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ARTICLE

Climate Change and its Profound Effects on Marine Climate

Youssef Yaisien, Yahya Fayek,* and Haytham Sharawi

Department of Civil Engineering, Faculty of Engineering, Shobra, Banha University, Cairo, Egypt
*Corresponding author: yahya.fay@feng.bu.edu.eg

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Abstract
Climate change is exerting profound effects on marine climates, significantly impacting oceanic ecosystems and the species that inhabit them. Rising global temperatures lead to increased ocean warming, causing thermal expansion and contributing to sea level rise. This warming disrupts marine life, affecting breeding cycles, migration patterns, and food availability. Additionally, the increased absorption of carbon dioxide by oceans results in acidification, which harms coral reefs, shellfish, and other calcifying organisms. Melting polar ice caps and glaciers contribute to habitat loss for species like polar bears and penguins, while altering ocean currents and weather patterns. These changes exacerbate the frequency and intensity of extreme weather events, such as hurricanes and typhoons, further stressing marine environments. Climate change also affects the distribution and abundance of fish stocks, threatening global fisheries and the livelihoods dependent on them. Understanding and mitigating the impacts of climate change on marine climates is crucial for preserving biodiversity, ensuring food security, and maintaining the health of our planet's oceans.

Keywords: Acidification; Biodiversity; Fisheries; Global Warming; Habitat Loss; Ocean Currents; Sea Level Rise

Abbreviations: EU: European Union, GMSL: Global mean sea level, IPCC: Intergovernmental Panel on Climate Change, MPA: Marine Protected Area

1. Introduction

The marine climate, encompassing oceans and coastal areas, is profoundly impacted by climate change. Rising sea levels, warming waters, and acidification are among the threats causing wide spread degradation to marine ecosystems worldwide. Storms, precipitation patterns, and temperate climate zones near the highlands, west coasts, and mountain ranges are also influenced by these changes. This article examines the profound effects of climate change on the marine climate. It explores rising sea levels, ocean warming, acidification, coral reef degradation, sea ice melting, coastal ecosystem disruption, and marine species migration. Additionally, it discusses adaptation and mitigation strategies to address these challenges in humid temperate climate zones and vulnerable coastal areas [1, 2, 3, 4, 5].

2. Rising Sea Levels

Rising sea levels pose a significant threat to coastal regions and marine ecosystems worldwide. According to the Intergovernmental Panel on Climate Change (IPCC), global mean sea level (GMSL) has been rising at an accelerating rate since the late 19th century, with the rate almost doubling from 1.7 ± 0.2 mm/year for 1900 to 2009 to 3.2 ± 0.4 mm/year for 1993 to 2009. The primary factors contributing to this rise include [6, 7]:

1. **Thermal Expansion**: As oceans warm due to climate change, the seawater expands, causing sea levels to rise.
2. **Melting of Glaciers and Ice Caps**: The melting of land-based glaciers and ice caps, such as those in Greenland and Antarctica, adds significant amounts of water to the oceans, increasing sea levels.
3. **Changes in Terrestrial Water Storage**: Changes in the storage of water on land, such as the depletion of groundwater resources or the filling of reservoirs, can also influence sea level rise.

Estimates suggest that thermal expansion and melting of glaciers/ice caps accounted for about 75% of the observed GMSL rise from 1972-2008. However, there is significant regional variation in sea level changes, with some areas experiencing relative sea level rise due to factors like land subsidence [8, 9] (see Fig. 1).

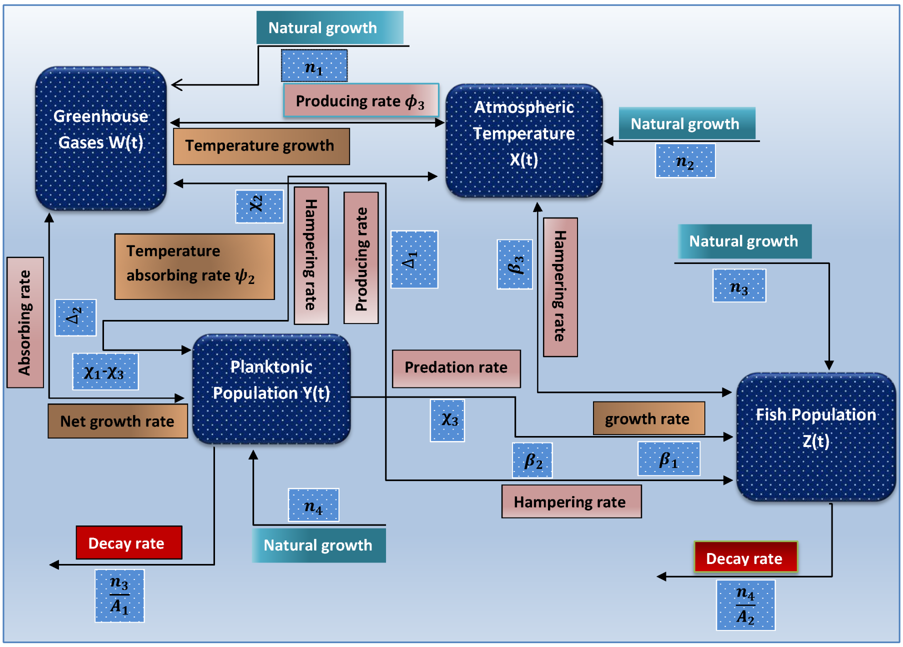

Figure 1. The effect of greenhouse gas on temperature rise and the effect on marine environment and fishing community.

Projections for future sea level rise by 2100 vary, with the IPCC's process-based models estimating a range of 18-59 cm, while semi-empirical models that account for potential ice sheet dynamics project a range of 50-140 cm. In 2022, global mean sea level was 101.2 mm (4 inches) above 1993 levels, the highest annual average on record. Furthermore, the rate of sea level rise has accelerated, with global mean sea level rising by 3.6 mm/year from 2006-2015, 2.5 times the average rate of 1.4 mm/year in the 20th century [10].

The consequences of rising sea levels are severe and far-reaching:

- Coastal infrastructure, including roads, buildings, and critical facilities, is at risk of inundation and damage from storm surges and high-tide flooding.
- Coastal ecosystems, such as wetlands and estuaries, are under stress and may be lost due to erosion

and saltwater intrusion.

- Low-lying coastal communities and small island nations face the threat of displacement and loss of land and resources.
- Saltwater intrusion into freshwater supplies can contaminate drinking water and harm aquatic plants and animals.

Marine climateis profoundly affected by rising sea levels, withstorms, precipitation patterns, and temperate climate zones near the highlands, west coasts, and mountain rangesalso influenced by these changes. Urgent adaptation and mitigation strategies are required to address this pressing issue and protect coastal regions and marine ecosystems from further harm [11, 12, 13, 14].

2.1 Ocean Warming

Ocean warming is a critical consequence of climate change, with far-reaching implications for marine ecosystems and global climate patterns. The oceans have absorbed a staggering amount of heat from the atmosphere, with the total heat stored by the oceans rising by 187 zettajoules from 1992 to 2019. This excess heat is causing a cascade of effects, including:

1. **Coral Bleaching and Disease Outbreaks**: Rising temperatures are leading to more frequent coral bleaching events, where corals expel their symbiotic algae, and disease outbreaks that threaten the survival of coral reefs.
2. **Melting Sea Ice and Albedo Changes**: As warming temperatures melt sea ice over time, fewer bright surfaces are available to reflect sunlight back into the atmosphere. This leads to more solar energy being absorbed at the surface, causing ocean temperatures to rise further [15]. The Arctic Ocean is transitioning from a white, ice-covered region to a blue, open-water region in the summer, changing the albedo (reflectivity) of the region and causing increased absorption of solar radiation. The loss of Arctic sea ice is estimated to be equivalent to adding 25% to global greenhouse gas emissions in terms of the additional heat absorbed by the darker open waters.
3. **Extreme Weather Events**: Less ice means less reflected heat, leading to more intense heatwaves worldwide. Additionally, the destabilization of the polar jet stream can also bring more extreme winters.

The impact of ocean warming is profound and global. Globally, oceans are experiencing warming, with temperatures 0.88°C higher in 2011-2020 compared to 1850-1900. Climate change is having a profound effect on life in the oceans, including warming oceans, rising sea levels, ocean acidification, changing ocean currents and productivity, and shifts in species distribution and abundance. Annual average Arctic sea ice extent has decreased between 3.5% and 4.1% per decade, with September sea ice extent decreasing between 10.7% and 15.9% per decade [16] (see Fig. 2).

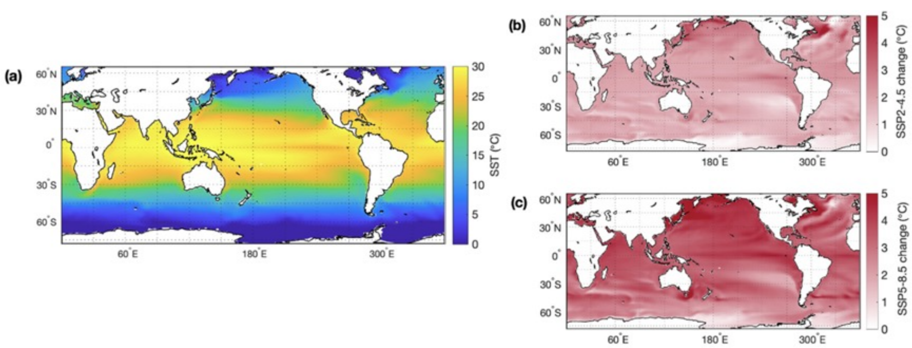

Figure 2. Present-day annual mean sea surface temperature.

Coastal areasare also vulnerable to the effects of ocean warming. Coastal waters have warmed during the last century and are very likely to continue warming, potentially by 4-8°F. Higher sea surface temperatures increase the risk of coral bleaching, which can lead to coral death and the loss of these vital ecosystems [17, 18, 19, 20].

2.2 Ocean Acidification

Ocean acidificationis a direct consequence of rising atmospheric carbon dioxide (CO2) levels from human activities like burning fossil fuels and deforestation. As CO2 dissolves in seawater, it undergoes a series of chemical reactions that increase the concentration of hydrogen ions, making the ocean more acidic. This process is known asocean acidification.

The impact of ocean acidification on marine life is profound and far-reaching:

1. **Reduced Calcification Rates**: Increased acidity reduces the availability of carbonate ions, making it harder for organisms like corals, shellfish, and plankton to build and maintain their calcium carbonate shells and skeletons. This can lead to slower growth, weaker shells, and even dissolution of existing structures.
2. **Disruption of Marine Food Chains**: As calcifying organisms struggle to survive, the entire marine food chain is disrupted. Plankton, which forms the base of many marine food webs, is particularly vulnerable, with potential cascading effects on larger species that rely on them for food.
3. **Coral Reef Degradation**: Coral reefs are among the most sensitive ecosystems to ocean acidification. Studies have shown a 14% decline in coral calcification rates since 1990, threatening the survival of these vital habitats that support a quarter of all marine species.
4. **Economic Impacts**: The economic consequences of ocean acidification are significant. In the United States alone, the shellfish industry could lose over $400 million annually by 2100, and the loss of recreational benefits from coral reefs could cost $140 billion.

The scale and pace of ocean acidification are unprecedented in Earth's history. The ocean's average pH has decreased by 0.1 units since the pre-industrial era, representing a 30% increase in acidity. Projections suggest that if emissions continue unabated, the ocean's surface waters could become more than twice as acidic by the end of this century, reaching levels not seen in 14-17 million years when major extinction events occurred [21, 22, 23, 24].

While adaptation strategies, such as monitoring and cultivating acidification-resistant species, are important, the most effective solution is to dramatically reduce CO2 emissions from fossil fuel use and deforestation. Protecting and enhancing natural carbon sinks like forests can also help mitigate ocean acidification. Addressing this issue is crucial for safeguarding marine ecosystems and the countless species that depend on them.

3. Coral Reef Degradation

Coral reefs are among the most vulnerable ecosystems to the impacts of climate change. Rising ocean temperatures, ocean acidification, and more intense storms are causing widespread degradation and loss of these vital marine habitats.

- **Coral Bleaching**: Elevated sea surface temperatures, even just 1-2°C above normal, can trigger coral bleaching events. During bleaching, corals expel the symbiotic algae that provide them with food and color, leaving them vulnerable to disease and starvation. Severe or prolonged bleaching can lead to mass coral die-offs.
- **Reduced Calcification**: Ocean acidification, caused by the absorption of excess atmospheric CO2, reduces the availability of carbonate ions in seawater. This makes it harder for corals and other

calcifying organisms to build and maintain their calcium carbonate skeletons and shells, leading to slower growth, weaker structures, and potential dissolution.

- **Physical Damage**: Stronger and more frequent storms, fueled by warmer ocean temperatures, can physically break apart and destroy coral reefs through powerful waves and storm surges. Changes in ocean currents and precipitation patterns can also disrupt the food sources and larval dispersal that corals rely on for survival and reproduction.

The consequences of coral reef degradation are far-reaching and severe. Coral reefs support an estimated 25% of all marine species, providing food, shelter, and breeding grounds for a vast array of organisms. Their loss would have devastating impacts on marine biodiversity and the communities that depend on them for food, income, and coastal protection (see Fig. 3).

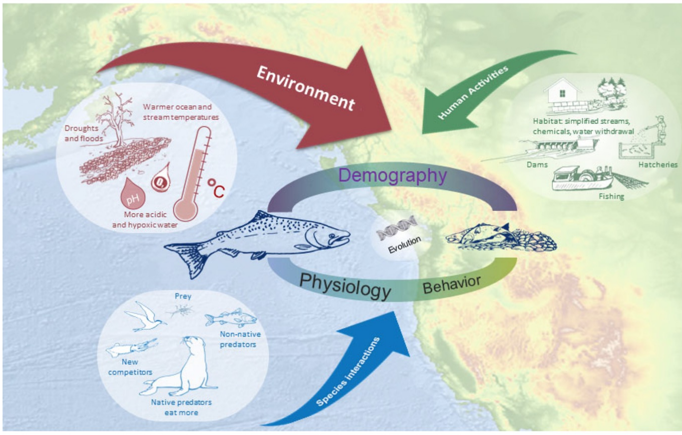

Figure 3. Multiple biological processes shape the impact of climate change on salmon.

According to UNESCO, if greenhouse gas emissions continue unabated, all 29 reef-containing World Heritage sites would cease to exist by the end of this century. The economic cost of losing these vital ecosystems is staggering, with the climate-related loss of reef ecosystem services projected to cost $500 billion or more per year by 2100. In the United States alone, the loss of recreational benefits from coral reefs is expected to reach $140 billion by 2100 [25, 26, 27].

Marine climateis profoundly impacted by the degradation of coral reefs, which play a crucial role in supporting marine life and regulatingcoastal areas. Limiting global temperature rise to well below 2°C, as outlined in the Paris Agreement, provides the only chance for the survival of coral reefs globally. Local measures, such as protecting existing reefs, restoring hydrology, and reducing pollution, can also help mitigate the impacts on these invaluable ecosystems.

4. Sea Ice Melting

Sea ice plays a crucial role in regulating global ocean temperatures and the movement of ocean waters. When sea ice forms, much of the salt is pushed into the ocean water below, making it denser and causing it to sink and circulate as part of the global ocean conveyor belt. Changes in the amount of sea ice can disrupt this normal ocean circulation, leading to changes in global climate patterns [28, 29] (see Fig. 4).

The polar regions are the most sensitive areas to climate change on Earth, and even a small increase in temperature can lead to greater warming over time in these regions. Ice acts as a protective cover that reflects excess heat back into space, keeping the planet cooler. Additionally, glaciers provide a

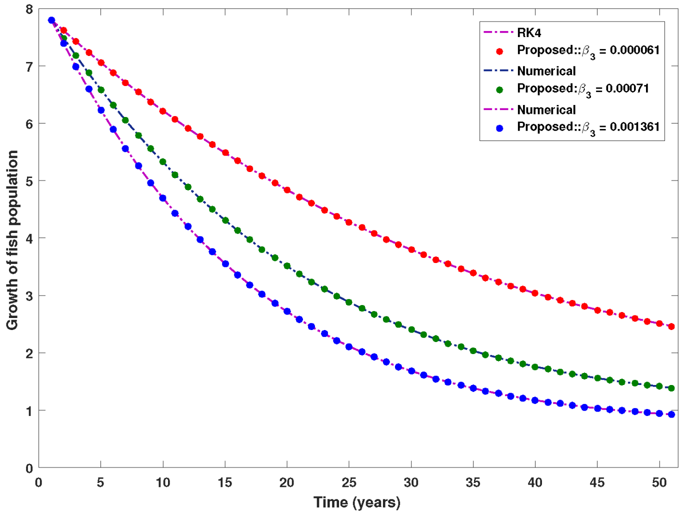

Figure 4. Comparison between the numerical reference solution and the proposed RP-LMS through SNN for fish population.

scientific record of how climate has changed over time. Approximately 10% of land area on Earth is covered with glacial ice, with 90% in Antarctica and 10% in the Greenland ice cap [15].

However, the extent of Arctic sea ice has declined by more than 50% in summer since the 1970s, and the total volume of Arctic sea ice in late summer has declined by 75% in the past 50 years. This alarming trend is exacerbated by several factors:

1. **Increased Wave Action and Storm Activity**: In the ice-free Arctic Ocean, increased wave action and storm activity are breaking up ice floes and bringing up heat absorbed during the summer, making it harder for ice to form in the fall.
2. **Methane Release**: The release of methane from thawing Arctic seafloor permafrost and methane hydrates is a major concern, as methane is a potent greenhouse gas that could lead to rapid, catastrophic warming.
3. **Accelerated Melting**: If emissions continue to rise unchecked, the Arctic could be ice-free in the summer by 2040, according to projections.

The consequences of sea ice melting are severe and far-reaching:

- **Habitat Loss**: The loss of sea ice and melting permafrost threatens the survival of many Arctic species, such as polar bears, walruses, and arctic foxes.
- **Human-Wildlife Conflicts**: Increased contact between wildlife and Arctic communities is leading to more conflicts as animals seek new habitats.
- **Disruption ofMarine Climate**: Changes in sea ice cover can alter ocean circulation patterns, affectingstorms, precipitation, temperate climate zones, and coastal areas.

Urgent, meaningful, and concrete climate action is needed, along with efforts to help communities and wildlife adapt to the changes already underway in the Arctic region and its marine climate [30].

5. Coastal Ecosystem Disruption

Coastal ecosystems are particularly vulnerable to the impacts of climate change, facing threats from rising sea levels, increased storm intensity, and habitat degradation. These changes can have far-reaching consequences for both the environment and the communities that depend on these ecosystems [31].

- **Sensitive Coastal Areas**: Semi-enclosed seas like the Baltic Sea and Adriatic Sea, as well as shallow coastal areas, are more susceptible to climate change compared to deeper, offshore regions. These areas are more susceptible to changes in temperature, salinity, and nutrient levels, which can disrupt the delicate balance of marine life.
- **Loss of Critical Habitats**: Climate-driven changes can affect the feeding, breeding, and resting places for many wildlife species, such as the declining saltmarsh sparrows on the East Coast. Wetlands play a crucial role in providing habitats, attenuating coastal storm impacts, and absorbing carbon dioxide. Their loss reduces these critical ecosystem services.
- **Economic Impacts**: Coastal counties produce more than $9.5 trillion in goods and services each year and support over 58 million jobs. Damage to coasts from hurricanes and flooding can have negative economic impacts through property damage, business disruptions, and supply chain interruptions. Hurricane Katrina, the costliest hurricane on record, incurred $182.5 billion in damages in 2021 dollars as given in Table 1 [32, 33, 34].

Table 1. Threats and Impacts

Threat	Impact
Rising Sea Levels	Coastal erosion, saltwater intrusion, habitat loss
Increased Storm Intensity	Property damage, business disruptions, supply chain interruptions
Habitat Degradation	Loss of critical ecosystem services, species decline

Climate change is expected to worsen existing inequities affecting socially vulnerable populations in coastal areas, such as the elderly, low-income households, and Indigenous communities. These communities often have limited resources to adapt to or recover from the impacts of climate change [35, 36, 37, 38, 39, 40].

Coastal development can exacerbate these challenges by reducing the ability of natural systems to respond to climate changes. For example, coastal development can block the inland migration of wetlands and accelerate erosion, causing wetland loss. Efforts are being made to protect and preserve coastal ecosystems, such as allowing room for them to migrate inland and paying landowners for the carbon stored in these habitats [41].

6. Marine Species Migration

The profound impacts of climate change on the marine environment are causing widespread shifts in the distribution and migration patterns of many marine species. As ocean temperatures rise and habitats become less hospitable, species are seeking more favorable conditions, often moving poleward or to deeper waters [42, 43, 44].

Storms, precipitation patterns, and temperate climate zones near the highlands, west coasts, and mountain rangesare also being affected by these changes, further disrupting marine ecosystems and the delicate balance they rely on as mentioned in Table 2.

- Many marine species are shifting poleward at a rate of about 44 miles per decade. This migration is driven by the warming of ocean waters, which can disrupt the intricate food webs and ecosystems that these species depend on.

- Fish populations, in particular, are shifting their geographic ranges in response to changing ocean conditions. This can lead to regulatory challenges as species cross jurisdictional boundaries, and can also disrupt established fishing practices and communities that rely on these resources.

Table 2. Species and impacts

Species	Impact
Plankton	Shifts in distribution can disrupt marine food webs
Fish	Geographic range shifts, disrupting ecosystems and fisheries
Coral	Bleaching and degradation due to warming and acidification

- Warmer and more acidic oceansare likely to disrupt coastal and marine ecosystems, leading to further species migration and potential extinctions. Coral reefs, which provide vital habitats for countless species, are particularly vulnerable to these changes.

As species migrate and ecosystems are disrupted, it is crucial to monitor and adapt management strategies to protect these valuable resources. Efforts to mitigate climate change and preserve critical habitats will be essential in ensuring the long-term survival of marine species and the health of our oceans [45, 46].

7. Adaptation and Mitigation Strategies

Addressing the profound impacts of climate change on the marine climate requires a multifaceted approach involving adaptation and mitigation strategies. These strategies aim to protect vulnerable ecosystems, facilitate species migration, and reduce the overall effects of climate change on coastal and marine environments (see Fig. 5) [47, 48, 49, 50].

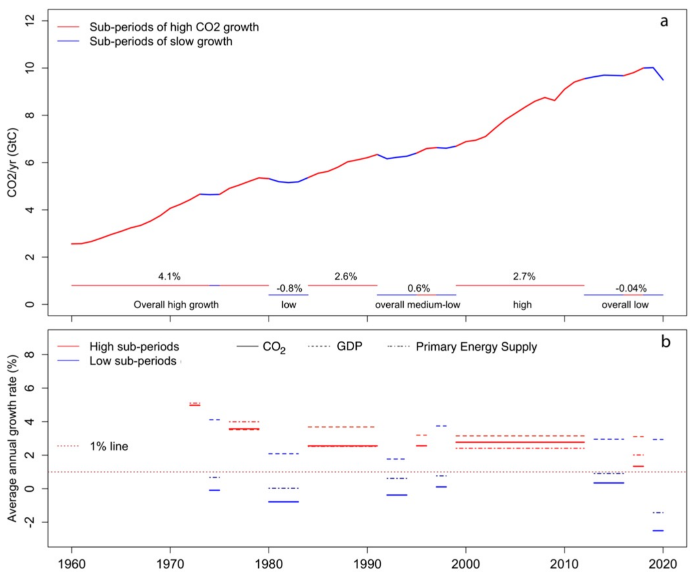

Figure 5. Development in global CO2 emissions from fossil fuels and industry, 1960–2020.

- **Protecting Cultural Heritage and Traditional Knowledge**: Climate change threatens to destroy valuable information about how communities have adapted to environmental changes in the past, including traditional ecological knowledge and native languages. To mitigate this loss, it is crucial to:

1. Conduct vulnerability assessments to identify high-risk cultural heritage resources.
2. Develop appropriate strategies such as relocation, protection in place, or research before loss.
3. Implement 'no regret' strategies that provide benefits regardless of climate impacts, such as structural reinforcement of cultural sites, locating and recording vulnerable sites, and prioritizing the study of vulnerable sites [51, 52].

- **Marine Protected Areas (MPAs)**: MPAs can significantly contribute to climate change mitigation and adaptation through various ecological and social pathways. However, the level of protection in MPAs is crucial – most benefits are only achieved in fully or highly protected areas and increase with their age. Opportunities exist to leverage the scientific basis on MPAs to:
  - Guide public policy and private sector initiatives.
  - Expand the consideration of MPAs in national climate strategies.
  - Allocate resources to accelerate the expansion of blue carbon strategies.
- **Ecosystem-Based Adaptation Strategies**: To enhance the resilience of marine and coastal ecosystems, a range of strategies can be employed [53]:
  - **Enhance Resistance**: Protect vulnerable areas, improve runoff water quality, practice climate-informed habitat restoration, reduce erosion, reduce recreational impacts, and reduce invasive species pressure.
  - **Promote Resilience**: Incorporate changing climate conditions into policy, planning, and regulations; enhance habitat and species resilience.
  - **Facilitate Transition and Response**: Prepare the landscape for change, remove vulnerable structures, acquire high-value properties, upgrade infrastructure, and anticipate and facilitate species migration.
  - **Increase Knowledge**: Enhance understanding of vulnerability, increase or enhance monitoring, improve availability and use of spatial information, and practice climate-informed research.
  - **Enhance Coordination**: Work across jurisdictions to increase communication, collaboration, and leverage resources; engage the public through education and outreach.

The European Union (EU) is taking actions to restore marine ecosystem health and services, including revising the Marine Strategy Framework Directive, implementing the EU Biodiversity Strategy, and expanding marine protected areas.

8. Conclusion

The profound impacts of climate change on the marine climate are far-reaching and alarming. Rising sea levels, ocean warming, acidification, coral reef degradation, sea ice melting, coastal ecosystem disruption, and marine species migration are all interconnected challenges that demand urgent attention. These issues not only threaten marine ecosystems but also have broader implications for global climate patterns, coastal communities, and industries dependent on marine resources. While the challenges are daunting, there is still a window of opportunity to mitigate the most severe consequences through decisive action. Adapting to the changes already underway is crucial, but ultimately, reducing greenhouse gas emissions and protecting natural carbon sinks will be key to safeguarding our oceans and marine climate. By prioritizing climate action, embracing ecosystem-based adaptation strategies, and fostering international collaboration, we can work towards preserving the delicate balance of our marine environments for generations to come.

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