Apocalypse now? Communicating extreme forecasts

David C. Rode*

Carnegie Mellon Electricity Industry Center,
Carnegie Mellon University,
Pittsburgh, PA 15213, USA
Email: rode@andrew.cmu.edu
*Corresponding author

Paul S. Fischbeck

Carnegie Mellon Electricity Industry Center,
Carnegie Mellon University,
Pittsburgh, PA 15213, USA
and
Department of Social and Decision Sciences,
Carnegie Mellon University,
Pittsburgh, PA 15213, USA
and
Department of Engineering and Public Policy,
Carnegie Mellon University,
Pittsburgh, PA 15213, USA
Email: fischbeck@cmu.edu

Abstract: Apocalyptic forecasts are unique. They have, by definition, no prior history and are observed only in their failure. As a result, they fit poorly with our mental models for evaluating and using them. However, they are made with some frequency in the context of climate change. We review a set of forecasts involving catastrophic climate change-related scenarios and make several observations about the characteristics of those forecasts. We find that mentioning uncertainty results in a smaller online presence for apocalyptic forecasts. However, scientists mention uncertainty far more frequently than non-scientists. Thus, the bias in media toward coverage of non-scientific voices may be 'anti-uncertainty', not 'anti-science'. Also, the desire among many climate change scientists to portray unanimity may enhance the perceived seriousness of the potential consequences of climate catastrophes, but paradoxically undermine their credibility in doing so. We explore strategies for communicating extreme forecasts that are mindful of these results.

Keywords: apocalypse; climate change; communication; extreme event; forecast; forecasting; global warming; media; policy; prediction; risk; risk communication; uncertainty.

Reference to this paper should be made as follows: Rode, D.C. and Fischbeck, P.S. (2021) 'Apocalypse now? Communicating extreme forecasts', *Int. J. Global Warming*, Vol. 23, No. 2, pp.191–211.

Biographical notes: David C. Rode received his PhD in Social and Decision Sciences from Carnegie Mellon University and has worked for nearly 20 years in the electric power sector. His research interests are in the economics of power and energy markets, valuation and risk management for power generating assets, decision analysis, simulation, and quantitative risk analysis. He has published in *Applied Energy*, *Energy Policy*, *Environmental Science & Technology*, *The Appraisal Journal* and *The Journal of Behavioral Finance*, as well as a variety of practitioner-oriented publications.

Paul S. Fischbeck received his PhD from Stanford University and a Professor in the Departments of Social and Decision Sciences and Engineering and Public Policy at Carnegie Mellon University. His research focuses on the quantification and communication of uncertainty. This work covers both theoretical improvements to decision analysis and numerous applied real-world problems, including environmental risks, emissions from ships, risk management for the tiles of the space shuttle, and insurance-buying decisions.

"I've been warned that telling people to panic about the climate crisis is a very dangerous thing to do, but don't worry – it's fine – I've done this before and I can assure you: it doesn't lead to anything."

– Greta Thunberg, climate activist

World Economic Forum, Davos, 21 January 2020

1 Introduction

The purpose of forecasting is not solely to inform, but most often to initiate a process of action. The forecaster seeks to warn, to call for a change in behaviour, or to seek mitigation (or amplification) of the consequences. As a result, the value of any forecast is based in part on the decisions it precipitates – a result encoded in the very foundations of decision theory (Howard, 1966). Others have reached similar conclusions. Gerjuoy (1977) notes that the metric for evaluating a forecast is not whether it is accurate, but whether it is 'useful'. Similarly, Fischhoff and Davis (2014, p.13665) note that "people will judge science's value by the apparent wisdom of recommendations based on it."

Further, decisions are made not just based on 'forecasts', but on forecasts *as they are communicated and understood*. This is especially true for forecasts involving extreme outcomes for several reasons. First, people are notoriously prone to biases and errors in tasks that involve low-probability, high-consequence events. Second, the aphorism (attributed to Carl Sagan) that 'extraordinary claims demand extraordinary evidence' implies that information-processing capacity must be considered. Third, our ability to evaluate evidence implies that there is evidence to evaluate.

In particular, we believe this third reason makes *apocalyptic* extreme forecasts unique. By their very nature, there are no historical analogues for such forecasts. Plenty of low-probability, high-consequence extreme events (e.g., stock market crashes, severe earthquakes) have historical antecedents with which to evaluate forecast utility. But because the modern world has never experienced an apocalyptic event before, the only observations we have of prior apocalyptic forecasts are of forecast *failures*. There is no rational model of decision making that attributes increasing credibility to forecasts upon successive failures.

Consequently, once generic (e.g., noting that a positive cosmological constant would imply the ultimate heat death of the universe) or ambiguous (e.g., "the earth also and the works that are therein shall be burned up"[1]) apocalyptic predictions are excluded, only one type of event is the subject of apocalyptic forecasts with any frequency. In this paper, we review this class of extreme predictions and explore its implications for policymaking and risk communication. We examine a unique set of apocalyptic predictions related to environmental and climate-related risks and classify our findings according to research on uncertainty in behavioural decision making, risk analysis, and communication. This is *not* a paper about climate change per se, or the evidence for or against it. However, because of the importance of climate change to public policy, when scientists, policymakers, and others with authority make extreme event forecasts, they should have a duty to ensure that the forecasts are communicated effectively. We examine these predictions in search of common factors that can shed light on the nature of making extreme predictions in the hope of improving how such predictions can be communicated.

A forecast of an impending apocalypse carries with it awesome implications, whether that forecast is for tomorrow or for decades into the future. It follows, then, that the makers of such claims should have the support of extraordinary evidence prior to making them. The actions taken in response to an extreme event forecast are likely to be equally extreme in terms of cost, time, disruption, and irreversibility. Thus, it is not merely the consequences of a correct forecast that must be considered, but the consequences of *incorrect* [e.g., the Xhosa cattle-killing movement and famine of 1856 (Peires, 1989), Iben Browning's 1990 New Madrid earthquake forecast (Spence et al., 1993)] or *inadequately-communicated* [e.g., the 1997 Red River flood forecast (Pielke, 1999)] forecasts that must be considered as well.

In the next section, we review literature from behavioural decision making, sociology, policy analysis, and media studies as it relates to forecasting and communicating risky events. We centre apocalyptic forecasts in this body of work to highlight several well-established principles in relation to our data on extreme climate-change forecasts. In Section 3, we describe the data used in our analysis. Section 4 presents our results and further discussion. We discuss our conclusions for improving policy and communication in Section 5. We conclude in Section 6.

2 Forecasting extreme events as a multidisciplinary process

The forecasting of extreme events is a multidimensional problem. Pielke et al. (2000) call it a 'prediction enterprise' to convey its scope. Such forecasts must be communicated faithfully. They must be perceived in a manner that objectively characterises their uncertainty, and they must acknowledge that beliefs about the future (and reactions to those beliefs) are formed within a social construct. Ideally, they must facilitate informed, rational judgment. As a result, it is important to draw upon insights from a variety of disciplines in evaluating forecasts of extreme events. In this section, we divide these issues into four areas, review the relevant literature, and discuss each in turn.

2.1 Media, communication, and forecasts

Combs and Slovic (1979) showed early on that the frequency of reporting influences the perceived frequency of occurrence of an event. It is now well-settled that media coverage influences risk perceptions (Af Wåhlberg and Sjöberg, 2000; Johnson and Covello, 1987; Slovic, 1986). Doulton and Brown (2009) performed a study of UK newspaper articles on climate change between 1997 and 2007 and found that 'potential catastrophe' was the most common discourse in news coverage, concluding that the media were prone to 'attention cycles' that tended to be self-amplifying, and led to the news provoking a 'rising sense of impending catastrophe' from climate. This type and frequency of media coverage tends toward sensationalism and an increased (but unjustified) certainty in reporting (Ladle et al., 2005; Smith, 2005; Weingart et al., 2000). Painter (2013) found similar results in examining newspaper articles on climate change in six countries, noting that 'disastrous consequences' was the most common frame in the stories, while references to risk or likelihood was the least common frame.

The challenge we face in regard to apocalyptic climate-related events is that media coverage is focused on events that have no direct historical precedent. As Weitzman (2009, p.3) notes explicitly about extreme climate events, there are limits to inductive knowledge when it comes to "extreme events outside the range of experience." When news instead takes on a 'consciousness-raising' objective (Taubes, 1997), instead of only an informational objective, it becomes explicitly intended to raise the visibility of an issue. Without a base rate established by historical experience, that increased visibility is likely to inflate disproportionately our perception of an event's subjective likelihood.

2.2 Expertise and the perception of risk

"People respond to the hazards they perceive." So begins a classic paper by Slovic et al. (1982a, p.463) on risk perception. An apocalyptic prediction is usually made in order to propose that action be taken to forestall it or to prepare for it. As Slovic et al. (1982a) note, however, human judgment plays a significant role in how we perceive, interpret, and respond to such predictions, and such judgment is often subject to biases and further influenced and mediated by social and institutional factors (Kasperson et al., 2003, 1988). To this complex mix, Skrimshire (2014) adds that apocalyptic discourse is often invoked specifically to introduce a moral element as well. Therefore, individuals making predictions should take such factors into account in the communication process.

A long line of research has demonstrated that experts and non-experts conceptualise risk differently (Bostrom, 1997; Slovic et al., 1982b; Fischhoff et al., 1982). In general, scientists and experts tend to focus on objective measures such as the expected number of fatalities, while non-scientists/non-experts are motivated by more abstract characteristics of the risk in question. When the presentation of risks is 'sensationalised' through the media, non-scientists are apt to perceive a risk as a greater, more immediate threat.

Further, it has been suggested that the media treatment of expert versus non-expert sources differs, and that the proliferation of 'new media' sources (e.g., blogs and social media) has favoured non-experts (Petersen et al., 2019). Petersen et al. divided climate-change researchers into two groups: 'scientists' and 'contrarians'. The authors then went to some lengths to show that the contrarians were overall 'less expert' (i.e., less scientifically credentialed) than the scientists. Despite this, the non-scientist contrarians were featured in 49% more new media articles overall than scientists, although both groups were featured equally prominently among 'mainstream media' articles. As a result, Petersen et al. (2019) conclude that the non-scientist contrarians have a disproportionately large voice in the public conversation about climate change. Competition for public attention may then lead scientists to reframe their messages by making them more 'sensational'.

2.3 The social context of forecasts

In the absence of domain expertise, the public often resorts to heuristics to guide their actions. Specifically, belief in climate change is based on perceptions of scientific consensus and certainty (McCright et al., 2013; Ding et al., 2011). Increasing the *perceptions* of consensus and certainty contributes to greater public interest and belief in climate-related threats. The observation that uncertainty is often ignored or understated in reporting on issues such as climate change has led to a characterisation of the media's coverage as adopting a 'fundamentalist posture', in that it becomes resistant to change amidst increasing fervour (Paterson, 2011). Booker (2018) refers to this as a form of climate 'groupthink'. Oppenheimer et al. (2019, p.165) refers to this as 'univocality', the perceived need of experts to speak as a single voice out of concern that differences of opinion will be conflated for ignorance and dismissed.

Although good forecasting practice requires conservatism in forecasts subject to uncertainty (Green and Armstrong, 2007), Painter (2013) and Skolnikoff (1990) have asserted that policy processes that deal with high levels of problem uncertainty or disagreement rarely produce actual policy – especially when the costs of the contemplated policy are high. In many cases, an effort is being made to use such apocalyptic predictions to alter public perceptions in order to achieve policy goals. Or, perhaps more correctly, there is an effort to make predictions seem 'more apocalyptic' in order to focus attention.

This process of overstating agreement is not without risks. When this influence is contained within a social group, a simple model of information processing shows that in-group communications alone can increase judged probabilities – independent (at first) of the underlying objective likelihood (Butts, 1998). Festinger et al. (1956) noted this very phenomenon in their seminal study of a UFO cult in the 1950s and demonstrated that it was largely independent of the nature of the information transmitted. Each study of apocalyptic prediction shares one common element: as far as we can tell, the apocalypse has not actually occurred (yet). What Festinger et al. noted, however, was that receipt of disconfirming evidence (the apocalypse not occurring as scheduled), did not diminish belief in the prediction. Rather, it tended to *strengthen* it – at least for a time.

The social dynamics that encourage this convergence of beliefs, which may emerge from a desire for univocality, lead not just to an underestimation of the uncertainty involved, but also to a premature consensus as to the conclusions. The conclusions themselves become part of the social negotiation among participants to arrive at a particular forecast not necessarily because it is objectively justified, but because it is the least mutually objectionable forecast to the members of the group. The convergence of predictions, however, is not necessarily a sign of accuracy (Pielke et al., 2000).

2.4 Uncertainty about apocalyptic beliefs

Tying the above findings together is uncertainty. Few would suggest that the probability of a climate-related apocalyptic event at some time in the future occurring is zero, but neither is it certainty. Asayama et al. (2019) attribute such claims to 'climate deadline-ism' creating an 'illusory cliff-edge' through the use of a constructed quantitative index to quantify what 'dangerous' climate change means.

Such statements, of course, neglect the compound uncertainties of identifying a specific date, whether or not such an index (e.g., cumulative carbon emissions) is the most reliable single metric of dangerous climate change, and the presence of uncertainty in the causal chain linking the proxy *index* to the occurrence of apocalyptic *events*. There is, of course, considerable evidence in favour of a finite carbon budget (MacDougall, 2016; Millar et al., 2016), but it is not without critique (Geden, 2018; Peters, 2018), and clearly neglects the impact of mitigation and adaptation in response to elevated carbon levels. A nuanced statement of model results then becomes a cliff-edge facing oblivion.

Such apocalyptic predictions are often pronounced to effectuate specific policy outcomes. Their communication is very often designed to convey a high degree of certainty in the predicted outcome. Meanwhile, the public at large can become inured to such predictions. The paradox, therefore, is that recognition of the legitimate uncertainties present may complicate policymaking [as Weitzman (2009) asserts with his 'dismal theorem'], but overstatement of, or failure to recognise, uncertainties impairs the credibility of the underlying forecast (Whitmarsh, 2011; O'Neill and Nicholson-Cole, 2009). The solution – well-calibrated forecasts – is equally challenging.

Consider a simple model. Let $P(A)$ be the (prior) probability of an apocalyptic event occurring within a particular horizon. Let $P(\text{‘}A\text{’})$ be the probability that a forecaster forecasts an apocalyptic event to occur within that same horizon. Similarly, we define $P(\text{‘}A\text{’}|A)$ as the sensitivity of the forecast (the likelihood that the forecaster predicted an apocalyptic event given that an apocalyptic event occurs). Application of Bayes' theorem then produces the posterior probability of observing an actual apocalyptic event given an apocalyptic forecast is received: $P(A|\text{‘}A\text{’}) = P(A)P(\text{‘}A\text{’}|A) / P(\text{‘}A\text{’})$. Extending this result to n independent, sequential forecasts of equal accuracy, we arrive at equation (1).

$$P\left(A|\text{‘}A_1\text{’} \wedge \text{‘}A_2\text{’} \wedge \ldots \wedge \text{‘}A_n\text{’}\right) = P(A)\frac{P(\text{‘}A\text{’}|A)^n}{P(\text{‘}A\text{’})^n} \quad (1)$$

What this very simple model illustrates is that over successive forecasts, the forecast receiver's posterior belief as to the likelihood of an apocalyptic event occurring either grows [if $P(\text{‘}A\text{’}|A) > P(\text{‘}A\text{’})$] or shrinks [if $P(\text{‘}A\text{’}|A) < P(\text{‘}A\text{’})$]. This is particularly problematic because we almost never observe forecasts of a 'non-apocalypse' [i.e., $P(\text{‘}A^c\text{’})$].[2] Thus, if $P(\text{‘}A\text{’})$ is very large (approaching 1), then successive forecasts can only lead to a decline in beliefs about an apocalyptic event. Achieving public credibility in such forecasts requires both acknowledgement of uncertainty in the outcome *and* calibration of the forecasting mechanism to that uncertainty.

3 Data used in the analysis

Let us be clear at the outset. The apocalyptic forecasts we concern ourselves with in this paper are specific as to date and descriptive as to cause:

> "*Before this century is over*, billions of us will die, and the few breeding pairs of people that survive will be in the Arctic *where the climate remains tolerable*." [emphasis added] (James Lovelock, Fellow of the Royal Society and developer of the Gaia Hypothesis, 20 January 2006, in the Irish newspaper *The Independent*)

In this example, a specific time (before the year 2100) and a specific cause (a climate-related catastrophe) are noted.

We should also be clear about what we mean by an 'apocalyptic extreme forecast'. Although our use of the term apocalyptic here may be considered a 'small-A' apocalypse (as in 'great disaster'), rather than a 'big-A' biblical apocalypse, Skrimshire (2014, p.238) notes that climate change forecasts often use the "imaginative power of [apocalyptic] religious narratives" to encourage belief. We use 'apocalypse' to imply that the forecasted consequences of an extreme forecast have a negative valence. Such forecasts should call for mass casualty events where loss of life and/or property is extensive (forecasts often refer to 'millions' or even 'billions' of fatalities), such as mass starvation, regional drought, country-scale flooding, etc. These events should be extreme, in the sense of not within the range of historical experience. Further, these events should be directly related to climate change, and their impacts should be long-lasting and/or irreversible. We qualify this further by noting that our forecasts generally deal with the prediction of the *outcomes* of climate extremes, rather than the prediction of climate extremes alone. A hallmark of these forecasts is that they make an explicit (and often certain) coupling between the occurrence of a climate extreme and the realisation of negative consequences of that extreme.

Our data comprise the 79 predictions of an 'apocalyptic' nature relating to climate change or climate-related environmental factors provided in Rode and Fischbeck (2019). To be included as a forecast, several conditions had to be satisfied. First, the forecast had to specify an explicit date (e.g., December 2050) or time horizon (e.g., in three decades) by which the event in question would occur. Second, the forecast must include a specific description of the outcome (e.g., "major European cities will be sunk beneath rising seas") and attribute the outcome to a climate change or environment-related factor. Third, there must be documentation of the claim, either in an original document or in a prominent newspaper or magazine (when such predictions are made orally, for example).

The forecasts were gathered from a systematic online search using Google for ('climate' OR 'global warming' OR 'global cooling') AND ('apocalypse' OR 'catastrophe' OR 'collapse') AND ('forecast' OR 'prediction'). All of the searches and the related search data were obtained on 24 July 2019.

For each forecast, we identified the 'speaker' or *prognosticator*, the time until the event is forecast to occur[3] (which we call the *horizon*), the nature of the forecast, the forecast medium, and a key quote. In most cases, the speaker is an individual, but in some cases, the forecast is attributed to an organisation (e.g., via a press release) and noted as such. The nature of the forecast is used to differentiate between forecasts of the form "disaster will occur on ____" (which we call *event* predictions) and of the form "we must act by ____ to prevent ____" (which we call *must act* predictions). The medium of communication is classified as either written (a report, published article, etc.), spoken (a prepared speech), or an interview (a formal interview, a press conference, etc.). Separately, we collected information about the speaker (year of birth and educational background or position[4]), which allowed us to determine whether or not they have a scientific background[5] and whether they could reasonably be expected to be alive on or after the predicted event (based on an average life expectancy of 79 years).

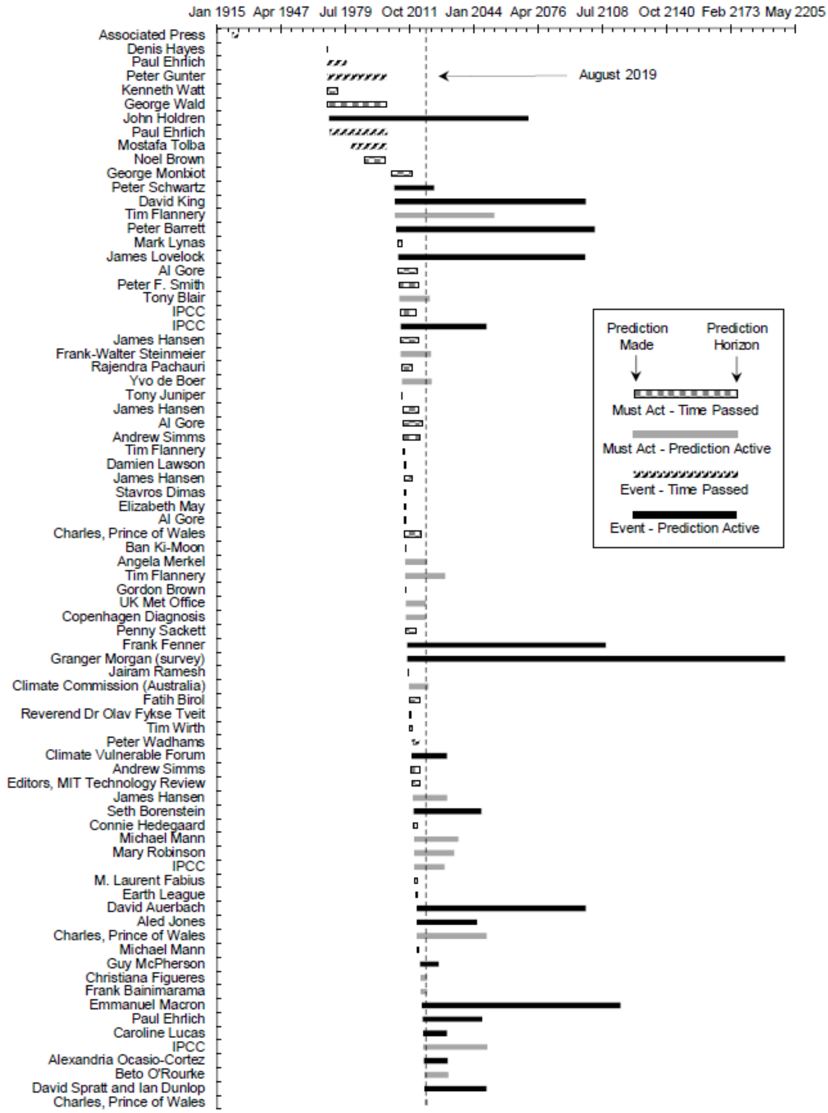
We also collected, when available, any information provided about the uncertainty behind the forecast. As communication of uncertainty is the common theme running through this paper, it is striking that just under half (43%) of the forecasts were communicated *without* any information indicating uncertainty. On the other hand, as we have noted, various authors have written about the bias toward increased certainty as a means of drawing attention and emphasis. But making a prediction is inherently a scientific act; it is a testable hypothesis. Even among the 57% of forecasts that made *some* reference to uncertainty, often the statements were of the most ambiguous and generic sort: ‘could be’, ‘a fair chance’, ‘likely’. At the other extreme, several statements were highly specific: ‘certainty exceeding 99%’, ‘one-third chance’, and ‘guaranteed’.

When we refer to uncertainty, we are referring to the level of uncertainty associated with an apocalyptic event occurring. For example, high uncertainty means that there is significant doubt as to whether the relevant event will happen. Because many of the references to uncertainty were qualitative, we subjectively assigned them to three categories: low uncertainty (e.g., numerical quantity greater than or equal to 0.67, ‘will’, ‘almost certain’), medium uncertainty (e.g., numerical quantity between 0.33 and 0.67, ‘even chance’, ‘fair chance’), and high uncertainty (e.g., numerical quantity less than or equal to 0.33, ‘could’, ‘not likely’).

Undoubtedly, some of the speakers were indulging in rhetorical flourish, as their statements were often intended for a general audience. Nevertheless, we would argue that given the expected consequences of the forecasts, *some* statement of uncertainty was essential. Further, that this is precisely when baroque statements of uncertainty may be ill-advised. While policymakers or those in a role as an advocate might be forgiven for using rhetorical license to emphasise and persuade, those with an objective scientific background might be expected to be held to a different standard.

In addition to forecast-specific data points, we also compiled several time series of data related to public interest in these subjects. We collected the number of results for Google searches for each speaker’s name, as well as the conjunction of the speaker’s name and the word ‘climate’, and the conjunction of the speaker’s name, the word ‘climate’, and the specific quote recorded about the forecast.[6] Internet search data has been used in a wide variety of academic research as a means of measuring societal trends and aggregate expressions of interest. This work has included predicting unemployment trends (Ettredge et al., 2005), consumer spending behaviour (Choi and Varian, 2012), and even epidemiological trends in public health (Ginsberg et al., 2009). In this paper, we use the search data as an indicator of public interest in specific subjects. Subjects and individuals of greater public interest have both more material related to them available on the internet and also receive more interest via search queries. Figure 1 displays the set of predictions graphically, illustrating the speaker, the type of prediction made, and the prediction.

Figure 1 Summary of apocalyptic predictions by speaker, prediction horizon, and type of prediction (*event* or *must act*) as of 24 July 2019



Note: The data is available from Rode and Fischbeck (2019).

Before turning to exploration of the themes identified in Section 2, we present some basic descriptive statistics of the data. We observed more *must act* predictions than *event* predictions. Unsurprisingly (but importantly), the event predictions had longer horizons than the *must act* predictions. The majority of the forecasts were transmitted in written form, as opposed to in a speech or interview (see Table 1a). Most of the forecasts were made by prognosticators with non-scientific backgrounds. However, the *must act* predictions were disproportionately made by non-scientists, while the *event* predictions were disproportionately made by scientists (see Table 1b).

Table 1 (a) Average horizon in years from date of forecast and number of forecasts (in parentheses) observed by type of forecast and medium of forecast (b) Number of forecasts of each type by prognosticators background

(a)

Type of forecast	*Written*	*Interview*	*Spoken*	*Subtotals*
Must act	12.2 (24)	7.3 (13)	5.5 (17)	8.9 (54)
Event	44.6 (16)	46.8 (6)	71.3 (3)	48.3 (25)
Subtotals	25.2 (40)	19.8 (19)	15.4 (20)	21.4 (79)

(b)

Background of prognosticator	*Must act*	*Event*	*Subtotals*
Science	16	15	31
Non-science	30	6	36
Group	8	4	12
Subtotals	54	25	79

Notes: Group prognosticators are classified separately. Most of the groups, however, have a scientific focus, and their inclusion in the 'science' category does not alter the substance of the results.

4 Results and discussion

4.1 Suppressing uncertainty raises visibility

Much of the media operates with an express intent to do what Taubes (1997) refers to as 'consciousness-raising'. In doing so, the media tends to sensationalise the consequences and suppress references to uncertainty in reporting apocalyptic climate-related forecasts. Our analysis suggests that these two actions are related. One may expect, then, to find forecasts *without* any statement of uncertainty receiving more prominence (as measured by the number of search results). We compared the average number of Google search results across all forecasts returned for queries (prognosticator AND 'climate') and (prognosticator and quote fragment). In each case, for both *must act* and *event* predictions, we find that forecasts without a statement of uncertainty receive more search results (Table 2). The results for (prognosticator AND 'climate') are significant at the 0.10 level. The results are substantively unchanged if we use median instead of average.

It will come as no surprise that a headline of 'humanity doomed in ten years' will get more prominence than a headline of "negative event of unknown severity might occur in the next ten to one hundred years." Thus, if achieving the most visibility (in the form of quantity of search results) is the objective, remaining silent on the uncertainty present appears to be a viable strategy. For publications seeking a reputation for quality and comprehensiveness of reporting, however, we would expect to observe the opposite. That is, such 'reputable' publications may choose to focus instead on forecasts that explicitly reference uncertainty in order to communicate faithfully the underlying scientific results.[7] To evaluate this, we made the same comparison described above, but limited the search corpus to the internet domains of our reputable sources. For publications deemed reputable, this finding is supported for the search for (prognosticator AND 'climate'), but not for (prognosticator and quote fragment) (Table 2). That is, forecasts in our sample that referenced uncertainty in some form received more search results in reputable publications than forecasts that did not reference uncertainty.

Table 2 Average number of search results returned by type of forecast and mention of uncertainty

Search	*Mentions uncertainty?*	*All sources NO > YES*		*Reputable sources only NO < YES*	
		Must act	*Event*	*Must act*	*Event*
Prognosticator name and ‘climate	YES	1,018,625	83,485	2,992	2.07
	NO	3,744,400	9,733,147	2,605	0.37
	Test statistic (d.f.)	$t(30) = 1.57$	$t(6) = 1.91$	$t(46) = 0.22$	$t(27) = 1.46$
	Significance	$p = 0.063$	$p = 0.053$	n.s.	$p = 0.079$
Prognosticator name and quote fragment	YES	2,330	160	228	0.44
	NO	5,338	1,944	37,519	1.43
	Test statistic (d.f.)	$t(31) = 0.59$	$t(6) = 1.10$	$t(6) = -1.25$	$t(7) = -1.09$
	Significance	n.s.	n.s.	n.s.	n.s.

Notes: Two searches were used:
1. a Google search for the prognosticator’s name and the word ‘climate’
2. a Google search for the prognosticator’s name and the quote fragment containing the apocalyptic reference.

For the ‘reputable’ search results, the searches were restricted to the domains of the sources referenced in the text. The test statistic is for a two-sample t-test for means.

4.2 Scientist vs. non-scientist discourses and visibility

Previous research has already established that scientists are more likely to focus on objective measures in evaluating risk (as opposed to the more abstract measures used by laypersons). Because of this, scientists may be more likely to refer to uncertainty in their communications. Whereas non-scientists may focus on vivid consequences, scientists may be more likely to focus on expressions of likelihood. In fact, our data show that while 81% of scientists’ forecasts make reference to uncertainty, only 44% of non-scientists’ forecasts do.

This is important, because Petersen et al. (2019) have suggested that there is an anti-science bias in the media. In their data, forecasters with less scientific authority (by their measure) are featured disproportionately in media references to climate change scientists. We offer a different explanation. If scientists are more likely to refer to uncertainty in their forecasts, and as we noted in the previous section, forecasts that reference uncertainty result in fewer search results, could it not be an ‘anti-uncertainty’ bias at work, rather than an anti-science bias?

If the public’s aversion to uncertainty in forecasts is at work, we must ask whether or not it actually matters when it comes to forecasts. Implicit in Petersen et al. (2019) is the assumption that scientific forecasts are more valuable, ceteris paribus, than the forecasts of non-scientists. But Tetlock (2005), among others, has suggested that expert forecasts may not be as useful as they are perceived to be. We need not immediately address their relative *usefulness* and instead ask whether or not they are fundamentally *different*. If there is consensus between scientists and non-scientists as to the forecasts being made, then one might conclude that *who* makes them is less relevant.

We note, for example, that despite scientists making more references to uncertainty, there is substantial agreement in both groups' *expressions* of uncertainty. Given that uncertainty is mentioned, both groups are highly confident in their forecasts (68% of scientists and 75% of non-scientists suggest that the uncertainty in their forecasts is low). By comparison, only 20% of scientists and 25% of non-scientists who mention uncertainty suggest that it is high. Similarly, Table 3 reports the average forecast horizon between different groups. Again, there is substantial uniformity in the expressed beliefs. There are no significant differences in forecast horizon between the scientist and non-scientist groups across either type of forecast (*must act* vs. *event*) or whether or not uncertainty was mentioned.

Table 3 Average forecast horizon (in years) among forecasters grouped by scientific background, reference to uncertainty, and type of forecast

	Mentions uncertainty		*Uncertainty not mentioned*	
	Scientists	*Non-scientists*	*Scientists*	*Non-scientists*
Must act	15.0 (4.9)	6.9 (1.4)	7.7 (3.1)	6.2 (2.4)
	$t(11) = -1.61$ (n.s.)		$t(20) = -0.34$ (n.s.)	
Event	45.4 (10.2)	59.5 (25.5)	N/A	38.5 (20.9)
	$t(15) = 0.48$ (n.s.)		N/A	

Notes: Standard errors are provided in parentheses. The differences in scientist-non-scientist mean horizons were compared using Welch's test for unequal variances.

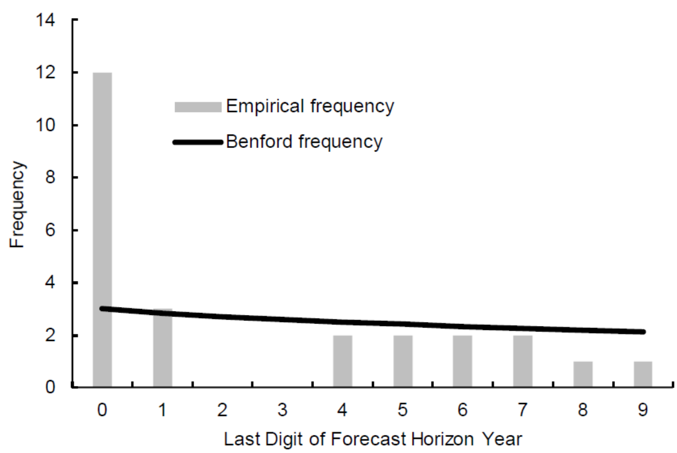
As a result, even though public discourse tends to be dominated by voices that do not mention uncertainty, and those voices are disproportionately those of non-scientists, the substance of the forecasts such as horizon and level of uncertainty, remain substantially equal on average. Thus, if media sources are more inclined to feature forecasts that do not mention uncertainty, and those forecasts are more frequently from non-scientists, we cannot conclusively say that it is an anti-science bias at work (as Petersen et al., 2019) assert), rather than an anti-uncertainty bias. And regardless of such a bias, the public appears to be getting approximately the same messages. The damage that may be done from the exclusion of information about uncertainty may arise more from a loss of the prognosticator's credibility in the wake of failed forecasts. The coupling of univocality with apparent certainty may result in costly losses of credibility.

4.3 Univocality and the convergence of forecasts

The meaning behind forecasts may vary. There is the forecast *qua* forecast; that is, as a prediction of a future outcome. Then, there is the forecast as symbol; as a 'consciousness-raising' alarm. We see this difference in the two types of forecasts we capture: must act and event. A *must act* forecast is literally a call to action. These forecasts have tended to have been made around significant policy events. In particular, the Copenhagen (December 2009) and Paris (November–December 2015) meetings, held under the United Nations Framework Convention on Climate Change, have served as focal points for the issuance of apocalyptic forecasts. For these *must act* forecasts, the intent may not be literal, but emphatic, in order to encourage a belief in fear over rational scientific discourse (Skrimshire, 2014). These apocalyptic forecasts may be issued specifically to apply political pressure to policymakers to take action on the meetings' agendas.

In contrast, we note an entirely different pattern with the *event* forecasts. The event forecasts can be interpreted just as they are: statements about the expected future state of the world. It is noteworthy, then, that future apocalyptic events are overwhelmingly forecast to occur in years divisible evenly by ten. The pursuit of univocality has caused the forecasts to converge – in part – to a specific set of years. The years 2000, 2030, 2050, and 2100 appear more frequently than any other years in our sample as the date on which an apocalyptic climate event is forecast to occur. This is unusual. The so-called law of anomalous numbers (Benford, 1938) determines the frequency distribution for certain digits to occur. If we refer to years by their final two digits (2015 = 15, 2016 = 16, etc.), we can determine the expected frequency we should observe if the horizon dates were the result of a random process.[8] Instead, as Figure 2 illustrates, this is most definitely not the case. There is a substantial clustering of forecasts at years ending in zero, and we can easily conclude that the empirical distribution differs significantly from Benford's (1938) distribution (Kolmogorov-Smirnov $D = 0.80$, $p < 0.01$). As the empirical distribution is most decidedly not random, we can conclude that it is the result of a forecasting environment that encourages convergence of results.

Figure 2 Frequency plot of *event* predictions by last digit of horizon year



Note: The black line illustrates the frequencies implied by Benford's law.

This process is akin to the well-known phenomenon of 'heaping', or digit preference, that affects estimation decision processes. In some ways, heaping is an expression of uncertainty, in that rounded numbers are often assumed to be approximate. By itself, nothing is unusual about this. Few would be shocked that an extreme forecast was uncertain. And yet, there is a seeming reluctance to actually vocalise that position. If scientists bring different models and their results to the table, and it is only the desire for univocality that causes them to converge on a specific year, the result is not confidence in a single number, but overconfidence attributed to the least mutually-objectionable number. Herrmann and Thomas (2005) examined professional financial analysts' forecasts of company earnings, which show a disproportionately high frequency at nickel intervals. As these forecasts are high-stakes decisions, the authors sought to determine if the heaping analysts were materially different from non-heaping analysts. They found, in fact, that analysts who engaged in heaping were less accurate, less informed, and made lower effort than analysts in general. In our data, there was no significant difference in heaping behaviour between scientists and non-scientists (two-tailed χ^2 test for equality of proportions, $T = -0.42$, n.s.). It is worth asking, then, if the uncommon frequency of years ending in zero in apocalyptic climate forecasts is merely the social and professional pressure to converge to a single voice, or whether it reflects an estimation process among less accurate and less informed prognosticators. In neither of these explanations, however, is an objective scientific process.

4.4 On the certainty of sceptics' forecasts

Although it is not the direct focus of this paper, we would be remiss not to comment on the forecasts of the *absence* of an apocalyptic event. As our dataset covers only forecasts of apocalyptic events, one may well ask how certain climate-change 'sceptics' are of their implied forecasts of the absence of an apocalyptic event. This is, of course, a fair question, but one short of data. Media outlets rarely cover a pronouncement that "disaster not to occur in 2030." Nevertheless, statements by those sceptical of climate change declaring that apocalyptic predictions are wrong are implicitly forecasts of the absence of such an event.

Just as an apocalyptic forecast should be stated with some degree of uncertainty, so too should its contradiction. It would be of interest, data permitting, to investigate whether there is a more 'fundamentalist posture' (Paterson, 2011) on one side or the other. We suspect there is an excess of certainty on both sides, and do not mean to imply that the forecasting issues we identify, including univocality, are applicable only to climate-change 'believers'. As a simple example, we note that of the 4,156 pages of the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (IPCC, 2014a, 2014b, 2013), 1,035 pages (24.9%) include the word 'uncertainty'. In contrast, the 'sceptical' Heartland Institute's 'Climate Change Reconsidered' reports (Bezdek et al., 2019; Idso and Singer, 2009) mention 'uncertainty' on only 118 of their combined 1,650 pages (7.2%). Nevertheless, the available data do not allow us to explore this avenue further.

5 Implications for policy and risk communication

Uncertainty is a core challenge for climate change science. It can undermine public engagement (Budescu et al., 2012) and form a barrier to public mobilisation (Pidgeon and Fischhoff, 2011). Our findings in this paper support these results and suggest that the exclusion of uncertainty from communication of apocalyptic climate-related forecasts can increase the visibility of the forecasts. However, the increased visibility comes at the cost of emphasising the voices of speakers without a scientific background. But focusing only on the *quantity* of communications, and not the 'weight' attached to them, neglects the important role that their credibility plays in establishing trust.

Trust (in subject-matter authorities and in climate research) influences perceived risk (Visschers, 2018; Siegrist and Cvetkovich, 2000). The impact of that trust is significant.

Although belief in the existence of climate change remains strong, belief that its risks have been exaggerated has grown (Wang and Kim, 2018; Poortinga et al., 2011; Whitmarsh, 2011). Gaps have also emerged between belief in climate change and estimates of the seriousness of its impact (Markowitz and Guckian, 2018). To the extent that failed predictions damage that trust, the public's perception of climate-related risk is altered. If the underlying purpose of making apocalyptic predictions is to recommend action, and if the predictions fail to materialise, the wisdom of the recommendations based on those predictions may be called into question. Climate science's perceived value is thereby diminished. If the perceived value (or the certainty of that value) is diminished, policy action is harder to achieve.

It is not simply the presence of uncertainty that is an impediment, it is that communications characterised by 'hype and alarmism' also undermine trust (Howe et al., 2019; O'Neill and Nicholson-Cole, 2009). The continual failure of the predictions to materialise may be seen to validate the public's belief that such claims *are* in fact exaggerated. Although such beliefs may be the result of outcome bias (Baron and Hershey, 1988), recent evidence has also suggested that certain commonly accepted scientific predictions may indeed be exaggerated (Lewis and Curry, 2018). The model of belief we presented in Subsection 2.4 demonstrates that observing only failures will inevitably result in a reduction in subjective beliefs about apocalyptic risks.

To build trust, any forecasts made must be 'scientific' – that is, able to be observed both incorrect *and* correct (Green and Armstrong, 2007). Under such circumstances, they should also incorporate clear statements acknowledging uncertainty, as doing so may work to increase trust (Joslyn and LeClerc, 2016). It is important to provide settings where the audience can 'calibrate' its beliefs. "A climate forecast can only be evaluated and potentially falsified if it provides a quantitative range of uncertainty" [Allen et al., (2013), p.243]. The acknowledgement of the uncertainty should include both worst-case and best-case outcomes (Howe et al., 2019).

One key to increasing credibility is to build up a series of shorter, simpler (non-apocalyptic) predictions (Nemet, 2009). Instead of predicting solely an apocalyptic event 50 years out, offer a series of contingent forecasts of shorter characteristic time (Byerly, 2000) that lead toward the ultimate event. Communications about climate change – and especially climate change-related predictions – should emphasise areas of the science that are less extreme in outcome, but more tangibly certain in likelihood (Howe et al., 2019). This implies, *inter alia*, that compound forecasts of events and the consequences of events should be separated. The goal may even be to exploit an outcome bias in decision making by moving from small- to large-scale predictions. By establishing a successful track record of smaller-scale predictions, validated with *ex post* evaluations of forecast accuracy, the public may be more inclined to increase its *trust* of the larger-scale predictions – even when such predictions are inherently less certain.

This approach has been advocated directly by Pielke (2008) and Fildes and Kourentzes (2011) and supports the climate prediction efforts of Meehl et al. (2014), Smith et al. (2019), and others. To that end, we propose four concrete steps that can be taken to improve the usefulness of extreme climate forecasts. First, the authors of the forthcoming Sixth Assessment Report of the IPCC should be encouraged to tone down 'deadline-ism' (Asayama et al., 2019). Forecasters should make an effort to influence the interpretation of their forecasts; for example, by correcting media reporting of them. The sequential releases of the IPCC's Assessment Reports, for example, should consider calling out particularly erroneous or incomplete interpretations of statements from *previous* Assessment Reports.

Second, given the extensive evidence about the limited forecasting abilities of individual experts (Tetlock, 2005), forecasters should give more weight to the unique ability of markets to serve as efficient aggregators of belief in lieu of negotiated univocality. So-called prediction markets have a strong track record (Wolfers and Zitzewitz, 2004). Although they have been suggested multiple times for climate change-related subjects (Lucas and Mormann, 2019; Vandenbergh et al., 2014), they have almost never been used. An exception is the finding that pricing in weather financial derivatives is consistent with the output of climate models of temperature (Schlenker and Taylor, 2019).

Third, efforts to provide reliable mid-term predictions should be encouraged. The multi-year and decadal prediction work of Smith et al. (2019) and Meehl et al. (2014) is in this direction. But what should (also) be developed are *repeated* and *sequential* forecasts in order to facilitate learning about the forecasting process itself. That is, not just how current climate forecasting models perform in hindcasts, but how previous climate forecasts have performed (and hopefully improved) over time. Efforts to determine the limits of predictability are also important (Meehl et al., 2014) and should be studied in conjunction with the evaluation of forecast performance over time.

Fourth, extreme caution should be used in extrapolating from forecasts of climate events (e.g., temperature or CO_2 levels) to their social and physical consequences (famine, flooding, etc.) without the careful modelling of mitigation and adaptation efforts and other feedback mechanisms. While there have been notable successes in predicting certain climate characteristics, such as surface temperature (Smith et al., 2019), the ability to tie such predictions to quantitative forecasts of *consequences* is more limited. The efforts to model damages as part of determining the social cost of carbon (such as with the DICE, PAGE, and FUND integrated assessment models) are a start but are subject to extreme levels of parameter sensitivity (Wang et al., 2019); uncertainty should be reflected in any forecasts of apocalyptic forecasts of climate change *consequences*.

Scientists are often encouraged to 'think big', especially in policy applications. What we are suggesting here is that climate policy analysis could benefit from thinking 'small'. That is, from focusing on the lower-level building blocks that go into making larger-scale predictions. One means by which to build public support for a complex idea like climate change is to demonstrate to the public that our understanding of the building blocks of that science are solid, that we are calibrated as to the accuracy of the building block forecasts, and that we understand how lower-level uncertainty propagates through to probabilistic uncertainty in the higher-level forecasts of events and consequences.

6 Conclusions

Predicting an apocalyptic event carries with it grave and awesome responsibilities. To the extent that such an event *can* be predicted, its prediction deserves to be based on the best scientific evidence available. We began this paper, however, by suggesting that there were factors outside of climate science itself that could influence such predictions. For a forecast to be useful, it must be properly understood by an audience capable of calibrating their beliefs to the uncertainty involved, and it must be credible.

Based on our dataset of apocalyptic climate-related forecasts, we observed that neglecting uncertainty results in greater visibility, but shifts focus away from prognosticators with scientific backgrounds. Further, the omission of quantitative information about uncertainty tends to undermine trust in the forecast – even when conclusions about uncertainty and horizon are similar between scientists and non-scientists. We also found that efforts to encourage univocality among scientific voices may unintentionally lead to less credible forecasts, in that they are based on an artificial consensus, rather than legitimate uncertainty. Policymakers must exercise considerable caution in communicating complex and uncertain ideas to the public because the perceived credibility of beliefs can be influenced by factors that are not entirely objective, and that scientists ought not to neglect that *communication* of their results deserves no less thought and care than the *production* of their results.

We propose an approach that deemphasises making extreme predictions (that can only be observed in their failure) and instead emphasises making a set of smaller, shorter-term, 'building-block' predictions that can be used to better motivate a public acceptance of climate science that has been plagued with growing scepticism. These results serve as a caution to climate scientists that the *act* of communicating an extreme prediction itself conveys information – and that information may not be entirely consistent with the *substance* of what is being communicated. We therefore assert a corollary to Sagan's aphorism: extraordinary predictions require extraordinary caution in communication.

Acknowledgements

The authors gratefully acknowledge the research assistance of Max Yeh. All responsibility for any errors remains with the authors.

References

Af Wåhlberg, A. and Sjöberg, L. (2000) 'Risk perception and the media', *Journal of Risk Research*, Vol. 3, No. 1, pp.31–50.

Allen, M., Mitchell, J. and Stott, P. (2013) 'Test of a decadal climate forecast', *Nature Geoscience*, Vol. 6, No. 4, pp.243–244.

Asayama, S., Bellamy, R., Geden, O., Pearce, W. and Hulme, M. (2019) 'Why setting a climate deadline is dangerous', *Nature Climate Change*, Vol. 9, No. 8, pp.570–572.

Baron, J. and Hershey, J. (1988) 'Outcome bias in decision evaluation', *Journal of Personality and Social Psychology*, Vol. 54, No. 4, pp.569–579.

Benford, F. (1938) 'The law of anomalous numbers', *Proceedings of the American Philosophical Society*, Vol. 78, No. 4, pp.551–572.

Bezdek, R., Idso, C., Legates, D. and Singer, S. (2019) *Climate Change Reconsidered II: Fossil Fuels*, Nongovernmental International Panel on Climate Change, The Heartland Institute, Arlington Heights, IL.

Booker, C. (2018) *Global Warming: A Case Study in Groupthink*, Global Warming Policy Foundation Report 28 [online] https://www.thegwpf.org/content/uploads/2018/02/Groupthink.pdf (accessed 4 April 2018).

Bostrom, A. (1997) 'Risk perceptions: experts vs. lay people', *Duke Environmental Law and Policy Forum*, Vol. 8, No. 1, pp.101–113.

Budescu, D., Por, H. and Broomell, S. (2012) 'Effective communication of uncertainty in the IPCC reports', *Climatic Change*, Vol. 113, No. 1, pp.181–200.

Butts, C. (1998) 'A Bayesian model of panic in belief', *Computational and Mathematical Organization Theory*, Vol. 4, No. 4, pp.373–404.

Byerly Jr., R. (2000) 'Prediction and characteristic times', in Sarewitz, D. et al. (Eds.): *Prediction: Science, Decision Making, and the Future of Nature*, pp.327–340, Island Press, Washington, DC.

Choi, H. and Varian, H. (2012) 'Predicting the present with Google Trends', *The Economic Record*, Vol. 88, No. S1, pp.2–9.

Combs, B. and Slovic, P. (1979) 'Newspaper coverage of causes of death', *Journalism Quarterly*, Vol. 56, No. 4, pp.837–849.

Ding, D., Maibach, E., Zhao, X., Roser-Renouf, C. and Leiserowitz, A. (2011) 'Support for climate policy and societal action are linked to perceptions about scientific agreement', *Nature Climate Change*, Vol. 1, No. 9, pp.462–466.

Doulton, H. and Brown, K. (2009) 'Ten years to prevent catastrophe? Discourses of climate change and international development in the UK press', *Global Environmental Change*, Vol. 19, No. 2, pp.191–202.

Ettredge, M., Gerdes, J. and Karuga, G. (2005) 'Using web-based search data to predict macroeconomic statistics', *Communications of the ACM*, Vol. 48, No. 11, pp.87–92.

Festinger, L., Riecken, H. and Schachter, S. (1956) *When Prophecy Fails*, University of Minnesota Press, Minneapolis, MN.

Fildes, R. and Kourentzes, N. (2011) 'Validation and forecasting accuracy in models of climate change', *International Journal of Forecasting*, Vol. 27, No. 4, pp.968–995.

Fischhoff, B. and Davis, A. (2014) 'Communicating scientific uncertainty', *Proceedings of the National Academy of Sciences*, Vol. 111, pp.13664–13671.

Fischhoff, B., Slovic, P. and Lichtenstein, S. (1982) 'Lay foibles and expert fables in judgments about risk', *The American Statistician*, Vol. 36, No. 3b, pp.240–255.

Geden, O. (2018) 'Politically informed advice for climate action', *Nature Geoscience*, Vol. 11, No. 6, pp.380–383.

Gerjuoy, H. (1977) 'Validity of forecasting systems', in Boucher, W. (Ed.): *The Study of the Future: An Agenda for Research*, pp.33–37, US Government Printing Office, Washington, DC.

Ginsberg, J., Mohebbi, M., Patel, R., Brammer, L., Smolinski, M. and Brilliant, L. (2009) 'Detecting influenza epidemics using search engine query data', *Nature*, Vol. 457, No. 7232, pp.1012–1014.

Green, K. and Armstrong, J. (2007) 'Global warming: forecasts by scientists versus scientific forecasts', *Energy & Environment*, Vol. 19, 7–8 pp.997–1021.

Herrmann, D. and Thomas, W. (2005) 'Rounding of analyst forecasts', *The Accounting Review*, Vol. 80, No. 3, pp.805–823.

Howard, R. (1966) 'Information value theory', *IEEE Transactions of Systems Science and Cybernetics*, Vol. 2, No. 1, pp.22–26.

Howe, L., MacInnis, B., Krosnick, J., Markowitz, E. and Socolow, R. (2019) 'Acknowledging uncertainty impacts public acceptance of climate scientists' predictions', *Nature Climate Change*, Vol. 9, No. 11, pp.863–867.

Idso, C. and Singer, S. (2009) *Climate Change Reconsidered: 2009 Report of the Nongovernmental Panel on Climate Change*, The Heartland Institute, Chicago, IL.

IPCC (2013) 'Climate Change 2013: The Physical Science Basis', in Stocker et al. (Eds.): *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, NY.

IPCC (2014a) 'Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects', in Field et al. (Eds.): *Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, NY.

IPCC (2014b) 'Climate Change 2014: Mitigation of Climate Change', in Edenhofer et al. (Eds.): *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, New York, NY.

Johnson, B. and Covello, V. (1987) 'Agenda-setting, group conflict, and the social construction of risk', in Johnson, B. and Covello, V. (Eds.): *The Social and Cultural Construction of Risk*, pp.179–181, D. Reidel Publishing, Dordrecht, Netherlands.

Joslyn, S. and LeClerc, J. (2016) 'Climate projections and uncertainty communication', *Topics in Cognitive Science*, Vol. 8, No. 1, pp.222–241.

Kasperson, J., Kasperson, R., Pidgeon, N. and Slovic, P. (2003) 'The social amplification of risk: fifteen years of research and theory', in Pidgeon, N. et al. (Eds.): *The Social Amplification of Risk*, Cambridge University Press, Cambridge, UK, pp.13–46.

Kasperson, R., Renn, O., Slovic, P., Brown, H., Emel, J., Goble, R., Kasperson, J. and Ratick, S. (1988) 'The social amplification of risk: a conceptual framework', *Risk Analysis*, Vol. 8, No. 2, pp.177–187.

Kirshenbaum, S. (2019) *No, Climate Change Will Not End the World in 12 Years*, Scientific American, 13 August [online] https://blogs.scientificamerican.com/observations/no-climate-change-will-not-end-the-world-in-12-years/ (accessed 3 January 2020).

Ladle, R., Jepson, P. and Whittaker, R. (2005) 'Scientists and the media: the struggle for legitimacy in climate change and conservation science', *Interdisciplinary Science Reviews*, Vol. 30, No. 3, pp.231–240.

Lewis, N. and Curry, J. (2018) 'The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity', *Journal of Climate*, Vol. 31, No. 15, pp.6051–6071.

Lucas, G. and Mormann, F. (2019) 'Betting on climate policy: using prediction markets to address global warming', *Davis Law Review*, Vol. 52, No. 3, pp.1429–1486, University of California.

MacDougall, A. (2016) 'The transient response to cumulative CO_2 emissions: a review', *Current Climate Change Reports*, Vol. 2, No. 2, pp.39–47.

Markowitz, E. and Guckian, M. (2018) 'Climate change communication: challenges, insights, and opportunities', in Clayton, S. and Manning, C. (Eds.): *Psychology and Climate Change*, pp.35–63, Academic Press, Cambridge, MA.

McCright, A., Dunlap, R. and Xiao, C. (2013) 'Perceived scientific agreement and support for government action on climate change in the USA', *Climatic Change*, Vol. 119, No. 2, pp.511–518.

Meehl, G. et al. (2014) 'Decadal climate prediction: an update from the trenches', *Bulletin of the American Meteorological Society*, Vol. 95, No. 2, pp.243–267.

Millar, R., Allen, M., Rogelj, J. and Friedlingstein, P. (2016) 'The cumulative carbon budget and its implications', *Oxford Review of Economic Policy*, Vol. 32, No. 2, pp.323–342.

Nemet, G. (2009) 'Interim monitoring of cost dynamics for publicly supported energy technologies', *Energy Policy*, Vol. 37, No. 3, pp.825–835.

O'Neill, S. and Nicholson-Cole, S. (2009) ''Fear won't do it': promoting positive engagement with climate change through visual and iconic representations', *Science Communication*, Vol. 30, No. 3, pp.355–379.

Oppenheimer, M., Oreskes, N., Jamieson, D., Brysse, K., O'Reilly, J., Shindell, M. and Wazeck, M. (2019) *Discerning Experts: The Practices of Scientific Assessment for Environmental Policy*, University of Chicago Press, Chicago, IL.

Painter, J. (2013) *Climate Change in the Media*, I.B. Tauris, New York, NY.

Paterson, J. (2011) *Tim Flannery: Climate Prophet*, IPA Review, June [online] https://ipa.org.au/wp-content/uploads/archive/1312242846_document_flannery.pdf (accessed 4 April 2018).

Peires, J. (1989) *The Dead Will Arise: Nongqawuse and the Great Xhosa Cattle-killing Movement of 1856-7*, Indiana University Press, Bloomington, IN.

Peters, G. (2018) 'Beyond carbon budgets', *Nature Geoscience*, Vol. 11, No. 6, pp.378–380.

Petersen, A., Vincent, E. and Westerling, A. (2019) 'Discrepancy in scientific authority and media visibility of climate change scientists and contrarians', *Nature Communications*, Vol. 10, Article ID 3502.

Pidgeon, N. and Fischhoff, B. (2011) 'The role of social and decision sciences in communicating uncertain climate risks', *Nature Climate Change*, Vol. 1, No. 3, pp.35–41.

Pielke Jr., R. (1999) 'Who decides? Forecasts and responsibilities in the 1997 Red River flood', *Applied Behavioral Science Review*, Vol. 7, No. 2, pp.83–101.

Pielke Jr., R. (2008) 'Climate predictions and observations', *Nature Geoscience*, Vol. 1, No. 4, p.206.

Pielke Jr., R., Sarewitz, D. and Byerly Jr., R. (2000) 'Decision making and the future of nature: understanding and using predictions', in Sarewitz, D. et al. (Eds.): *Prediction: Science, Decision Making, and the Future of Nature*, pp.361–387, Island Press, Washington, DC.

Poortinga, W., Spence, A., Whitmarsh, L., Capstick, S. and Pidgeon, N. (2011) 'Uncertain climate: an investigation into public skepticism about anthropogenic climate change', *Global Environmental Change*, Vol. 21, No. 3, pp.1015–1024.

Rode, D. and Fischbeck, P. (2019) *List of Climate-Related Apocalyptic Predictions*, Mendeley Data, v2 [online] http://dx.doi.org/10.17632/473mjg7y7z.2 (accessed 3 January 2020).

Schlenker, W. and Taylor, C. (2019) *Market Expectations about Climate Change*, Working Paper 25554, National Bureau of Economic Research [online] http://www.nber.org/papers/w25554 (accessed 14 August 2019).

Siegrist, M. and Cvetkovich, G. (2000) 'Perception of hazards: the role of social trust and knowledge', *Risk Analysis*, Vol. 20, No. 5, pp.713–720.

Skolnikoff, E. (1990) 'The policy gridlock on global warming', *Foreign Policy*, Summer, Vol. 79, pp.77–93.

Skrimshire, S. (2014) 'Climate change and apocalyptic faith', *WIREs Climate Change*, Vol. 5, No. 2, pp.233–246.

Slovic, P. (1986) 'Informing and educating the public about risk', *Risk Analysis*, Vol. 6, No. 4, pp.403–415.

Slovic, P., Fischhoff, B. and Lichtenstein, S. (1982a) 'Facts versus fears: understanding perceived risk', in Kahneman, D. et al. (Eds.): *Judgment Under Uncertainty: Heuristics and Biases*, pp.463–489, Cambridge University Press, New York, NY.

ˆSlovic, P., Fischhoff, B. and Lichtenstein, S. (1982b) 'Why study risk perception?', *Risk Analysis*, Vol. 2, No. 2, pp.83–93.

Smith, D. et al. (2019) 'Robust skill of decadal climate predictions', *NPJ Climate and Atmospheric Science*, Vol. 2, Article 13.

Smith, J. (2005) 'Dangerous news: media decision making about climate change risk', *Risk Analysis*, Vol. 25, No. 6, pp.1471–1482.

Spence, W., Herrmann, R., Johnston, A. and Reagor, G. (1993) *Responses to Iben Browning's Prediction of a 1990 New Madrid, Missouri*, Earthquake, U.S. Geological Survey Circular 1083, U.S. Government Printing Office, Washington, DC [online] https://pubs.usgs.gov/circ/1993/1083/report.pdf (accessed 12 November 2019).

Taubes, G. (1997) 'Apocalypse not', *Science*, Vol. 278, No. 5340, pp.1004–1006.

Tetlock, P. (2005) *Expert Political Judgment*, Princeton University Press, Princeton, NJ.

Vandenbergh, M., Raimi, K. and Gilligan, J. (2014) 'Energy and climate change: a climate prediction market', *UCLA Law Review*, Vol. 61, No. 6, pp.1962–2017.

Visschers, V. (2018) 'Public perception of uncertainties within climate change science', *Risk Analysis*, Vol. 38, No. 1, pp.43–55.

Wang, J. and Kim, S. (2018) 'Analysis of the impact of values and perception on climate change skepticism and its implication for public policy', *Climate*, Vol. 6, No. 4, pp.99–126.

Wang, P., Deng, X., Zhou, H. and Yu, S. (2019) 'Estimates of the social cost of carbon: a review based on meta-analysis', *Journal of Cleaner Production*, Vol. 209, pp.1494–1507.

Weingart, P., Engels, A. and Pansegrau, P. (2000) 'Risks of communication: discourses on climate change in science, politics, and the mass media', *Public Understanding of Science*, Vol. 9, No. 1, pp.261–283.

Weitzman, M. (2009) 'On modelling and interpreting the economics of catastrophic climate change', *Review of Economics and Statistics*, Vol. 91, No. 1, pp.1–19.

Whitmarsh, L. (2011) 'Scepticism and uncertainty about climate change: dimensions, determinants and change over time', *Global Environmental Change*, Vol. 21, No. 2, pp.690–700.

Wolfers, J. and Zitzewitz, E. (2004) 'Prediction markets', *Journal of Economic Perspectives*, Vol. 18, No. 2, pp.107–126.

Notes

1 2 Peter 3:10, King James Bible.

2 $P(`A^c\text{'}) = 1 - P(`A\text{'})$. Exceptions do exist (e.g., Kirshenbaum, 2019), but are rare.

3 For instances in which a range has been provided, we have used the maximum horizon indicated.

4 This data consists of either their highest degree obtained or, if it was clear that they were speaking on behalf of an organisation, their position within the organisation.

5 A speaker was determined to have a scientific background if their degree was in a physical, biological, or social science. All other degrees, such as humanities, law, journalism, and politics, were determined to be 'non-scientific' for classification purposes.

6 We note that at least three of the speakers shared names with other prominent people, which may have inflated their general search results (but presumably not those searches made in conjunction with the term 'climate'). Specifically, Aled Jones is also the name of a Welsh radio and television presenter, Michael Mann is also the name of a television and film director, and Peter Smith is also the name of a professor at the University of Aberdeen who has not (to our knowledge) made any apocalyptic predictions about climate. Petersen et al. (2019) concluded that the impact of the name misattribution problem was minimal.

7 Characterisation of a source as 'reputable' is obviously subjective. For this paper, we used a list of sources deemed to be reputable prepared by a Forbes magazine columnist (https://www.forbes.com/sites/berlinschoolofcreativeleadership/2017/02/01/10-journalism-brands-where-you-will-find-real-facts-rather-than-alternative-facts). The included sources are the New York Times, the Wall Street Journal, the Washington Post, the BBC, the New Yorker, the Associated Press, the Atlantic, and Politico.

8 We use Table 3 in Benford (1938) to determine the frequency of digits in the second place of two-digit numbers.