Climate Change: Stressor on Marine Buffer System

Suchismita Jana and Shirsak Mondal

Abstract

Oceans are natural carbonate buffer systems and work as a carbon sink in the environment which is much larger than the atmospheric and terrestrial carbon content. The global carbon cycle is maintained by the continuous gaseous exchange during photosynthesis and respiration. The atmospheric CO_2 also gets dissolved into the ocean water and forms weak carbonic acid. Thus, ocean water is a mixture of various numerous weak acids and bases and stays in contact with the atmosphere and other minerals as sediments. All of them together make the ocean an excellent buffer for neutralizing small changes in its composition. But the recent increase in industrialization and anthropogenic activities are causing the increase in atmospheric CO_2 and climate change. More atmospheric CO_2 is being dissolved in ocean water and carbon is being released from oceanic carbon sink making the ocean more acidic. Since industrialization, ocean water pH has dropped by 0.1 unit which indicated approximately a 30% increase in hydrogen ion concentration and 16% decrease in carbonate ion concentration relative to the preindustrial value. As a result of ocean acidification, there are devastating effects on ocean biota. An increase in sea surface temperature and deoxygenation are other climate change-related stressors on the ocean system.

Keywords

Carbonate buffer system · Climate change · Ocean acidification · Sea surface temperature · Deoxygenation

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1 Introduction

Oceans are well-known buffer systems, defined as carbonate buffer systems, and act as a reservoir for carbon. This reserved carbon is more than terrestrial and atmospheric carbon content and helps to control the global carbon cycle. This carbon dioxide-carbonate system works as a sink for atmospheric CO_2 and absorbs more CO_2 than they release into the atmosphere (Turley et al. 2010). The ocean surface pH and alkalinity have been unchanged for the last 750,000 years (NIWA n.d.). Plants and animals add CO_2 to the atmosphere by respiration and again balance by plant photosynthesis. There is also a continuous gaseous carbon exchange between the atmosphere and the ocean. The CO_2 form carbonic acid in contact with ocean water. This weak acid is neutralized in the ocean carbonate buffer system. In the last few decades, there is a constant increase in atmospheric CO_2 content because of the rapid anthropogenic activities, abundant fossil fuel burning, and changes in land use. This leads to carbon pollution both in the atmosphere and the ocean. Increasing CO_2 content is causing warming of both the atmosphere and ocean system and ultimately changing the physico-chemical phenomena that usually happen and control the ocean buffer system (Climate Reality 2016).

2 Ocean Alkalinity

Alkalinity is the buffering capacity of any water body. It can be defined as the excess number of bases or proton acceptors over acids or proton donors in a water system. In the ocean system, several factors can contribute to controlling and affecting the alkalinity. Where the oxidation process can reduce the alkalinity, anaerobic reactions can increase the water's alkalinity. There are numerous reports about ocean alkalinity and its interpretations in different ways (Middelburg et al. 2020). Dickson (1992) came up with an extensive conclusion regarding the relation between chemical models of marine water, its relation with alkalinity, and the measuring of alkalinity. The ocean alkalinity is balanced by various factors such as ions released into the open ocean by weathering of rocks (Mackenzei and Garrels 1966) and again deposition and precipitation of sediment after the calcification process. This phenomenon is generally represented as (Urey 1952):

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$$

This equation establishes the transfer and removal of atmospheric CO_2 in the form of sediment. Middelburg et al. (2020) described possible factors that affect or balance the ocean alkalinity directly which are alkalinity sources and alkalinity sinks:

Alkalinity sources are riverine DIC (dissolved inorganic carbon), riverine PIC (particulate inorganic carbon), submarine groundwater, submarine silicate, sulfur burial, denitrification, and organic matter burial (Fig. 1).

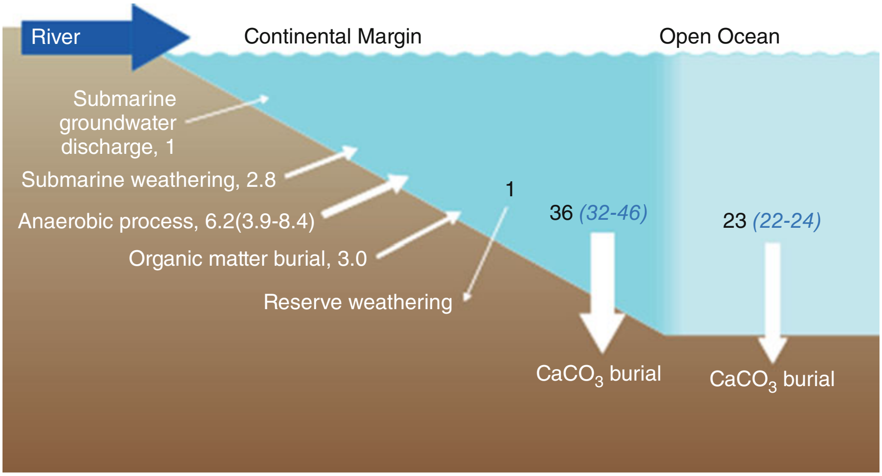

Fig. 1 Ocean alkalinity balance (fluxes are in Tmol/year). (Source: Middelburg et al. 2020)

Alkalinity sinks are open ocean carbonate burial, ocean margin carbonate burial, and reverse weathering.

Ocean alkalinity can be measured and referred to as titration alkalinity and charge balance alkalinity (CBA). The understanding of these alkalinities is used to quantify calcification and carbonate dissolution and also helps to determine the impact of biogeochemical processes on components of the carbon dioxide system in the ocean. Titration alkalinity or as known as total alkalinity is the mostly used alkalinity for experiment and observational purposes in the ocean. CBA is used for theoretical, modeling, and geological studies. CBA is essential for quantifying the buffering capacity and pH changes in natural environments and this is often used to denote excess negative charge in the freshwater system (Turchyn and DePaolo 2019).

3 Marine Buffer System

Ocean water is a mixture of numerous weak acids and bases and stays in contact with the atmosphere and other minerals as sediments. There is a continuous exchange of various gases between ocean water surface and atmosphere. All of them together have the potential to react if there is any physical or chemical variation in the composition. In general, ocean water having multiple weak acids, bases, and minerals has an excellent capacity to buffering any small changes in the acidity of alkalinity by transforming the proton (Middelburg et al. 2020). Ocean alkalinity is the central idea to understanding its buffering capacity and its role in CO_2 uptake. Seawater also contains multiple sensitivity and buffering factors which are just opposite to each other. Sensitivity factors are those which induce changes in chemical features but buffering factors restrain that change. Buffering capacity of seawater is homogenous and heterogeneous. Homogenous buffering is more instantaneous and spatially distributed in the ocean. Heterogenous buffering occurs due to the dissolution, precipitation, and deposition of minerals and sediments on the seafloor (Archer et al. 1998; Boudreau et al. 2018).

4 Climate Change

According to United Nations (n.d.), climate change is a long-term change in temperature and weather patterns. These changes are mostly driven by anthropogenic activities. After the 1800s, rapid industrialization triggered the changing of weather patterns. Excess carbon pollution is the prime reason behind this rapid climate change (Fig. 2). As a result of that, our planet Earth is now 1.1 °C hotter than that was in the 1800s.

Fossil fuel burning and changes in land-use patterns are erupting CO_2 and other greenhouse gases. These gases work as a shield and help in trapping the reflected sunlight. This incident is causing global warming and ultimately leading to changing the climatic pattern (The Royal Society, US National Academy of Sciences 2020). Atmospheric CO_2 has increased by upto 49% from the preindustrial concentration of about 280 ppm. As per the report by Siegenthaler (2005), the recent atmospheric CO_2 increase is almost 100 times faster than what occurred in the last 650,000 years.

5 Ocean Acidification

The ocean has a vast contribution to the global carbon cycle. Its inorganic carbon reservoir is roughly 37,400 Gt (10^{15} g), which is about 50 times and more than 18 times higher than that of the atmosphere and terrestrial realm, respectively (Fig. 3). Ocean water acts as a sink for CO_2 due to its carbonate buffer system which is the

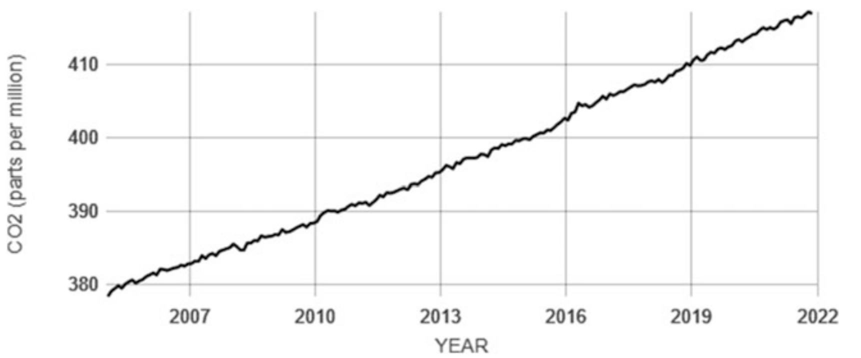

Fig. 2 Change in carbon dioxide concentration in the atmosphere globally. (Source: climate.nasa.gov, NASA n.d.)

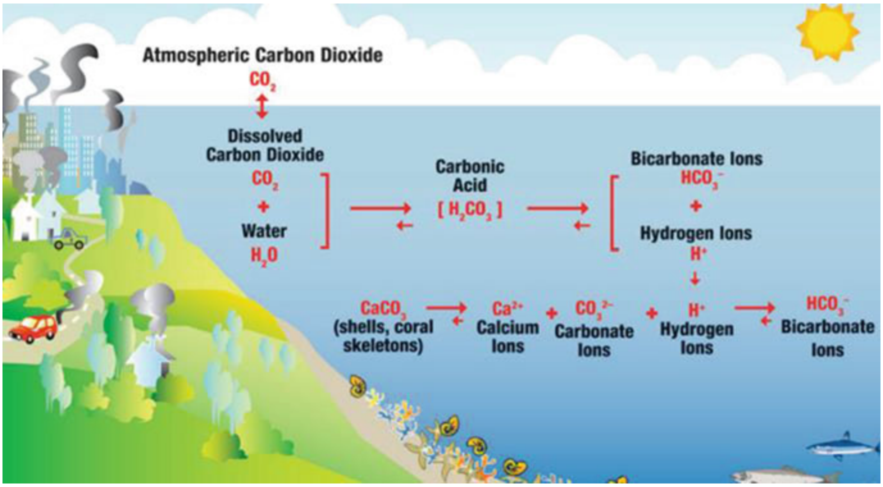

Fig. 3 Chemical reactions involve ocean acidification. (Source: The National Academies 2013)

result of the reaction of water with CO_2 forming carbonic acid, bicarbonate, and carbonate ions (Boudreau et al. 2018). Since industrialization, the ocean has played an important role in uptaking 28–34% of the CO_2 produced by anthropogenic activities. Within this period, ocean water pH has dropped by 0.1 unit which indicated approximately a 30% increase in hydrogen ion concentration and a 16% decrease in carbonate ion concentration relative to the preindustrial value (Turley et al. 2010). Researchers predicted more pH increase which is about 0.3–0.4 units by the end of this century (Caldeira et al. 2007). This rapid change in ocean water pH has not occurred in the last 20 million years of Earth's history. There is a series of chemical reactions that involve when then atmospheric CO_2 came in contact with ocean water and getting absorbed.

The ocean water stays in equilibrium with available carbon and bicarbonate ions where Ω is the calcium carbonate saturation state:

$$\Omega = \left[\mathrm{Ca}^{2+}\right]\left[\mathrm{CO_2}^{-3}\right]/K_{\mathrm{sp}}$$

Here, K_{sp} is the stoichiometric solubility product for $CaCO_3$; $[Ca^{2+}]$ and $[CO_2{}^{-3}]$ are the in situ calcium and carbonate concentrations (Guinotte and Fabry 2008). When the atmospheric CO_2 reacts with ocean water it first forms carbonic acid (H_2CO_3) which subsequently dissociates into H^+ ions and bicarbonate ions. Thus, there is an increase in H^+ ion concentration. These again react with available carbonate ions ($CO_3{}^{2-}$) and form more bicarbonate ions. These incidents lead to a shift in the form of inorganic carbon storage in the ocean (Lenton et al. 2018). Thus, a reduction in the carbonate ions $[CO_2{}^{-3}]$ concentration also leads to decreasing calcium carbonate saturation state (Ω) (Guinotte and Fabry 2008).

6 The Rise in Sea Surface Temperature

Climate change affects the marine environment in various ways. One of these is the rise in sea surface temperature. The increased fossil fuel burning and land-use change have led to the emission of excess greenhouse gases which mostly are CO_2. These gases trap the reflected energy in the atmosphere and the rest gets trapped in the ocean. The heat capacity of water determines its heat-absorbing capacity. Substances that have higher heat capacity require a larger amount of heat to increase a small amount in temperature. The water has 1000 times higher heat capacity than the air which helps in absorbing about 90% of additional heat (Sutton 2018). Bindoff et al. (2007) reported about 20 times more heat absorption by ocean water than the atmosphere since the 1960s. As per reports, this heat led to a globally averaged SST increase of ~0.67 °C from 1901 to 2005 with a warming rate of 0.06 °C/decade (Cravatte et al. 2009).

7 Oxygen Depletion

Another adverse effect of climate change on the ocean is oxygen depletion. Oxygen is a crucial element for marine life, to live and breathe. The recent event of climate change and global warming are causing changes in the gaseous composition of ocean water and ultimately deoxygenation. Climate change and sea surface temperature change have reduced the oxygen-holding capacity of ocean water. The ocean currents are also changing along with strongly stratified ocean water columns which cause less mixing of water and a lower amount of oxygen content in the deep ocean (O'Boyle 2020). Since the 1950s the oceans worldwide have lost about 2% of total dissolved oxygen expected to lose about 3–4% of dissolved oxygen. The reason behind this phenomenon is mainly climate change and global and ocean warming.

8 Impact on Marine Ecosystem

Climate change and related threats like ocean acidification, rise in ocean surface temperature, and deoxygenation have devastating effects on marine lives and the environment. It has been projected that these phenomena are affecting all areas of the ocean from the coastal to the deep-sea floor (Feely et al. 2009). The changes in the carbonate buffer chemistry of ocean water may disturb the calcification process of organisms, accelerate the dissolution of calcifying organisms and their other metabolic activities, acid-base regulations, blood circulation, also the nervous system of the organisms (Frommel et al. 2012). Such an important calcifying organism is coral which is severely under the stress of ocean acidification. The decreased pH of the ocean reduced the ability of reef-building corals to form the skeleton. Albright et al. (2010) revealed in their paper that ocean acidification affects the fertilization, settlement, and growth of reef-building corals thus reducing their recovering capacity from any disturbance. It is predicted that by the end of this century, the coral reef will erode faster than they could rebuild again and thus affecting the habitat of estimated one million species (Kibria 2015). Likewise, other calcifying organisms like sea urchins, nematodes, bivalves, and gastropods also get affected by ocean acidification. About 62% reduced growth rate have been found in sea urchin due to ocean acidification (Hendriks et al. 2010). Changing ocean pH has also affected the calcifying plankton like Coccoolithophores (unicellular calcifying phytoplankton) and foraminifera (calcifying protozoans). This cascading effect on the base level organism of the food chain in a marine environment can alter the species composition of the world's ocean (Kibria 2015). However, Hendriks et al. (2010) reported the beneficial effects of ocean acidification. They reported a higher growth rate of seaweed and seagrasses due to increased levels of dissolved CO_2 in the water.

The rise in sea surface temperature has a detrimental effect on marine biodiversity and is predicted to reduce the primary productivity and increase consumption and cycling of the organic matter on the ocean surface through heterotrophic processes and overall reduction of carbon export to the deep sea. The rise in ocean temperature is also helping in the redistribution of ocean biodiversity. For example, there is more plankton in the arctic. The temperature rise has also caused the sea level rise which is affecting mangroves, and corals by hampering their biology (Laffoley and Baxter 2016).

9 Impact on Human Health

Human health and well-being are directly related to the hydrosphere or the ocean. The ocean has provided humans with food, medication, and mental as well as physical health benefits. It also helps to control climate change to a certain extent and in coastal protection. Ocean acidification can negatively impact human health in four possible ways (Fig. 4). These are: (a) through malnutrition and poisoning by altering the food quantity and quality; (b) through respiratory issues by altering the air quality; (c) through the impact on mental health by modifying and altering the natural space; (d) through the decreased opportunity to obtain the natural medicines and cures. The effects of ocean acidification are not experienced singularly. Rather they show combined effects and affect us in various ways. It can be said that the effects of ocean acidification are the outcome of various complex combinations of linkages (Falkenberg et al. 2020).

10 Conclusion

Climate change is affecting the land and ocean equally and causing the warming worldwide. It also is the main reason behind the excessive increase in the atmospheric CO_2 content which is ultimately altering the ocean pH. Though ocean acidification increases the direct impact on a specific group of organisms, it ends up impacting every organism to a certain extent (Laffoley and Baxter 2016). Along with other climate-related stressors like sea surface temperature increase, and oxygen

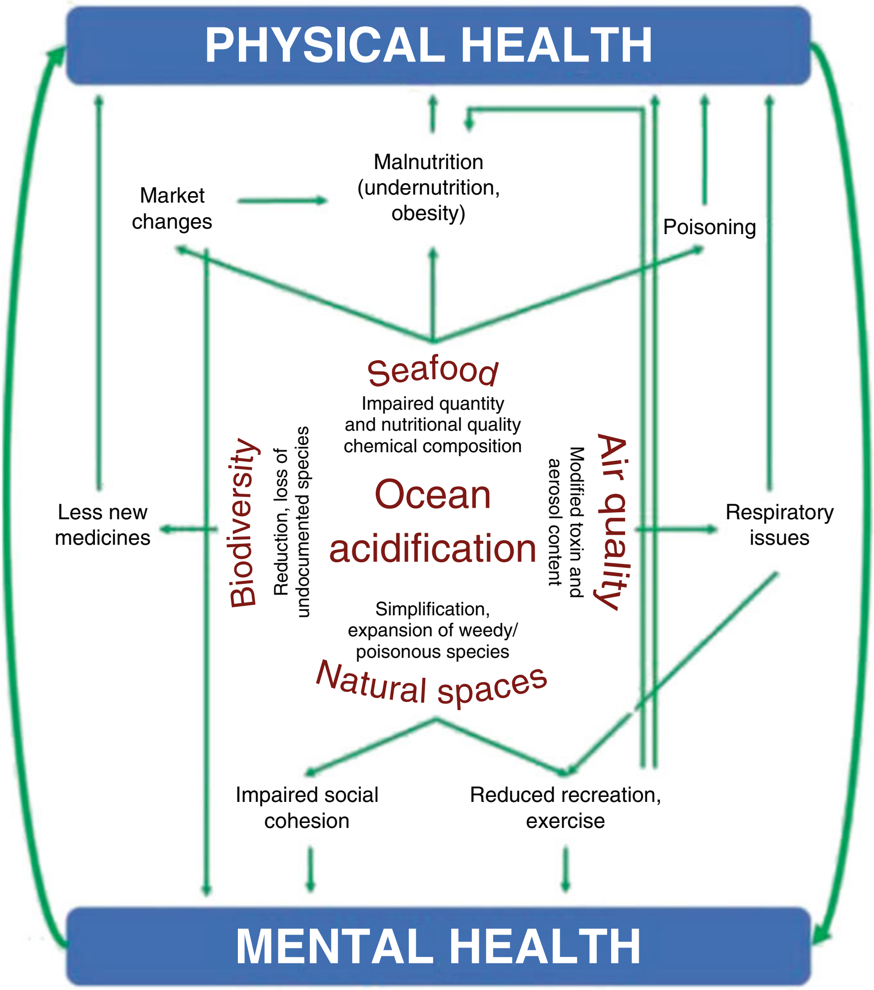

Fig. 4 Effects of ocean acidification on human health. (Source: Falkenberg et al. 2020)

depletion, the adverse effect of ocean acidification becomes more intensive (Falkenberg et al. 2020). Laffoley and Baxter (2016) suggested a few measures to control the uncontrolled climate change-related stressors on the marine environment which are: (a) there is a knowledge gap about the severity of impact due to the climate change-related stressor on the ocean system, which should come in people's attention; (b) there is an urgent need of taking serious actions and policies to redeem the adverse impacts; (c) a re-evaluation of risks to the environment and human beings and an analysis of economic impact due to the changes in the ocean buffer system are needed; (d) last but not least, the input of greenhouse gases mainly CO_2 into the atmosphere should be cut off as much as possible.

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