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Explaining How Long CO_2 Stays in the Atmosphere: Does It Change Attitudes Toward Climate Change?

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Despite overwhelming scientific consensus about climate change, the majority of Americans are not very worried about it. This may be due in part to insufficient understanding of the urgency and seriousness, which may be related among some, to distrust of the scientific community. We test these hypotheses in an experimental study using a broadly nationally representative sample. An explanation of the delay between the reduction of greenhouse gas emissions and cessation of global warming was compared to two control groups, one with basic climate change information and another with no information. Participants also received climate predictions that either included or excluded uncertainty estimates for a 3 × 2 complete factorial design. Results suggest that the delay explanation increased participants understanding of this issue and reduced their agreement with a wait-and-see strategy, especially among conservatives. Moreover, uncertainty estimates increased trust in climate predictions and ratings of climate scientists' expertise and understanding. Uncertainty estimates also increased concern about climate change and the perception of scientific consensus. Although in some cases small, these positive effects were seen across political ideology groups.

Public Significance Statement
This experiment demonstrated that targeted scientific explanations can help members of the public understand complex but important climate change issues. It also demonstrated that providing uncertainty estimates along with climate predictions increased trust in the predictions themselves as well as in the climate scientists who produced them and the perception of scientific consensus about climate change.

Keywords: reasoning, decision making, climate change, uncertainty

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From a scientific perspective we have reached a critical point with regard to global warming (Ripple et al., 2017). Indeed, there is overwhelming scientific consensus that the effects of anthropogenic climate change are already being felt. Moreover, historically unprecedented atmospheric and environmental change will continue, even under the best-case scenario, for the next several decades if not centuries (Wuebbles et al., 2017). However, Americans' attitudes and perceptions have lagged behind the scientific evidence. Only 23% of Americans sampled in one study reported being very worried about climate change in 2019 (Leiserowitz, Maibach, Rosenthal, Kotcher, Bergquist, et al., 2019). Worse, recent polls show that political polarization in the U.S. around global warming has increased recently, with the percent of conservatives supporting climate issues declining (Gustafson et al., 2019), and fewer conservatives being worried about climate change than in 2008 (Leiserowitz, Maibach, Rosenthal, Kotcher, Ballew, et al., 2019).

This may be due, at least in part to insufficient understanding of the urgency and seriousness of this complex problem. Laypeople often try to understand complex topics by building on information they already have, also referred to as mental models. These are mental representations of how something works (Gentner & Stevens, 1983; Johnson-Laird, 1983). Mental models that include the basic links between human behavior, global warming, and specific relevant consequences may lead to both a better understanding of climate change and a greater appreciation of the seriousness of the problem (Morgan et al., 2002). Although many researchers agree that knowledge deficits alone do not fully account for attitudes toward climate change (Corner et al., 2017; Irwin et al., 2018), knowledge *does* appear to play an important role. Objectively measured climate knowledge (Hornsey et al., 2016) and increased understanding of the causal mechanisms that lead to global warming (Ranney & Clark, 2016; Ranney et al., 2019; Van Der Linden et al., 2017; Velautham et al., 2019) have been shown to increase acceptance of climate change.

Conversely, specific misunderstandings may be at the root of low concern about climate change. For example, many nonexperts fail to realize the extended time frame of climate recovery following the onset of the reduction of greenhouse gas emissions (on the order centuries, barring successful geoengineering). They think instead that it will take only a few years or a decade at most (Dryden et al., 2018).

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Nonexperts' misunderstanding of this issue may be related to a general misunderstanding of problems involving stocks and flows (Sterman & Sweeney, 2007). People's mental models tend to omit the fact that stock accumulates when production exceeds distribution, leading to the false assumption that the output of a system is positively correlated with its inputs (Cronin et al., 2009; Sterman & Sweeney, 2007; Sweeney & Sterman, 2000). A similar accumulation occurs as a result of the rate at which greenhouse gasses enter (production) and leave (distribution) the atmosphere. Because of the slow absorption rate of greenhouse gasses, global average temperature will continue to rise long after reduction in emissions. Nonetheless, people tend to think that both will decline at a similar rate, suggesting that their mental models do not distinguish these rates but rather make the simplifying assumption that they are the same. Although reasoners may be unaware of the process that led to it, this misunderstanding could support a wait-and-see attitude because people mistakenly think that the problem can be solved soon after we start cutting emissions. This may, in turn, reduce concern as well as the urgency for taking action. Therefore, explicitly pointing out the delay may allow people to correct their mental models so that the rate of emission reduction and accumulations of greenhouse gases in the atmosphere are represented separately. That would allow them to differ from one another, accumulations continuing to increase for an extended period after emissions have been reduced. This is one of the main issues that we tackle in the research reported here. Although there is evidence that interactive sessions improve people's understanding of stock–flow problems (Cronin et al., 2009; Ranney & Clark, 2016), here we test whether a much simpler intervention (Figures 1 and 2) improves understanding. This explanation alone may increase appreciation of the long delay between carbon emission reduction and slowed global warming because it makes each step in the reasoning process explicit. That, in turn, may increase concern about global climate change and decrease willingness to endorse a "wait-and-see" policy.

However, this intervention may not have the same effect on individuals across the political spectrum. On average, conservatives report less concern about global warming (Bostrom et al., 2019; Joslyn & Demnitz, 2019) as well as less trust in, and willingness to respond to climate communications (Bolsen & Druckman, 2015; Feldman & Hart, 2016; Mossler et al., 2017). This is important because motivated reasoning theory asserts that people process new information in a manner that reinforces their prior beliefs or what they wish to see (Dieckmann et al., 2017; Goidel et al., 1997; Hart & Nisbet, 2012; Kahan, 2015; Sunstein et al., 2016; Tappin et al., 2017). Therefore, explanations could conceivably have the opposite or boomerang effect among conservatives in the context of climate change because they have different beliefs about climate change to begin with (Hart & Nisbet, 2012). To test this question, we used a broadly nationally representative sample (see Table 1) and examined the impact of political ideology as well as explanation on understanding, attitudes toward climate change and trust.

Indeed, trust may be particularly important to the highly politicized issue of climate change. We have evidence that trust in climate predictions increases when uncertainty estimates in the form of predictive intervals (range of possible values with specified probability) are included compared to predictions without uncertainty estimates (Joslyn & Demnitz, 2019; Joslyn & Leclerc, 2012). This is probably because people know intuitively that predictions, such as those for weather or climate, involve uncertainty (Joslyn & Savelli, 2010; Morss et al., 2008). Therefore, acknowledging uncertainty may make climate predictions more plausible. However, other evidence suggests that conservatives tend to distrust scientists in general, especially when it comes to climate change (Gauchat, 2012; Hamilton, 2015; Hartman et al., 2017). For that reason, uncertainty estimates may appear to be a hedge or a signal of incompetence to some (Johnson, 2003; Johnson & Slovic, 1995, 1998). Similarly, probabilistic predictions, in that they describe a range of possible values, may fuel the misperception that there is a lack of scientific consensus about the fact of climate change (Ding et al., 2011; Freudenburg & Muselli, 2010; Lewandowsky et al., 2013; Moser, 2010). Thus, although describing the inherent uncertainty may increase trust in climate predictions for some users, this strategy may have the opposite impact on others.

In addition, uncertainty may decrease concern. According to Construal Level Theory (Wakslak, et al., 2006), increased uncertainty increases abstraction, and therefore, psychological distance. Based on this perspective, one might expect a decrease in concern when probabilities are included. Indeed, evidence suggests that increases in psychological distance reduce both concern about climate change and willingness to take mitigative actions

Figure 1

Basic Explanation Provided to Participants Explaining the Mechanisms Leading to Climate Change

Scientists tell us that human activities are changing Earth's atmosphere and increasing Earth's average temperature. What causes these climate changes? First, let's understand Earth's "normal" temperature: When Earth absorbs sunlight, which is mostly visible light, it heats up. Like the Sun, Earth emits energy—but because it is cooler than the Sun, Earth emits lower energy infrared wavelengths. Greenhouse gases in the atmosphere (methane, carbon dioxide, etc.) let visible light pass through but absorb infrared light—causing the atmosphere to heat up. The warmer atmosphere emits more infrared light, which tends to be re-absorbed—perhaps many times—before the energy eventually returns to space. The extra time this energy hangs around has helped keep Earth warm enough to support life as we know it. However, since the industrial age began the quantity of atmospheric carbon dioxide and methane has increased (even as energy from the sun stays basically the same), causing *extra* infrared light absorption and *further* heating Earth above its typical temperature range. In other words, energy that gets to Earth has an even harder time leaving it now, causing Earth's average temperature to increase and producing global climate change.

Figure 2
Delay Explanation Provided to Participants in the Basic + Delay Condition

*If we start reducing greenhouse gas emissions **today**, and reduce them every year, concentrations in the atmosphere would continue to rise for **100** years.*
*The global average temperature would rise for **200** years.*
*And only fall after **300** years.*

Note. Participants in this condition received this information after reading the basic explanation paragraph (Figure 1).

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(Cameron, 2005; Spence et al., 2011). These questions regarding the impact of probabilistic predictions were also tested in the research described below.

In summary, in the experiment reported here, we tested the effect of a short explanation of the delay between the reduction in carbon emissions and the cessation of global warming on attitudes toward climate change and the urgency of responding to it. There were two control groups. In the first, no information was provided, and in the second, to test for effects of receiving *any* information (not specific to the delay issue) a basic explanation of the mechanisms leading to climate change (Figure 1) was provided. In addition, we tested the impact of climate predictions that included uncertainty estimates, compared to single-value predictions, on trust, concern and attitudes toward climate scientists. This resulted in a three (explanation: none, basic, delay) by two (prediction format: deterministic, probabilistic) full factorial design. We used a broadly nationally representative sample to determine whether either intervention interacts with political ideology.

Hypotheses

Our main hypotheses were that those with the delay explanation would (1) better understand the delay between the reduction in greenhouse gas emission and the reduction of concentrations in the atmosphere. As a result, they would be (2) less likely to endorse a "wait-and-see" strategy, (3) more concerned about climate change, and (4) more willing to donate to a climate related cause. We also predicted that those with probabilistic predictions would have (5) greater trust in the information provided as well as in the climate scientists who produced it, but might be less concerned and less convinced of scientific consensus. However, we thought that there might be an interaction such that the combination of delay explanation and uncertainty information would be particularly concerning in that it would result in greater understanding of the urgency and greater trust. Finally, (6) we expected that liberals would have higher scores on all measures than would conservatives and that moderates would fall between the two.

Table 1
Characteristics of Sample Compared to 2017 U.S. Census

Variable	Level	U.S. 2017 census	Sample
Sex	Male	49.2%	52.4%
	Female	50.8%	47.6%
Race	White	73%	73.4%
	Black	12.7%	8.3%
	Latino	17.6%	11.3%
Political ideology	Conservative	36%	35.4%
	Moderate	34%	35.4%
	Liberals	25%	29.2%
Education	Less than high school	10.4%	8.2%
	High school graduate	28.8%	25.8%
	Bachelor's or associate's	31.6%	31.2%
	Graduate or professional degree	12.9%	15.2%
Income	Less than $5,000	3.4%	2.5%
	$5,000–$24,999	16.65%	11.1%
	$25,000–$74,999	38.32%	36.7%
	$75,000–$199,999	33.5%	43.1%
	$200,000 or more	8.1%	6.6%

Note. Political ideology comes from the Gallup poll (2016) because Census does not record political ideology: https://news.gallup.com/poll/245813/Leans-conservative-liberals-keep-recent-gains.aspx.

Experiment

The experiment, approved by the University of Washington Human Subjects Division, was conducted between the dates in January 8th and 22nd, 2018 using an online research panel that was randomly recruited by a consumer information research company, Knowledge Networks (GfK) with telephone and mail surveys. The sampling frame included both listed and unlisted numbers, those with and without a landline telephone and those with and without computer and internet access. Details are shown in Appendix A. Prior to running the main experiment, a pilot study was conducted on Amazon Mechanical Turk (MTurk) to ensure that the explanations were understandable and to refine the dependent variables (Appendix B).

Explanations

Participants were randomly assigned to one of three explanation groups. In the experimental group, participants received a basic explanation of the mechanisms leading to climate change (Figure 1) adapted from the study by Ranney and Clark (2016). This explanation improved understanding among a broad range of participants including high school students in previous research (see Ranney & Clark, 2016; experiment 5). In addition, our participants received an explanation of the delay between reduction in carbon emissions and cessation of global warming (Figure 2).[1] Although the specific numbers were calculated using several assumptions (see Appendix C), the general principle shown in Figure 2 holds regardless. We refer to this as the basic + delay group. There were two control groups. In the first, no information was provided, and in the second, the basic explanation was presented alone.

[1] The Flesch-Kincaid reading levels of the basic and the basic + delay conditions were roughly similar (12.5 and 11.9 respectively).

Climate Predictions

In addition, all participants received two climate predictions, one describing temperature increase and the other precipitation change (see Table 2 in Appendix C). Both were described as being for "a location in the USA." In fact, they were both for the Puyallup River watershed and the city of Tacoma, Washington,[2] although this information was not made explicit to avoid any biases that could have occurred by specifying the location. Temperature predictions were based on the Coupled Model Intercomparison Project Phase 5 (CMIP5). Precipitation predictions were obtained by combining the 10 model projections for each of the 2 greenhouse gas scenarios (high and low), 20 in all. Half of participants received single values (averages) and the other half received 90% predictive intervals. We refer to the single-value predictions as "deterministic" because they imply that the exact value will be observed, and to the 90% predictive intervals as "probabilistic."

Procedure

After providing informed consent, participants (except those in the "no information" control), received a statement that the information they were about to receive was true, could be checked later, and shared with others (adapted from the study by Ranney & Clark, 2016). Then, they received the explanation(s) and rated their trust in the information on a 6-point scale between "*Not at all*" and "*Completely*." The trust rating was taken to provide a possible explanation for unexpected results. To gauge understanding and memory for the content, participants indicated the current trend in greenhouse gas concentrations in the atmosphere, choosing between "Not Changing," "Decreasing," or "Increasing." They also indicated how long concentrations of greenhouse gases in the atmosphere would continue to rise "if we start reducing emissions today and reduce them every year" (1 year, 10 years, 50 years, 100 years, 500 years, and 1,000 years).[3] The same questions were asked of the control group, although they did not see either paragraph, to gauge the degree to which the information was known preexperimentally.

To determine whether any explanation altered attitudes toward climate change, all participants answered questions about how concerned they were about global climate change (6 point scale between "*not at all*" and "*completely*"), whether they thought it was important to "take action now" (5-point scale between "*strongly disagree*" and "*strongly agree*"), or wait until it was clear that global warming was a problem (5-point scale between "*strongly disagree*" and "*strongly agree*"). We refer to this as endorsing a "Wait-and-See" strategy. To determine whether any variables affected participants' willingness to support efforts to slow global warming, they were asked what proportion of a $100 prize they would donate to an organization engaged in addressing global warming.[4] Because we hypothesized that answers to these four questions would be impacted by the explanation manipulation and were interested in the durability of such effects, this group of questions was asked either immediately after the paragraph (or first in the no information control) or last, after all the other questions. However, order had very little impact and will only be mentioned in the one analysis in which it did.

Participants then received the two climate predictions, one for average temperature increase and the other for precipitation increase. Half received deterministic estimates and half probabilistic estimates (see Table 2). Immediately afterward, they answered questions about the predictions to determine whether they had read them carefully and were paying attention. They indicated whether temperature or precipitation would increase (if so by how much), decrease (if so by how much), or stay the same. They also indicated the range of values that would not surprise them, by filling in blanks after the phrases "as little as" and "as great as."

Then, participants answered questions to determine the impact of the prediction format (deterministic vs. probabilistic). They indicated how much they trusted each prediction on a 6-point scale between "*not at all*" and "*completely*," and how concerned they were about each prediction on a 6-point scale between "*not at all*" and "*extremely*." Finally, all participants answered questions about their attitudes toward climate scientists. They indicated how much agreement there was among scientists about climate change (6-point scale from "*no agreement*" to "*complete agreement*"). They also indicated their assessment of climate scientists' expertise (6-point scale from "*none*" to "*all*") and understanding (6-point scale from "*not at all*" to "*completely*") of climate issues (questions based on those used in a study by Allum, 2007). Demographic information, including political ideology, was provided by GfK.

Design

The experiment employed a 3×2 complete factorial design. Explanation had three levels, no information, basic, and basic + delay. Prediction format had two levels, deterministic and probabilistic. Participants were randomly assigned to one of the six resulting conditions.

Participants

A total of 1,331 people participated and passed the attention check questions. We assumed that those who entered estimates that were four times the prediction provided (Table 2) and/or whose "as little as" estimates exceeded their "as great as" estimates, were not paying attention or not taking the task seriously.[5] The mean age was 51.59 years ($SD = 17.12$) and ranged between 18 and 91 years, 48% were female, 29.2% classified themselves as liberals, 35.4% as moderates, and 35.4% as conservatives. The sample was similar to the U.S. national census in terms of gender, race, education, income, and political ideology (see Table 1). The n's are slightly different in the analyses reported below because GfK does not require participants to answer all questions and some did not.

[2] A specific location was chosen because the effects of climate change on precipitation are difficult to appreciate as a global average because there will be greater totals in some locations and smaller totals in others.

[3] Two other questions were asked but slight errors in the administration invalidated them.

[4] GfK policies prevented us from offering an actual cash prize.

[5] The 157 participants who were omitted did not differ significantly from the main group in terms of age, gender, or political ideology. The results of all analyses were essentially the same regardless of whether or not they were included, although in two cases, noted below, the effect changed from significant to approaching significance. In one case, noted below, the effect no longer reached significance.

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Table 2
Climate Predictions and Climate Prediction Formats

Deterministic	Scientists estimate that by the end of the next century, the average yearly *temperature will increase by 7°F* compared to the end of the last century.
	Scientists estimate that by the end of the next century the average yearly *precipitation will increase by 3 inches* compared to the end of the last century.
Probabilistic	Scientists estimate that by the end of the next century, the average yearly *temperature will increase by 7°F* compared to the end of the last century, with a *90% chance that the increase will be between 4°F and 11°F.*
	Scientists estimate that by the end of the next century, the average yearly *precipitation will increase by 3 inches* compared to the end of the last century, with a *90% chance that the increase will be between 1 and 5 inches.*

Note. Half of the participants received deterministic estimates, single-value predictions for temperature and precipitation increase. The other half also received probabilistic estimates, the 90% predictive interval for the same events. Each set was preceded by this statement: "Please read the following climate predictions for a location in the USA and answer the questions thoughtfully."

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Results

Analytic Approach

Prior to conducting the main analyses, we examined political ideology, a categorical variable that included liberals, moderates, and conservations. Because this was a potentially critical factor, Pearson Chi Square analyses were conducted to verify that random assignment had resulted in proportions of liberals, moderates, and conservatives that were roughly the same across conditions.

Then, logistic regressions were conducted on the accuracy of participants' answers to the "understanding" questions to determine whether they were more accurate when the relevant information was presented. Analyses of variance were conducted on continuous dependent variables (trust, concern, and attitudes toward global warming) with categorical independent variables including political ideology (liberal, moderate, and conservative), explanation (none, basic, and basic + delay), and prediction format (deterministic and probabilistic). Prediction format was not included in the analysis of dependent variables measured prior to the presentation of the predictions. Otherwise, all main effects and interactions (where more than one independent variable was included) were tested to address the key hypotheses listed above. For all analyses we used an alpha level of .05, unless otherwise stated. All pairwise comparisons were conducted with SPSS Bonferroni adjustments.[6] Effect sizes are reported using Partial Eta squared or Cohen's D and include 95% confidence intervals. No sampling weights were used. Please note that in the Results section below each of the hypotheses (listed at the end of the Introduction) is addressed under a separate subhead with the exception of Hypothesis 6 (liberals would be higher on all measures than conservatives and moderates in between) which is addressed in all analyses.

Hypothesis 1: Effect of Explanations on Understanding

To determine whether participants better understood the information when they received the explanations compared to the control conditions, logistic regressions were conducted on the answers to the two multiple-choice questions, coded as "correct" or "error." Explanation (no information, basic, and basic + delay) and political ideology (liberal, moderate, and conservative) were entered as predictor variables.

For the first logistic regression conducted on participants' answers to the question asking about current trend in greenhouse gases described in the basic explanation, most participants (69.1%) chose the correct answer ("increasing") and it did not matter whether or not they received the explanation ($p > .05$) suggesting that this information was known preexperimentally by most participants. However, correct response did depend on ideology. Liberals (88% correct) were three times more likely than were moderates [68.5% correct, $\text{Exp}(B) = .33$, $p < .01$] and seven times more likely than were conservatives [45% correct, $\text{Exp}(B) = .14$, $p < .01$] to correctly indicate that greenhouse gasses are increasing. None of the interactions reached significance.

In contrast, for the second logistic regression conducted on answers to the question about the delay between reduction in carbon emissions and decline of concentrations in the atmosphere, very few (9.8%) chose the correct answer *without* the basic + delay explanation. Indeed, participants were over 13 times more likely to choose the correct answer when the delay explanation was included compared to the no explanation [$\text{Exp}(B) = .07$, $p < .01$] and 14 times more likely compared to the basic explanation alone [$\text{Exp}(B) = .07$, $p < .01$]. Moreover, the majority (60.9%) of those in the control groups selected 10 years or less (Figure 3). Neither the main effect of political ideology nor any of the interactions reached significance. Thus, the hypothesis that the explanations, in particular the delay, would improve understanding was confirmed.

The improved understanding due to the basic + delay explanation is particularly surprising in light of the fact that it was trusted (rating between 1 and 6) significantly less ($M = 3.39$, $SD = 1.37$) than was the basic explanation ($M = 3.67$, $SD = 1.46$) according to an ANOVA on mean trust, F (1, 852) = 8.05, $p < .015$ (Cohen's $D = .19$, 95% CI [.06, .33]). There was also a main effect of political ideology such that liberals trusted the explanations most ($M = 4.44$, $SD = 1.27$), then moderates ($M = 3.47$, $SD = 1.22$), and conservatives least ($M = 2.74$, $SD = 1.25$), F (2, 852) = 130.09, $p < .01$ ($\eta^2 = .23$, 95% CI [.19, .28]).

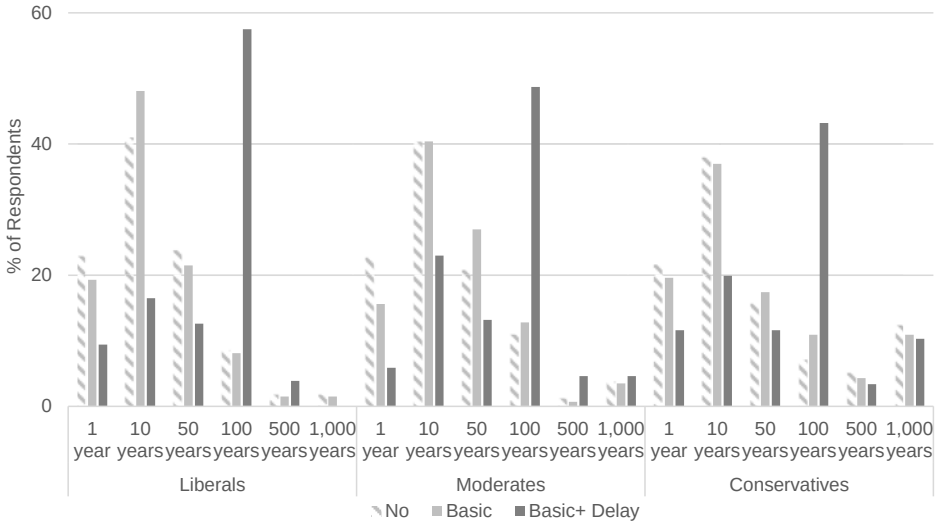
Hypotheses 2 and 3: Effect of Explanations on Endorsement Climate Strategies and Concern

Next, we examined participants' agreement with the "wait-and-see" strategy to determine whether the explanation had any impact on it. Indeed, supporting our hypothesis, the delay explanation *reduced* agreement with "wait-and-see," but mainly among conservatives (Figure 4). The interaction between explanation and political ideology, $F(4, 1268) = 2.18$, $p = .07$ ($\eta^2 = .01$, 95% CI [0, .02]), approached significance. Post hoc analyses revealed that among

[6] SPSS takes the observed (uncorrected) p value and multiplies it by the number of comparisons made.

Figure 3

Percentage of Participants in Each Explanation Group and Ideology, Choosing Each Delay Period



Note. The correct answer is 100's of years.

conservatives, those with the basic + delay explanation indicated significantly less agreement (5-point scale) with the "wait-and-see" strategy ($M = 2.88$, $SD = 1.29$), than those with the basic explanation alone ($M = 3.20$, $SD = 1.19$), $t(291) = 2.57$, $p = .03$ (Cohen's D =.3, 95% CI [.03, .49]). No other pairwise comparisons reached significance. Liberals ($M = 1.58$, $SD = .88$) and moderates ($M = 2.27$, $SD = 1.05$) were less willing to endorse "wait-and-see" regardless of explanation compared to conservatives ($M = 3.07$, $SD = 1.23$), and the main effect of ideology was significant, $F(2, 1268) = 196.45$, $p < .01$ (η^2 =.24, 95% CI [.2, .27]).

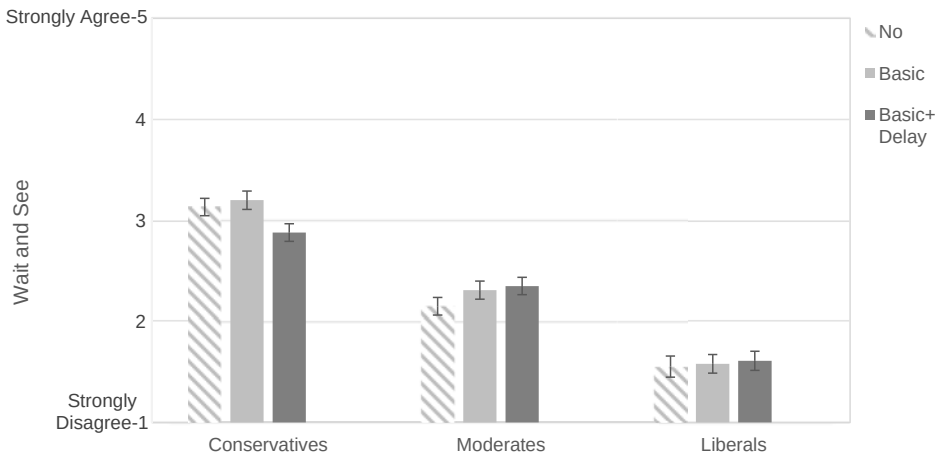
Only the effect of political ideology reached significance in both the "take action now" (liberals, $M = 4.39$, $SD = .89$; moderates, $M = 3.92$, $SD = .90$; conservatives $M = 3.03$, $SD = 1.17$, $F(2, 1268) = 196.07$, $p < .01$ ($\eta^2 = .24$, 95% CI [.20, .27]) and concern about climate change analyses (liberals, $M = 4.66$, $SD = 1.32$, moderates, $M = 3.54$, $SD = 1.47$; conservatives $M = 2.47$, $SD = 1.40$, $F(2, 1268) = 243.49$, $p < .01$ ($\eta^2 = .28$, 95% CI [.24, .32]).

Hypotheses 4: Effect of Explanations on Donations to Climate Cause

To determine whether explanations influenced climate-related decision making, participants were asked what proportion of a hypothetical $100 bonus they would donate to a climate worthy cause. Here, there was a significant effect of order such that those given Order 1 in which this question was asked immediately after the explanation ($M = 29.28\%$, $SD = 33.84\%$) chose to donate slightly but significantly more than those given Order 2 ($M = 26.05\%$, $SD = 32.55$) in which the question was asked at the end of the survey, $F(1, 1259) = 5.51$, $p = .02$ (Cohen's $D = .1$,

Figure 4

Mean Agreement With the "Wait-and-See" Strategy by Political Ideology



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95% CI [−.01, .21])). Although neither the main effect of explanation or the interaction between explanation and order reached significance, post hoc tests indicated that in Order 1, those with the basic explanation specified a significantly higher mean donation ($M = 30.14\%$, $SD = 33.99\%$) than those with no explanation ($M = 24.75\%$, $SD = 32.1\%$), $t(836) = 2.52$, $p = .04$ (Cohen's $D = .16$, 95% CI [.03, .3.]). The mean donation in the basic + delay condition ($M = 27.87\%$, $SD = 33.34\%$) did not differ significantly from the mean amount in the no information condition or the basic condition. There was, of course, a significant main effect of political ideology such that liberals donated more ($M = 42.82\%$, $SD = 34.62\%$), then moderates ($M = 29.46\%$, $SD = 33.20\%$), and conservatives least ($M = 13.16\%$, $SD = 24.97\%$), $F(2, 1259) = 93.11$, $p < .01$ ($\eta^2 = .13$, 95% CI [.01, .16]).

Thus, despite differences due to political ideology, the delay explanation allowed participants to correctly identify the length of delay between reduction of carbon emissions and the decline of greenhouse gas concentrations in the atmosphere. Moreover, for conservatives, it also changed their attitudes toward climate policies: They were less likely to endorse a wait-and-see strategy. Interestingly, it was the basic explanation, which was trusted more, that increased participants willingness to donate to a climate worthy cause. Although there was no effect on concern about climate change in general, it is clear that there were no "boomerang" effects among conservatives.

Hypothesis 5: Effect of Climate Prediction Format on Trust and Concern

Recall that we hypothesized that probabilistic predictions would be more trustworthy than deterministic predictions and that the effect might extend to attitudes toward the climate scientists who produced them. The ANOVAs reported in this section were conducted on the trust and concern ratings taken immediately after the predictions were presented. Although it was theoretically possible for explanation, viewed at the start of the survey, to impact these analyses, none of the main effects for explanation or any of the interactions with this variable reached significance. Therefore, in the interest of brevity, the independent variable "explanation" was omitted here.

In support of our hypothesis, probabilistic predictions received higher trust ratings than did deterministic predictions. Trust was averaged across the ratings taken for the temperature and precipitation predictions for each participant.[7] The main effect of format indicated that trust in probabilistic predictions was significantly higher ($M = 3.36$, $SD = 1.44$) than trust in deterministic predictions ($M = 3.10$, $SD = 1.43$), $F(1, 1271) = 10.36$, $p < .01$ (Cohen's $D = .18$, 95% CI [0.07, 0.29]). There was also a significant main effect of political ideology. Trust was highest among liberals ($M = 4.33$, $SD = 1.22$), then moderates ($M = 3.21$, $SD = 1.14$), and least among conservatives ($M = 2.33$, $SD = 1.24$), $F(2, 1271) = 283.73$, $p < .01$ ($\eta^2 = .31$, 95% CI [.27, .35]).

Similarly, concern, averaged across temperature and precipitation,[8] was significantly higher for the probabilistic ($M = 3.39$, $SD = 1.60$) than for the deterministic predictions ($M = 3.15$, $SD = 1.59$), $F(1, 1271) = 5.46$, $p = .02$ (Cohen's $D = 0.13$, 95% CI [.04, .22]). Again, there was a significant main effect of political ideology such that concern was highest among liberals ($M = 4.44$, $SD = 1.37$), then moderates ($M = 3.29$, $SD = 1.33$), and least among conservatives ($M = 2.26$, $SD = 1.32$), $F(2, 1271) = 269.95$, $p < .01$ ($\eta^2 = .3$, 95% CI [.26, .34]).

Next, we asked whether the effect of uncertainty estimates extended beyond the predictions themselves to attitudes toward the climate scientists who produced them. Indeed, confirming our hypotheses, probabilistic predictions enhanced participants' perception of both climate scientists' expertise and understanding. In the expertise analysis, ratings were significantly higher with probabilistic ($M = 3.80$, $SD = 1.24$) as compared to deterministic predictions ($M = 3.62$, $SD = 1.35$), $F(1, 1271) = 5.29$, $p = .02$[9] (Cohen's $D = .13$, 95% CI [.01, .25]). There was a significant main effect of political ideology such that liberals rated climate scientists' expertise highest ($M = 4.56$, $SD = 1.04$), followed by moderates ($M = 3.67$, $SD = 1.15$), and conservatives rated the lowest ($M = 3.03$, $SD = 1.23$), $F(2, 1271) = 179.03$, $p < .001$ ($\eta^2 = .22$, 95% CI [.18, .26]). Similarly, understanding ratings were significantly higher with probabilistic ($M = 3.89$, $SD = 1.34$) than with deterministic predictions ($M = 3.72$, $SD = 1.39$), $F(1, 1271) = 4.33$, $p = .04$[10] (Cohen's $D = .11$, 95% CI [.0, .23]). There was also a significant main effect of political ideology such that liberals rated climate scientists' understanding highest ($M = 4.70$, $SD = 1.12$), followed by moderates ($M = 3.78$, $SD = 1.25$), and conservatives rated the lowest ($M = 3.02$, $SD = 1.27$), $F(2, 1271) = 182.38$, $p < .01$ ($\eta^2 = .224$, 95% CI [.19, .26]).

Importantly, the positive effect of probabilistic predictions extended to the perception of scientific consensus. Those with probabilistic predictions indicated that there was significantly greater agreement about climate change ($M = 3.64$, $SD = 1.34$) than did those with deterministic predictions ($M = 3.45$, $SD = 1.41$), $F(1, 1271) = 4.58$, $p = .03$[11] (Cohen's $D = .11$, 95% CI [.0, .22]). There was, of course, a significant main effect for political ideology such that liberals indicated the greatest degree of scientific agreement ($M = 4.50$, $SD = 1.14$), followed by moderates ($M = 3.48$, $SD = 1.25$), and conservatives indicated the least ($M = 2.82$, $SD = 1.34$), $F(2, 1271) = 197.52$, $p < .001$ ($\eta^2 = .231$, 95% CI [.19, .27]).

Thus, probabilistic predictions increased trust in the predictions themselves, regardless of political ideology. Probabilistic predictions also increased the perception of the understanding and expertise of the climate scientists who produced them. Somewhat surprisingly, probabilistic predictions also increased concern about the information in the predictions and increased (rather than decreased) the perception of scientific consensus.

General Discussion

Here, we report the impact of two simple climate communication strategies on people's understanding and response to climate change. Taken together, these results suggest that psychologically

[7] For the five participants who failed to answer one of the trust questions, the single rating was used as the two trust scores were highly correlated with one another ($r = .89$).

[8] For the 16 participants who failed to answer one of the concern questions, the single rating was used, as the two concern scores were highly correlated with one another ($r = .88$).

[9] When participants omitted in the attention check failure were included, the p value was .074.

[10] When participants omitted for attention check failure were included, the p value was .073.

[11] When participants omitted for attention check failure were included, the p value was .143.

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targeted climate communication can change attitudes toward global warming despite political ideology.

We found that explaining the delay between the reduction in carbon emissions and the cessation of global warming provided previously unknown information to this diverse sample. Unlike the fact that greenhouse gas emissions are increasing, known by most liberals and moderates regardless of whether or not they received the explanation, the correct delay (100 years) was only chosen significantly more often by participants who received the delay explanation. The majority of those who did not receive the explanation chose much shorter time frames (1–10 years) regardless of political ideology. This suggests both that some key facts about global warming are not widely understood by the members of the public and that simple explanations can be effective if they are targeted to known misunderstandings. In this case, the misunderstanding was likely based on a mental model in which the rate of input into the system (of greenhouse gases) and rate of accumulation operate roughly in parallel, such that soon after reduction in carbon emissions, the concentration of greenhouse gases in the atmosphere and global average temperature would also begin to decline. Indeed, there is considerable evidence that people make this simplifying assumption for stock/flow problems such as this (Cronin et al., 2009; Newell et al., 2016; Sweeney & Sterman, 2000). Although it is unlikely that they are aware of the assumption, when we provided a simple explanation that specifically contradicted it, participants were more able to accurately identify the long delay between the reduction of carbon emissions and the decline of accumulation of greenhouse gases in the atmosphere. It is important to note that this effect was seen across political ideologies. In other words, there were no boomerang effects.

Some would argue that information alone is insufficient to change attitudes toward politically charged issues such as global warming because information is processed through the lens of prior beliefs (Dieckmann et al, 2017; Goidel et al., 1997; Kahan, 2015; Sunstein et al., 2016; Tappin et al., 2017). If this were the case, we would expect to see the effects on understanding among liberals and moderates but not conservatives. On the contrary, for the effect of the delay explanation on understanding, the interaction did not reach significance. In other words, we saw the same improvement in all three groups, indicating that the impact of the explanation prevailed over motivated reasoning in this context. These results are in line with recent evidence demonstrating the positive effects of simple explanations across the political spectrum (Ranney & Clark, 2016; Van Der Linden et al., 2017; Velautham et al., 2019) as well as research showing that certain manipulations are particularly effective in increasing support for climate mitigation among conservatives (Feldman & Hart, 2018). The reason for this probably varies depending on the manipulation. It may be that the facts themselves are convincing, that some approaches align well with existing value structures, or simply that conservatives are lower on key measures to begin with, providing more room to increase. This is clearly an important issue that warrants more research.

Although accurate identification of the answers to the factual questions is encouraging, it could be argued that participants were simply repeating back what they read in the explanation. In other words, participants do not necessarily have to accept or incorporate the information into their own belief systems to answer factual questions correctly. For that reason, we asked a set of questions that were not directly related to the information in the explanations but rather to overall attitudes toward climate change. Here, the biggest impact was among conservatives: They were less likely to endorse a wait-and-see strategy after receiving the delay explanation. Importantly, this result was not impacted by question order, suggesting that it endured, at least the length of the experiment, after participants received the climate predictions and answered several unrelated questions. This suggests that, not only did participants understand the information but also that it was incorporated in their attitudes toward how we should approach climate change. In addition, there was a small increase among all ideology groups in donation amount with both explanations, although it reached significance only in the more highly trusted basic explanation condition. This suggests that an impact on climate-related decision making is possible as well. Extended effects of scientific climate change information such as this have also been seen in the work by Ranney and Clark (2016) and Ranney et al. (2019).

The other major result concerned the positive impact of uncertainty estimates. Here, we saw that predictive intervals increased trust regardless of political ideology. For this manipulation in particular, motivated reasoning theory would predict a boomerang effect among conservatives such that admission of uncertainty could have reduced rather than increased trust. That was not the case here and aligns with other recent evidence demonstrating positive effects among conservatives of including uncertainty estimates in climate predictions (Joslyn & Demnitz, 2019). Nonetheless, a potential explanation for the increase in trust with predictive intervals among conservatives, in keeping with the motivated reasoning argument, is that predictive interval ranges included lower values than those in the deterministic condition (see Table 1). As such, probabilistic predictions may be more in line with the prior beliefs of conservatives. However, if this were the sole cause of the increase in trust, we would not expect to also see an increase in concern among conservatives with probabilistic prediction. The increase in concern observed here suggests that participants were focusing on the upper bound of the interval as well. If they had been focusing on the lower bound alone, concern might even decrease in the probabilistic condition. Thus, the increase in both trust and concern, combined with the fact that predictive intervals led to more positive perceptions of climate scientists understanding and expertise, suggests that the mechanism behind the effect is a genuine change in attitude.

Moreover, none of the potential negative effects of uncertainty estimates were observed. Uncertainty estimates increased rather than decreased the perception of scientific consensus. Thus, instead of being taken as an indication of disagreement or incompetence among climate scientists as some have feared, the uncertainty estimates tested here may have conveyed the idea that the range of values is a function of the prediction process itself. In addition, the increase in concern in the probabilistic condition suggests that uncertainty did not lead to an increase in psychological distance as one might expect from the predictions of construal level theory.

That said, there are two main limitations with this work. First, as with most survey experiments, we were unable to measure the impact on actual behaviors but rather on attitudes and intended behaviors. However, the gain in experimental control has allowed us to pinpoint the mechanisms that lead to the observed effects and provided important insights into how people process scientific information in the context of a politically charged issue. The second limitation is that many of the effect sizes observed here were small. Nevertheless, it is encouraging to note that the key effects of the delay explanation and uncertainty estimates were also seen in the pilot study (see Appendix B) despite differences in the procedure

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and the fact that it was conducted on a less representative sample. In addition, it is important to realize that this experiment tested a single exposure in an experimental setting. As such, it likely accounts for a very small proportion of the exposure to climate relevant information for most respondents. Nonetheless, the effects were significant and extended beyond the primary dependent variables. This suggests that if carefully explained scientific informations were incorporated in climate communication more generally, we might expect to see larger effects. It is clear, based on the results presented here and that of others (Feldman & Hart, 2018; Ranney & Clark, 2016; Van Der Linden, et al. 2017; Velautham et al., 2019) that members of the public are capable of understanding more complex issues than those for which they are often given credit. Much of the climate science that reaches the public today is simplified and omits any mention of uncertainty. If instead, climate communication was designed to present more complete scientific information, including uncertainty estimates, in a manner that takes into account the cognitive processes and mental models of the recipient, we might expect to see much larger cumulative changes in trust, understanding, and an appreciation of the urgency of these issues.

Importantly, these results contribute to a growing body of evidence that suggests that clear explanations and numeric uncertainty estimates can change peoples' understanding of and attitudes toward climate change and climate science regardless of political ideology. In other words, communication that takes into account the cognitive mechanisms by which people process information can be successful in conveying complex but critical information to members of the public across the political spectrum to help them appreciate the seriousness of the problems we face.

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Appendix A

Knowledge Networks Sampling Procedure

Knowledge Networks (GfK) panel members are randomly selected using an Address Based Sampling (ABS) methodology via the Delivery Sequence File (DSF) of the United States Postal Service for recruiting panel members, a technique that has been shown to reduce the rate of "bogus" responders to trace levels (Kennedy et al., 2020). Moreover, this method allows GfK to include hard-to-reach individuals, such as young adults and those from various minority groups. Under the ABS recruitment, households without internet connection are provided with a web-enabled device and free internet service. Once panel members are recruited and profiled by providing basic demographic information, they become eligible for selection for client surveys. The specific sample for this experiment was collected with an equal probability selection method (EPSEM) from the panel for general population surveys using a patented methodology. The first step was to weight the pool of active members to the geodemographic benchmarks secured from the latest March supplement of the Current Population Survey (sponsored jointly by the U.S. Census Bureau and the U.S. Bureau of Labor Statis0tics) along several dimensions as follows:

- Gender (male/female)
- Age (18–29, 30–44, 45–59, and 60+)
- Race/Hispanic ethnicity (White/Non-Hispanic, Black/Non-Hispanic, Other/Non-Hispanic, 2 + Races/Non-Hispanic, Hispanic)

(*Appendix continues*)

- Education (less than high school, high school, some college, bachelor, and beyond)
- Census region (northeast, midwest, south, west)
- Household income (under $10k, $10k to <$25k, $25k to <$50k, $50k to <$75k, $75k to <$100 k, $100k to <$150k, and $150k+)
- Home ownership status (own, rent/other)
- Metropolitan area (yes, no)

Using the resulting weights as a measure of size, in the next step, a probability proportional to size (PPS) procedure is applied to those who accept. It is the application of this PPS methodology with the imposed size measures that produces fully self-weighing samples from the GfK panel, for which each sample member can carry a design weight of unity. Of those invited, 57.1% responded and completed the survey. Out of these 2,087 cases, 77 cases were excluded due to speeding through the survey, refusing to answer more than one-third of the substantive survey questions, and/or refusing to answer any of the first five questions they were shown. These procedures led to a sample (see Table 1) with similar proportions of individuals in each category of key demographic variables as the U.S. census conducted the year before the experiment was run. Chi Square analyses indicated no significant differences between our sample and the U.S. census in gender, race, political ideology, education, or income.

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Appendix B

Pilot Study

To refine the measures used in the main experiment, we first conducted a pilot study over the summer of 2017 (June–July) using Amazon Mechanical Turk (MTurk), a data collection domain administered by Amazon. The basic methods and procedure were the same as those described in the main experiment, although there was also a set of questions on climate acceptance (see Ranney & Clark, 2016) to determine whether the basic explanation adapted from previous research yielded the same increase. In addition, there were a number of questions on relational trust and efficacy that were not affected by any of the manipulations and were omitted from the main study to reduce the overall time required to administer it. The pilot study did not include the concern question asked immediately after the explanation and included only the positive wording of the "wait-and-see" question (see below).

Participants

A total of 1,320 people participated and passed the attention check questions. The mean age was 35.8 years (SD = 12.43) and ranged between 18 and 77 years, 61.3% were female, 43.3% classified themselves as Democrats, 35.2% as Independents, and 21.4% as Republicans.

Replicating Climate Acceptance

An ANOVA conducted on climate acceptance with explanation (no, basic, and basic + delay) as independent variable was significant, $F(2, 657) = 6.87$, $p < .01$ ($\eta^2 = .02$, 95% CI [0, .054]). The basic + delay explanation rated the highest acceptance ($M = 7.69$, $SD = 1.45$), the basic the next highest ($M = 7.43$, $SD = 1.64$) and no explanation, the least ($M = 7.10$, $SD = 1.73$). Post hoc tests revealed that the basic + delay explanation yielded significantly higher acceptance than did no information, $t(430) = 3.69$, $p = .01$ (Cohen's $D = 0.36$; 95% CI [0.2, 0.95]) and that the difference in acceptance between the basic explanation and the no information condition approached significance, $t(452) = 2.14$, $p = .1$ (Cohen's $D = 0.2$; 95% CI [−.04, .69]).

Hypothesis 1: Effect of Explanations on Understanding

For the first logistic regression, conducted on participants' answers to the question asking about the current trend in greenhouse gases described in the basic explanation, most participants (90%) chose the correct answer ("increasing") and it did not matter whether or not they received the explanation ($p > .05$) suggesting that this information was known preexperimentally by most participants. However, correct response did depend on ideology. Democrats (96% correct) were over 4 times more likely than were Independents [86% correct, Exp(B) = .24, $p < .01$] and 11 times more likely than were Republicans [70% correct, Exp(B) = .09, $p < .01$] to correctly indicate that greenhouse gasses are increasing. None of the interactions reached significance.

In contrast, for the second logistic regression conducted on answers to the question about the delay between the reduction in carbon emissions and the decline of concentrations in the atmosphere, very few (10%) chose the correct answer in the control condition or in the basic condition (10%) compared to the basic + delay condition (82%). Indeed, participants were 24 times more likely to choose the correct answer when the delay explanation was included compared to the no explanation [Exp(B) = .04, $p < .01$] and 27 times more likely compared to the basic explanation [Exp(B) = .04 $p < .01$] conditions. Neither the main effect of political party nor any of the interactions reached significance.

Hypotheses 2: Effect of Explanations on Climate Strategies

In the pilot study, only the positively framed version of the "Wait-and-See" endorsement statement was included, "The only way to avoid possible future serious changes in the climate is to take action to stop them now." Mean agreement depended on the explanation, $F(2, 1311) = 4.23$, $p = .02$ ($\eta^2 = 0.006$; 95% CI [0, .02]), and the interaction between political party and explanation approached significance, $F(4, 1311) = 2.24$, $p = .06$ ($\eta^2 = 0$; 95% CI [0, .02]). Post hoc tests revealed that the impact was greatest among Republicans. As with the main experiment, the basic + delay explanation led to higher agreement ($M = 3.89$, $SD = 1.15$) than did the basic explanation ($M = 3.38$, $SD = 1.32$), $t(162) = 3.35$, $p < .01$ (Cohen's $D = .40$; 95% CI [.14, .86]), or no explanation ($M = 3.53$, $SD = 1.16$), $t(187) = 2.49$, $p = .04$ (Cohen's $D = .31$; 95% CI [.01, .7]). No other pairwise comparisons reached significance, although the main effect for political ideology was significant, $F(2, 1311) = 113.13$, $p < .001$ ($\eta^2 = .15$; 95% CI [.11, .18]). Ratings were highest for Democrats (4.63, SD=.63), next for

(*Appendix continues*)

Independents (4.11, $SD = 1.09$), and least for Republicans (3.57, $SD = 1.22$).

Hypotheses 4: Effect of Political Party on Donations to Climate Cause

In the pilot study, only the effect of political party reached significance in the ANOVA on donations to a climate cause. Donations were highest among Democrats ($40.83, $SD = 32.40$), next Independents ($35.37, $SD = 31.57$), and Republicans were the least ($24.52, $SD = 32.13$), $F(2, 1302) = 22.43$, $p < .001$ ($\eta^2 = 0.03$; 95% CI [0.02, 0.05]).

Hypothesis 5: Effect of Climate Prediction Format

An ANOVA conducted on mean trust measured immediately after prediction presentation with format (probabilistic/deterministic) and political party (Democrat/Independent/Republican) as the independent variables revealed that probabilistic predictions (4.04, $SD = 1.43$) received significantly higher trust ratings than did deterministic (3.86, $SD = 1.44$) predictions, $F(1, 1314) = 8.03$, $p < .01$ (Cohen's $D = .16$; 95% CI [.05,.27]). There was also a significant main effect of political party. Trust was highest among Democrats (4.59, $SD = 1.12$), then Independents (3.79, $SD = 1.41$), and lowest among Republicans (2.94, $SD = 1.41$), $F(2, 1314) = 160.8$, $p < .01$ ($\eta^2 = .197$; 95% CI [.2, .23]).

Only the effect of political party reached significant in the analyses on concern $F(2, 1314) = 188.42$, $p < .01$ ($\eta^2 = 0.22$; 95% CI [.18, −.26]), scientists' expertise $F(2, 1314) = 113.24$, $p < .01$ ($\eta^2 = 0.147$; 95% CI [.11, .18]), and understanding $F(2, 1314) = 127.35$, $p < .01$ ($\eta^2 = .16$; 95% CI [.12, .19]). Democrats were most concerned and Republicans the least concerned. Democrats thought climate scientists had the most understanding and expertise and Republicans thought they had the least.

Appendix C

Delay estimates were based on a 1.5% per year reduction until an emission rate of 1% of today's emission rate is reached, with emissions stabilizing at that level. This estimate accounts for removal of CO_2 from the atmosphere using the response function of the multimodel mean in the study by Joos et al. (2013). Each year's emissions were treated as an additional pulse. A two-layer energy balance model was used to estimate the temperature evolution accounting for ocean heat uptake, as in the studies by Geoffroy, Saint-Martin, Olivié, et al. (2013) and Geoffroy, Saint-Martin, Bellon, et al. (2013). Although these are aggressive emissions reductions, even more aggressive assumptions are included in some Intergovernmental Panel on Climate Change scenarios, involving negative emissions later this century that are achieved with currently nonexistent technologies (Fuss et al., 2014).

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