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Ocean Acidification: Impacts on Marine Ecosystems

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ABSTRACT

Ocean acidification, driven primarily by increased atmospheric CO_2 absorption, is one of the most pressing environmental challenges of our time. This paper examines the chemical mechanisms underlying acidification, its historical trends, and the widespread implications for marine organisms and ecosystems. It examines physiological and ecological effects on species ranging from microscopic plankton to coral reefs and addresses broader ecosystem-level disruptions and their cascading impacts. The socioeconomic implications, particularly for coastal communities and fisheries, are evaluated alongside mitigation strategies and the importance of long-term research and monitoring. The study underscores the urgency of interdisciplinary approaches to understanding and combating ocean acidification as part of the global climate agenda.

Keywords: Ocean acidification, carbon dioxide, marine biodiversity, carbonate chemistry, ecosystem services, calcifying organisms.

INTRODUCTION

Ocean acidification is the ongoing decline in the pH of Earth's oceans, caused by the uptake of carbon dioxide (CO_2) from the atmosphere. The oceans have absorbed approximately one-third of anthropogenic CO_2 emissions since the Industrial Revolution. As a result, the oceans are experiencing a rapid decline in pH, with an increase in acidity (H^+ ions) of approximately 30% in the last 150 years. Ocean acidification, together with the effects of climate change, land-use change, and pollution, poses one of the most significant threats to global biodiversity and ecosystem functioning worldwide. Whether it be desolate polar regions or the tropical coral-reef system, the foreshadowed impacts of ocean acidification are felt by all marine organisms to some degree. More than 90% of marine biodiversity resides in the ocean, suggesting that the impact of ocean acidification on marine biodiversity is far more extensive than that on terrestrial biodiversity. Studies on the impacts of ocean acidification on marine biodiversity have been growing. Many marine organisms are impacted by it to various degrees, from the micro-sized pteropods in polar ocean waters to calcifying corals in the tropics; from tolerance-inducing physiological functions in juvenile fish to plasticity-altering behavior in adult fishes. Ocean acidification continues to develop along with anthropogenic upper-level changes such as stratification, high temperatures, and lower oxygen levels. The consequences and degree of impacts will be more pronounced per unit change. There are three divergent idealistic gradients of acidification in the global ocean: location latitude, oceanic biogeographic provinces, and ecosystem-type velocity etc. The change in carbonate chemistry over time due to increased anthropogenic carbon input has been primarily evidenced by the changes in the ratio of the borate buffer's $B(OH)_4^-$ and $B(OH)_3$. A decrease of around 0.2 lay in Southern Ocean Sea surface waters is a robust signal that cannot vary due to hydrological effects or local variability. Whether this decrease in pH can produce significant physiological effects on marine organisms is not yet fully understood [1, 2].

Chemical Processes of Ocean Acidification

Ocean acidification, which lowers the seawater pH, is a complex phenomenon. The ocean, as a global sink for atmospheric CO_2, is experiencing acidification via several processes. In surface seawater, the dissolution of airborne CO_2 is mostly responsible for pH changes, along with approximately 3300 Gt C added via community metabolism at global to local scales, including primary production and subsequent mineralization of organic matter, degradation of dissolved organic matter, and coastal sediment respiration. The net outcome of these contributions is the change in the aquatic concentrations of different CO_2 species, which is quantified as changes in pCO_2. CO_2 addition increases the concentrations of HCO_3^- and H^+, and decreases that of CO_2. The chemical reactions raising H^+ upon the addition of dissolved inorganic carbon (DIC) species and the equations relating respective equilibrium constants and concentrations to the seawater pH are listed. Atmospheric heat, primarily transferred via ocean warming, is another contributor to ocean acidification (or pH changes) due to its heat capacities and heat storage, which impact biological processes and signal transfers. In addition to temperature, salinity is another physicochemical property of seawater, which impacts the partitioning of dissolved inorganic species and their thermodynamic equilibria, along with their bioavailability. Excessive terrestrial runoff may alter the aquatic processes, leading to inorganic carbon. Expanding coastal urbanization, agriculture, and industry release more organic matter and nutrients to rivers and lakes, primarily via terrestrial runoff, which discharge to the ocean globally. Many of the above terrestrial processes either directly occur in these runoffs or are modified/augmented, generating more CO_2 and protons, which, via river and lake transports, impact the biogeochemical cycling in the ocean [3, 4].

Carbon Dioxide Absorption

The direct effect of ocean acidification is a decrease in pH and carbonate ion concentration. Since the beginning of the Industrial Revolution, the ocean has absorbed approximately one-third of the carbon dioxide (CO_2) emitted through human activities. Consequently, anthropogenic CO_2 has entered the ocean and altered marine carbonate chemistry. The increase in dissolved CO_2 in seawater results in a series of equilibria that govern the behavior of CO_2 species in seawater. CO_2 combines with water to form carbonic acid, which dissociates into bicarbonate ions (HCO_3^-) and protons (H^+). Hence, two closely correlated, but opposite, equations characterize ocean acidification. First, the rise in converted to dissolved inorganic carbon (DIC) and the decrease in – a key constituent of marine biocalcification. To focus on the impacts of ocean acidification on living organisms, it is customary to refer to the former as 'ocean acidification' even though the pH changes in seawater are small. In seawater, concentrations of dissolved inorganic carbon are on the order of 2 10 (3 mol kg^{-1}, where DIC can be made up of a number of species in seawater, mainly CO_2, HCO_3^-, and $CO_3^{=}$ ions. During the uptake of anthropogenic CO_2 by the oceans, the concentration of CO_2 increases, and the overall carbonate ion concentration decreases. The present acidification of the oceans is estimated to be around 0.1 pH. The decrease in carbonate ion concentration leads to a decrease in the saturation state, Ω (omega), of the relevant calcium carbonate polymorph, either aragonite or calcite. Such biogeochemical modifications are referred to as ocean acidification. Current projections suggest that atmospheric CO_2 concentrations will reach between 540 ppm and 970 ppm by 2100, corresponding to oceanic decreases in pH of between 0.15 and 0.30. There are important implications of this biogeochemical phenomenon for marine fauna, foretold by some of the earliest experimental work directed at key marine calcifiers [5, 6].

PH Levels and Ocean Chemistry

Ocean chemistry is undergoing a major human-induced change resulting from the increasing carbon dioxide (CO_2) concentrations in the atmosphere. Since the beginning of the industrial era, approximately 520 Gt C has been emitted to the atmosphere through fossil fuel burning and land-use change. The observed increase of atmospheric CO_2 during that time is now about 250 Gt C. The sequestration of the remaining 270 Gt C has resulted in significant changes in ocean chemistry. Depth-resolved pH levels, total alkalinity, and total dissolved inorganic carbon are all available globally in data repositories, with basic properties, such as temperature, salinity, and pressure, also available. Model-based calculations indicate that the release of anthropogenic CO_2 to the atmosphere and subsequent flux into the ocean have, to date, reduced the global average surface pH by approximately 0.1 unit, equivalent to approximately 30% increase in H^+. At the ocean surface, the mean pH between the eastern and western basins of the North Pacific Ocean differs by ~ 0.05, in part due to strong outgassing in the equatorial region. Since 1990, surface ocean pH has been directly measured or calculated at several locations. Long-term time-series stations reveal well-established records. These sites are located in the three major ocean basins, one in the western North Pacific, one in the western central North Atlantic, and one in the eastern subarctic North Atlantic. Recent estimates of the average recent decrease in surface ocean pH are ~ 0.0019 pH units yr^{-1}, 0.0017, 0.0012, and 0.0017. For the first two areas, these values are not statistically different from each other [7, 8].

Historical Context of Ocean Acidification

Since their origin some 700 million years ago, animals have played an increasingly large role in oceanic carbon cycling, primarily through the production and dissolution of calcium carbonate ($CaCO_3$) in the surface ocean and deep sea, respectively. From fossil coccolithophores, bivalves, and foraminifera of the last two million years, it is apparent that natural variations in surface ocean pH or pCO_2 have occurred, consistent with other indicators of glacial/interglacial climatic changes. However, the rapid and extensive change in the modern era is unprecedented. Anthropogenic carbon dioxide (CO_2) emissions are altering the natural carbon cycle in a manner and at a speed thought to be without precedent over geological time. This has far-reaching consequences for the structure and functioning of marine ecosystems. One consequence is reduced seawater pH (ocean acidification). This has the potential for consequences at a wide range of biological scales (molecular, cellular, individual, population, community) and ultimately at broader scales, such as biogeography, ecosystem functioning, and fisheries. Yet there is considerable uncertainty in understanding how marine ecosystems will respond to ongoing ocean acidification. Changes are likely to occur not only in response to ocean acidification per se, but also in concert with concurrent ocean change (temperature, hypoxia, deoxygenation, eutrophication, and changes in circulation patterns). In addition to emissions of CO_2 from fossil fuel burning, artificial upwelling of nutrient-rich deep-sea waters and re-fertilization of large oligotrophic regions of the oceans have been suggested as a geoengineering option to reduce the rising CO_2 excess from the atmosphere into the ocean [9, 10].

Impacts on Marine Organisms

Ocean acidification is projected to significantly impact marine ecosystems. Marine organisms exhibit a range of physiological and ecological controls on calcifying, metabolic, and biogeochemical processes, allowing for adaptation to various environmental changes. Some processes occur over thousands of years, while others happen within seconds. Understanding these physiological and ecological responses is vital for predicting future marine ecosystem functionalities. Recent experimental work combining multiple environmental influences on marine organisms over ecologically relevant time scales has increased, highlighting the need for long-term studies to assess organism- and ecosystem-level effects. Ocean acidification results from coastal upwelling of cold, lower pH water, potentially leading to coral reef dissolution. Understanding this process is essential for predicting near-shore pelagic and benthic productivity and the plasticity of marine ecosystems in the past and future. Research on marine biodiversity in relation to oceanic pCO_2 history focuses on various proxies, including planktonic foraminifera and coccolithophores. This includes examining the response of Calcareous Nannoplankton to the Ocean Change event to better understand reactions to a high pCO_2 future, similar to studies of extinction patterns during the Paleocene-Eocene Thermal Maximum [11, 12].

Ecosystem-Level Effects

Marine ecosystems are the most effective natural CO_2 sinks on Earth, sequestering carbon primarily through plankton and associated organisms via photosynthesis or calcification. Ocean acidification (OA) from anthropogenic CO_2 reduces carbon sequestration efficiency, contributing to climate warming. The impacts of OA on higher trophic levels remain unclear. High CO_2 transitions affect phytoplankton community composition in a species-specific manner, prompting evolutionary adaptations over generations. Both short- and long-term OA exposure influence plankton community structure and the processing of organic matter. Marine organisms range from massive to microscopic, operating across various spatial and temporal scales, resulting in complex ecosystems. This diversity leads to emergent properties, such as biogeochemical cycles that regulate temperature and nutrient distribution. Simultaneous stressors can cause ecosystem regime shifts, leading to rapid structural and functional changes. Organisms act as ecosystem engineers, modifying environments and influencing species existence through increased complexity and habitat heterogeneity. However, multiple stressors may impair their ability to create new habitats. Thus, understanding these dynamics is crucial for the sustainable use of marine resources in the face of interacting stressors [13, 14].

Socioeconomic Implications

The expected socioeconomic impacts of OA are likely to fall most heavily on Pacific Island countries where coastal reef systems represent the foundation of food, tourism, and other services, but these impacts are expected to be widespread. The potential for unique insights into the resilience of human coastal and ocean use is offered by small-scale or subsistence fisheries in South Africa, Kerala, and Guyana. The large uncertainty in the economic impacts of OA arises from the uncertainty surrounding the economic valuation of ecosystem services, the emergence of new market services not currently valued, and the further rise in the uncertainty surrounding climatic changes and their interaction with anthropogenic stressors. More direct studies of the socioeconomic aspects of the likely direct impacts of OA, and the adaptation responses of reef and fishery management are needed, especially for coastal ecosystems that are historically understudied or data-poor. Knowledge is also lacking about the socioeconomic impacts of OA on oceans outside of coral reef ecosystems, which are likely to be large, especially concerning shelled organisms in oligotrophic seas (calcification). Furthermore, knowledge about the cascading knock-on impacts, such as changes in benthos and phytoplankton on pelagic fisheries, is generally lacking, and future studies need to consider multiple stressors acting together, especially in margin ecosystems that may be susceptible to acidification and reduced oxygen. Nonetheless, this outline of knowledge and data gaps highlights significant opportunities for future research into the socioeconomic impacts of OA on marine ecosystems and human societies. The solution options for the OA problem and the enormous conservation opportunities for targeted ecosystems are presented in the final section [15, 16].

Mitigation Strategies

Ocean acidification is a critical environmental issue with significant impacts on marine ecosystems and potential socio-political conflicts. Scientific research ranges from species-specific responses to CO_2 increases to broader socio-economic assessments of its effects on fisheries and coastal communities. Mitigating climate change is essential to slow ocean acidification. Current projections indicate that atmospheric CO_2 levels could double (around 560 ppm) by 2045. While climate uncertainties may rise post this threshold, some ocean changes, such as warming, oxygen decline, and acidification in high-latitude regions, are expected to continue with or without mitigation efforts. The severity of ocean acidification's consequences is predicted to grow with ongoing high emissions. Rates of ocean acidification—indicated by surface water pH and aragonite saturation—are anticipated to rise linearly with increased emissions, though the rate of change per unit CO_2 will decrease. Options to mitigate ocean acidification are fewer than for warming. Efforts to cut greenhouse gas emissions are extensive, yet strategies to enhance ocean alkalinity remain in early development. Locally, ecosystems can potentially counteract acidification through biogeochemical processes, although whether these can significantly impact overall acidification is uncertain. Seagrass meadows may enhance local buffering due to their high photosynthesis and calcification rates, which can raise pH and carbonate levels. This paper summarizes the ability of temperate seagrass meadows to help mitigate ocean acidification in estuaries and coastal marine environments [17, 18].

Research and Monitoring

The Gulf of Maine, rich in coastal salt marshes, estuaries, and bays, supports various commercially vital fish and seafood species. Maine's fishing industry offers jobs and income to many workers. Historically, excessive fishing has led to resource crashes and bans. Recently, the Gulf of Maine has warmed nearly three times faster than global oceans due to human actions like greenhouse gas emissions and deforestation. Coastal and ocean acidification (COCA) is predicted to intensify, impacting aquatic ecosystems globally, which has spurred increased research interest. Maine's waters are showing the effects of these changes on ecology and local resources. The Maine State Water Plan highlights threats to freshwater, marine, and estuarine habitats from development, pollution, climate change, and overharvesting, advocating for the conservation of water resources. Despite these issues, knowledge of acidification is limited among scientists and agencies in the state. Most focus on fish and marine invertebrates, yet assessing acidification is complex and requires understanding various physical and biochemical processes. No single monitoring station captures the whole picture, emphasizing the need to consider different data sources and the complexities of the terrestrial-ocean-atmosphere system for effective monitoring [19, 20].

Public Awareness and Education

Public awareness and education about ocean acidification (OA) are essential for effective mitigation planning and management strategies. Despite advancements in scientific understanding, public knowledge of OA is still inadequate, particularly in developing countries where more than 80% of the global coastal population resides. The "Ocean Summit" initiative highlights OA, yet global science communication efforts on the issue remain limited compared to other climate change aspects. Enhancing science communication capacities in developing countries is crucial for effective public outreach. Additionally, explaining the connection between OA and the carbon cycle in oceans should be prioritized.

The observed decrease in pH in coastal waters due to changes in ocean chemistry requires further study and communication. Access to current research and news on OA needs to be broadened in small islands and developing nations. Collaboration with local researchers and resource managers should promote open information sharing and knowledge building. Scientists must convey their findings more effectively to audiences lacking formal expertise. Educational initiatives targeting children, youth, and adults in various institutions should be carefully designed with professional education input. Assessments of public knowledge about OA at national and local levels must be conducted, with results evaluated to support specific educational programs. Catalyst programs should be established to raise awareness and encourage public support for ocean acidification issues [21, 22].

Future Directions in Research

Ocean acidification (OA) is a process that affects all types of marine ecosystems and impacts many marine organisms and their ecosystems. As the oceans absorb anthropogenic CO_2, increased chemical reactions with seawater result in decreased pH and increased bicarbonate, proton, and carbonate ion concentrations. As a consequence, marine organisms that calcify are under threat, which includes marine calcifying microorganisms. In examples of low oxygen systems in the coastal ocean, this impairment to calcification is compounded by ocean warming. Presently, over the decade, regions of decreased oxygen and increased acidity have been observed around the world, and local and unmonitored systems will be negatively impacted by their respective processes. An urgent international research need is to understand the process of ocean change, its consequences to marine ecosystems, and its potential to be mitigated. Recent national and international research efforts to investigate acidification are comparatively recent in relation to the previous decade-long commitment to warming. The necessary interdisciplinary approach to marine research embraces the integration of research disciplines and technologies, proximity to end-users, and breadth and depth of science. Widely employed geoengineering technologies can impact the ocean in multiple potentially complex pathways, including CO_2 storage in deep water through physical or chemical methods, alteration of algae blooms or biogenic species composition, and promotion of exclusion of light from the ocean surface to limit warming. Of these, the most relevant to OA is the deliberate introduction of iron or other nutrients to stimulate regional algal blooms to sequester CO_2. However, through the in-depth study of a single technology with a single species, the more general question of the risks of geoengineering technology to marine systems has not previously been assessed in a broad-ranging review [23, 24].

CONCLUSION

Ocean acidification represents a profound and accelerating threat to marine ecosystems, biodiversity, and the human societies that depend on them. Its origins lie in the anthropogenic increase of atmospheric CO_2, which alters ocean chemistry, reduces carbonate ion availability, and impairs the physiological functions of numerous marine organisms, especially calcifiers. These biological changes ripple through food webs, destabilize ecosystem structures, and reduce the resilience of key marine environments such as coral reefs and seagrass beds. The socioeconomic consequences are particularly dire for communities reliant on marine resources for food security, cultural identity, and economic livelihoods. While mitigation through CO_2 emissions reduction remains paramount, adaptive local strategies such as ecosystem restoration and enhanced monitoring are also essential. Continued interdisciplinary research is crucial to fill existing knowledge gaps and inform policies aimed at safeguarding the oceans' ecological integrity and the services they provide to humanity.

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