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Ocean Acidification and the Southern Ocean

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Ocean Acidification and the Southern Ocean

Abstract

Ocean acidification poses severe potential threats to marine ecosystems, including the Southern Ocean. The relative undersaturation of $CaCO_3$ in the Southern Ocean suggests that ocean acidification will have its greatest initial impacts there if greenhouse gas emissions continue on their projected trajectory.

Aragonite is a form of calcium carbonate essential to shell forming organisms such as the pteropods that form the base of much of the Southern Ocean food chain. Orr et al (2005) predicted that under the Intergovernmental Panel on Climate Change (IPCC) IS92a warming scenario[1], which assumes "business as usual" - emissions leading to 778 ppm of CO_2 in the atmosphere by 2100 - aragonite will be undersaturated throughout the Southern Ocean. Even under the more conservative IPCC S650 scenario, which assumes that atmospheric CO_2 will only reach 563 ppm by 2100, the aragonite saturation horizon[2] is likely to have shrunk from 730 to 60 m by 2100, with the entire Weddell Sea undersaturated with respect to aragonite.

Current greenhouse gas emission projections make it imperative that CCAMLR Members develop research programs to fill in the gaps of current research on Southern Ocean impacts as soon as possible. Longer-term studies of acidification for the entire lifecycle of important species are needed, including implications for non-calcifying organisms and impacts of ocean acidification on other biological processes besides calcification in invertebrates and vertebrates.

Ocean acidification is relevant to consideration of the impacts of fishing on benthic organisms (including cold water corals) and the management of vulnerable marine ecosystems (VMEs). Acidification is likely to negatively affect recovery period and whether species can recover.

1. Introduction

Ocean acidification is the process by which rising atmospheric CO_2 levels lower the pH of ocean water, thereby making the water more acidic. It occurs because as a gas, CO_2 is subject to Henry's Law: the solubility of a gas above a liquid is directly proportional to the partial pressure of that gas above the solution. Therefore, as the concentration of CO_2 in the air above the ocean surface increases and air pressure remains constant, the concentration of CO_2 in the surface ocean water will also necessarily increase. The concentration of CO_2 in the atmosphere has increased from 278 ppm (pre-industrial) to about 390 ppm in 2010.

Increasing concentrations of CO_2 have significant consequences for ocean chemistry. When dissolved in seawater, CO_2 reacts with H_2O to form H_2CO_3, or carbonic acid. Carbonic acid will break down into H^+ ions and HCO_3^- (bicarbonate ions). This increase in H^+ ions decreases the pH of ocean water and leads to increased acidity. CO_3^{2-} (carbonate ions) react with these H^+ ions to form more bicarbonate ions. Carbonate ion concentrations decreases while H^+, H_2CO_3 and HCO_3^- concentrations increase. When carbonate ions are less available, calcium carbonate ($CaCO_3$) dissolution is more likely to occur, and consequently its formation is less likely to occur.

Colder water is naturally lower in calcium carbonate concentration. Many ocean organisms have shells made of calcium carbonate, so any decrease in its availability is of concern. Numerous experiments have reported that calcium carbonate-dependent organisms (also called calcifying organisms or calcifiers) experience significant problems when exposed to lower pH environments. Current atmospheric CO_2 concentrations have resulted in a drop of about 0.1 pH units (a 30% increase in acidity), and if current trends continue, ocean pH could drop by an average of 0.5 units to about 7.8 around the year 2100 under the IS92a "business as usual" emissions scenario. The latter represents an ocean that is 320% more acidic than it was in pre-industrial times. Despite that change, the ocean will still be in a slightly alkaline state, the boundary between acid and alkali lying at a pH of 7.

Calcifying organisms play critical roles in marine ecosystems, such as the Southern Ocean, and declining populations will have serious consequences for the food web. Scientists believe that ocean acidification will affect the Southern Ocean food webs first[3] because the Southern Ocean is closer to undersaturation levels with respect to $CaCO_3$ than other oceans.[4]

The ATME on Climate Change held in Norway in April 2010 recommended that CCAMLR and the CEP coordinate with each other to address climate change related issues. In its report the meeting also considered (para. 131) that "ocean acidification must come

[1] This is the 'business as usual' scenario of the IPCC for future emissions of anthropogenic carbon dioxide.
[2] This is the limit between undersaturation and supersaturation of ocean waters in aragonite, the 'weak' form of calcium carbonate (the strong form being calcite.
[3] The Royal Society (2005). Ocean acidification due to increasing atmospheric carbon dioxide. Policy document 12/05, 29.
[4] Ibid, 11.

high on the list of climate change related issues most likely to have maximum impact, likely as it is to have significant and 'rapid' impacts for management."[5]

2. *Ocean Acidification Impacts on Invertebrates*

There are two forms of calcium carbonate that are used by calcifying organisms - calcite and aragonite. Aragonite is used by pteropods and cold water corals, and calcite is used by coccolithophores and foraminifera.[6] The saturation horizon for aragonite - the area in which it is the least soluble in seawater - is closer to the ocean surface than that of calcite and will shrink further and faster under a scenario of increasing CO_2 concentrations. Although the calcite saturation horizon in the ocean is further away from the ocean surface, it will still narrow as oceans become more acidic.

The current evidence on the impacts of ocean acidification on invertebrates is scant. One 2008 review found fewer than 10 papers on early invertebrate developmental stages.[7] A subsequent review noted that although this number is increasing, much of the literature remains uncertain and contains notable gaps, such as the exclusion of non-calcifiers and a focus on calcification and not other physiological processes that could be affected by ocean pH changes.[8] Another gap is that little research has been done on species that appear to benefit from ocean acidification, such as non-calcifying tunicates.[9] While the decline of one species is obviously of concern, sudden population growth among other species would also have significant consequences for ecosystems and should be examined. Overall, however, "in all tested species but tunicates… ocean acidification is associated with a reduction in developmental rate."[10]

Other evidence is mixed. Research on the impact of a 0.2 increase in pH on brittlestar (*Ophiothrix fragilis*) larvae found 100% mortality within 8 days, compared to a 70% survival rate for controls.[11] Calcifying coccolithophores, however, appear to have responded to acidifying oceans by thickening their shells. Coccolithophores found in sediments dating to 1780 had shells 40% thinner than those found today, and coccolithophores in water with CO2 concentrations close to those expected over the next century seem to increase calcification as pH decreases.[12] Coccolithophores differ from other calcifiers in that they form their shells internally so may be less susceptible than organisms that produce them externally.[13] One difficulty in assessing the importance of research findings is the variation in experimental procedures. A study using different experimental methods to examine the responses of coccolithophores to acidified environments found that shells were malformed,[14] suggesting that researchers may need to reevaluate their methods to determine which ways of altering pH best approximate actual ocean conditions. Another calcifying phylum, Foraminifera, shows decreased shell weights under acidified conditions.[15] Pteropods have exhibited shell dissolution under laboratory conditions designed to approximate pH levels predicted for 2100.[16]

Though many of these results are sobering, they are currently inadequate to make accurate predictions about the impacts of ocean acidification. More targeted research programs are needed. There is also the problem that CO_2 levels were high at times in the geological past (such as the Eocene) without there being much evidence for significant deleterious effects on marine planktonic organisms at those times. That may be because they were slow changes that enabled organisms to evolve to adapt to gradually rising CO_2 levels, whereas today the rate of rise in CO_2 and acidification is, in comparison, extremely fast.[17]

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[5] See also Guinotte, JM and Fabry, VJ 2008. Ocean Acidification and Its Potential Effects on Marine Ecosystems. Ann. N.Y. Acad. Sci. 1134: 320–342.

[6] Pteropods are a type of pelagic mollusk. Coccolithophores are shell-forming single-celled algae, protists, and phytoplankton. Foraminifera are single-celled protists that also form shells. All are important low trophic level species.

[7] Kurihara, H (2008). Effects of CO_2-driven ocean acidification on the early developmental stages of invertebrates. *Marine Ecology Progress Series* 373: 275-284.

[8] Dupont, S and Thorndyke, MC (2009). Impact of CO_2-driven ocean acidification on invertebrates early life-history – What we know, what we need to know and what we can do. *Biogeosciences Discussions* 6: 3109 – 3131.

[9] Ibid, 3112.

[10] Ibid, 3112.

[11] Dupont, S, Havenhand, J, Thorndyke, W, Peck, L & Thorndyke, M (2008). Near-future level of CO2-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. *Marine Ecology Progress Series* 373:285-294

[12] "Chalk one up for coccolithophores." 28 Apr 2008. PHYSorg.com. www.physorg.com/news128613620.html

[13] Ibid.

[14] Wright, S and Davidson, A (2006). Ocean acidification: a newly recognized threat. *Australian Antarctic Magazine* 10: 26-27.

[15] Guinotte, JM and Fabry, VJ (2008). Ocean acidification and its potential effects on marine ecosystems. *Annals of the New York Academy of Sciences* 1134: 320 – 342.

[16] Ibid, 331.

[17] Ridgewell, A and Schmidt, DN (2010). Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release. *Nature* 3: 196 – 200.

3. *Ocean Acidification Impacts on Vertebrates*

Environments of above-normal acidity do not only affect calcifiers, but also animals that breathe water. Research in this area has been somewhat more limited, but indicates that detrimental effects on fish are likely, although the impacts of these changes are unknown. According to one survey of the literature, "short-term effects of elevated CO_2 on fishes include alteration of the acid–base status, respiration, blood circulation, and nervous system functions, while long-term effects include reduced growth rate and reproduction."[18] According to a review by The Royal Society, "acidification of body fluids of marine animals as a result of increasing external CO_2 [hypercapnia] occurs rapidly, in a matter of hours."[19] Hypercapnia appears to lower respiratory rates and rates of protein synthesis, and might affect reproduction as well.[20]

Langenbuch and Portner (2003) found that protein synthesis for two Antarctic fish species, *Pachycara brachycephalum* and *Lepidonotothen kempi*, decreased by 80% under acidic conditions, and that this is likely to be detrimental to the organism in the long term.[21] However, like many other researchers they used conditions that are far more acidic than those predicted to occur for the next several hundred years. Nevertheless even a smaller reduction in protein synthesis under less acidic conditions could have a long-term impact. One study that examined the non-polar clownfish under pH conditions similar to those anticipated by 2100 found that acidified environments caused the fish to be unable to respond to the olfactory cues that typically help them locate appropriate habitats.[22] Research on clownfish larvae reared in CO_2 concentrations closer to those predicted to occur within the next 200 years (700 ppm and 850 ppm) had sobering results. At 700 ppm, the level that is predicted to occur under the business as usual IS92a scenario, half of the fish seemed oblivious to predator cues.[23] Fish in an 850 ppm environment were almost all attracted to the predator cue.[24] When damselfish reared under the control, 700 ppm and 850 ppm environments, were reintroduced to a reef, the mortality rates from predation were significantly higher for the 700 and 850 ppm groups than for the control.[25] Thus there appears to be strong initial evidence that relatively near-term increases in CO_2 will have detrimental impacts on fish behavior. In a review of the literature on fish and increased CO_2 concentration, Ishimatsu et al. (2008) identified several key gaps in research that are currently hampering our ability to predict the effects of ocean acidification on non-calcifiers, including research into the impacts of acidified oceans on reproduction and long-term research examining acidification's impacts over an organism's entire lifespan.[26]

4. *Ocean acidification and the Southern Ocean*

As noted above, the relative $CaCO_3$ undersaturation of the Southern Ocean indicates that ocean acidification will have its greatest initial impacts in the Southern Ocean. Orr et al. (2005) predict that under the IS92a warming scenario, which assumes "business as usual" emissions leading to 778 ppm of CO_2 in the atmosphere by 2100, aragonite will be undersaturated throughout the Southern Ocean.[27] Even under the more conservative S650 scenario, which assumes that atmospheric CO_2 will reach only 563 ppm by 2100, the aragonite saturation horizon will have shrunk from 730 to 60 m, with the entire Weddell Sea undersaturated with respect to aragonite.[28]

It is expected that calcite-forming organisms such as coccolithophores and foraminifera will not be as affected by ocean acidification, but Moy et al. (2009) have already found a 30% to 35% reduction in the shell weights of planktonic foraminifera (*Globigerina bulloides*) in the Southern Ocean.[29] Their experiment compared the shell weights of foraminifera from similar size ranges in sediment cores to those obtained from sediment traps moored at various depths. Not only was it confirmed that modern *G. bulloides* shell weights have decreased, but results from the sediment core confirm that over the past 50,000 years the shell weights have been highest when atmospheric CO_2 is lowest and lowest when CO_2 is highest.[30]

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[18] Ibid, 332
[19] The Royal Society (2005), 19.
[20] Ibid 19 – 20.
[21] Langenbuch, M and Portner, HO (2003). Energy budget of hepatocytes from Antarctic fish (*Pachycara brachycephalum* and *Lepidonotothen kempi*) as a function of ambient CO2: pH-dependent limitations of cellular protein biosynthesis? *Journal of Experimental Biology* 206: 3895 – 3903.
[22] Munday PL, Dixson, DL, Donelson, JM, Jones, GP, Pratchett, MS, Devitsina, GV, Doving KB (2009). Ocean acidification impairs olfactory discrimination and homing ability of a marine fish. Proceedings of the National Academy of Sciences 106: 1848 – 1852.
[23] Munday, PL, Dixson, DL, McCormick, MI, Meekan, Ferrari, M, , MCO and DP Chivers (2010). Replenishment of fish populations is threatened by ocean acidification. *Proceedings of the National Academy of Sciences* 107: 12930-12934.
[24] Ibid, 12931.
[25] Ibid, 12932.
[26] Ishimatsu, A, Hayashi, M and Kikkawa, T (2008). Fishes in high-CO2, acidified oceans. *Marine Ecology Progress Series* 373: 295-302.
[27] Orr, JC et al. (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437: 681 – 686.
[28] Ibid, 683.
[29] Moy, AD, Howard, WR, Bray, SG, Trull, TW (2009). Reduced calcification in modern Southern Ocean planktonic foraminifera. *Nature Geoscience* 2, 276 – 280.
[30] Moy et al. (2009), 279.

Another study predicts that due to seasonal variations, the Southern Ocean will become undersaturated with aragonite by 2038 under the IS92a scenario.[31] Aragonite in the Southern Ocean is already low during winter due to the circulation of deep waters south of the Polar Front, and thus there is a lower threshold for undersaturation.[32] The researchers conclude that the "tipping point" for Southern Ocean acidification is 450 ppm atmospheric CO_2 as this is the level at which their models predict wintertime undersaturation of aragonite.[33] This tipping point will have significant consequences for Southern Ocean pteropods because the main species of this group present in the Southern Ocean, *Limacina helicina*, is in the shell-forming veliger stage during the winter. Pteropods are important to the Antarctic foodweb, comprising "up to one-quarter of total zooplankton biomass in the Ross Sea, Weddell Sea, and East Antarctica…and dominate carbonate export fluxes south of the Antarctic Polar Front..."[34]

5. Recommendations

Much of the literature on ocean acidification thus far does not offer conclusive predictions for the effects of ocean acidification on marine ecosystems and species. It is imperative that research programs to fill in the gaps of current research on Southern Ocean impacts by this phenomenon be designed and implemented as soon as possible. This is particularly important, since one of the main areas currently lacking understanding is related to longer-term studies of acidification on the entire lifecycle of important marine species. The work that is underway in the Southern Ocean Observing System (SOOS)[35] will help produce useful information but much more targeted research is required. In this context, it is very positive that SCAR has created a new specialists group focusing on acidification.

Acidification should be considered when assessing the impacts of bottom fishing on vulnerable marine ecosystems given the effect on calcifying organisms including cold water corals.

ASOC calls on the Scientific Committee at this year's meeting to begin considering what targeted research programs will help fill the key research gaps, and to advise the Commission and its Members about priorities to be considered. Among the main research gaps are:

- Impacts of ocean acidification over long timescales
- Impacts on non-calcifying organisms
- Impacts of acidification on other biological processes besides calcification in invertebrates and vertebrates
- Impacts of acidification on recovery rates from the impact on vulnerable marine ecosystems such as cold water corals.[36]

ASOC recommends that the Commission add the issue of ocean acidification to its agenda for next year's CCAMLR meeting, and that during the next year Members consider how they can facilitate the scientific research that is needed to better understand the phenomenon and address its implications.

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[31] McNeil, BI, Matear RJ (2008). Southern Ocean acidification: A tipping point at 450-ppm atmospheric CO2. *Proceedings of the National Academy of Science* 105: 18860 – 18864.
[32] Ibid.
[33] Ibid.
[34] McNeil and Matear (2008), 18863.
[35] http://www.scar.org/soos/
[36] See Dupont and Thorndyke (2008), McNeil and Matear (2008), and Ishimatsu et al. (2008) for more detailed research suggestions and recommendations.