The anthropogenic increase in atmospheric carbon dioxide (CO_2) concentration is changing the global climate and causing rising temperatures, altered weather patterns and rising sea levels. One effect of rising CO_2 levels that is under-reported is the change in the chemistry of the oceans. The acidity of the oceans is increasing as they absorb CO_2 from the atmosphere at a rate of 20 million tonnes per day[1]. This process, known as ocean acidification is a predictable consequence of rising atmospheric CO_2 and does not suffer from uncertainties associated with other climate change forecasts[2]. The rate of ocean acidification will accelerate over this century unless future CO_2 emissions are reduced dramatically[2]. It is likely that ocean acidification is already having significant biological impacts on the marine environment, some of which will become severe within a few decades.

Carbon Dioxide and Ocean Chemistry

Ocean acidification can be defined as the change in ocean chemistry driven by the oceanic uptake of chemical inputs to the atmosphere[3]. The overwhelming cause of ocean acidification is anthropogenic atmospheric carbon dioxide (CO_2), driven by fossil fuel combustion and deforestation. Since the beginning of the industrial revolution atmospheric CO_2 concentration has increased by 40% from 280 parts per million (ppm) to 387 ppm. The rate of increase over the last 250 years has been 100 times faster than has occurred for millions of years[4] and the current concentration is the highest experienced on earth for at least 800 000 years[5].

To date the oceans have absorbed between a quarter to a third of all the anthropogenic CO_2 emitted into the atmosphere[6], acting as a buffering system to the effects of climate change. Without this oceanic uptake the earth's atmosphere would now have a CO_2 level of approximately 450 ppm [2]. Although beneficial in moderating atmospheric CO_2 levels, oceanic uptake comes with a significant cost. The absorbed CO_2 dissolves in seawater to form carbonic acid, reducing ocean pH (increasing acidity). Since pre-industrial times ocean surface water pH has dropped by 0.1 units on average, from 8.21 to 8.1 [7], which corresponds to a 30% increase in acidity over the last 250 years. Under a business-as-usual emission scenario[8] the predicted CO_2 concentration of 800 ppm by the end of the 21st century is expected to reduce surface pH by a further 0.3-0.4 units, equivalent to a 150% increase in acidity[9]. This predicted rate of change in acidity is about 100 times faster than any change seen in the last 20 million years. It will take tens of thousands of years for the oceans to eventually stabilise pH at a lower level than current values[10, 11].

As seawater becomes more acidic there is a decrease in the concentration of available carbonate ions, the basic building block of the shells and skeletons of many marine organisms[12]. A drop in carbonate ion concentration reduces the calcium carbonate saturation state (Ω)[13]. The larger the saturation state value the more suitable the environment is for organisms that use calcium carbonate in their shells and skeletons. Currently, the vast majority of the surface ocean is super-saturated with respect to calcium carbonate. The depth in the oceans at which $\Omega = 1$ is known as the saturation horizon[11]. Calcium carbonate saturation states are highest in shallow, warm tropical waters and lowest in cold high-latitude waters and at depth[14]. The saturation horizons for aragonite and calcite (two forms of calcium carbonate) are moving to shallower depths in the world's oceans[9] as the surface layers absorb atmospheric CO_2. Some coastal waters in the Northeast Pacific have recently become undersaturated with respect to aragonite during spring through the upwelling of intermediate waters enriched in anthropogenic CO_2 onto the continental shelf[15]. Near Iceland, anthropogenic CO_2 is causing deep waters to undergo this same transition to 'corrosive' conditions to the extent that every day, another 1 km^2 of seabed is exposed, along with the associated bottom-dwelling (benthic) organisms[16]. This transition to undersaturated conditions in surface waters is projected to occur within decades over much of the polar oceans[9, 17].

Previous Global Acidification Events

Throughout Earth's history there have been a number of natural ocean acidification events caused by large scale input of carbon into the oceans. The best studied event occurred 55 million years ago when there was a rapid input of carbon into the atmosphere and oceans which was linked to major changes in marine plankton communities and the mass extinction of one group of marine calcifiers living on the sea bed[18]. The five major coral mass extinction events in the past have been associated with high and increasing CO_2 levels in the atmosphere which led to changes in temperature, oxygen and pH levels in the oceans Coral reefs have taken millions of years to re-establish themselves after these extinction events[19]. Although ocean acidification is a suspected factor in the previous demise of coral reefs, it has been too difficult to separate this factor from the effects of climate and oceanographic changes.

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Biological Effects of Ocean Acidification

The predicted changes in marine carbon chemistry are highly likely to have an enormous impact on the health and function of many marine organisms[7]. Experimental studies are showing that ocean acidification will not only directly affect calcifying organisms but also influence survival of early life stages and the physiology and behaviour of both larvae and adults.

Many marine organisms are calcifiers, they absorb calcium carbonate from seawater and use it for a number of functions, particularly protection and support in the form of skeletons and shells. Marine calcifiers include molluscs such as oysters and mussels, crustaceans, echinoderms, both tropical and cold water corals, crustose coralline algae, calcified macroalgae and planktonic fauna such as coccolithophores, pteropods and foraminifera. Most experimental studies to date for calcifying organisms have shown reduced net calcification rates in response to elevated CO_2 concentrations[2,20]. Reduced calcification has been shown by all tropical coral species tested so far, for oysters and mussels, sea urchins, coralline algae and both pteropod and foraminifera species. However results for species of coccolithophores have been more varied[3].

The early developmental stages of marine organisms, which generally tend to be more vulnerable than later or adult stages, can also be affected by high CO_2 conditions. Most benthic marine invertebrates have one or more free swimming larval stages before settling on to the sea bed and mortality rates up to settlement are naturally very high (e.g. 98% for bivalve molluscs[21]). The few studies completed so far on early life stages have shown that eggs or larvae become increasingly malformed or developed more slowly in high CO_2 conditions[11]. Settlement success can also be reduced. As larvae only have a short window to settle, slower development that delays settlement is likely to affect the chances of survival to the next life stage. For example, recent work on larval clownfish indicates that when they are exposed to lower pH levels they lose the ability to detect or discriminate between chemical (olfactory) cues in seawater which are necessary to find the right habitat (sea anemones) for settlement[22]. Losing the ability to detect such clues is likely to reduce the survival of individuals and the sustainability of populations for those species affected.

As well as reduced calcification rates as an adult, marine organisms can be affected by ocean acidification in more subtle ways. Recent studies on intertidal snails have found that their behaviour was altered in lower pH conditions which may influence feeding, survival of predation and alter energy budgets[23]. Altered behaviour was also observed at the embryonic stage with reduced and slower movement in acidified conditions[24].

The physiology of marine organisms is also likely to be affected by lower pH levels in the ocean. Short-term experiments have shown that CO_2 can diffuse across animal surfaces and lower the pH levels of internal (intracellular) fluids. It is essential that internal pH levels of an organism are maintained in a narrow range to allow countless cellular functions and regulations to occur[25]. Many marine organisms can regulate internal pH levels for short time periods (24-48 hours) but the long-term effects of continual exposure to elevated CO_2 levels in the future by predictable ocean acidification scenarios are not yet known[11]. Respiratory pigments of some marine organisms including vertebrates (fish, mammals, turtles) and crustaceans are also affected by acidity and are less able to bind to oxygen molecules when pH is reduced[26].

Interactions and Synergistic Effects

The effects of ocean acidification may increase the vulnerability of marine organisms to changes in other environmental conditions such as temperature or oxygen levels, particularly for those species on the edge of their geographical range. High CO_2 levels can act as a bleaching agent for corals and crustose coralline algae by acting synergistically with warming to lower the thermal bleaching thresholds[27]. High CO_2 levels are also known to act synergistically with low oxygen levels (hypoxia) on the respiratory responses of various marine invertebrates found in estuaries and tidepools[26]. Individual or combined effects can also reduce the health of marine organisms making them more susceptible to infection and disease. At lower pH levels the immune response of mussels may be reduced[28] while a combination of high CO_2 and low oxygen levels has been demonstrated to reduce the ability of some marine organisms to combat bacterial infection.

There are currently few published studies investigating the effects of ocean acidification at the ecosystem level. However, the evidence at the species level suggests that acidification will have an influence on populations and their interactions with other species such as predator/prey relationships or competition for resources. In particular if populations at the bottom end of food webs are negatively affected this can have significant knock on impacts on predators higher up in the chain. For example planktonic pteropods are important components of polar and sub-polar regions and are integral parts of the food web, being prey for a range of zooplankton and fish species such as salmon (North Pacific), herring, and mackerel and also for baleen whales[29]. Pteropod shells start to dissolve when aragonite falls below saturation point in seawater[14]. Given that high latitude regions are predicted to show the effects of ocean acidification prior to low latitudes a reduction in pteropod populations in polar regions may be one of the first large scale effects of acidification on oceanic foodwebs.

Socio-economic Impacts

The effects of ocean acidification on marine ecosystems through changes in marine food webs and ecosystem functions could in turn have a significant impact on large scale commercial fisheries and shellfish industries as well as threaten protein supply and food security for millions of the world's poorest people. Coral reefs are thought to have a passed a tipping point by a number of leading marine scientists and be in terminal decline through the combined effects of elevated temperatures and ocean acidification[30]. The predicted socio-economic consequences of a large-scale collapse of coral reef ecosystems are not fully understood yet, but severe consequences are already occurring. For more detail on the effects of climate change on coral reefs and the potential consequences please refer to a separate draft Globe working paper on this subject.

Summary and Recommendations

The predicted changes in seawater chemistry caused by the uptake of anthropogenic CO_2 from the atmosphere are not in doubt. The amount of scientific evidence of the effects of ocean acidification on marine organisms is rather low but the research completed to date does indicate that more acidic conditions generally have a negative effect on processes such as calcification, other aspects of physiology and on early life stages. However, as this field of research is relatively new it is imperative that extensive research programmes are implemented to fully investigate the potential effects of acidification at the species, food web and ecosystem level. We will then be in a better position to predict and plan for the anticipated socio-economic impacts caused by changes in the ocean chemistry through acidification. Scientific research priorities were identified at the Second International Symposium on The Ocean in a High CO_2 world[12]. At this symposium the Monaco Declaration was released in which 155 scientists from 26 countries urged policy makers to launch four main initiatives to:

- help improve understanding of impacts of ocean acidification by promoting research in this field, which is still in its infancy;
- help build links between economists and scientists that are needed to evaluate the socioeconomic extent of impacts and costs for action versus inaction;
- help improve communication between policymakers and scientists so that *i*) new policies are based on current findings and *ii*) scientific studies can be widened to include the most policy-relevant questions;
- prevent severe damages from ocean acidification by developing ambitious, urgent plans to cut emissions drastically.

To help speed up the transfer of scientific information and recommendations to end users, policy advisors and decision makers a Reference User Group has been set up by the European Project on Ocean Acidification (www.epoca-project.eu). Two recent summary guides about ocean acidification for policy and decision makers are also available from the Monaco symposium[31] and the EPOCA project[32].

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