Lay interpretations of numerical uncertainty ranges *Risk Anal.* **35** 1281–95

[54] Kause A, Townsend T and Gaissmaier W 2019 Framing climate uncertainty: frame choices reveal and influence climate change beliefs *Weather Clim. Soc.* **11** 199–215

[55] Budescu D V, Broomell S and Por -H-H 2009 Improving communication of uncertainty in the reports of the intergovernmental panel on climate change *Psychol. Sci.* **20** 299–308

[56] Juanchich M and Sirota M 2017 How much will the sea level rise? Outcome selection and subjective probability in climate change predictions *J. Exp. Psychol. Appl.* **23** 386–402

[57] Smithson M, Budescu D V, Broomell S B and Por -H-H 2012 Never say "not": impact of negative wording in probability phrases on imprecise probability judgments *Int. J. Approx. Reason.* **53** 1262–70

[58] Daron J D, Lorenz S, Wolski P, Blamey R C and Jack C 2015 Interpreting climate data visualisations to inform adaptation decisions *Clim. Risk Manage.* **10** 17–26

[59] McMahon R, Stauffacher M and Knutti R 2015 The unseen uncertainties in climate change: reviewing comprehension of an IPCC scenario graph *Clim. Change* **133** 141–54

[60] Patt A and Dessai S 2005 Communicating uncertainty: lessons learned and suggestions for climate change assessment *C. R. Geosci.* **337** 425–41

[61] Shen W *et al* 2011 Samples in applied psychology: over a decade of research in review *Applied Psychology* **96** 1055–64

[62] Kennedy C *et al* 2020 (Washington DC: Pew Research Center) (https://www.pewresearch.org/methods/2020/02/18/assessing-the-risks-to-online-polls-from-bogus-respondents/)

[63] Lewandowsky S and Oberauer K 2020 Low replicability can support robust and efficient science *Nat. Commun.* **11** 1–12

[64] Rad M S, Martingano A J and Ginges J 2018 Toward a psychology of Homo sapiens: making psychological science more representative of the human population *Proc. Natl Acad. Sci. USA* **115** 11401–5

[65] Retchless D P and Brewer C A 2016 Guidance for representing uncertainty on global temperature change maps *Int. J. Climatol.* **36** 1143–59

[66] Lundhede T, Jacobsen J B, Hanley N, Strange N and Thorsen B J 2015 Incorporating outcome uncertainty and prior outcome beliefs in stated preferences *Land Econ.* **91** 296–316

[67] Taylor A L, Dessai S and Bruine de Bruin W 2014 Public perception of climate risk and adaptation in the UK: a review of the literature *Clim. Risk Manage.* **4–5** 1–16

[68] Patt A G and Weber E U 2014 Perceptions and communication strategies for the many uncertainties relevant for climate policy *Wiley Interdiscip. Rev. Clim. Change* **5** 219–32

[69] Bosetti V *et al* 2017 COP21 climate negotiators' responses to climate model forecasts *Nat. Clim. Change* **7** 185–9

[70] Budescu D V, Por H H and Broomell S B 2012 Effective communication of uncertainty in the IPCC reports *Clim. Change* **113** 181–200

[71] Smithson M, Budescu D V, Broomell S B and Por H H 2012 Never say 'not': impact of negative wording in probability phrases on imprecise probability judgments *Int. J. Approx. Reason.* **53** 1262–70

[72] Hohle S M and Teigen K H 2015 Forecasting forecasts: the trend effect *Judgment. Decis. Mak.* **10** 416–28

[73] Mastrandrea M D *et al* 2010 Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties (Geneva Switzerland: IPCC) (https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf)

[74] Harold J, Lorenzoni I, Shipley T F and Coventry K R 2016 Cognitive and psychological science insights to improve climate change data visualization *Nat. Clim. Change* **6** 1080–9

[75] Lohre E 2018 Stronger, sooner, and more certain climate change: a link between certainty and outcome strength in revised forecasts *Q. J. Exp. Psychol.* **71** 2531–47

[76] Hohle S M and Teigen K H 2018 When probabilities change: perceptions and implications of trends in uncertain climate forecasts *J. Risk Res.* **9877** 1–15

[77] Benjamin D M and Budescu D V 2018 The role of type and source of uncertainty on the processing of climate models projections *Frontiers Psychol.* **9** 1–17

[78] Lewandowsky S, Ballard T, Oberauer K and Benestad R 2016 A blind expert test of contrarian claims about climate data *Glob. Environ. Change Policy Dimens.* **39** 91–97

[79] Joslyn S L and Leclerc J E 2016 Climate projections and uncertainty communication *Top. Cogn. Sci.* **8** 222–41

[80] McKenzie C R M and Nelson J D 2003 What a speaker's choice of frame reveals: reference points, frame selection, and framing effects *Psychon. Bull. Rev.* **10** 596–602

[81] Hohle S M and Teigen K H 2018 More than 50% or less than 70% chance: pragmatic implications of single-bound probability estimates *J. Behav. Decis. Mak.* **31** 138–50

[82] Teigen K H, Filkuková P and Hohle S M 2018 It can become 5 °C warmer: the extremity effect in climate forecasts *J. Exp. Psychol. Appl.* **24** 3–17

[83] Adler C E and Hadorn G H 2014 The IPCC and treatment of uncertainties: topics and sources of dissensus *Wiley Interdiscip. Rev. Change* **5** 663–76

[84] Budescu D V and Wallsten T S 1995 Processing linguistic probabilities: general principles and empirical evidence *Psychol. Learn. Motiv. Adv. Res. Theory* **32** 275–318

[85] Patt A G and Schrag D P 2003 Using specific language to describe risk and probability *Clim. Change* **61** 17–30

[86] Garcia-Retamero R, Okan Y and Cokely E T 2012 Using visual aids to improve communication of risks about health: a review *Sci. World J.* **2012** 1–10

[87] Milne A E *et al* 2015 Communicating the uncertainty in estimated greenhouse gas emissions from agriculture *J. Environ. Manage* **160** 139–53

[88] Taylor A L, Dessai S and Bruine de Bruin W 2015 Communicating uncertainty in seasonal and interannual climate forecasts in Europe *Philos. Trans. R. Soc. A* **373** 20140454

[89] Doyle E E H, Johnston D M, Smith R and Paton D 2019 Communicating model uncertainty for natural hazards: a qualitative systematic thematic review *Int. J. Disaster Risk Reduct.* **33** 449–76

[90] Corner A, Markowitz E and Pidgeon N 2014 Public engagement with climate change: the role of human values *WIRes Clim. Change* **5** 411–22

[91] Whitmarsh L 2011 Scepticism and uncertainty about climate change: dimensions, determinants and change over time *Glob. Environ. Change* **21** 690–700

[92] Corner A, Whitmarsh L and Xenias D 2012 Uncertainty, scepticism and attitudes towards climate change: biased assimilation and attitude polarisation *Clim. Change* **114** 463–78

[93] Ma Y N, Dixon G and Hmielowski J D 2019 Psychological reactance from reading basic facts on climate change: the role of prior views and political identification *Environ. Commun. J. Nat. Cult.* **13** 71–86

[94] Hinnant A, Subramanian R and Young R 2016 User comments on climate stories: impacts of anecdotal vs. scientific evidence *Clim. Change* **138** 411–24

[95] Nisbet E C, Cooper K E and Garrett R K 2015 The partisan brain: how dissonant science messages lead conservatives and liberals to (dis)trust science *Ann. Am. Acad. Pol. Soc. Sci.* **658** 36–66

[96] Lewandowsky S, Gignac G E and Vaughan S 2012 The pivotal role of perceived scientific consensus in acceptance of science *Nat. Clim. Change* **3** 399–404

[97] Peters E *et al* 2006 Numeracy and decision making *Psychol. Sci.* **17** 407–13

[98] Cacioppo J T, Petty R E and Kao C F 1984 The efficient assessment of need for cognition *J. Pers. Assess.* **48** 306–7

[99] Newell B, McDonald R I, Brewer M and Hayes B K 2014 The psychology of environmental decisions *Annu. Rev. Environ. Resour.* **39** 443–67

[100] Wynne B 1992 Uncertainty and environmental learning: reconceiving science and policy in the preventive paradigm *Glob. Environ. Change* **2** 111–27

[101] Markon M-P L and Lemyre L 2013 Public reactions to risk messages communicating different sources of uncertainty: an experimental test *Hum. Ecol. Risk Assess.* **19** 1102–26

[102] Flynn J, Slovic P and Mertz C K 1994 Gender, race, and perception of environmental health risks *Risk Anal.* **14** 1101–8

[103] Baumeister R F, Vohs K D and Funder D C 2007 Psychology as the science of self-reports and finger movements: whatever happened to actual behavior? *Perspect. Psychol. Sci.* **2** 396–403

[104] Tourangeau R, Conrad F G and Couper M P 2013 *The Science of Web Surveys* (Oxford: Oxford University Press)

[105] Hertwig R 2017 When to consider boosting: some rules for policy-makers *Behav. Public Policy* **1** 143–61