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Early Warning, Emerging Issues and Futures

Revisiting ocean acidification, food security and our earth system

Background

The UN Environment Foresight Briefs are published by UN Environment to, among others, highlight a hotspot of environmental change, feature an emerging science topic, or discuss a contemporary environmental issue. The public is thus provided with the opportunity to find out what is happening to their changing environment and the consequences of everyday choices, and to think about future directions for policy.

Introduction

Approximately 40 Gigaton (Gt) of carbon dioxide (CO_2) is currently released into the atmosphere every year from fossil fuel combustion, cement production and land-use change. This is known as anthropogenic CO_2.
A fraction of this, about 23% or 9 Gt CO_2, is taken up by the oceans. Over the industrialised period, the oceans have absorbed CO_2 corresponding to 27 % of our accumulated emissions, or 620 Gt CO_2.

In this way, the oceans have slowed down the pace of climate change. Without the oceans taking up anthropogenic CO_2, atmospheric carbon dioxide levels would now have been 480 parts per million (ppm) and the global temperature increase since preindustrial times more than two degrees Centigrade (2°C), breaching the limit for 'acceptable climate change', as globally vetted through the Paris Agreement. However, this invaluable service of the oceans comes at a cost. The absorption of the anthropogenic CO_2 decreases the concentration of carbonate ions in the ocean and also lowers its pH. The process of lowering ocean pH is known as ocean acidification and is likely to have severe impacts on marine ecosystems.

The chemical reaction that gives the ocean its large CO_2 uptake capacity also introduces the problem of ocean acidification:

$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$$

(Carbon dioxide + carbonate ion + water → 2 bicarbonate ions)

Through this reaction, 95% of the anthropogenic CO_2 that enters the ocean reacts with dissolved carbonate ions to form bicarbonate. Without it, all CO_2 molecules would remain as dissolved CO_2 in the water leading to a rapid increase in the ocean's CO_2 backpressure to the atmosphere and a stop of the uptake. Instead, only 5% of the anthropogenic CO_2 entering the ocean increases this backpressure, while the rest is transformed to dissolved bicarbonate according to the reaction above. Thus, the consumption of carbonate ions enables uptake of more CO_2 from the atmosphere. However, the ocean's carbonate ion inventory is only replenished very slowly, by the weathering of rocks or dissolution of sediments and these processes cannot keep up with the consumption caused by the recent uptake of CO_2. Therefore, the concentration of carbonate ions in the ocean is now decreasing, while the concentration of bicarbonate is increasing. As bicarbonate is more acidic than carbonate, this acidifies the oceans and hence lowers the oceanic pH. In addition, the 5% CO_2 that remains as dissolved CO_2 in seawater is quite a strong acid, which lowers the pH even further. Hence, the more CO_2 the ocean absorbs, the more it acidifies. This is the nature of ocean acidification.

- Anthropogenic CO_2 refers to sources of carbon dioxide due to human activity, such as burning of fossil fuels, deforestation and land use change.
- $pC0_2$ = partial pressure of CO_2
- 1Gt, 1 Gigaton = 1 billon metric tons
- ppm = parts per million
- The pH is in fact a measure of hydrogen ion concentration; a measure of the acidity or alkalinity of a solution. The pH scale ranges from 0 to 14. Aqueous solutions at 25°C with a pH less than seven are acidic, while those with a pH greater than seven are basic or alkaline).

Why is this important?

Ocean acidification is a global issue, which is affecting all ocean regions. It is important as it may have severe impacts on marine organisms and ecosystems. Loss of biodiversity is a likely result, accompanied by a reduction of harvestable resources, including those associated with human food resources. If CO_2 emissions continue at the same rate, ocean acidification will have a considerable influence on marine-based diets for billions of people worldwide. The only way to stop ocean acidification is to curb emissions of CO_2.

What are the findings?

Observations of ocean carbon uptake and acidification

We are able to document the ocean CO_2 uptake and acidification because the global science community has made systematic measurements in the oceans over the past decades. The data clearly show that CO_2 levels are increasing and pH is decreasing. In particular, time series stations, where observations are made several times each year, show that in the surface ocean, CO_2 is increasing at approximately the same rate as in the atmosphere and pH follows suit. The total amount of anthropogenic CO_2 in the ocean can be determined from the measurements. It is now approximately 620 gigatons of CO_2, which corresponds to 27% of the total emissions from 1800 to 2016. The pH in the surface ocean has declined by 0.1, from approximately 8.2 to approximately 8.1 on average. This corresponds to an increase in acidity of 25%, as pH is given on a logarithmic scale. Neither the anthropogenic CO_2 nor ocean acidification is uniformly distributed in the ocean, though. Most of the anthropogenic CO_2 is found in the North Atlantic Ocean and the Southern Ocean (Figures 1 and 2) because these regions contain links between the surface and the deep ocean, which makes it possible to transport anthropogenic CO_2 all the way to the bottom, enhancing the carbon uptake at the surface. The anthropogenic CO_2 that has been transported to the deep will further be transported around the world's oceans with the ocean conveyor belt and eventually impact all ocean regions.

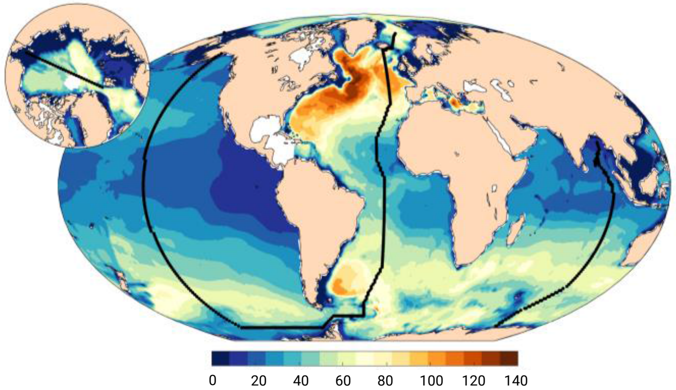

Figure 1. Distribution of anthropogenic CO_2 in the ocean. The colours indicate the amount of carbon (measured in mol C m^{-2}); brown colours represent high values. The black lines mark a path through the oceans. The amount of carbon stored along this path, from sea surface to seabed, is shown in Figure 2. (Map credit: Siv K. Lauvset. Data source: GLODAPv2 data as published by Lauvset et al (2016) at http://www.earth-syst-sci-data.net/8/325/2016/)

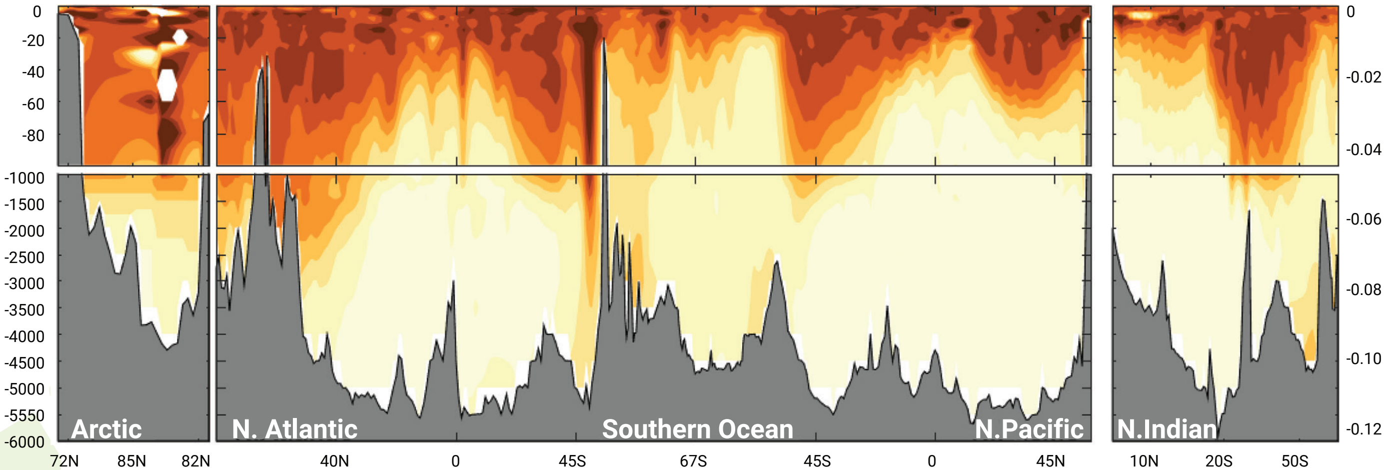

Figure 2. A transect through the Atlantic Ocean, Southern Ocean, and Pacific Ocean showing the total anthropogenic carbon. (Chart credit: Siv K. Lauvset)

Future projections

The emission scenarios are used as input for Earth System Models. These models project future climate and ocean CO_2 uptake in relation to emissions using mathematical and physical principles. Several models are operated by scientific institutes and universities around the world. They all show that the future ocean carbon uptake and acidification are first and foremost determined by the amount of CO_2 emitted by humankind (see Figure 3b). Hence, it is 100% certain that CO_2 emissions have to be reduced in order to avoid further ocean acidification. The Earth System Models also show that the Southern Ocean and the North Atlantic will continue as hotspots for carbon uptake. In both regions, the carbon uptake is dependent on ocean circulation and biological production, but models disagree about the relative importance of these processes for the carbon uptake and about the degree of change that these processes undergo with climate change (Goris et al., 2018; Kessler et al., 2016). Nevertheless, the models agree that climate change will somewhat slow down the ocean CO_2 uptake, leading to a larger fraction of our emissions remaining in the atmosphere and hence accelerated climate change.

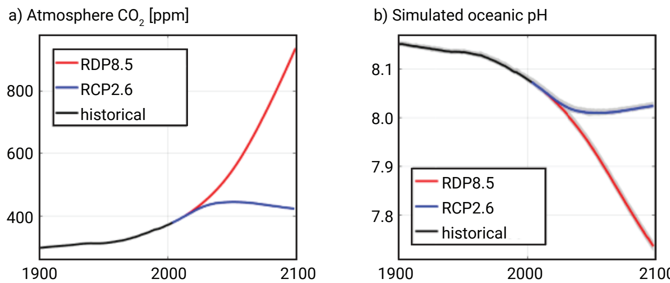

Figure 3: a) Atmospheric CO_2 concentrations as assumed for a "business as usual" scenario (RCP8.5) as well as for a future scenario with strong mitigation (RCP2.6). b) The rate of future global ocean acidification as simulated by eight Earth System Models (differences between the models are marked with grey shades) (Credit: Nadine Goris).

Acidification in Coastal Oceans from treated wastewater

Ocean acidification is compounded by other non-climate related impacts, including pollution, which add pressure to already strained marine ecosystems that provide food for human consumption. Approximately 64% of global municipal wastewater is treated before discharge especially in the coastal areas of developed countries where wastewater treatment plants are increasingly common. This means that inorganic carbon is the primary export form for over half of municipal wastewater, because more than 90% of organic carbon is removed during wastewater treatment prior to discharging into natural waters. This treated wastewater effluent high in dissolved inorganic carbon is characterized by low pH. The main detrimental environmental effect caused by treated wastewater is to lower the pH level of the receiving waters, leading to acidification in coastal waters (Yang et al., 2018).

Ecosystem impacts

Unhealthy Antarctic pteropod showing effects of ocean acidification including ragged, dissolving shell ridges on upper surface, a cloudy shell in lower right quadrant , and severe abrasions and weak spots. Photo: courtesy of NOAA

Several species have been demonstrated to respond negatively to increased ocean acidification. Examples include corals, pteropods, and shellfish who use carbonate minerals for their reef and shell structures. As the concentration of dissolved carbonate ions is reduced under ocean acidification, they will find it harder to precipitate the carbonate minerals needed for their reefs or shells. At undersaturated levels, they actually start to dissolve. If CO_2 emissions continue to increase at the current speed, the Earth System Models agree, ocean acidification will lead to undersaturated conditions for aragonite, which is a form of carbonate mineral, in the Arctic and Southern Ocean within this century. This may have detrimental effects for the pteropods and cold water corals in these regions, as their shells and reef structures are made of aragonite.

A study by Guinotte and colleagues published in 2003 showed that warm water/tropical coral reefs are not found in ocean water where the aragonite saturation (Ω) is lower than 3. The position of the boundary between waters with aragonite saturation below and above 3, may therefore delineate suitable habitats. Figure 4 shows how these have been reduced over the last 200 years in response to ocean CO_2 uptake and acidification. The Earth System Models projections show that if CO_2 emissions continue on the current trajectory (RCP8.5), then all of these habitats will be lost by year 2100.

Some studies also show that higher trophic levels may be affected. For example, some species of fish show reduced response to predator cues under decreasing pH, related to its effects on neural signal transmission. Others, such as the clown fish start to fail seeking shelter. Increased mortality among fish larvae, and organ damage, has also been observed. On the other hand, many species of fish exhibit no response. Finally, while most adult fish likely have good tolerance for ocean acidification in itself, the effects of ocean acidification on plankton and coral reefs may adversely affect their food supply and/or habitats.

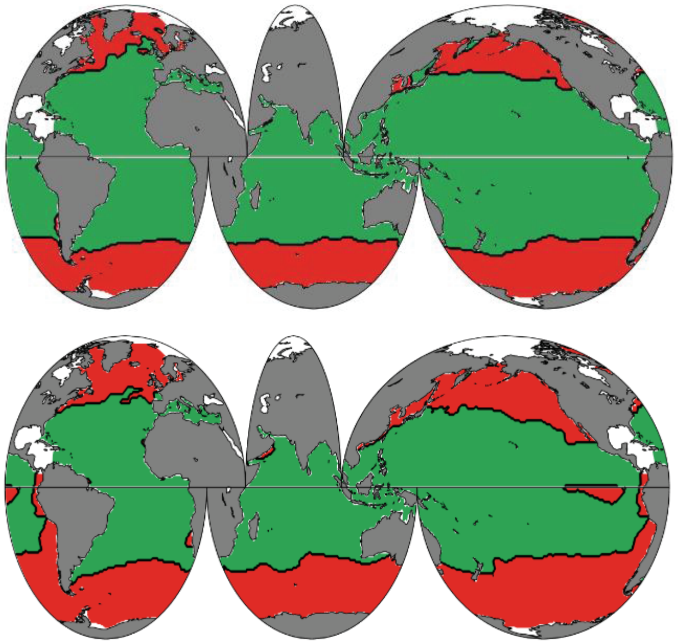

Figure 4. Green areas - suitable habitats for warm water corals (year 1800 on top, situation in 2002 below)((Guinotte et al 2003) Map credit: Siv K. Lauvset

Anemone and clown fish at Baker Island. Photo Credit: Image courtesy of NOAA Coral Reef Ecosystem Program

Ocean acidification will act in combination with other stressors of marine ecosystems. Climate change leads to ocean warming and deoxygenation. Lower levels of nutrients in the upper ocean is also expected, a consequence of the increased stratification of a warming ocean, which reduce vertical mixing. These will aggravate the effects of ocean acidification. For example, maintaining carbonate shells under ocean acidification require more energy, which will be less accessible in a future ocean with lower levels of upper ocean nutrients. Determining the effects of such multiple stressors on marine ecosystems is one of the current major scientific challenges, in particular as experiments are difficult to design, and maintain in the long term. Additionally, marine ecosystems and marine organisms are, by nature, highly diverse, and since most of the studies to date have been conducted on single species or even strains, it is not quite clear how entire ecosystems will respond to the increasing marine carbon content and ocean acidification. The effect of the full set of multiple stressors is even less resolved. Notwithstanding, large, and most likely negative, ecosystem impacts are expected.

Marine food resources and ocean acidification

Marine productivity 'hotspots' such as upwelling regions often supply the main protein source for coastal communities. However, many of these areas are also projected to be very vulnerable to ocean acidification this century. As world populations rise including in coastal areas, the demand for ocean protein products is also likely to rise. Fish stocks, already declining in many areas due to over-fishing and habitat, now face the new threats posed by ocean acidification (UNEP, 2010).

As shell growth and physiology are sensitive to increases in ocean acidity, the production and quality of many of marine invertebrate species such as mussels, lobsters and shrimp is at risk. In fact, they are the most vulnerable group in the aquaculture sector. Wild fisheries, shellfisheries and aquaculture are therefore of great importance to current and future food security. However, these industries are now also at risk from ocean acidification both directly through the impact on the organisms themselves and indirectly through the food webs and habitats they depend on (UNEP, 2010).

Reef scene at Pohnpei. in the Pacific Ocean. Credit: David Burdick, NOAA Photo Library

What has been done?

The only way to stop ocean acidification is to curb the emissions of CO_2 to the atmosphere, as any increases of its CO_2 level will lead to ocean uptake and acidification. Many activities towards this goal have been instigated over the past years. The most important is the Paris Agreement, reached in 2015. Here the world's nations committed to reduce the carbon emissions so that global warming will not exceed more than 2°C.

Despite this agreement, the Global Carbon Project has estimated that carbon emissions increased again in 2017, after the previous success of some years of a low growth trend. Such estimates are very important as they tell us if we are on the right track with respect to the commitments of the Paris Agreement. Observations are indispensable for this purpose, but also to track the level of ocean acidification that our marine ecosystems are already exposed to.

In the scientific community, several networks have been established for monitoring and quantifying the ocean carbon uptake and acidification. Examples are the Global Ocean Acidification Observation Network (www.goa-on.org) and its regional networks, the Ocean Acidification International Reference User Group of the European Project on Ocean Acidification, and the International Alliance to Combat Ocean Acidification (www.oaalliance.org). Another important network is the Integrated Carbon Observatory System (www.icos-ri.eu). This is a European infrastructure that is monitoring and quantifying carbon fluxes from the atmosphere, ocean and land.

Data products like GLODAP (www.glodap.info) and SOCAT (www.socat.info) provide quality controlled measurement data for the scientific community. Even though there are ongoing monitoring activities, there is a lack of sustained funding. The scientific community and the oceanic ecosystems need a global effort to financially support long term monitoring of ocean acidification.

What are the implications for policy?

The ocean will not be healthy once we stop emitting carbon. Instead, the CO_2 that we have emitted in the last 200 years will still be taken up by the oceans in the future. It will take thousands of years to recover, as ocean acidification is only neutralised by the very slow weathering of rocks or dissolution of sediments releasing carbonate ions to the oceans. Nevertheless, reducing emissions of CO_2 to the atmosphere is the most efficient way of stopping ocean acidification. Importantly, some geoengineering measures aim to only cool the Earth under growing CO_2. These will not stop ocean acidification, as it is the increasing atmospheric CO_2 that causes ocean uptake and acidification.

At the same time, ocean acidification is only one of several stressors for the ocean ecosystem. Others are warming, deoxygenation, upper ocean nutrient loss, fisheries, untreated wastewater and plastic pollution. On a small scale, mitigation can be accommodated by reducing CO_2 and ocean acidification by planting kelp, seagrass and other algae. But these will be difficult to maintain in the long term. Reducing greenhouse gas emissions will not only help to reduce ocean acidification globally, but also to reduce warming and many of the other stressors. Corals are especially vulnerable to increasing temperatures. Incidents of coral bleaching in the last years is a result of high ocean temperatures.

While the biological consequences of ocean acidification remain uncertain, they are most likely adverse, in particular when combined with other stressors. To secure a healthy planet the precautionary principle should be applied; and emissions of CO_2 to the atmosphere must be stopped now.

Reducing local factors of ocean acidification provides another lever for mitigating acidification in the coastal ocean. The potential for local- and national scale pollution control could be of critical importance in areas where the chemical effects of terrestrial inputs rival CO_2-driven acidification. Where local and national economies rely heavily upon marine ecosystem services, for example shellfish farming and coral tourism, reducing local acidifying factors could produce results both faster and in a more politically feasible manner than would a global CO_2 solution alone.

Public awareness activities on ocean acidification and its environmental impact on marine ecosystems and fisheries at regional and national level should consider measures to minimize impacts of ocean acidification in coastal areas, such as by reducing the inflow of organic matter from land.

There is need to increase international cooperation and contribute to the international framework of data sharing, such as the Global Ocean Acidification Observation Network (GOA-ON) and its sub-networks. Capacity development activities should be aggressively promoted and scientific research such as in monitoring of marine ecosystems should be supported.

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