Impact and Potential Solutions toward Ocean Acidification

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Abstract. Ocean acidification is a new problem for humans that rose recently. It has been drawing attention from people. It is getting more serious and important with the continuous carbon emission to the atmosphere. The threats from ocean acidification are affecting multiple characters, especially organisms like marine animals and marine plants. Researches show the change in the pH will affect the lifespan and the reproduction process of marine organisms. Besides the impact on organisms, ocean acidification is also likely to impact the global climate. For places located around the tropical area, ocean acidification will bring more frequent storms and hurricanes. Focused on the problem, we want to seek solutions. However, currently, there are no direct ways to address the problem of ocean acidification. Some hypotheses have been made, such as managing the seaweed and the precipitation method, but these approaches are immature and currently inapplicable. The most practical method to slow down ocean acidification is to make agreements and regulations to directly control carbon emission. Future agreements should increase the collaboration internationally and apply the most suitable measures locally. This research aims to provide background knowledge for future studies about the ocean.

1 Introduction

Ocean acidification is becoming a more and more serious problem globally. The progress of ocean acidification has drawn the attention from many countries. The trace of ocean acidification had come into human’s view range since the Industrial Revolution. Since then, the pH of the ocean had decreased by 0.1 units. However, the prediction suggests that the ocean’s acidity will become 150% higher at the end of the 21st century with the current decreasing rate. Meantime it will reach the peak of ocean acidity in about the past 20 million years. As we mentioned above, the main income of carbon dioxide in the ocean is human activities. Since 1750, about 30% to 50% of carbon dioxide released into the atmosphere has entered the ocean. To control this problem, they had several conferences and came up with some regulations. The second item of [UNFCC] (UN framework convention on climate change) has regulated the total amount of the greenhouse gases in the atmosphere as "Stabilize the concentration of greenhouse gases in the atmosphere at a level that prevents the climate system from dangerous human interference." As we can see, currently, the goal of this policy is to regulate the greenhouse gas in the atmosphere rather than to directly control the carbon in the ocean. Later, the [UNCLOS] (United Nations Convention on the Law of the Sea) had regulated the pollution more specifically. Item 201–6 of [UNCLOS] mentions, “The effectiveness of domestic laws, regulations, and measures to prevent, reduce and control marine pollution caused by dumping shall not be lower than that of global rules and standards.”

In general, ocean acidification results from the DIC increase in the ocean, caused by the carbon dioxide increase in the atmosphere. When the ocean absorbs carbon dioxide, there will be the reaction: “CO$_2$(aq)+H$_2$O $\rightarrow$ H$_2$CO$_3$ $\rightarrow$ HCO$_3$+H’ $\rightarrow$ CO$_3^{2-}$+2H’” In this relationship, the reactions are dynamic. This means that these reactions could go either way. However, ultimately there will be hydrogen ions produced, which will result in a decrease of pH in the ocean. The hydrogen ions are the direct determinant of acidity. When the carbon dioxide dissolves into seawater, the carbonic acid will form. However, the carbonic acid is not stable. It will decompose into hydrogen ions and bicarbonate ions. Consequently, the pH of the ocean decreases. As carbon emission is the main cause of ocean acidification, other activities such as erosions could also affect the pH in the ocean. The erosion sometimes leads to the run-off of nutrients in the soil. When the nutrients in the ocean reach a certain level, eutrophication events happen. The eutrophication events could lead to a decrease in the pH of the water. Eutrophication events usually occur in coastal areas, which are usually next to the region of human activities. Besides these, events like chemical pollutions from factories can also affect the acidity in the ocean.

This research aims to comprehensively analyze the effects of ocean acidification (with respect to organisms,
humans, climate) and discuss some possible measures and policies that can reduce ocean acidification. It will provide background support for studies that will focus on ocean acidification in the future.

2 Impact of Ocean acidification

2.1. Crustaceans

Ocean creatures, like snails, are equipped with calcium carbonate-based shells to protect them from predators. However, when humans emit more CO₂ to our atmosphere, our ocean acidifies, thus, inhibiting creatures from forming shells from calcium carbonate, even dissolving crabs’ shells and their navigating devices will be compromised as well. Shell-based animals require calcium and carbonate to generate and maintain hard shells and skeletons. Still, elevated acidity level in ocean dissolves their skeleton, and they need more energy to maintain that shell. Recently, the concept of oxygen- and capacity-limited thermal tolerance of aquatic ectotherms [1] was extended to incorporate CO₂-driven effects predicting that the acute CO₂ stress will increase the sensitivity of an organism to temperature change [2, 3]. As a bivalve Marine organism, the oyster is usually sensitive to the change in temperature and OA. Most of the oysters inhibit the coastal area where the temperature changes more drastically than the marine environment. Therefore, oysters could be less sensitive to OA and global temperature change. However, the previous study shows that OA had little impact on oysters given acclimation temperature (15°C). However, SMR (standard metabolism rate) of CO₂-exposed animals was significantly above that of the normocapnic controls during acute warming. It indicates that hypercapnia resulted in elevated energy demand when combined with temperature stress [2]. Figure 1 shows that, given the CO₂ level, the higher the temperature there is, the higher the SMR of the oyster living at the higher temperature will be. Under the premise of increasing temperature, oysters living at lower pH value have higher SMR. For crabs, the young shells of Dungeness crab larvae are corroded due to acidification, and their ability to deter predators is compromised. Although, in the feeding rate study, CO₂ enrichment had no significant impact on the feeding rate of Metacarcinus magister or Hemigrapsus oregonensis larvae [2]. However, crab’s larvae will be damaged as a result of OA. The long-term effect cannot be ignored. At about 40 days, the survival rate of them living at pH 7.9 is much higher than that of living at pH 7.6.

Fig. 1 Normalized standard metabolic rate (SMR) in control (normocapnia, seawater PCO₂ ~ 0.054 kPa) and CO₂-exposed (hypercapnia, seawater PCO₂ ~ 0.15 kPa) oysters, C. gigas during acute warming (5 °C/48 h) [4].

The experience led by Gisela Lannig and other scientists also shows that OA exposure leads to unstable metabolic intermediates in oysters. If the temperature is high and pH value is low, the basal maintaining cost would be higher [5]. Following OA exposure, extracellular pH (pHe) dropped by 0.2 units, and the standard metabolic rate (SMR) of the mussels decreased by about 60%, indicating metabolic depression [3].

2.2. Fish

Ocean acidification is even fatal for non-calcifying species, fish. Baumann experimented with newly-fertilized silverside eggs. Then, the larvae were exposed to acidification. Data shows that the larvae that grow in acidified water need more time to grow [6]. The longer time they require to grow, the more vulnerable they are to plankton-eating fish and other predators. In another word, the death rate is dependent on ocean acidification: death rate of these larvae increase as ocean acidification increase [6]. The author also speculates that the egg embryo could be damaged, provided that they live in a lower pH environment [6]. For instance, after growing in seawater equivalent to 410 ppm for 5 days, fertilized eggs were exposed to 780ppm once they hatched [1]. However, because the survival rate only changes a little, OA mainly affects fish at the larval stage rather than at other stages. Around 2010, a series of experiments of clownfish, which dwells in the coral reef, indicate that in lower pH environments, larvae begin to lose their senses. Levels of dissolved CO₂ in this range (700–850 ppm) impaired the ability of larvae to respond to predator odors and caused them to exhibit riskier behavior in natural coral-reef habitat [4].

2.3. Coral Reef

The calcareous bones leftover forms corals after death by a large number of coral polyps that gather together. Corals face numerous challenges, such as the bleaching of corals that can cause organisms to lose their habitat. When the environment changes, such as temperate, the algae called
zooxanthellae live within the coral reef, will leave coral, and then the coral loses its color because of the algae’s left. There are increasing shreds of evidence that indicate that CO$_2$ has a tremendous impact, like bleaching on the coral reef. For instance, high CO$_2$ is a bleaching agent for corals and CCA under high irradiance, acting synergistically with warming to lower thermal bleaching threshold [6]. Specifically, high-CO$_2$ dosing led to a two- to threefold increase in bleaching relative to the control. In contrast, high temperature led to only a 20% increase in bleaching for these species [6], and meant coral abundance was projected to fall by more than 50% by the highest CO$_2$ level (1000 ppm) [7]. The coral reefs that are facing threats have gradually lost their role in protecting organisms and providing habitats. The study also showed the richest macroinvertebrate communities in quadrats occupied by living coral, suggesting that live corals represent essential habitats rather than competitors for space or food for many groups [8].

2.4. Commercial fisheries

Ocean acidification may affect humans through various socio-economic connections, potentially beginning with reduced harvests of commercially important species. The decrease of marine pH value hinders the growth of calcium carbonate shells and bones of many marine animals and plants. It directly affects human beings through the harvest of shellfish, their predators and coral reef habitats, and the decline of fishery income. Suppose ocean acidification causes widespread damage to marine habitats, changes the availability of marine resources, and disrupts other ecosystem services. In that case, there may be significant declines in income, unemployment and disrupts other ecosystem services. For example, even if carbonate-forming organisms can form shells and bones under high carbon dioxide conditions, they may pay a high energy price, thus reducing their survival and reproductive capacity. The loss of plankton, juvenile shellfish, and other prey can also change or eliminate nutritional pathways, intensify food competition among predators, and reduce the harvest of economically important predators. At the same time, an acidic environment will damage corals, prevent their regeneration, destroy important benthic habitats, and disturb the hunting and reproduction of a series of species. After the coral is disturbed, it will sometimes change to the excessive growth of macroalgae and the decline of species diversity, thus forming a stable new ecosystem state dominated by herbivores and species with low commercial value.

Also, ocean acidification is an important factor affecting fishery production. Among the various complex relationships affecting fishery production, the economic output value of fishery production is affected by the change of seawater chemical properties, which cannot be ignored. Because of the decreasing trend of marine catch in the global total fishery production year by year, the potential of the ecological system, and the strengthening of human measures to adapt to climate change. It is reasonable to assume that the direct effects associated with ocean acidification may increase the cost of marine fishery production by about 10%, about the US $10 billion per year. In figure 2, according to the statistics accessed October 2008 [9], the total or major value of the U.S. commercial harvest onboard comes from processing costs in U.S. waters and seas of nearly $4 billion in 2007 (all currency values are expressed in U.S. dollars). Among them, mollusks accounted for 19% (red tone), crustaceans accounted for 30% (yellow tone), finfish accounted for 50% (green tone); 24% of the total revenue from us ship exports comes from fishing for fish that directly prey on the calcified matter. The supplementary information lists the species tracked by the NMFS included in each category. Different groups dominate the regional income; Molluscs are more important in New England and the South Central Atlantic, and crustaceans contribute greatly to fisheries in New England and the Gulf of Mexico, with predators dominating Alaska, Hawaii, and the Gulf of Mexico Fisheries in the Pacific.
Secondary economic losses following decreased fishery harvests will be concentrated in specific regions, many of which have less economic resilience for enduring losses of fishing revenues. The Food and Agriculture Organization of the United Nations estimates that more than 500 million people in the world rely on fishing and aquaculture as a source of protein intake and economic income [10]. For the poorest 400 million of them, fish provides about half of their daily animal protein and trace elements. The impact of seawater acidification on marine life is bound to endanger the livelihood of these people.

2.4. Climate

Research by the Antarctic Cooperative Research Center for ecology and climate (ACE CRC) shows that ocean acidification weakens the coral and algae structures that form reefs. It can lead to low-lying island countries and make tropical islands more vulnerable to rainstorms and hurricanes, such as Kiribati and Maldives [11]. At the same time, by reducing the production of sulfur-containing compounds from biological sources, ocean acidification has the potential to aggravate climate warming. According to a study in *nature-climate change* [11], as the ocean absorbs carbon dioxide from the atmosphere, the decrease in the pH value of seawater leads to the decrease in the concentration of dimethyl sulfide. Plankton, photosynthetic microorganisms that float on the surface of the water exposed to sunlight, produce a compound called dimethyl sulfide (DMS). Some of the DMS enters the atmosphere and reacts to produce sulfuric acid, forming aerosols or tiny atmospheric dust. Aerosols can further form clouds, which can help cool the earth by reflecting sunlight.

Marine biological emissions are the largest natural source of sulfur in the atmosphere. Sulfur in the atmosphere can enhance the reflectivity of the atmosphere to radiation, promote the formation of clouds, reduce the earth’s surface temperature and slow down global warming. Compared with ocean acidification, DMS release may be more affected by temperature rise. Higher temperature seawater tends to produce more DMS, thus increasing its overall level in the future. After evaluating the changes in sulfur emission from marine organisms under different climatic conditions in the future, the study shows that the sulfur emission from marine organisms will decrease by about 18% by 2100, which will cause additional significant radiative forcing, and the earth temperature will rise by 0.23 °C ~ 0.48 °C. In short, ocean acidification will greatly accelerate global warming.

Researchers, headed by Katharina Six [12] with the Max Planck Institute for Meteorology, tested how acidification affects phytoplankton in the laboratory by lowering the pH in plankton-filled water tanks and measuring DMS emissions. When they set the ocean acidification levels for what is expected by 2100 (under a moderate greenhouse gas scenario), they found that cooling DMS emissions fell. Plugging the results into a global modeling system creates a positive feedback loop that will likely impact anything but positive. A warmer world does not necessarily mean a more productive world for phytoplankton. The basis for plant growth is the supply of nutrients. As the oceans will stabilize in the warmer climate, fewer nutrients will be transported into the sunlight zone. Like the MPI-ESM that was used for the project, Earth system models decreased in primary production by 17 percent at the end of this century for a moderate climate scenario. The impact of climate change alone led to a decrease in DMS emissions of 7 percent [13].
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3 Technology to solve ocean acidification

3.1. cultivate kelp

From 2000 to 2016, kelp production in China keeps growing [15], beneficial to environmental protection and economic development.

Kelp plays an important role in storing inorganic carbon through highly autotrophic processes, 16% of the primary production will be buried in seafloor sediments [16], and some are transferred to the surrounding environment. Kelp absorbs CO$_2$ through photosynthesis or directly absorbs HCO$_3^-$ in the water. Since kelp has fast growth metabolism and a self-sufficient system which do not need external support, kelp has the irreplaceable advantage in ocean carbon sequestration. Research shows that the carbon sequestration of the kelp growing on the continental shelf could be $0.7 \times 10^9$ tons per year, equivalent to 35% of the global average annual carbon sequestration in the ocean. [14] Aquaculture of kelp helps remove excessive inorganic carbon while it can also alleviate the eutrophication of seawater and optimize the structure of the Marine ecosystem. Meanwhile, harvest can be achieved quickly, which becomes the economic benefit guarantee of high yield and high utilization rate, while under the premise of not introducing exotic...
3.2 artificial ocean alkalinization

Among the ocean-based NETs, artificial ocean alkalinization via the dissolution of Ca(OH)$_2$, known in short as ocean liming, has attracted attention due to its capability of solving ocean acidification. A new study shows the case of ocean alkalinization in detail. [18] The research, conduct by the Euro-Mediterranean Center on Climate Change Foundation (CMCC) and the Politecnico di Milano within the Desarc-Maresanus project, presents an analysis of marine alkalinization applied to the Mediterranean Sea, taking into consideration the regional characteristics of the basin. Researchers used a set of simulations of alkalinization based on current shipping routes to quantitatively assess the alkalinization efficiency via a coupled physical-biogeochemical high-resolution model (NEMO-BFM) for the Mediterranean Sea (1/16° horizontal resolution that is ~6 km) under an RCP4.5 scenario over the next decades. The alkalinization strategies applied in this study to the Mediterranean Sea illustrate the potential of ocean alkalinization to mitigate climate change by increasing the air-sea flux of CO$_2$ across the basin and counteracting acidification. In contrast to previous studies, the analyzed scenarios offer a relatively clear pathway to solving ocean acidification.

3.3. Usage of Compounds

Carbon is not the only factor causing ocean acidification because the run-off of sediments can also contribute to ocean acidification. The reason behind this that the run-off of land sediments will disturb the balance of the coastal ocean. For example, the nutrients in the sediment will cause eutrophication events in the coastal area. As a result of eutrophication, excessive organic matter is produced. When the organic matter sinks, the respiratory process would release carbon dioxide and lower the pH of the water. So, eutrophication often increases the degree of acidification. Therefore, an idea to reduce this acidity is to reduce the nutrients input into the ocean. As we can see, most of the input of nutrients comes from human activities. From the experiment, the major contributor to the eutrophication events is phosphorus. According to experiments, the phosphorus input directly controls the algae blooms. Therefore, the method is to remove the phosphorus from the wastewater. One way that can reduce the eutrophication events effectively is through chemical precipitation. This method involves using PAC (Propylammonium chloride) and Flock & Lock mixture (lanthanum-modified bentonite, Phoslock). The PAC and the Phoslock are chemical compounds that can restrain the growth of the algae. [19] According to the experiment, after using the PAC&Phoslock in the experimental lake, the algae abundance has decreased by 80% [19]. As we can see, this is a possible way if we want to reduce ocean acidification in the coastal area.

4 Conclusion

Based on the discussion, we can see that ocean acidification has a large impact on marine organisms, climate, and humans. To organisms, their reproduction and lifespan will be affected. Besides that, global warming will get worse as a result of ocean acidification. Also, more consequences may include problems like mass extinctions, global warming, and extreme weather. We have realized the importance of treating ocean acidification. Still, currently, we can only control the problem by control the origin of ocean acidification, which is to control the carbon emission. In the future, we are likely to have regulations to directly address the ocean acidification problems. At the same time, we will need to have more mature technologies to address the problem. In total, we need to have taken more action before the situation becomes worse. This review will provide helpful background support for future studies about ocean acidification.

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