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Ocean acidification and its impacts: an expert survey

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Abstract The oceans moderate the rate and severity of climate change by absorbing massive amounts of anthropogenic CO_2 but this results in large-scale changes in seawater chemistry, which are collectively referred to as anthropogenic ocean acidification. Despite its potentially widespread consequences, the problem of ocean acidification has been largely absent from most policy discussions of CO_2 emissions, both because the science is relatively new and because the research community has yet to deliver a clear message to decision makers regarding its impacts. Here we report the results of the first expert survey in the field of ocean acidification. Fifty-three experts, who had previously participated in an IPCC workshop, were asked to assess 22 declarative statements about ocean acidification and its consequences. We find a relatively strong consensus on most issues related to past, present and future chemical aspects of ocean acidification: non-anthropogenic ocean acidification events have occurred in the geological past, anthropogenic CO_2 emissions are the main (but not the only) mechanism generating the current ocean acidification event, and anthropogenic ocean acidification that has occurred due to historical fossil fuel emissions will be felt for centuries. Experts generally agreed that there will be impacts on biological and ecological processes and biogeochemical feedbacks but levels of agreement were lower, with more variability across responses. Levels of agreement were higher for statements regarding calcification, primary production and nitrogen fixation than for those about impacts on

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foodwebs. The levels of agreement for statements pertaining to socio-economic impacts, such as impacts on food security, and to more normative policy issues, were relatively low.

1 Introduction

Among the services provided by the oceans is the uptake of between 24 % and 33 % of anthropogenic CO_2 emissions during the past five decades (Le Quéré et al. 2009), which has moderated the rate and severity of climate change. However, the massive amount of CO_2 absorbed, about 1 million tons per hour, generates large-scale changes in seawater chemistry that are collectively referred to as anthropogenic ocean acidification. The concentrations of dissolved inorganic carbon and bicarbonate increase while seawater pH and the concentration of carbonate decrease (Gattuso et al. 1999). Numerous physiological and biological processes depend on pH and other parameters of the carbonate system, making ocean acidification an important, if somewhat neglected, factor of global environmental change (Denman et al. 2007), sometimes referred to as "the other CO_2 problem".

The number of scientists performing research on ocean acidification and its consequences, as well as the number of papers published, has increased dramatically in the past few years (Gattuso and Hansson 2011; Gattuso et al. 2011). While these advances support improved assessment, the volume and rapidity of the scientific developments, as well as the inevitable emergence of some contradictory results, have created challenges for evaluating the current state of knowledge and informing policy makers. Two strategies have been used to synthesize the information available: narrative reviews (Doney et al. 2009 and several chapters in Gattuso and Hansson 2011) and meta-analysis (Hendriks et al. 2010; Liu et al. 2010; Kroeker et al. 2010). Although there is a consensus that the production of calcium carbonate shells and skeletons will be negatively affected as pH falls, disagreements and uncertainties remain given differences in methods used and sometimes given varying results of a single approach.

Harrould-Kolieb and Herr (2011) recently noted that, despite ocean acidification's potential to be globally disruptive, the issue is still largely absent from many policy discussions relating to CO_2 emissions. It has only recently and timidly been included in discussions within the United Nations Framework Convention on Climate Change. These authors explain that a busy agenda and difficult negotiations focused almost exclusively on climate change have prevented ocean acidification from emerging as a key policy issue. The relatively recent emergence of ocean acidification research, and the inevitable inconsistent results and uncertainties, has prevented the scientific community from delivering a clear message to decision makers. When they are delivered, scientific findings often refer to the *potentially* dramatic consequences of anthropogenic ocean acidification. Clearer statements about the extent of expert agreement on key statements, and the associated level of uncertainty, should prove useful to decision makers.

Gattuso et al. (2011) estimated levels of evidence and confidence, as defined by the Intergovernmental Panel on Climate Change (IPCC; Mastrandrea et al. 2010), for 15 key issues related to ocean acidification. But this first attempt to provide key metrics on ocean acidification was limited in scope, involving only five experts.

To expand the scope of expert assessment, here we present results from an online survey of 53 ocean acidification experts, conducted after those experts participated in a workshop on ocean acidification in Okinawa, Japan, organized by Working Groups I and II of the IPCC in January 2011. Subsequent to the Okinawa workshop, and independent of the IPCC, a set of 22 declarative statements was prepared in consultation with several of the meeting's expert participants. The statements were grouped into three categories: chemical, biological and biogeochemical, and

Table 1 Summary of probabilistic judgments that statements 1–8 on chemical issues are true, sorted by self-reported level of knowledge. If respondents provided a range for a statement, the lower bound is used here. Full responses are reported in the Supplementary Information

Statement	Respondents reporting good or expert knowledge			Respondents reporting limited or no knowledge (or NA)		
Assessed probabilty	≥0.98	≥0.8 but <0.98	<0.8	≥0.98	≥0.8 but <0.98	<0.8
1. Anthropogenic ocean acidification is caused by CO_2 emissions to the atmosphere that end up in the ocean.	25	13	2	2	9	1
2. Non-anthropogenic ocean acidification events have occurred in the geological past.	13	4	1	9	15	8
3. Anthropogenic ocean acidification is currently in progress and is measurable.	27	9	1	0	12	4
4. The rate of CO_2 emissions is as important for determining ocean acidification impacts as is the total magnitude of emissions.	13	15	3	0	7	9
5. Over the next century, assuming business as usual CO_2 emission scenarios, anthropogenic ocean acidification will continue at a rate faster than non-anthropogenic acidification has ever occurred in the past 55 Myr.	6	9	5	3	9	17
6. Human activities beyond CO_2 emissions, such as eutrophication and runoff, affect ocean acidification in coastal regions	16	8	6	3	10	10
7. The magnitude of future anthropogenic ocean acidification depends on CO_2 emission pathways.	18	8	2	2	4	13
8. Anthropogenic ocean acidification that has occurred due to historical fossil fuel emissions will affect ocean chemistry for centuries.	16	13	2	3	9	8

NA no answer

policy and socio-economic issues (Tables 1, 2, and 3). Using a scale that ran from 0 to 100, experts were asked to assess the degree to which they agreed with each statement. In addition for each statement, they could indicate a range of second-order uncertainty (confidence) and provide a self-assessment of their level of expertise. Further details on the implementation of the survey as well as the complete data set are available as supplementary information.

2 Results

On average for a given statement, 47 of the 53 surveyed experts indicated a level of agreement or a range of levels of agreement (ranging from 32 responses for statement 15 to 53 responses for statements 3, 6 and 14). For all statements, most respondents had some level of expertise. The lowest overall expertise occurred for statement 15 for which 16 % of the respondents indicated that they had “almost no knowledge about this issue”.

Table 2 Summary of probabilistic judgments that statements 9–18 on biological and biogeochemical issues are true, sorted by self-reported level of knowledge. If respondents provided a range for a statement, the lower bound is used here. For statements 9–14 and 16–18, respondents were asked to consider ranges of pCO_2, pH, calcium carbonate saturation state, etc. projected for 2100 under business as usual CO_2 emissions. Full responses are reported in the Supplemental Information

Statement	Respondents reporting good or expert knowledge			Respondents reporting limited or no knowledge (or NA)		
Assessed probabilty	≥0.98	≥0.8 but <0.98	<0.8	≥0.98	≥0.8 but <0.98	<0.8
9. Anthropogenic ocean acidification will adversely affect calcification for most calcifying organisms	3	11	21	0	4	11
10. Anthropogenic ocean acidification will stimulate primary production in some primary producers	7	6	9	1	6	19
11. Anthropogenic ocean acidification will stimulate nitrogen fixation in some nitrogen fixers	3	2	4	1	8	16
12. Some species or strains are tolerant when tested today at levels of anthropogenic ocean acidification projected for 2100	12	9	8	4	6	10
13. Some species or strains will be tolerant by 2100 because they have acclimated or adapted to anthropogenic ocean acidification	2	6	15	1	6	12
14. Anthropogenic ocean acidification will impact ecosystems, some of them negatively (e.g. coral reefs)	13	14	8	5	7	6
15. Recovery (e.g. of coral reefs) from past ocean acidification events has taken as long as 1 to 10 million years	1	5	2	2	6	16
16. Anthropogenic ocean acidification will reduce biodiversity	4	5	14	1	3	18
17. Anthropogenic ocean acidification will negatively impact higher trophic levels by altering food web structure	1	4	14	0	5	20
18. Anthropogenic ocean acidification will impact biogeochemical processes at the global scale	10	13	6	2	6	11

NA no answer

2.1 Interpretation of results

Before reporting specific results we consider how true Bayesians might respond if they viewed their response on the 0-1 scale as indicating their assessed probability that the given statement is true (Lee 2004). If they believe themselves to be truly expert, and are confident that a statement is true, then they should give an answer of >0.98, but not 1, so that their prior distribution places a bit of probability on the alternative, allowing for updating if unexpected countervailing evidence were to arise in the future. If those respondents chose to

Table 3 Summary of probabilistic judgments that statements 19–22 on policy and socio-economic issues are true, sorted by self-reported level of knowledge. If respondents provided a range for a statement, the lower bound is used here. For statements 19 and 20, respondents were asked to consider ranges of pCO_2, pH, calcium carbonate saturation state, etc. projected for 2100 under business as usual CO_2 emissions. Full responses are reported in the Supplemental Information

Statement	Respondents reporting good or expert knowledge			Respondents reporting limited or no knowledge (or NA)		
Assessed probabilty	≥0.98	≥0.8 but <0.98	<0.8	≥0.98	≥0.8 but <0.98	<0.8
19. Anthropogenic ocean acidification will negatively impact food security	1	4	7	1	6	21
20. Anthropogenic ocean acidification will reduce the socio-economic value of some marine ecosystems	5	8	7	2	10	17
21. It is possible to define a threshold for ocean acidity, either globally or for some specific ecosystems or regions, that must not be exceeded	1	5	21	0	7	11
22. Some geoengineering approaches will not reduce anthropogenic ocean acidification	17	2	4	11	4	9

NA no answer

report a range with their responses, that range should lie entirely above 0.5 and should not include 1. In Tables 1, 2, and 3 that summarize the results, we use three cut points: responses (including ranges) >0.98, responses (including ranges) that lie below 0.98 but are >0.8, and responses with ranges that extend below 0.8. All individual responses and comments are included in the supporting information.

The responses we obtained from those reporting good or expert knowledge are largely consistent with the expected patterns. The assessed probabilities for Bayesians who say they are not expert, but know something about the topic and think a statement is "probably true" should be >0.5 but a bit lower than those given by the experts, since as Bayesians they should want their prior to have more probability on the negative hypothesis so that it will get updated faster if they learn more. The less expert Bayesian's second order uncertainty should probably express a wider range than that reported by the experts. It should not extend up to 1.0 or .98 and should not extend much below 0.5 if they think the statement is probably true. The inverse should be true if they think the statement is probably false. Performance in this case was more mixed.

2.2 Statements about chemical issues

While there was general agreement by most respondents with statement 1 that "anthropogenic ocean acidification is caused by CO_2 emissions to the atmosphere that end up in the ocean" (Table 1), several respondents noted a number of other processes also contribute to acidification. For example expert 14 noted that "human emissions of acidic species (NO_x, SO_x, etc.) [have] been shown to exacerbate pH change in some areas, especially coastal regions downwind of urban zones (Doney et al. 2007)." At the same time this respondent noted that "[g]lobal ocean models cannot replicate present…trends [in ocean acidification] without including [anthropogenic] CO_2…from the atmosphere (Sabine et al. 2004)." In a similar vein, while agreeing with the statement, respondent 29 noted that "[a] couple of percent of the observed acidification may be due to other chemical species originating from anthropogenic activities than CO_2, but in coastal environments these can have a significant effect," and expert 44 observed that "[t]he uptake of CO_2 by the ocean can result in acidification, but the reduced ventilation of the mid-water due to ocean warming can induce the O_2 reducing and that result[s] in acidification, too."

Statement 2, that "non-anthropogenic ocean acidification events have occurred in the geological past," also evoked general agreement. Respondent 5 noted, however, that how one answers "depends on the specifics of how you defined 'ocean acidification' for ancient events." Expert 14 observed that while "[m]odel reconstructions (by Zeebe, Ridgwell, etc.) show that ocean pH has indeed changed widely in the geological past… changes in alkalinity and other ocean chemical parameters during those periods have not been the same as those today that accompany the ocean pH decrease." While indicating the statement was true, respondent 42 cautioned that it "requires the caveat that the slow rate…of change in the geological past resulted in quite small changes due to the ameliorating effects of the weathering of carbonate rocks and other processes. This perspective is backed up by information from tools such as the boron isotope series for determining ancient ocean pH." Respondent 50 observed that "[t]here does not exist—to present knowledge—any good paleo-analog to ongoing ocean acidification…Of course, ocean pH and CO_3-saturation have undergone changes in the past, but respective events cannot really be compared to ongoing acidification (either too small, too slow, or accompanied by other forcing factors such as meteorite impacts)."

Statement 3 asserted that "anthropogenic ocean acidification is currently in progress and is measurable." 36 of 37 respondents who said they had good or expert knowledge agreed that this statement was absolutely or nearly certainly true. Several of these respondents noted the availability of good time series. For example respondent 7 indicated that "[t]here are good time series measurements at several sites which directly show changes in ocean pH over decadal time scales that are highly likely to be a result of anthropogenic ocean acidification," and respondent 12 referenced a 15-year time series collected "in the western North Pacific including coastal ocean off of Japan." Several noted that measuring pH in the open ocean is much more straightforward than doing so in coastal waters where there can be other confounding factors. Respondent 33, who reported only limited knowledge and a probability range of 0.3 to 0.5, disagreed with those reporting good or expert knowledge, suggesting that "the presently available global data on pH are not sufficient to justify such a statement. Moreover, the data from some regions, especially from marginal areas of the oceans, apparently disagree with it. Finally, even if the global negative trend is true, its anthropogenic origin is hypothetical rather than firmly established."

There was a greater diversity of opinion among those reporting good or expert knowledge about statement 4, "the rate of CO_2 emissions is as important for determining ocean acidification impacts as is the total magnitude of emissions." Respondent 42 noted that "[t]here is little doubt that the rate of emissions is a critical factor—if it is slow as it has been in the past, then weathering of carbonate rocks can buffer the chemical changes of slow rises in carbon dioxide. The reverse is true if it is fast." In a similar vein, respondent 27 observed that "[r]ate differences amounting to a few years would not significantly alter the end result but rate differences on scales similar to natural buffering processes (100 s–1000 s) years would be significant." For similar reasons expert 50 argued that "[t]he question is ill posed," and respondent 23 explained, "I've put 80 % (followed by a range of 0–100 %) because the importance of the rate of change depends on the time scale. For example, if we consider a 500 ppm CO_2 increase over 10,000 years versus 100 years, then there would be very significant differences in the changes to ocean chemistry at these different rates of increase because of the greater capacity for geological buffering over long times intervals with a very slow rate of increase. However, if we consider a 500 ppm CO_2 increase over 200 years versus 100 years, the differences in ocean chemistry would be much smaller (possibly insignificant) due to limited capacity for geological buffering over either of these time intervals, even though they have different rates of increase."

Statement 5 read: "over the next century, assuming business as usual CO_2 emission scenarios, anthropogenic ocean acidification will continue at a rate faster than non-anthropogenic acidification has ever occurred in the past 55 Myr.' As Table 1 indicates, among those with good or expert knowledge, this statement received the lowest rate of high agreement of the chemistry-related statements. The concern expressed by several respondents was well characterized by expert 29 who noted that the truth of the statement depends "on what we know from the Paleo-record, which becomes increasingly uncertain the farther back in time we go." Respondent 37 observed that, "[i]f any events since the [Paleocene–Eocene Thermal Maximum (PETM)] caused [ocean acidification] at a rapid pace over a short time, it might have been possible that this signal was not detectable in the ice core record or marine sediments due to the resolution in time of those records. This seems highly unlikely, however, and it is far more likely that the current and future rates of [ocean acidification] will exceed any that have occurred since the PETM (55.8 mya)."

The issue of coastal impacts, raised by a number of respondents in connection with statement 3, was addressed by statement 6, which read: "human activities beyond CO_2 emissions, such as eutrophication and runoff, affect ocean acidification in coastal regions." Several respondents noted that, whatever the causal mechanism, several processes other than acidification were more important in coastal waters. Expert 5 stated, "I do not think eutrophication and runoff will be huge impacts on ocean acidification, but I think eutrophication, runoff, and ocean acidification will jointly affect coastal ecosystems." Expert 31 observed, "[t]hough it is highly possible that human activities beyond CO_2 emission will affect ocean acidification in coastal region…there are very few studies that have evaluated the direct link between ocean acidification and other anthropogenic issue[s]."

There was of course some overlap between statement 4 on rate of change in emissions and statement 7, which read: "the magnitude of future anthropogenic ocean acidification depends on CO_2 emission pathways." In responding, several experts noted this overlap, as summarized for example by expert 7: "[a]nthropogenic ocean acidification (in non-coastal areas) is a direct result of uptake of atmospheric CO_2, therefore the rate and magnitude of atmospheric CO_2 change will impact directly on ocean pH."

The final statement in this first section of the survey, statement 8, read: "anthropogenic ocean acidification that has occurred due to historical fossil fuel emissions will affect ocean chemistry for centuries." Independent of their level of self-assessed knowledge all respondents assessed significant agreement (>0.5) with this statement. Some noted that "centuries" was open-ended. Expert 42 wrote: "This is physical chemistry—work done by Ken Caldeira and others is completely convincing on this issue. I don't think there is any other possibility." Expert 14 noted that "[l]ong-term model projections (Ridgwell) show that it takes on the order of centuries for the initial acute [ocean acidification] signal to be overcome, but it still takes millennia for ocean chemistry to recover completely to a completely preindustrial pH level."

2.3 Statements about biological and biogeochemical issues

Fourteen of the 35 respondents who reported good or expert knowledge assigned a high probability (>0.8) that statement 9, "anthropogenic ocean acidification will adversely affect calcification for most calcifying organisms," was true (Table 2). A number of respondents indicated that the word "most" was important in their evaluation, as succinctly stated by expert 42, "[m]ost but not all," and as elaborated by expert 14, "I am uncomfortable with the word 'most." Many respondents further discussed variability in organismal responses observed to date, for example as summarized by expert 21: "there is a large variability in the responses and only a small fraction of organisms has been investigated." Respondents indicated that the effects of longer-term processes added to uncertainty in their responses. For example, respondent 15 stated that "[t]he uncertainty in my response reflects lack of knowledge about acclimation and adaptation over longer time scales," and respondent 7 similarly noted that "effects of natural selection, adaptation, evolution and population dynamics are not yet well understood." In a related vein, respondent 5 indicated that "[t]here is a subtlety to this question: What does "adversely affect calcification" mean?… I am answering the question above largely at the organism level, and not the level of calcification per se."

About 60% of respondents who reported good or expert knowledge assigned a high probability to the veracity of statement 10: "anthropogenic ocean acidification will stimulate primary production in some primary producers." A number of respondents indicated the importance of the word "some" for their evaluation of the statement. For example, respondent 35 indicated that "[o]f course we can expect some stimulation in 'some' species. But we can expect a lot of variability in responses." Respondent 5 similarly noted that, "if 'some' is intended to mean a few producers in special circumstances, then I would have high confidence in the statement. If 'some' is intended to mean an amount that is significant at global scale, then I would have low confidence in the statement," and expert 36 stated, "[g]iven the diversity of primary producers in the ocean, it is nearly certain that at least some subset of primary producers will benefit from ocean acidification (this is just a statistical problem, not a biological one). The important (biological) question is whether or not this subset is large enough to matter or to dominate community-level responses."

Statement 11, that "anthropogenic ocean acidification will stimulate nitrogen fixation in some nitrogen fixers," evoked a roughly similar proportion of respondents in agreement, although fewer respondents reported good or expert knowledge. Respondent 6 summarized the state of knowledge as follows: "This is true for some species of nitrogen fixers, if indeed, the experiments conducted to date represent what will happen over longer time scales."

Statement 12, that "some species or strains are tolerant when tested today at levels of anthropogenic ocean acidification projected for 2100," was assigned a high probability (>0.8) of being true by most respondents with good or expert knowledge, as summarized for example by respondent 37: "Several species have been shown to tolerate/acclimate to… levels [of ocean acidification projected for 2100]." A number of participants indicated that, given the relatively short durations of experiments to date, questions remain regarding responses over longer periods. For example, respondent 19 stated, "most experimental evaluations seem to be too short in their exposure durations." One respondent (10) requested further specificity for evaluation of the statement: "Tolerant to what is not indicated, is the question about [primary productivity] or calcification or fitness?"

Respondents indicated fairly low agreement for statement 13: "some species or strains will be tolerant by 2100 because they have acclimated or adapted to anthropogenic ocean acidification." Several respondents pointed to the limitations in understanding and available evidence. For example, respondent 21 stated that "mechanisms setting limits to acclimation or adaptation capacity are presently unknown," and expert 31 noted that "[t]o my knowledge there are only very few studies that have evaluated the acclimation or adaptation capacity of the organism to the ocean acidification." Respondent 35 questioned the formulation of the statement, saying that "[f]or sure, some species already have enough plasticity and/or variability to cope with future pH/pCO_2 changes," a point echoed by several other experts. Expert 42, as well as 48, noted the importance of multiple stressors organisms encounter: "the current set of studies are generally not looking at the impacts of ocean acidification in combination with rising sea temperatures. This is a great shortcoming…"

Among respondents with good or expert knowledge, statement 14, that "anthropogenic ocean acidification will impact ecosystems, some of them negatively (e.g. coral reefs)," received high agreement. Several respondents emphasized that this statement was particularly relevant to coral reefs, with respondent 50 stating for example, "100 % yes for coral reefs, for others we do not know much yet." Some respondents indicated the importance of other, potentially synergistic stressors. For instance, respondent 33 said, "I think that other stressors associated with the climate change, such as temperature changes, wind and wave climate changes, incidence of severe storms, hypoxia, etc, are likely to have more profound impact on the ecosystems such as reefs than the pH trends," and expert 52 noted that "temp[erature] and pH both seem to have interactive & complex effects." Further, respondent 37 emphasized that, although "the magnitude of effects…for most ecosystems" are unclear, "there is little to no doubt that [ocean acidification] will have some impact."

Respondents reporting good or expert knowledge provided moderate agreement for statement 15: "recovery (e.g. of coral reefs) from past ocean acidification events has taken as long as 1 to 10 million years." Several respondents indicated difficulties in linking past extinctions to ocean acidification given geologic records. For example, expert 9 stated that "[t]here is no past [ocean acidification] event which has coral mass extinction and quantified pH changes. Therefore, the question is impossible to answer. Coral extinction events led to a coral gap but the causality to [ocean acidification] is not clear yet." Several other respondents also indicated importance of other stressors and variables, as summarized by respondent 22, "[r]ecovery in response to one variable over such long time scales is a very difficult (I'd say impossible) thing to measure because most ecosystems are dynamic over millions of years due to changes in multiple abiotic variables (e.g. temp[erature] as well as pH) and biotic processes (e.g. change in species ranges, invasions, extinctions, etc.)."

Approximately forty percent of respondents with good or expert knowledge indicated high agreement with statement 16, that "anthropogenic ocean acidification will reduce biodiversity." Respondents 42 and 45 indicated that coral reefs and their high diversity are likely to be affected by ocean acidification. Several respondents noted that current understanding and available experimental evidence limit projections of future biodiversity, as described for example by respondent 19: "in case of ocean acidification, data are not sufficient to predict what happens to biodiversity." Respondent 37 further noted that the evaluation of the statement hinged on how one defined biodiversity: "Biodiversity can be measured as the number of species in an area (species richness—a common metric of biodiversity), but is also used to indicate the genetic diversity of a population or populations, or functional diversity, taxonomic diversity, and others—all described as 'biodiversity'. Will we lose species richness? Probably. Will we lose genetic diversity? Almost certainly. Will it influence the function of ecosystems? It depends upon the magnitude and type of change in biodiversity."

Statement 17, that "anthropogenic ocean acidification will negatively impact higher trophic levels by altering food web structure," met with low agreement among respondents reporting good or expert knowledge. Several respondents again pointed to the limitations in available evidence, as summarized for example by expert 15, who noted that "there is very little direct evidence" of effects "on higher tropic levels." Comments from other respondents focused on the word "negatively." Respondent 23, for instance, stated, "[y]es, I am certain that some species at higher tropic levels will be negatively affected by changes in abundance at lower tropic levels, but others species may be positively affected by these changes in food web structure, for example if a competitor or key predator is adversely affected. Changes to food web structure are rarely negative for ALL species." Respondent 37 similarly noted that "[i]t is likely that there will be winners and losers, in terms of the direct impacts on species. These changes will lead to indirect impacts (positive and negative) on other species."

Most respondents with good or expert knowledge indicated a high probability that statement 18 was true: "anthropogenic ocean acidification will impact biogeochemical processes at the global scale." Respondent 5 noted that the "biogeochemical processes" under consideration influence evaluation of the statement: "If we include, say, enhanced carbonate mineral dissolution as a "biogeochemical process" then this is highly certain. If you define 'biogeochemical process' differently, you can get different answers." Characterizing a range of processes, expert 14 stated that "[m]ultiple biogeochemical cycles stand to be affected: C, N, metals; and perhaps other pH-sensitive nutrient forms (Si? P?) [w]ill also be affected. There is no reason to suspect that [ocean acidification] will NOT affect these processes on a global scale; uncertainty comes from how much, and how these effects will interact."

2.4 Statements about policy and socio-economic issues

For statement 19, "anthropogenic ocean acidification will negatively impact food security," 5 of 12 respondents reporting good or expert knowledge indicated a high probability (> 0.8) of the statement being true (Table 3). Several respondents noted that evaluation of the statement depended on temporal and spatial scales under consideration. For example, respondent 5 stated that, "If we are talking about poor fisherman living on isolated islands, then 'yes, almost certainly.' If we are talking global scale, then I think this is likely to be a secondary concern except for communities tightly tied to coral reefs for food," and respondent 33 said that "it is my feeling that at the time scales under consideration, other manifestations of climate change will be more important for food security, so the effect of acidification (if any) will be largely masked by the effects from other stressors." Respondent 21 noted that it was "[u]nclear what is meant by food security. Certainly, food availability will change in some areas, 100 % sure, but positive developments may also be possible." A number of experts also indicated that uncertainties regarding biological responses to ocean acidification, as relevant to fisheries, limited certainty in the statement. For instance, respondent 19 said, "[e]ven though fish in general seem to be relatively robust, impacts on fish through food web change have not been well understood," and respondent 37 noted, "[i]t remains unclear what the effects of [ocean acidification] will be on energy flow through marine food webs." Finally, two respondents (51 and 52) indicated that multiple stressors and confounding factors, from "geopolitical to other aspects of global environ[mental] change," complicated interpretation of the statement.

Statement 20 read: "Anthropogenic ocean acidification will reduce the socio-economic value of some marine ecosystems." About two thirds of respondents reporting good or expert knowledge indicated a high probability (0.8) that the statement was true. Expert 5 stated that "[c]oral reef systems [are] most likely to be adversely impacted in terms of value," a perspective reiterated by respondents 8, 37, 42, 43, 45, and 51. Respondent 14 explained that "[a]ny shift away from biodiversity, seafood harvests, or the general health of a culturally important ecosystem can decrease the economic or social value of an ecosystem," while respondent 48 indicated that "we need more details on the (potential) losses (in M$) to specific systems (e.g. coral reefs, coastal fishery, deep-sea fishery)." As for statement 19, respondent 51 indicated that ocean acidification "will act in synergy with other anthropogenic stressors" in affecting marine ecosystems.

Agreement among respondents was notably lower for statement 21: "it is possible to define a threshold for ocean acidity, either globally or for some specific ecosystems or regions, that must not be exceeded." Indicating that the statement required clarification to allow fruitful evaluation, expert 4 stated that a threshold could be defined "only for limited regions. And then only once expectations for function are defined. Depending on what you expect from the ocean, any level is possible. So the question is poorly posed." Respondent 5 similarly noted that a threshold could be defined although it would "[p]robably not" be meaningful: "From my perspective, we are looking at a monotonic dose–response curve with increasing effect at increasing concentration in ways that are not well characterized by specific thresholds." Providing another reason for complications in evaluating thresholds, respondent 26 indicated that defining a threshold "involve[s] assessing what is an acceptable 'loss' which is more of a value judgment." Several other experts questioned the utility of defining thresholds, with respondent 15 stating for example that "[r]esponses to CO_2 are not 'all or nothing' and depend on the level of CO_2 as well as the physiological state of the organisms and evolved capacity for acid–base balance among other things. Putting a specific value on a CO_2 level is not really possible or useful in my opinion." Other respondents, such as 19 and 21, posited the necessity of adopting "precautionary" approaches in defining thresholds.

Statement 22, that "some geoengineering approaches will not reduce anthropogenic ocean acidification," received high agreement among respondents with good or expert knowledge. A number of respondents, such as 4, 5, 7, 8, 24, 26, 37, and 52, indicated or implied that the statement was true "by definition," as summarized for example by respondent 5: "Many geoengineering techniques will not address ocean acidification, so clearly some approaches will not reduce ocean acidification." Several respondents indicated that geoengineering approaches may be able to reduce anthropogenic ocean acidification at local, although not global, scales. Expert 14, for instance, noted that "[g]eoengineering that focuses on other acidic anthropogenic species (SO_x, NO_x, etc.) may make local differences in [ocean acidification] but not global differences," while respondent 5 stated, "I think there are approaches that might at great expense protect an individual bay or reef. I do not think there are approaches that are feasible to apply at the scale of the global ocean."

3 Discussion

The levels of agreement of respondents who had some expertise (expert, good, or some limited knowledge about the issue) are summarized for each survey statement in Fig. 1, and the median values of assessed probabilities for statements is considered in this section. The levels of agreement for the 8 statements concerning chemical aspects of ocean acidification are high or very high (median for each at or above 89 %) despite the fact that a few respondents provided large ranges (up to 90 %). With the exception of a few outliers, overall there is strong support that anthropogenic ocean acidification is currently in progress and is measurable (S3; median of 98 %), is caused by CO_2 emissions to the atmosphere that end up in the ocean (S1; 99 %) and is affected by human activities beyond CO_2 emissions, such as coastal eutrophication and runoff (S6; 90 %). There is also a large consensus that non-anthropogenic ocean acidification events have occurred in the geological past (S2; 95 %) and that the rate of CO_2 emissions is as important for determining ocean acidification impacts as is the total magnitude of emissions (4; 90 %).

Concerning the chemistry of the future ocean, it is largely accepted that, over the next century assuming business as usual CO_2 emission scenarios, anthropogenic ocean acidification will continue at a rate faster than non-anthropogenic acidification has ever occurred in

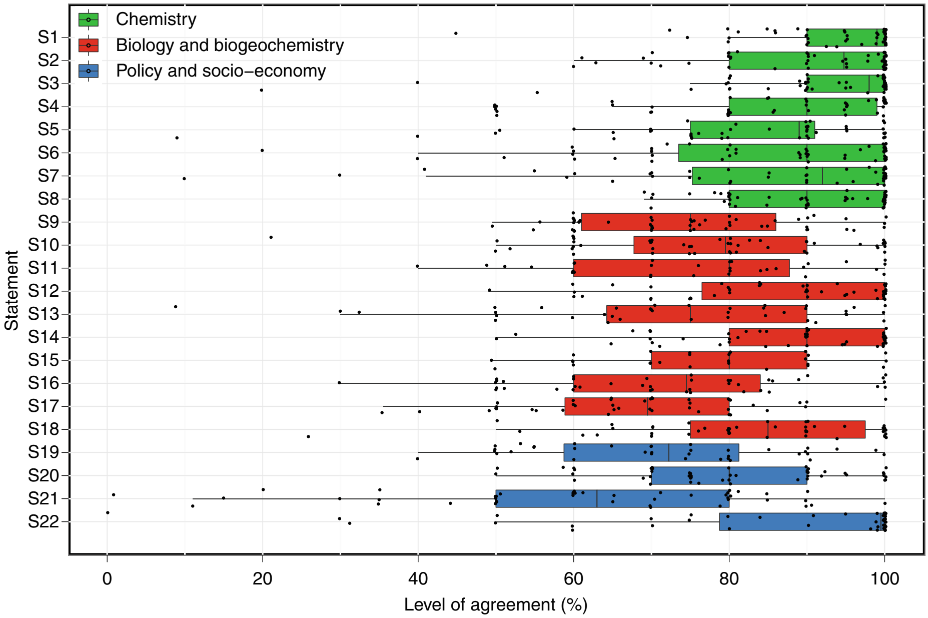

Fig. 1 Box plot summary of the single estimates and mid-range values from respondents who have some level of expertise. The lower and upper ends of the boxes represent the 25 % and 75 % quantiles; the median (50 % quantile) is shown as a vertical line inside each box; the lower and upper whiskers respectively represent the 25 % quantile - (1.5 × interquartile range) and the 75 % quantile + (1.5 × interquartile range). Values smaller than the lower whisker are outliers but are nevertheless taken into account to calculate median and quantiles

the past 55 Myr (S5; 89 %). Similarly, there was general agreement that the magnitude of future anthropogenic ocean acidification depends on CO_2 emission pathways (S7; 92 %) and that anthropogenic ocean acidification that has occurred due to historical fossil fuel emissions will affect ocean chemistry for centuries (S8; 90 %).

Levels of agreement were significantly lower regarding ocean acidification impacts on biogeochemical processes such as calcification, primary production and nitrogen fixation. The statement "anthropogenic ocean acidification will adversely affect calcification for most calcifying organisms" (S9) met a median level of agreement of 75 %. This relatively high level of agreement is unexpected because responses of calcification to ocean acidification have been a controversial issue, with several data sets indicating that calcification is not affected or is even stimulated in some organisms (Andersson et al. 2011; Riebesell and Tortell 2011; Gattuso and Riebesell 2011). Overall, the respondents appear to believe that the balance of evidence indicates many organisms will be adversely affected. This is consistent with the high level of agreement that "some species or strains are tolerant when tested today at levels of anthropogenic ocean acidification projected for 2100" (S12; 90 %).

There is also a relatively high level of agreement that anthropogenic ocean acidification will stimulate primary production in some primary producers (S10; median of 80 %) and nitrogen fixation in some nitrogen fixers (S11; 80 %). Primary producers and, to a lesser extent, nitrogen fixers demonstrate a large range of responses to ocean acidification (Andersson et al. 2011; Riebesell and Tortell 2011). The focus of the statements on "some" organisms probably explains the high overall level of agreement, but the ranges in respondents' estimates suggest remaining uncertainties as well.

Understanding of adaptation and acclimation of organisms to ocean acidification is complicated because most of the experimental information has been collected on timescales shorter than generation times. The survey reflects that challenge, given a large range in responses to the statement that "some species or strains will be tolerant by 2100 because they have acclimated or adapted to anthropogenic ocean acidification" (S13; median of 75 %, with values ranging from 9 to 100 %).

There is a consensus that anthropogenic ocean acidification will impact ecosystems, some of them negatively (e.g. coral reefs; S14; median of 90 %), reduce biodiversity (S16; median of 75 %, with the lowest assessed probability at 30 %), negatively impact higher trophic levels by altering food web structure (S17; median of 70 %; min 36 %), and biogeochemical processes at the global scale (S18; 85 %, with minimum of 26 %). Finally, recovery (e.g. of coral reefs) from past ocean acidification events has taken as long as 1 to 10 million years (S15; 80 %).

Surprisingly considering the numerous uncertainties about the biological effects of ocean acidification, the levels of agreement on the socio-economic statements are not as low as one could have expected: anthropogenic ocean acidification will negatively impact food security (S19; median of 72 %) and will reduce the socio-economic value of some marine ecosystems (S20; 80 %). The policy statements are quite clear-cut. There is a low level of agreement that it is possible to define a threshold for ocean acidity, either globally or for some specific ecosystems or regions, that must not be exceeded (S21; 63 %). This is in contrast to suggestions that safe limits can be defined for changes in the seawater carbonate chemistry. Schubert et al. (2006) proposed that the pH value of near surface waters should not drop more than 0.2 units below its pre-industrial average to prevent undesirable or high-risk changes to the marine food web. While acknowledging that their choice was subjective, Rockström et al. (2009) proposed that the aragonite saturation state should remain above 80 % of its average surface ocean, pre-industrial value ± diel and seasonal variability. There is a very high consensus that some geoengineering approaches will not reduce anthropogenic ocean acidification (S22; 99.5 %).

In conclusion, this survey involved ocean acidification experts with wide ranging expertise and considerably expands the scope of expert assessment in the field. The results indicate a relatively strong consensus for most statements related to the past, present and future chemical aspects. Examples of consensual issues are: non-anthropogenic ocean acidification events have occurred in the geological past, anthropogenic CO_2 emissions are the main (but not the only) mechanism generating the current ocean acidification event, and ocean acidification will be felt for centuries. The experts generally agreed that there will be impacts on biological and ecological processes and biogeochemical feedbacks, but for such statements, the levels of agreement were lower overall, with more variability across responses. Levels of agreements among experts surveyed were comparatively higher for statements regarding calcification, primary production and nitrogen fixation, as compared to impacts on food-webs. The levels of agreement for statements pertaining to policy and socio-economic impacts are diverse with low levels of agreement for food security and economic impact and high levels of agreement on the threshold and geoengineering statements.

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References

Andersson AJ, Mackenzie FT, Gattuso J-P (2011) Effects of ocean acidification on benthic processes, organisms, and ecosystems. In: Gattuso J-P, Hansson L (eds) Ocean acidification. Oxford University Press, Oxford, pp 122–153

Denman KL, Brasseur G, Chidthaisong A et al (2007) Couplings between changes in the climate system and biogeochemistry. In: Solomon S, Qin D, Manning M et al (eds) Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Doney SC, Mahowald N, Lima I et al (2007) Impact of anthropogenic atmospheric nitrogen and sulfur deposition on ocean acidification and the inorganic carbon system. Proc Nat Acad Sci USA 104:14580–14585

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO2 problem. Ann Rev Mar Sci 1:169–192

Gattuso J-P, Hansson L (eds) (2011) Ocean acidification. Oxford University Press, Oxford

Gattuso J-P, Riebesell U (2011) Reconciling apparently contradictory observations. In: Field CB, Barros V, Stocker TF et al (eds) Workshop report of the Intergovernmental Panel on Climate Change workshop on impacts of ocean acidification on marine biology and ecosystems. IPCC Working Group II Technical Support Unit, Carnegie Institution, Stanford, California, pp 10–16

Gattuso J-P, Allemand D, Frankignoulle M (1999) Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: a review on interactions and control by carbonate chemistry. Am Zool 39:160–183

Gattuso J-P, Bijma J, Gehlen M, Riebesell U, Turley C (2011) Ocean acidification: knowns, unknowns and perspectives. In: Gattuso J-P, Hansson L (eds) Ocean acidification. Oxford University Press, Oxford, pp 291–311

Harrould-Kolieb ER, Herr D (2011) Ocean acidification and climate change: synergies and challenges of addressing both under the UNFCCC. Clim Pol 1–12

Hendriks IE, Duarte CM, Alvarez M (2010) Vulnerability of marine biodiversity to ocean acidification: a meta-analysis. Estu Coastal Shelf Sci 86:157–164

Kroeker K, Kordas RL, Crim RN, Singh GG (2010) Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol Lett 13:1419–1434

Le Quéré C, Raupach MR, Canadell JG et al (2009) Trends in the sources and sinks of carbon dioxide. Nat Geosci 2:831–836

Lee PM (2004) Bayesian statistics: an introduction, 3rd edn. Wiley, New York

Liu J, Weinbauer MG, Maier C, Dai M, Gattuso J-P (2010) Effect of ocean acidification on microbial diversity, and on microbe-driven biogeochemistry and ecosystem functioning. Aquat Microb Ecol 61:291–305

Mastrandrea MD, Field CB, Stocker TF et al (2010) Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC)

Riebesell U, Tortell PD (2011) Effects of ocean acidification on pelagic organisms and ecosystems. In: Gattuso J-P, Hansson L (eds) Ocean acidification. Oxford University Press, Oxford, pp 99–121

Rockström J, Steffen W, Noone K, Persson Ă, Chapin FS, Lambin E, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley J (2009) Planetary boundaries: exploring the safe operating space for humanity. Ecol Soc 14: ART 32.

Sabine CL, Feely RA, Gruber N et al (2004) The oceanic sink for anthropogenic CO2. Science 305:367–371

Schubert R, Schellnhuber H-J, Buchmann N, Epiney A, Grießhammer R, Kulessa M, Messner D, Rahmstorf S, Schmid J (2006) The future of oceans- Warming up, rising high, turning sour. 110. German Advisory Council on Global Change, Berlin