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Ocean Acidification in the Southern Ocean

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Ocean acidification is the other carbon dioxide problem and has been referred to as "the evil twin" of global warming.[1]

Introduction

The world's oceans are inexorably evolving toward a state of acidification dissimilar to what has been witnessed throughout human history, this anthropogenic phenomenon is termed Ocean Acidification (OA).[1] The coupled physical/chemical changes have far-reaching consequences for marine habitats, organisms, ecosystems and ecosystem services. Predicted intensification of OA in the coming decades will likely disrupt physiological processes and reduce calcification, development, and fecundity in a range of organisms (Gattuso et al. 2015, Sosdian et al. 2019). As with global temperatures, the rate of OA is as concerning as the degree of change (Turley et al. 2006, Table 1). Acidification is accelerating faster than previously estimated driven by the increasing rate of carbon dioxide (CO_2) emissions (Zeebe and Zachos 2013, Negrete-García et al. 2019).[2]

Table 1. Average world ocean surface pH (Orr et al. 2005)

Time	pH	Change in pH relative to pre-industrial	Source	Hydrogen ion concentration relative to pre-industrial	References
Preindustrial (18th century)	8.179		analyzed field		Key et al. 2004
Recent past (1990s)	8.104	-0.075	field	+18.9%	Key et al. 2004
Present Level	~8.069	-0.11	field	+28.8%	Hall-Spencer et al. 2008
2050 (2 x CO_2 = 560 ppm)	7.949	-0.230	model	+69.8%	Orr et al. 2005
2100 (IS92a)	7.824	-0.355	model	+126.5%	Orr et al. 2005

The mechanisms and processes that couple atmospheric CO_2 concentrations with ocean chemistry are well understood. About a third of the CO_2 humans have emitted since the beginning of the Industrial Revolution

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[1] Turley et al. 2005, Henderson 2006, Doney et al. 2009, and Morford 2015.

[2] Atmospheric gas trapped in Antarctic ice cores show that current concentrations of CO_2 are unprecedented in the last 800,000 years (Lüthi et al 2008). Since the last ice age, the rate of temperature and CO_2-increase has been two orders of magnitude lower than during the current era of anthropogenic change. The rate of change in ocean acidification today is seldom observed in the geological record and the resilience of ecosystems to gradual change in the past cannot be assumed to be the same as today.

has been taken up by the oceans (Doney et al. 2009, Le Quéré et al., 2016, Sosdian et al. 2019). It takes hundreds of years for the oceans come to equilibrium with the atmosphere. Therefore, **acidification will continue to increase even if atmospheric CO_2 concentrations were stabilized at today's levels**. The Southern Ocean is the dominant ocean for carbon storage – accounting for ~40% of global oceanic CO_2 uptake (Frölicher et al. 2015). The influx of anthropogenic CO_2 has resulted in a change in ocean surface water acidity expressed as a lowering of pH and carbonate saturation state (Bates et al. 2014, Sosdian et al. 2019). The pH scale is logarithmic (1 pH unit is a tenfold change in acidity) and over the last 250 years ocean acidity has increased twenty-nine percent (Hall-Spencer et al. 2008, Table 1). This rate of change is 10 times faster than that experienced by the oceans in millions of years (Turley et al. 2006, Hönisch et al. 2012, Negrete-García et al., 2019, Hall-Spencer and Harvey 2019).[2]

Oceanic uptake of CO_2 is not constant and varies by region.[3] Due to the long timescales of oceanic mixing, the distribution of CO_2 in the oceans is spatially and temporally heterogeneous. As CO_2 dissolves in the ocean, the partial pressure of carbon dioxide (pCO2) in seawater increases, pH declines and concentrations of other components of the marine carbonate system adjust. Concentrations of carbonate ions, the building blocks of aragonite and calcite (types of carbonate), may fall below saturation levels, threatening carbonate-habitats and the health and physiology of carbonate-exploiting species. The amount of CO_2 that can dissolve in seawater is greater at colder temperatures and higher pressures. As such, the lowest pH and carbonate ion concentrations are in the polar oceans and the deep sea[4]. These factors tend to amplify the effects of acidification in the Southern Ocean compared to other oceans. The depth within the water column below which seawater is corrosive to carbonate (the "Saturation Horizon") is becoming shallower impinging on larger areas of the sea floor[4]. As such, habitats exposed to seawater that is corrosive to aragonite are increasing. Predictions under the IPCC Representative Concentration Pathway 8.5 suggest that by 2100 oceanic pH (est. pH = 7.8, Table 1) will be at the lowest level ever reached over the last 14 million years (Sosdian et al. 2019).

The effects of OA on living systems are not well understood. Extrapolation of laboratory and mesocosm responses to real-world scenarios is uncertain and field observations are limited, especially for Antarctic environments. However, extreme and rapid OA in the geologic past resulted in mass extinctions (Clarkson et al. 2015, Sosdian et al. 2019).

Ocean Acidification has been on the ATCM/CEP agenda for more than a decade.[5]

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[3] In the 1990s, ocean CO_2 uptake decreased, before increasing again in the 2000s. Recent research shows that the Southern Ocean was central to these changes (DeVries et al. 2017). In the 1990s, strengthening winds circulating around Antarctica affected ocean currents and brought carbon-rich water to the surface decreasing ocean CO_2 uptake from the atmosphere. The rate at which CO_2 is transferred from the air into seawater depends on the difference in the concentration of CO_2 in the air, and that in the water. As human activities add more CO_2 to the atmosphere, this concentration difference increases, and the ocean absorbs more CO_2.

[4] For the Southern Ocean, the Saturation Horizon is estimated at ~750-1000 m for aragonite and ~3100–3400 m for calcite (Bostock et al. 2013). There is considerable regional variation in these depths, reflecting differences in water masses and their circulation.

[5] OA was first highlighted to ATCM XXXII (2008) in IP062 *Antarctic Climate Change and the Environment: A progress report*. OA was highlighted at ATCM XXXII (2009) and XXXVIII (2015) in SCAR science lectures (ATCM XXXII IP071 *The SCAR Lecture – Marine Life and Change in the Southern Ocean* and ATCM XXXVIII BP001 *SCAR Lecture: Southern Ocean Acidification*). The 2010 Antarctic Treaty Meeting of Experts (ATME) noted that "ocean acidification must come high on the list of climate change related issues most likely to have maximum impact". In subsequent years, further IPs were submitted by SCAR (see Annex A) and ASOC (ATCM XXXIV IP088 *Ocean Acidification and the Southern Ocean*). From 2018 onwards the CEP's five-year workplan has highlighted the 'assessment on impact of ocean acidification to marine biota and ecosystems as a Science knowledge and information need', and it is also highlighted in the CEP's current Climate Change Response Work Programme. The SCAR Action Group on Ocean Acidification ran from 2012-2018. As a cross-cutting issue, a range of SCAR groups have made contributions to understanding the impacts of OA on marine ecosystems (e.g., AnT-ERA, ICED, ASPeCt).

Southern Ocean Environments

In the open Southern Ocean, far from land, pH and carbonate saturation state are stable. In contrast, acidity in coastal areas is variable due to varying inputs of nutrients, freshwater and sediments from the surrounding land, and from melting ice. A changing climate is altering these inputs. In addition, the upwelling of cold CO_2-laden upper circumpolar deep water has increased in recent decades (Smith et al. 2017). Regardless, Antarctic coastal waters have a narrower pH range than temperate and tropical regions, with the highest levels occurring during periods of enhanced summer primary production (Hofmann et al. 2011, Matson et al. 2011; Conrad and Lovenduski 2015; Kapsenberg et al. 2015; Schram et al. 2015).

Biological responses to OA are expressed at the molecular, organismal, population, community and ecosystem levels. Different species have characteristics or traits (e.g., reproduction, dispersal, growth, feeding, habitat) which may be affected by OA. Vulnerabilities to acidification, and other environmental factors (e.g., warming and freshening), vary with life-stage. Larval forms are often more sensitive to environmental change. Understanding these complex interactions is crucial for forecasting biotic responses to increasing acidification but much remains unknown.

Marine organisms with shells or skeletons of calcium carbonate become vulnerable as sea water carbonate ion concentrations decrease to levels that dissolve these structures. However, non-calcifiers can also be affected by acidification. Effects may be direct (e.g., reduced pH disrupts organismal functions; Pörtner 2008), or indirect (e.g., altered food webs, behavioural changes). While studies in the Antarctic are limited, increased OA elsewhere, particularly at natural CO_2 vents that acidify surrounding waters, has caused shifts in algal community composition and alteration of coastal habitats. Increased availability of bicarbonate and pCO2 can stimulate primary production (Hall-Spencer and Harvey 2019). Carbon fixation is increased, enhancing standing stocks of large seaweeds and seagrasses. Many macrofauna are susceptible to the effects of OA. For example, there was a ~30% decline in animal biodiversity as pH decreased from 8.1 to 7.8.[6] Studies along pH gradients at northern, natural CO_2-seep sites documented that increased acidity reduced ecosystem diversity, species richness and spatial heterogeneity (Hall-Spencer and Harvey 2019). The complexity and multi-directional nature of biotic responses makes it difficult to generalize.

As in other regions of the world, studies of the ecophysiological responses of Antarctic organisms to OA have shown a wide range of effects. Changes in carbonate chemistry may negatively affect the ability of Antarctic molluscs to form and maintain shells (e.g., Manno et al. 2017, Bylenga et al. 2017, Gardner et al. 2018). Many shelled Antarctic benthic invertebrates are less calcified than their temperate or tropical counterparts (Watson et al. 2012) which may increase vulnerability to acidification. In closely related groups, other physiological processes can be, but are not always, negatively impacted.[7] The potential for organismal adaptation in the longer term has been noted.[8]

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[6] Corals are the most recognized habitat-forming marine animals, but a diverse range of other groups build calcareous seabed habitats such as sponges, serpulids, vermetids, oysters, mussels and bryozoans.

[7] For example, in three co-occurring benthic invertebrate species, gonadal development was reduced in a mollusc (scallop) but only in one of two echinoderms (sea urchin but not sea star; Dell'Acqua et al. 2019). In the keystone pelagic crustacean, adult Antarctic krill, short-term exposure resulted in several forms of likely physiological stress (Saba et al. 2012) but no detrimental impacts were observed in a year-long study (Ericson et al. 2018, 2019) indicating that the krill are able to physiologically adapt. In contrast, ecologically important benthic crustaceans (amphipods) can have high mortality (Schram et al. 2016a,b, Park et al. 2020). Microscopic and macroscopic algae can, although do not always, benefit physiologically from increased pCO_2 (e.g., Iñiguez et al. 2017, Cummings et al. 2019, Trimborn et al. 2019) but it can also decrease silica (cell wall) production in ecologically important planktonic microalgae (diatoms), potentially altering not only their vulnerability to herbivores but also carbon transport to the deep sea (Petrou et al. 2019). Overall, ocean acidification reduces the complexity, extent and species richness of biogenic reefs.

[8] For example, brachiopods produced a thicker shell, presumably as protection against dissolution in response to acidification (Cross et al. 2019). Further, *Sterechnius* urchins appeared to acclimate in longer-term studies (Morley et al. 2016, Suckling et al. 2015).

Studies of the effects of OA on higher trophic levels are limited. Direct – albeit minor – effects have been documented for some notothenioid fishes[9]. Direct effects of OA on other higher order taxa in the Southern Ocean are unknown (Constable et al. 2014). Marine mammals and birds respond to changes in the production, distribution and dynamics of prey species (Morley et al. 2019), including moving to alternative locations for food. This has energetic cost implications for species that are undertaking longer or more complex foraging trips, especially for those that are bound to breeding colonies (Constable et al. 2014). Understanding how prey species respond to OA is key to understanding predators' responses. Krill reproduction is predicted to decline under increasing acidification and krill-feeding predators may be negatively impacted (Kawaguchi et al. 2013).[10] Studies along pH gradients at northern, natural CO_2-seep sites documented that increased acidification degraded carbonate habitats compromising coastal protection and habitat provisioning for fisheries.

OA and warming have synergistic effects that exacerbate the risk of population declines in sensitive species. Combined with rising temperatures, sea-level rise and more frequent and higher magnitude/amplitude extreme events; OA threatens the goods and services provided by ecosystems.[11]

Concluding Remarks

The Southern Ocean will continue to acidify for decades, and possibly centuries, as the ocean equilibrates with atmospheric CO_2 concentrations. OA attributable to anthropogenic CO_2 already emitted is yet to be fully expressed in ocean chemistry.[12] Changes in Antarctic oceanic and coastal environments caused by OA will be amplified foretelling change in more northerly oceans. The vulnerabilities of sensitive species may be heightened by synergistic interactions with other climate-change effects (e.g., atmospheric and oceanic warming, sea-level rise, increased storminess and changes in sea ice distribution and dynamics). Biological and ecosystem responses to acidification in tropical, sub-tropical and temperate coastal systems must be cautiously applied when forecasting responses and effects in Antarctic marine biota and environments (Hall-Spencer and Harvey 2019). Studies of potential impacts on ecosystems are limited but altered food web interactions and shifts in community composition can be expected, along with changes in carbonate habitats, as carbonate stability deteriorates.[13] Mass extinctions in the geologic past were associated with levels of OA that some have projected by the year 2100, if CO_2 emissions remain unabated (Clarkson et al. 2015, Sosdian et al. 2019). As concerning, the current rate of CO_2 release is unprecedented in the geological record (Hönish et al. 2012). If the trend of increasing emissions continues, the magnitude and rate of future acidification will increase, causing biological and ecological responses to intensify and accelerate at a rate never observed in Earth's history. Consideration of OA trajectories and biotic impacts will be essential for predicting futures and planning conservation efforts in the Antarctic region.

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[9] Metabolic responses to CO_2 increases were negligible to minor but there were differences in the magnitude of responses between different species and life stages (Enzor et al. 2017; Davis et al. 2017; Flynn et al. 2015).

[10] Antarctic krill are the target of the largest fishery in the Southern Ocean. Recent local concentration of this fishery is likely causing reduced performance for penguins when local harvest rate is high in years of low krill biomass combined with poorer environmental conditions (Watters et al. 2020). The negative effect of acidification on krill reproduction projected into the future (Kawaguchi et al. 2013) could magnify this negative effect on krill predators.

[11] For example, although increased temperature had no effect alone on amphipod survival, it synergistically increased mortality in lower pH treatments (Schram et al. 2016a). Additionally, decreased pH alone had little impact on a variety of physiological or behavioural metrics in a fish but it inhibited the fish's ability to physiologically compensate for increases in temperature (Davis et al. 2018).

[12] The reason the planet takes several decades to respond to increased CO_2 is the thermal inertia of the oceans regulates responses to increased atmospheric CO_2 taking decades to be completely expressed.

[13] More information is needed on the ability of species to adapt to long-term changes (e.g. across generations, Byrne et al. 2019) given the rate of ocean acidification (and warming). Feedbacks with changes in sea-ice cover and warming temperatures (freshening, especially in coastal areas) are poorly understood but may be important in forecasting future responses.

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Annex A. List of SCAR ATCM papers (2019-2008) mentioning ocean acidification (obtained by a key word search of the SCAR website)

Paper Title	Date
BP003: Anthropogenic Noise in the Southern Ocean: an Update	31st July 2019
ATT046 to IP003: Antarctic Environments Portal Content Management Plan	22nd Jan 2019
IP033: Update on activities of the Southern Ocean Observing System	22 Jan 2019
BP001: SCAR Lecture: Southern Ocean Acidification	10 Jun 2015
Attachment to IP011: Scoping Workshop on Practical Solutions Final Report	07 May 2014
Overview of SCAR Papers Submitted to ATCM XXXVI and CEP XVI 2013	29 May 2013
IP052: Ocean Acidification: SCAR Future Plans	29 May 2013
IP002: The Southern Ocean Observing System (SOOS)	20 Jun 2012
IP035: Antarctic Conservation for the 21st Century: Background, Progress, and Future Directions	20 Jun 2012
IP040: SCAR Products Available to Support the Deliberations of the ATCM	20 Jun 2012
IP051: The Southern Ocean Observing System (SOOS): An Update	01 Jun 2011
IP050: The Southern Ocean Observing System (SOOS)	14 May 2010
IP071: SCAR Lecture 2009: Marine Life and Change in the Southern Ocean (Lecture Slides)	17 Apr 2009
IP062: Antarctic Climate Change and the Environment: A Progress Report (32nd meeting)	13 Jun 2008