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A Review: Mechanisms of Ocean Acidification in the Context of Global Warming

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Abstract: Global warming stems mainly from the accumulation of greenhouse gases, which leads to higher atmospheric and ocean temperatures and has far-reaching impacts on marine systems. This paper focuses on the impact of global warming on the El Niño phenomenon and ocean acidification. There are significant changes in the frequency and intensity of El Niño events in the context of global warming, but the exact trends are uncertain. At the same time, the increase in carbon dioxide has led to ocean acidification, which poses a threat to the growth of marine organisms and the stability of ecosystems. An in-depth understanding of the role of El Niño and ocean acidification in climate change is therefore essential for the protection of marine ecosystems. For future marine ecological conservation, a comprehensive analysis of the climatic effects of El Niño and ocean acidification is essential. Only an in-depth study of these factors can lead to a more effective response to the ecological challenges posed by global warming.

Keywords: Sea Level Rise, Climate Feedback Mechanisms, General Circulation Models (GCMs).

1. Introduction

As human civilization developed, people began burning fossil fuels in cars and factories and cutting down forests to create more farmland. These activities released huge volume of carbon dioxide (CO_2) gas in atmosphere and the CO_2 gas results in two main consequences: global warming and ocean acidification. The level of CO_2 has increased by nearly 40% in past 250 years [1]. The CO_2 in atmosphere is called greenhouse gas, which reduces the reflected heat radiation from the Earth to the space and increase the temperature of the earth surface. Such phenomenon is called global warming. Furthermore, the one third of CO_2 gas is uptake by the ocean. It does help on reducing volume of greenhouse in atmosphere, but it leads to another consequence, which is ocean acidification. It is the decreasing in pH value. Both of the global warming and ocean acidification are consequences of increasing CO_2 and these consequences will result in more and deeper negative impacts on the global climate and ocean ecology systems.

Ocean acidification was largely ignored by researchers in the past, as calcite saturation levels were maintained. To now, it is clarified that the lowering of pH value will weaken the calcification of shell-forming organisms. Such effect is strongly demonstrated on the coral reef. From a study, the corals lost their protective skeletons under low calcite saturation condition with high acidified [2]. Similarly, the ocean warming by rising temperature contribute to the bleaching of coral. Under high temperature,

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the efficiency of photosynthetic is decreased. The stress of food let algae leave coral and bleach them [3]. Moreover, ocean warming is shifting the climate variability, and the shifting lead to variations in weather condition in different areas of the world. The disturbing of ecosystem and climate will bring economic losses to production activities by damaging fishery and

The diverse and complicated consequences of ocean warming and acidification impact on the ocean climate and ecosystem [4]. However, the two problems mention above are not completely separated, in fact, there have strong coupling relation. For the coupling relation, the warming and acidification of ocean is reinforcing and accelerating each other. There’s necessity to do more researching and make progress on studying the relation. By gaining more comprehensive understanding to the coupling relation and making prediction on how the relation will divert the whole ocean system, it is able to reduce or solve the potential risks in different fields.

Thus, it is clear that the studying and investigation on ocean warming (OW) and ocean acidification (OA) and coupling relation are essential to the future. The investigation should be made on researching to qualify and quantify the impacts of OW and OA on marine organisms and ecosystems, to extend macroscopically, use existed data and model to make prediction on future possible programme.

2. Literature Review

Global warming primarily stems from the accumulation of greenhouse gases (GHGs) in the Earth's atmosphere, which trap heat and prevent it from escaping into space. The most prevalent GHGs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [5]. Human activities, particularly the burning of fossil fuels, deforestation, and industrial processes, have significantly increased the concentrations of these gases since the Industrial Revolution. As GHG levels rise, they enhance the greenhouse effect—a natural phenomenon that keeps our planet warm—leading to a gradual increase in global temperatures. This warming not only affects atmospheric conditions but also has profound implications for ocean systems.

As the atmosphere warms, the oceans absorb much of this excess heat, which leads to rising sea temperatures. Warmer ocean waters have several cascading effects on marine ecosystems. First, increased temperatures can disrupt marine life, leading to shifts in species distributions and impacting biodiversity. Additionally, warmer waters contribute to the melting of sea ice, particularly in polar regions. This reduction in ice cover not only threatens species that rely on ice habitats but also alters oceanic albedo (reflectivity), causing further warming as darker ocean surfaces absorb more sunlight.

Moreover, the frequency and intensity of ocean heatwaves—prolonged periods of excessively warm water—have increased in recent years, posing significant challenges for marine organisms. These heatwaves can lead to coral bleaching, fish kills, and the disruption of food webs. The thermal stress experienced by marine ecosystems can result in long-term changes in population dynamics and community structures. Furthermore, the absorption of excess heat by the oceans affects global weather patterns, influencing phenomena such as hurricanes and monsoons, which can have devastating effects on coastal communities and ecosystems.

In summary, global warming driven by greenhouse gas emissions has far-reaching impacts on both atmospheric and ocean temperatures. The resulting changes in ocean systems, characterized by rising sea temperatures, melting ice, and increased ocean heatwaves, threaten the health of marine ecosystems and pose significant challenges for human societies that depend on these resources. Addressing the root causes of global warming is crucial to mitigating its effects and protecting our planet’ s delicate balance.

The increase of carbon dioxide (CO_2) in the atmosphere directly influences the oceans, as they act as a significant carbon sink. When atmospheric CO_2 levels rise, a substantial portion of this gas is absorbed by the ocean's surface. This process occurs through diffusion, where CO_2 molecules move

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from the atmosphere into the water. Once in the ocean, CO_2 reacts with seawater to form carbonic acid (H_2CO_3), which subsequently dissociates into bicarbonate (HCO^{3-}) and hydrogen ions (H^+) [6]. The increase in hydrogen ions leads to a decrease in the pH of the ocean, resulting in what is known as ocean acidification.

As ocean acidity increases, the concentration of carbonate ions (CO_3^{2-}) decreases. Carbonate ions are crucial for many marine organisms, particularly those that build calcium carbonate structures, such as corals, mollusks, and certain plankton species. The carbonate system in the ocean is vital for maintaining the balance necessary for these organisms to thrive. A decrease in carbonate ions disrupts this balance, making it more challenging for marine organisms to calcify, or form their shells and skeletons. This reduction in calcification can lead to weakened structures, diminished growth rates, and increased vulnerability to environmental stressors [7].

Furthermore, ocean acidification can have cascading effects throughout marine ecosystems. Species that rely on carbonate ions for their growth and survival may struggle, leading to potential declines in populations and altering community dynamics. Coral reefs, often referred to as the "rainforests of the sea," are particularly at risk, as acidification compromises their structural integrity and resilience. This decline can impact biodiversity, fisheries, and the livelihoods of communities that depend on healthy marine environments. Ultimately, the interplay between rising atmospheric CO2, increased oceanic absorption, and the resulting acidification highlights the urgent need for measures to reduce carbon emissions and protect marine ecosystems.

3. Ecosystem impacts of global warming and ocean acidification

3.1. Impacts directly effect on marine ecosystem

Ocean acidification and rising ocean temperatures are significantly impacting marine organisms, with profound physiological effects across diverse species. Coral bleaching is one of the most visible consequences of warming waters. Corals have a symbiotic relationship with zooxanthellae algae, which live within their tissues and provide essential nutrients through photosynthesis. As temperatures rise, corals become stressed, expelling the algae and losing their color—a process known as bleaching. Without these algae, corals are deprived of vital nutrients, weakening them and often leading to death if high temperatures persist. This decline in coral health disrupts entire reef ecosystems, as coral reefs serve as critical habitats for a variety of marine species [8].

Acidification poses severe challenges to organisms that rely on calcium carbonate to form shells and skeletons, such as mollusks, crustaceans, and some planktonic species. As carbon dioxide dissolves in seawater, it forms carbonic acid, lowering the pH and reducing the availability of carbonate ions [9], which are essential for shell formation. Mollusks, like oysters and clams, face significant energetic costs as they struggle to build and maintain their shells in acidic conditions, often resulting in thinner, weaker shells. This makes them more susceptible to predation and reduces their survival rates. Such vulnerability has cascading effects on the food web, impacting both predators and the overall biodiversity of marine habitats.

Planktonic species, including phytoplankton and zooplankton, are crucial primary producers and form the base of most marine food webs. Temperature increases and acidification can affect plankton populations differently, altering their abundance, distribution, and reproductive cycles. Phytoplankton, which perform photosynthesis, may experience altered growth rates and shifts in species composition due to changing environmental conditions. Some species of plankton are more sensitive to temperature changes, while others are highly vulnerable to acidification, leading to imbalances that can affect the entire ecosystem. These shifts in plankton populations impact organisms across the food web, including fish and marine mammals that rely on plankton as a primary food source.

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The sensitivity of marine species to acidification and warming varies significantly. Coral and calcifying organisms are particularly vulnerable to both stressors due to their reliance on calcium carbonate structures. In contrast, certain species of algae and some forms of plankton may adapt more readily to changing pH levels and temperatures, though this depends on their genetic variability and reproductive adaptability. Key primary producers like phytoplankton play a vital role in the global carbon cycle and are foundational to marine ecosystems, so their response to these stressors is critical. Changes in these populations could impact nutrient cycling, carbon sequestration, and energy flow through marine food webs, ultimately influencing biodiversity and ecosystem stability.

3.2. Impacts on human activities

Global warming and ocean acidification are profoundly disrupting the ecosystem services provided by the ocean, which are crucial for maintaining global ecological and economic balance. One of the primary services affected is carbon sequestration. The ocean acts as a major carbon sink, absorbing approximately 25% of CO_2 emissions from the atmosphere. Phytoplankton play a vital role in this process through photosynthesis, converting CO_2 into organic carbon and contributing to the ocean's biological pump. However, warming waters and acidification threaten phytoplankton populations and alter their distribution, potentially decreasing their efficiency in carbon capture. Additionally, coral reefs and seagrass meadows, both significant carbon stores, are degraded by bleaching and acidification, further reducing the ocean's capacity to sequester carbon. This decline in sequestration could accelerate climate change, creating a negative feedback loop with more greenhouse gases remaining in the atmosphere.

Coastal protection is another essential ecosystem service impacted by warming and acidification. Coral reefs, mangroves, and seagrass beds serve as natural barriers, protecting coastlines from erosion, storm surges, and flooding by reducing wave energy. Coral bleaching weakens reef structures, while acidification reduces the growth rates of corals and shelled organisms, undermining the integrity of these natural defenses. With weakened reefs and dwindling mangroves, coastal areas are increasingly vulnerable to extreme weather events, particularly as the frequency and intensity of hurricanes and typhoons rise with global warming. This loss of natural barriers can lead to increased costs in coastal protection infrastructure and disaster recovery efforts, impacting the economies and safety of coastal communities.

Fishery resources, a vital source of food and income for millions worldwide, are also directly affected. Ocean acidification interferes with the development of shellfish, while warming temperatures drive fish species to migrate toward cooler waters, disrupting traditional fishing grounds [10]. Many commercially valuable species, such as cod, tuna, and shellfish, are experiencing shifts in population size and distribution, creating uncertainty and challenges for fisheries management. Declining fish stocks can lead to reduced catches, negatively impacting both subsistence and commercial fisheries. This, in turn, threatens food security in regions heavily reliant on seafood as a protein source and affects the livelihoods of fishing communities worldwide.

The economic benefits of tourism, particularly in regions with coral reefs and vibrant marine biodiversity, are also jeopardized. Coral reefs attract millions of tourists each year, supporting local economies and generating substantial revenue. However, coral bleaching events diminish the aesthetic and ecological value of these ecosystems, deterring tourism and reducing income for local communities dependent on eco-tourism. Dive and snorkel tourism industries are especially affected by coral degradation, as the diversity and beauty of marine life decrease. Additionally, declining marine biodiversity affects other recreational activities, such as sport fishing and whale watching, that depend on healthy and diverse marine environments. Overall, the economic costs associated with the loss of ocean ecosystem services are mounting, underscoring the need for urgent action to mitigate the impacts of climate change on marine ecosystems.

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4. Conclusion

This paper outlines how anthropogenic global warming and ocean acidification are having far-reaching impacts on climate and marine ecosystems. Since the Industrial Revolution, fossil fuel combustion and deforestation have greatly increased the concentration of carbon dioxide (CO_2) in the atmosphere, leading to an increase in the Earth's surface temperature and contributing to the absorption of large quantities of CO_2 by the oceans, which in turn triggers ocean acidification. The heat stress on marine organisms caused by global warming leads to phenomena such as coral bleaching, while ocean acidification reduces the concentration of carbonate ions, which affects the growth of organisms such as corals and shellfish that rely on calcium carbonate to build their skeletons. These environmental stresses disrupt the balance of ecosystems and pose a threat to biodiversity and the stability of food chains.

In addition, climate change has far-reaching impacts on human-dependent marine ecosystem services, including carbon storage, coastal defence and fisheries resources. The efficiency of carbon sequestration in the oceans, an important carbon sink, has been affected by global warming and acidification, while the weakening of natural barriers, such as coral reefs, has increased the vulnerability of coastal zones to extreme climate events. At the same time, the migration of fish and shellfish stocks and changes in their abundance challenge global fisheries resources and threaten food security in seafood-dependent areas. Degradation of marine ecosystems also affects coastal communities that depend on tourism. This paper highlights the urgent need to study and mitigate the coupling of global warming and ocean acidification, to further understand their relationship and their deep-seated impacts on marine systems, and thus to develop effective response strategies to protect global marine ecosystems and the services they provide.

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