PUBLIC UNDERSTANDING IN GREAT BRITAIN OF OCEAN ACIDIFICATION

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Public engagement with climate change is critical for maintaining the impetus for meaningful emissions cuts. Ocean acidification (OA) is increasingly recognised by marine scientists as an important, but often overlooked, consequence of anthropogenic emissions[1,2]. While substantial evidence now exists concerning people's understanding of climate change more generally[3], very little is known about public perceptions of OA. Here for the first time, we characterise in detail people's understanding of this topic using survey data obtained in Great Britain (n=2,501) during 2013 and 2014. We draw on theories of risk perception and consider how personal values influence attitudes towards OA. We find that public awareness of OA is very low compared to that of climate change and was unaffected by the publication of the IPCC 5th Assessment Reports. Using an experimental approach, we show that providing basic information can heighten concern about OA; however, we find attitude polarisation along value-based lines may occur if the topic is explicitly associated with climate change. We discuss the implications of our findings for public engagement with OA, and the importance of learning lessons from communications research relating to climate change.

As the risks of climate change become ever clearer, recognition of the importance of a robust and evidence-based approach to public engagement has grown[4]. To date, there has been no detailed assessment of people's understanding of ocean acidification (OA), and little analysis of how to promote wider engagement with this subject. This is despite the critical importance of the oceans as a carbon sink[5], the near-certainty that absorption by the oceans of anthropogenic carbon emissions is leading to significant acidification[1,2,5] – measurements show about a 30% increase in surface ocean hydrogen ion concentration since the 1980s[6] – and the substantial risk of widespread negative effects on many marine organisms, ecosystems and services under high emission scenarios[1,2,7]. Accordingly, OA presents risks for societies and economies worldwide as part of wider climatic and environmental changes[2,8], placing additional onus on governments and societies to reduce emissions.

While the implications of OA – and possible policies to address them – are uncertain and may seem remote for most people, research has increasingly stressed the importance of 'upstream' public engagement about risks: that is, early dialogue between scientists and citizens, prior to major policy decisions, and before social representations of an issue become entrenched[9]. Given its potential to act as a significant additional stressor on the marine environment there is a strong argument for involving citizens now in a dialogue about OA risks and possible responses, informed by systematic social sciences research into public understanding of the issue[4].

Recent research has shown that compared to other marine climate impacts, the public in Europe consider themselves least informed about OA[10,11]. At the same time, however, people express a comparable level of concern about this subject as they do about more familiar impacts such as increasing sea temperature[10,11]. In Alaska, a region vulnerable to OA due to the risks it poses for both commercial and subsistence fisheries, research points to public concern about its implications, even under conditions of limited understanding[12]. These findings together raise important questions about how this complex topic is coming to be perceived and understood by non-experts[10].

We examine the characteristics and determinants of perceptions of OA using two nationally representative online surveys of members of the British public administered just before, and then repeated immediately after, the publication period for the IPCC 5th Assessment Reports (total n=2,501). Perhaps surprisingly, four-fifths of survey respondents (80.4%) indicated that they had not previously heard of OA. This finding contrasts sharply with the near-universal public awareness of climate change across industrialised nations[13]. When asked in a separate item about their level of knowledge about OA, only a small minority (13.8%) reported knowing at least 'a little' about the subject (Figure 1).

Figure 1 about here

There was no convincing evidence for an increase in public awareness pre- and post- the IPCC 5th Assessment Reports; although caution would be required in causally attributing any change to IPCC reporting, this might reasonably be inferred. Nevertheless, the proportion of respondents stating they had heard of OA in September 2013 (n=1,001) increased only marginally to May 2014 (n=1,500), from 18.3% to 20.5%, with this difference not statistically significant (χ^2=1.93, p=.16).

While basic awareness is likely to be important for comprehending OA, formal knowledge constitutes only part of non-experts' appraisals of environmental risks. In particular, reliance on automatic or intuitive judgments of a subject in terms of its conceptual associations and their 'affect' (their emotional quality, in positive or negative terms) influences perceptions of topics such as climate change[14]; this has been termed the 'affect heuristic'[15]. To explore respondents' affective responses to the concept of OA, we used a standard open-ended elicitation technique[14,16] that asked for "the first three thoughts, images or phrases which come to mind" when hearing the term 'ocean acidification'; respondents then indicated on a 5-point scale how they felt towards these, from 'very bad' to 'very good'.

Figure 2 shows the six most commonplace image associations (excluding restatement of concepts such as 'acid' or 'oceans'), together with associated mean affect scores (negative values correspond to negative affect). Examples of participants' own depictions of these concepts are given in Table 1.

Figure 2 about here

The two most common image associations corresponded to 'pollution' and 'harm to marine organisms'. In the former case, responses primarily concerned localised contamination of the marine environment, such as through chemical waste or oil spills. The latter image category typically referred to effects on larger organisms such as fish, or to marine life in non-specific terms (e.g. 'sea creatures').

Those with prior awareness of OA were over five times more likely to make a first association with 'climate change' and related concepts than those without awareness (χ^2=102.9, p<.001, OR=5.72); likewise they were more likely to refer to 'harm to marine organisms' (χ^2=130.8, p<.001, OR=3.71). Those without prior awareness of OA were twice as likely to make a first association between OA and 'pollution' (χ^2=29.9, p<.001, OR=2.25).

Table 1 about here

Respondents indicated their level of concern about OA, using a standard item adapted from climate change perceptions research[17]; such a measure of 'concern' is typically applied to gauge the importance ascribed by study participants to this topic.

A sizeable research literature now demonstrates that concerns about environmental problems are underpinned by more fundamental beliefs and values. Accordingly, respondents completed the 'New Ecological Paradigm' (NEP) scale, which assesses beliefs about the vulnerability of the natural world to human influence[18] and predicts perceptions of climate change[19]. We also measured respondents' 'cultural worldviews', theorised to determine certain environmental risk perceptions through reflecting preferences for different types of social organisation[20]. Although an egalitarian worldview (favouring a cooperative and equal society) tends to be associated with relatively higher concern about climate change[20] as compared to an individualistic worldview (entailing preference for self-reliance and liberal economics), we sought to investigate if such a relationship also holds for the less familiar subject of OA.

Using a series of regression models we examined the extent to which concern about OA was predicted by these value orientations, as well as by respondents' prior knowledge of OA, perceptions of climate change causation, education level, and gender; modelling also incorporated respondents'

mean affect score across image ratings (in order to approximate overall affective response) and dummy variables corresponding to prominent image categories.

As shown in Table 2, the strongest predictors of concern were self-reported knowledge, NEP score, and egalitarianism. Concern about OA was also predicted by the extent to which people's overall image associations were affectively negative; individual image categories corresponding to 'harm to organisms' and 'harm to ecosystems' were found to be influential in a partial model but did not uniquely explain variance in the full regression model.

Table 2 about here

Given the way in which climate change scepticism has manifested as doubts about scientific consensus and evidence for the role of human causation[21], we sought to examine public perceptions in a comparable manner with respect to OA. Only around a third (35.3%) of respondents perceived there to be a strong consensus (the view of 'most experts') that OA is caused by anthropogenic carbon emissions, in contrast to the high degree of certainty present in formal scientific assessments[2].

This limited public recognition of the scientific consensus regarding causation of OA probably reflects low general awareness, but may also be influenced by an underlying 'attribution scepticism'; that is, doubts that human activity can be held responsible for global environmental change[21]. Indeed, perceived scientific consensus concerning a human component to OA appeared strongly influenced by respondents' positions on whether climate change is anthropogenic or natural in cause (β=.28, $p<.001$); conversely, we found no evidence that perceived consensus was related to self-reported knowledge of OA (β=.08, NS, where NS is 'not significant') or that knowledge moderated this relationship (β=.06, NS).

A separate survey item found that, of seven potential causes presented, the largest proportion of respondents (37.5%) selected absorption by the oceans of carbon dioxide from human activities as the main cause of OA, in line with scientific consensus. Nonetheless, the plausible but incorrect notion of OA caused by localised pollution from ships was almost as frequently chosen (34.1% of respondents). Concerning consequences of OA, respondents ranked unfavourable changes in conditions for larger marine animals and coral reefs as being the most significant impacts. Tables S1 and S2 (Supplementary Information) provide further details of respondents' perceptions of causes and consequences of OA.

Given the limited public awareness about OA, we sought to test whether providing further basic information might affect stated concern, and whether people would vary in their responses to this information. Part-way through the second survey (n=1,500) we applied an experimental manipulation whereby respondents read one of two texts outlining information about OA. In one version, no mention was made of climate change (OA-only text); in the second, explicit connections to climate change were emphasised in six places (OA-CC text). We hypothesised that direct reference to climate change would prompt polarisation in attitudes towards OA by value orientation, as in studies of climate change perceptions[20,22].

First, a substantial shift in concern occurred pre- and post- information provision, irrespective of information type. The mean level of concern (range from 0-3) prior to information provision was 0.82 (SD=1.08). Post information provision the level of concern reached 1.63 (SD=.90); $t=22.5$, $p<.001$.

There was no overall difference between the two information types regarding their effects on stated concern (Table S3, Supplementary Information). However, we observed some evidence of polarisation of attitudes in the form of a statistically significant interaction effect, whereby the information framing exerted a different degree of influence depending upon respondents' level of individualism ($\beta=-.05$, $p<.05$); those higher on this measure were less responsive to the OA-CC text

compared to the OA-only text. This suggests that information about OA including direct reference to climate change could be received differently by people depending on their underlying worldviews.

Our findings hold several implications for science communication and public engagement with OA, whether conducted by scientists, environmental policy makers and communicators, within educational materials, or fora such as deliberative workshops. First, the low level of current awareness suggests that a key task for climate science communicators – who have quite naturally focussed upon more obvious impacts such as changes to weather patterns and global temperature – is to develop new materials and narratives explicitly incorporating OA. Second, although information provision alone is unlikely to be sufficient for achieving broader public engagement, any discussion about potential policy responses to OA will require at least some basic understanding of the phenomenon[4]. Where significant misunderstandings persist (e.g. OA perceived as deriving from localised pollution) communication strategies should seek to counter these while stressing the role of carbon dioxide emissions. Third, the study indicates that strong negative emotions and images are evoked simply by mentioning the issue. While this might ostensibly seem an effective route for attracting attention and raising public concern, studies of fear-inducing messaging show that this often proves counter-productive if not simultaneously offering realistic ways of responding to threats[23]. As such, communications should also incorporate discussion of what actions individuals, communities and society can take to counter OA[24]. Fourth, a major barrier to public engagement with climate change, particularly in Anglophone nations[3], has been a polarisation of attitudes along political and ideological lines. Our experimental findings also suggest, albeit more tentatively, that the potential exists for a similar divergence in concern about OA; in effect a 'polarisation-by-association' could develop as awareness of the link between OA and climate change grows. As in the case of climate change more generally, it may be important here to emphasise the wider co-benefits[25] of addressing OA and the different ways in which the topic can be understood – e.g. as an economic issue[24] or pertaining to food security[26]. It may also promote comprehension and engagement if the rather technical concept of 'acidification' were reframed in terms of risks to

marine 'health'[27], particularly given the emphasis within respondents' image associations on threats to organisms and ecosystems.

Our results indicate that many people remain unaware of expert agreement on the anthropogenic causation of OA. Given that acknowledgement of scientific consensus and recognition of human causation constitutes a key precondition, or 'gateway belief', for generating wider public engagement with climate change more generally[28,29], communications about OA should stress expert consensus in this regard. By contrast, scientific uncertainties regarding the consequences of OA may be communicated most effectively to public audiences using the terminology of risk[30]. Finally, our findings underscore the remaining research challenges for understanding the perceptions, communication and engagement needs of this complex area, which has hitherto been a sorely neglected topic within the social sciences of climate change.

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Acknowledgements

The research was funded by the UK Ocean Acidification Research Programme (co-funded by the UK Natural Environmental Research Council; Department for the Environment, Food and Rural Affairs; and the Department of Energy and Climate Change). We thank Dr Phil Williamson of the University of East Anglia for helpful comments and advice, and Erin Roberts for assistance with coding of image associations.

Author contributions

SBC led the study design, analysis and writing. NFP, AJC and EMS contributed to study design, analysis and writing. PNP contributed to the study design and writing.

Figure 1 **Level of public knowledge about ocean acidification**

Respondents were asked: “How much, if anything, would you say you know about ocean acidification?” (n=2,501). Error bars show 95% C.I.

Figure 2 **Imagery and affective associations with ocean acidification**

Response percentages (derived from n=7,503 responses) are shown on the left-hand y axis with corresponding mean affect scores on the right-hand y axis. Affect was scored -2 to +2 with lower values corresponding to more negative affect. Note reversed right-hand y axis.

Table 1 Spontaneous imagery associated with ocean acidification

Response category (% of total n=7,503 responses)	**Summary description**	**Example responses**
Harm to marine organisms (19.3%)	Adverse consequences for marine life	Damage to fish and other sea flora and fauna Eroding and dying coral Depletion of wildlife
Pollution (13.9%)	Reference to harmful substances introduced to the marine environment	Pollution of the sea by acid effluent Spillage of chemicals Commercial waste disposal, untreated into the sea
Harm to marine ecosystems (7.7%)	Adverse consequences for ecosystems and habitats	Change and loss of habitat Decreasing biodiversity Oceans becoming unable to support life
Concern and negative language (6.2%)	Statements of concern or worry and/or negative concepts (e.g. horror, danger)	Deeply worrying Upsetting
Climate change (5.0%)	Reference to climate change and associated concepts	A less serious offshoot of global warming Climate change destroying the world's water
Harm to people (4.1%)	Adverse consequences for individuals or society	Not being able to swim Reduced fish stocks and hence negative impact on […] livelihoods of fishermen
Acid rain (2.0%)	Association with acid rain	Acid rain falling into the sea
Scepticism (0.8%)	Expression of doubt or dismissal	Some made-up name for spurious global warming effects
Generic reference to 'acid' or 'pH' (10.2%)	Mention of these and similar terms without additional context	Drop in pH
Generic reference to 'oceans' or marine environment (5.7%)	Mention of marine terms without additional context	Large expanse of water
Miscellaneous/ uncategorised (13.6%)	Meaningful response, uncategorised	/
No meaningful response/ don't know (11.4%)	/	/

Table 2 Regression models of concern about ocean acidification

Predictor	Model 1: knowledge	Model 2: values, attitudes + sociodemographic	Model 3: affect	Model 4: images	Model 5: full
Knowledge	.28***	-	-	-	.25***
Gender (ref: male)	-	-.01 (ns)	-	-	.04 (ns)
Education	-	-.02 (ns)	-	-	-.09*
Individualism	-	-.05 (ns)	-	-	-.05 (ns)
Egalitarianism	-	.20***	-	-	.19***
NEP score	-	.30***	-	-	.23***
Perceived climate change causation (higher score: human-caused)	-	.02 (ns)	-	-	.03 (ns)
Affect (negative scoring)	-	-	.25***	-	.15***
'Pollution'	-	-	-	.05 (ns)	-.02 (ns)
'Harm to organisms'	-	-	-	.18***	.05 (ns)
'Harm to ecosystems'	-	-	-	.08*	.05 (ns)
'Climate change'	-	-	-	.05 (ns)	-.02 (ns)
Adjusted R^2	**.08**	**.18**	**.06**	**.03**	**.27**

Dependent variable: level of concern about OA. Numbers displayed are standardised beta coefficients, except final row showing adjusted R^2. * p<.05, *** p<.001, NS is 'not significant'

Methods

Here we describe the survey design and measures used, sampling and administration procedures, experimental information framing, and analytic approach.

Survey design and measures used

The survey was designed to assess public awareness and understanding of ocean acidification (OA), and how this related to more general environmental attitudes, value orientations and sociodemographic factors. The survey also included an experimental component utilising an information framing design.

Awareness of OA and stated knowledge

Respondents first indicated whether they had previous awareness of OA, via a yes/no response to the question: "Before today, had you heard of ocean acidification?"

They were subsequently asked: "How much, if anything, would you say you know about ocean acidification?" Responses to this question were on a five point scale, ranging from "I have not heard of ocean acidification before taking part in this survey" to "I know a great deal about ocean acidification".

Stated concern about OA

Respondents indicated the extent of their concern about OA, in response to the question: "How concerned, if at all, are you about ocean acidification?" This question is a modification of a standard survey item used to measure concern about climate change, which is used as an indicator of perceived risk and importance of climate change[17]. Responses were provided on a four-point scale, ranging from "not at all concerned" to "very concerned". 'Don't know' and 'no opinion' options were also provided.

The measure of concern about OA was presented near the start of the survey, and subsequently repeated following the information framing experiment.

Affective image associations

Respondents were asked to indicate three concepts that they spontaneously associated with the term 'ocean acidification' through the use of an open-ended elicitation technique, adapted from research into climate change perceptions[14,16,31,32]. Such a spontaneous elicitation technique has particular utility in the case of OA, where formal knowledge may be limited but salient ideas can nevertheless be envisaged, providing the opportunity to assess 'first impressions' of the

phenomenon via so-called 'image associations'. In addition, those respondents who do possess more detailed knowledge of the topic have the scope to provide answers accordingly.

The item used to obtain image associations was: "When you hear the term 'ocean acidification' what are the first three thoughts, images or phrases which come to mind?" Respondents then indicated on a 5-point scale how they felt towards each answer provided, ranging from "I feel this is a very bad thing" to "I feel this is a very good thing".

Perceived causes and consequences of OA

We asked respondents to indicate: "Which, if any, do you think is the main cause of ocean acidification?"

They selected one response from the following seven options (a 'none of these' option was also provided); ordering was randomised in the online survey:

- Carbon dioxide in the atmosphere from human activities (e.g. burning fossil fuels) being absorbed by the oceans;
- Pollution from ships, such as from oil spills and discharge of waste products;
- Normal cycles of change in ocean chemistry;
- Increased seawater temperatures from climate change;
- Naturally-occurring carbon dioxide in the atmosphere being absorbed by the oceans;
- Over-fishing leading to disruption of ocean food chains;
- The accumulation of calcium carbonate rocks (e.g. limestone and chalk) in tidal waters;

Of the list of possible causes, only the first ('carbon dioxide… from human activities') is deemed to be an accurate representation of current scientific understanding. The remaining responses were included in order to assess the extent to which plausible-seeming but scientifically incorrect causes would be selected in comparison to the role of carbon dioxide emissions.

For three of these responses which were felt to be more technical in nature, additional information was available by hovering the cursor over the relevant text; e.g. for the option relating to 'over-fishing' we provided the following explanatory text: "over-fishing refers to quantities of fish being taken from the oceans, at levels which threaten recovery of fish stocks or disrupt the balance of life in the oceans".

Respondents also indicated which they perceived to be the main consequence of ocean acidification: "Which, if any, do you think is the main consequence of ocean acidification?"

One response was selected from among the following thirteen options (plus a 'none of these' option); ordering was again randomised:

- Damage to coral reefs; *P*
- Less favourable conditions for some very small marine organisms; *P*
- Less favourable conditions for some larger marine animals (including fish and squid); *P*
- Problems for people who make a living from the sea, for example due to decreased fish stocks; *P*
- Faster erosion of coastlines in certain parts of the world; *D*
- Reduction in the volume of ice-shelves in the Arctic and Antarctic; *D*
- Reduced ability of the oceans to absorb carbon dioxide from the atmosphere; *P*
- Changes to the chemistry of some land-based ice structures (e.g. glaciers); *D*
- Skin damage to those spending long periods of time at sea, such as fishermen; *D*
- Damage to the metal hulls of ships; *D*
- More favourable conditions for some very small marine organisms; *P*
- Increased ability of the oceans to absorb carbon dioxide from the atmosphere; *D*
- More favourable conditions for some larger marine animals (including fish and squid) *P*

Of the list of possible consequences presented, seven corresponded to potential impacts highlighted in the scientific literature (we indicate these above using 'P'), whereas six further options were included as distractor items (we indicate these above using 'D').

Perceptions of scientific opinion on the causation of OA

We asked respondents: "Which of the following statements do you think most accurately reflects scientific opinion on ocean acidification?"

Respondents selected from one of the following three options:

- Most experts are of the view that ocean acidification is caused by carbon dioxide (CO_2) emissions - from human activities - that end up in the ocean;
- Some experts are of the view that ocean acidification is caused by carbon dioxide (CO_2) emissions - from human activities - that end up in the ocean;
- Only a small number of experts are of the view that ocean acidification is caused by carbon dioxide (CO_2) emissions - from human activities - that end up in the ocean

Perceptions of climate change causation

Following a standard survey measure[21], we asked respondents: "Thinking about the causes of climate change, which, if any, of the following best describes your opinion?"

Respondents selected from one of the following seven options:

- Climate change is entirely caused by natural processes;
- Climate change is mainly caused by natural processes;
- Climate change is partly caused by natural processes and partly caused by human activity;
- Climate change is mainly caused by human activity;
- Climate change is entirely caused by human activity;
- I think there is no such thing as climate change;
- Don't know

This measure and further measures described below were obtained subsequent to the experimental framing manipulation.

New Ecological Paradigm (NEP)

Respondents indicated the extent to which they agreed or disagreed (5-point scale) with the following items comprising the revised NEP scale[18]:

- When humans interfere with nature, it often produces disastrous consequences;
- The balance of nature is strong enough to cope with the impacts of modern industrial nations [reverse coded];
- The balance of nature is very delicate and easily upset;
- Humans are severely abusing the environment;
- The so-called 'ecological crisis' facing humankind has been greatly exaggerated [reverse coded];
- If things continue on their present course, we will soon experience a major ecological catastrophe

Respondents' scores on the NEP scale (Cronbach's α=.82) were treated as an indicator of pro-environmental attitudes.

Cultural worldviews

Respondents indicated the extent to which they agreed or disagreed (5-point scale) with the following items corresponding to measures of egalitarianism and individualism:

- The world would be a better place if its wealth were divided equally among nations;
- Discrimination against minorities is still a very serious problem in our society;
- In my ideal society, all basic needs (food, housing, education, healthcare) would be guaranteed by the government for everyone;

- People should be allowed to make as much money as they can for themselves, even if others are not able to;
- When I have problems, I try to solve them on my own;
- If the government spent less time trying to fix everybody's problems, we'd all be a lot better off

These items are based on measures applied and developed in the risk perception and climate change perceptions literature[33,34,35]. From a principal components analysis (Varimax rotation) a two-factor solution was obtained across the six items. Variables for egalitarianism and individualism based on regression scores[36] were used in subsequent analyses as indicators of respondents' worldviews.

Level of education

Respondents indicated the highest level of education obtained on a 7-point scale from 'primary school' to 'postgraduate qualification'.

Sampling and administration procedures

Two nationally representative samples of British (England, Scotland, Wales) public opinion were obtained. Wave 1 took place during September 2013 and collected responses from 1,001 individuals. Wave 2, conducted during May 2014, collected responses from 1,500 further members of the public. No participants were surveyed in both waves.

Data collection was administered online by Ipsos MORI on behalf of Cardiff University using quota sampling via panel databases (members of the public who have previously agreed to participate in survey research). Samples were representative of the British population aged 18-80 in terms of age, gender and geographical region. Where descriptive statistics are given in the main text (e.g. percentage of respondents stating awareness of OA) these are representative of the British population to within a margin of error of approximately +/- 2% (95% confidence interval) for the full sample (n=2,501).

Data were collected in two waves to facilitate comparisons between two key time points: the first directly before the release of the first part of the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report, the second wave of data collection conducted immediately after the release of the third part of the Assessment Report. As previous IPCC launches have attracted significant media interest we sought to test whether this reporting would have a measurable effect on awareness and attitudes towards OA. Although demonstration of a causal link would not have been possible to verify, a significant change in attitudes towards OA at Wave 2 could reasonably be

attributed to the impacts of the report. Because we found no difference in basic awareness and knowledge across the two survey waves, however, descriptive statistics are aggregated (n=2,501) unless otherwise stated.

Experimental information framing

Part-way through the wave 2 survey, respondents were provided with one of two texts describing OA, with the prefacing information: "Please read the following short text about ocean acidification. We will then ask you some further questions".

In one of these texts, OA was described as a stand-alone issue (n=1,000 respondents received this version); in the second 'framing condition' (n=500 respondents) the material presented differed only in terms of emphasising an explicit connection with climate change within the text in six places (see Supplementary Information for texts used).

Analysis and analytic approach

Coding of open-ended image associations

In order to examine the characteristics, prevalence and influence of image associations, these were coded according to a framework developed by the research team.

The coding framework for the open-ended responses was established across several stages. In the first instance, a preliminary set of codes was developed by the survey organisation Ipsos MORI, based on data from the first survey wave (n=3,003 responses from n=1,001 respondents). This preliminary set of codes was arrived at using an inductive process; that is, based on an attempt to identify over-arching themes across the open-ended data without a predetermined notion of which concepts were relevant to the study or a prior intention to group the data in any particular way. The coding framework derived consisted of six main thematic categories, incorporating 96 codes in total.

This coding framework was subsequently reduced and refined, in order to achieve a more parsimonious and conceptually meaningful set of codes. Codes assigned to only a small number of responses were removed or combined, and thematic categories adjusted to more closely reflect topics aligned with both the public perceptions and OA science literature. The refinement of codes drew additionally on semi-structured interviews with lead scientists from the UK Ocean Acidification Research Programme and members of the public (unpublished data). The provisional coding framework derived from this process consisted of 17 categories. At this stage 150 responses from the full dataset were coded by three researchers independently in order to test the coding

framework; 17 coding categories were retained with minor amendments made to category definitions.

Two researchers coded the full dataset of 7,503 open-ended responses (three image associations for each of 2,501 respondents). For responses spanning more than one category, researchers assigned a primary code based on the more prominent category and/or that mentioned first, together with a second/third code for secondary categories (approximately 8% of responses were assigned a second code, with <1% assigned a third code). Restatement of categories corresponding to 'ocean' or 'acid' were treated as subsidiary to other associations.

From the full coding, 85% inter-rater agreement was obtained, based on the primary codes assigned for all respondents' first, second and third image associations. Cohen's kappa (a measure of inter-rater reliability accounting for agreement expected by chance) was .88, .83, and .80 for the first to third image associations respectively. This constitutes a very high level of inter-observer agreement.

Outstanding responses for which coding agreement had not been obtained were reviewed by two researchers and consensus reached based on a review of codes initially assigned and consideration of respondents' original open-ended responses. In addition, five codes corresponding only to a small number of responses were combined with other 'miscellaneous' responses. The full set of 7,503 coded responses was used to derive overall response prevalence (Table 1, main article). Response codes for the first image response, wave 2 data only (total 1,500 coded responses) were used as predictors in regression models.

Regression analyses

The determinants of concern about OA (pre information framing) were examined through five linear regression models. The first of these included only self-reported knowledge of OA; the second model incorporated values, attitudes and sociodemographic measures (gender, education, worldviews, pro-environmental attitudes, perceived causation of climate change); the third model assessed the role of affective responses (individuals' mean affect score across spontaneous image associations); the fourth model assessed the role of four prevalent image categories in the form of dummy variables; the fifth and full model incorporated all of these predictors.

For our analysis of an association between perceptions of climate change (human or natural causation) and perceptions of scientific consensus on the role of human activities in causing OA, we regressed perceived scientific consensus on OA onto climate change perceptions, self-reported knowledge of OA, and an interaction term (climate change perceptions * knowledge).

For our analysis of the framing experiment, linear regression using interaction terms was used to assess whether the information type exerted variable effects on respondents' level of concern about

OA, depending upon respondents' pre-existing value orientations. We incorporated all predictors as in the first regression models, with the exception of image categories (the information texts explicitly referred to aspects of these). In addition, we included the measure of concern obtained at the start of the survey (pre information framing), and an interaction term to account for the possibility that the effects of the experimental framing varied by level of prior concern (prior concern * experimental condition).

Regression modelling of concern used forced entry with pairwise deletion and was applied to the wave 2 data only (n=1,500) for which data were available for all predictor variables. Our interpretation of the measure of concern about OA applied two techniques. For our prediction of concern prior to information provision (initial regression modelling) we utilised data only from those expressing a stated level of concern (i.e. excluding 'don't know' or 'no opinion' responses) across the wave 2 data (n=656). For our subsequent assessment of the effects of information provision (pre/post comparison) we additionally assumed a value of zero (i.e. indicating an absence of concern) for all 'don't know' or 'no opinion' responses in order to account for change in concern following information provision, again using Wave 2 data (n=1,500).

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