Review

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Global warming impacts on marine diversity and key indicator species in East Asia

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ABSTRACT

Marine ecosystems in the northwest Pacific are known for their high biodiversity, with many marine species, from tiny plankton to huge macroalgae. Marine biodiversity is affected by irreversible global warming, mainly the increase of greenhouse gas emissions from anthropogenic activities. For the past several decades, marine ecosystems in East Asia have been changing due to the increase in sea surface temperature (SST), which has changed some important environmental factors, including rainfall patterns, extreme weather, and ocean circulation. Such modifications in the environmental parameters have altered the physiology, phenology, and distribution pattern of marine organisms. The SST increase has also altered population and community structure, and the functioning of the ecosystem. Certain subtropical and tropical fauna and flora are now extending their range of distribution from the warm southern area to the temperate regions, disrupting or modifying the biotic interactions in the temperate ecosystem. Collaborative conservation projects and responsible policies are crucial to safeguard the environmental value of East Asia's marine ecosystems for future generations and mitigate the negative effects of global warming on marine biodiversity. Conservation and management of East Asia's marine environments hold significant implications for global biodiversity and ecological balance, making them a pivotal focus in addressing climate change challenges in marine ecosystems.

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KEYWORDS EAST ASIA, MARINE ECOSYSTEMS, GLOBAL WARMING, MARINE BIODIVERSITY, POLEWARD MIGRATION

HIGHLIGHTS

- Global warming impacts marine ecosystems by elevating SST, extreme weather, and ocean circulation.
- Marine ecosystems in East Asia are diverse, vital, and teeming with marine life, nurturing unparalleled ecological significance.
- Global warming directly and indirectly impacts marine population dynamics, community structure, and ecosystem functioning.

1. INTRODUCTION

Over the past decades, numerous studies have contributed to understanding how global warming affects marine biodiversity on both global and regional scales (Tittensor et al., 2010). The SST level has gradually increased globally due to irreversible global warming, mainly driven by the alarming surge of greenhouse gas emissions from anthropogenic activities. In addition to the increase in SST, there have been substantial changes in climate extremes worldwide, encompassing reduced occurrences of cold days and nights, increased frequency of heatwaves, and alterations in the frequency, severity, and duration of compound extreme temperature and precipitation events (Albouy et al., 2020; Cheung et al., 2009; Worm & Lotze, 2016; You et al., 2022). The rapid increase in ocean temperatures, especially since 1991, has outpaced previous records, leaving scientists concerned about the implications for marine ecosystems (Cheung et al., 2009). Notably, changes in ocean temperature (Figure 1) significantly impact other important aspects of our planet's environment, including sea level, the extent of sea ice, and salinity which in turn changes precipitation and evaporation patterns, and their combined effect is already having a negative impact on marine life, leading to several unfavourable consequences (Albouy et al., 2020; Worm & Lotze, 2016).

The Northwest Pacific Ocean in East Asia comprises three large marine ecosystems (LMEs): the East China Sea, the Yellow Sea, and the East Sea (Rebstock & Kang, 2003). Even though it makes up only a small percentage of the ocean's surface, the East Asia marine ecosystem is known as the worldwide centre of marine biodiversity (Gonzales et al., 2019). It consists of a diverse range of coastal and oceanic habitats, holding unparalleled ecological significance as they stretch across the northwestern Pacific Ocean and harbour an impressive variety of marine life, supporting numerous species and contributing to marine diversity (Hu et al., 2022; Kang et al., 2000, 2012; Sugihara et al., 2009). Among these ecosystems, the coral reefs in East Asia stand out as one of the world's most biodiverse, nurturing a remarkable array of marine species by providing vital breeding grounds, shelter, and feeding areas for numerous fish, invertebrates, and other marine organisms (Muko et al., 2019; Nishihira, 2004). These coral reefs foster abundant marine life and act as natural barriers, safeguarding coastlines from erosion and mitigating the impact of extreme weather events (Veron, 2000). Additionally, East Asia's marine environments host a diverse range of macroalgae, playing a crucial role as primary producers through photosynthesis, and forming the foundation of the food web, thereby offering essential sustenance and habitat for various fish, invertebrates, and marine mammals (Lobban & Wynne, 1981; Lobban & Harrison, 1994; Vieira et al., 2016). The nutrient-rich waters of this region also nurture thriving phytoplankton blooms, attracting a diverse array of marine species, including fish, marine mammals, and seabirds (Hu et al., 2022; Jung et al., 2014).

Beyond local benefits in East Asia, the ecological importance of marine ecosystems extends globally as the region plays a crucial role in the migration patterns of many marine species, serving as a vital link in migration routes (Hu et al., 2022; Jung et al., 2014; Kang, Kim et al., 2020). Preserving and conserving these ecosystems becomes paramount

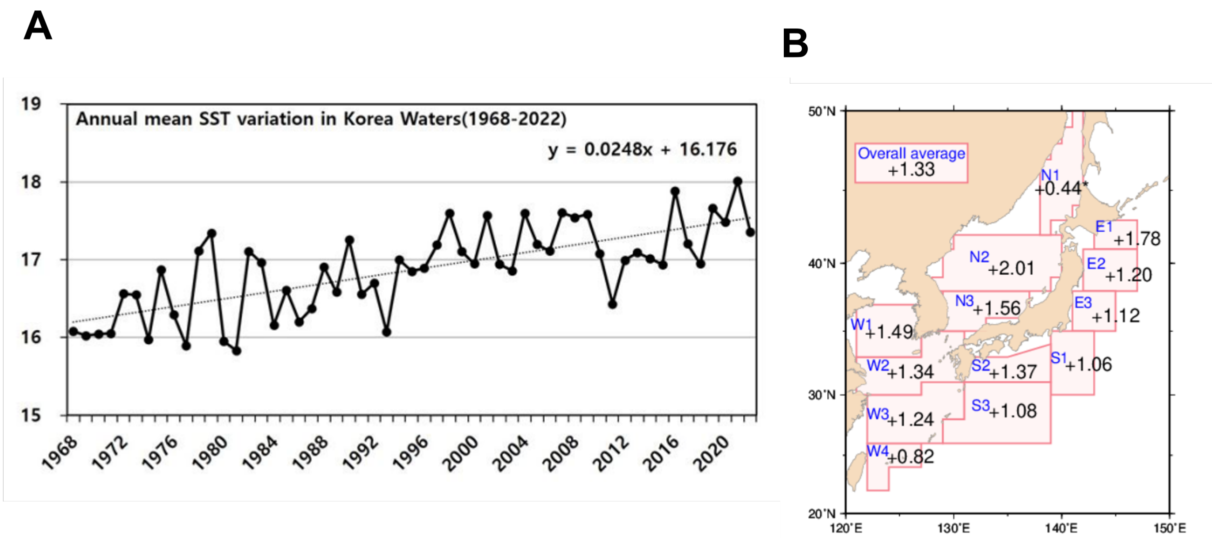

FIGURE 1. A: The long-term trends in annual mean sea surface temperature (SST) for Korean waters and the global average over the period 1968–2022 (unit: °C) (Cited from Han et al., 2023). B: Rates of increase in area-averaged annual mean SSTs around Japan from 1900 to 2023 (°C per century). Areas without symbols and those marked with [*] indicate statistically significant trends at confidence levels of 99% and 95%, respectively. N1 - Northeastern part of the Sea of Japan; N2 - Central part of the Sea of Japan; N3 - Southwestern part of the Sea of Japan; E1 - Sea off Kushiro; E2 - Sea off Sanriku; E3 - Eastern part of the sea off Kanto; S1 - Southern part of the sea off Kanto; S2 - Sea off Shikoku and Tokai; S3 - East of Okinawa; W1 - Yellow Sea; W2 - Northern part of the East China Sea; W3 - Southern part of the East China Sea; W4 - Sea around the Sakishima Islands (Source: Japan Meteorological Agency website https://www.data.jma.go.jp/gmd/kaiyou/english/long_term_sst_japan/sea_surface_temperature_around_japan.html).

for the sustainability of local marine life and coastal communities, and for maintaining worldwide biodiversity and ecological balance (Gonzales et al., 2019). In East Asia, safeguarding the rich biodiversity of marine environments requires collaborative efforts and responsible management practices to ensure these invaluable ecosystems thrive for generations. Unfortunately, marine ecosystems of East Asia face numerous threats, including overfishing, habitat destruction, pollution, and the impacts of climate change (Gonzales et al., 2019; Sekiyama, 2022; Zhang & Wang, 2019). Ensuring these invaluable ecosystems' long-term health and resilience requires concerted efforts at both regional and international levels. Collaborative conservation initiatives, sustainable fishing practices, and responsible coastal development are vital to preserving the ecological significance of East Asia's marine environments for future generations (Gonzales et al., 2019; Moore et al., 2018).

This review aims to present a comprehensive overview of the profound impacts of global warming on marine biodiversity in the East Asia region. Encompassing a range of essential aspects, the scope of this review will delve into the primary drivers of global warming and ecosystem-level impacts. Additionally, this review will specifically address the repercussions of rising sea temperatures on crucial habitats, focusing on coral ecosystems and other critical marine ecosystems in East Asia.

2. DRIVERS AND EFFECTS OF GLOBAL WARMING ON MARINE ECOSYSTEMS IN EAST ASIA

2.1. Primary drivers of global warming in East Asia

Global warming primarily results from anthropogenic activities, notably the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) from industrial processes, transportation, and deforestation, which contribute to the greenhouse effect, trapping heat in the Earth's atmosphere and causing a rise in global temperatures (Sekiyama, 2022; Zhang & Wang, 2019). Furthermore, the region's atmospheric and oceanic circulation patterns exacerbate global warming. For instance, the East Asian monsoon system can influence regional climate variability, affecting temperature and precipitation patterns, and changes in these circulation patterns can lead to altered weather conditions with subsequent impacts on the health and dynamics of marine ecosystems (Liu et al., 2023).

2.2. Effects of global warming on marine ecosystems in East Asia

In the 21st century, the majority of the oceans around the globe have shown a significant warming trend in increasing SST (Kim et al., 2011; Lee, Park et al., 2023). Numerous studies have documented rising SST, warming air temperatures, and changing precipitation patterns in East Asia (Lee, Park et al., 2023, Liu, 2020, Liu et al., 2023; Sekiyama, 2022; You et al., 2022; Zhang & Wang, 2019), and these observations align with global trends and indicate the progressive impact of global warming in the region (Zhang & Wang, 2019). In conjunction with anthropogenic interventions, extensive research has increasingly concentrated on the warming ocean as a central aspect influencing marine ecosystems (Jung et al., 2014). Climate models and projections for East Asia suggest that, if current emission trends continue, the warming trend is expected to intensify in the coming decades, leading to rising sea levels, shifting ocean currents, and altered weather patterns, thereby posing significant challenges to the region's coastal communities, marine biodiversity, and ecosystem dynamics (Cheung et al., 2009; You et al., 2022). Our understanding of how global warming affects atmospheric heatwave variabilities on both global and regional scales has greatly improved due to extensive research over several decades (Hong et al., 2021; Lee, Park et al., 2023; Wie et al., 2021). Extreme surface sea warming events, sometimes known as "marine heatwaves", are characterised by extremely high SSTs that continue for several days to many months. Over two decades, these events have become more frequent worldwide due to various atmospheric and oceanic variables (Hong et al., 2021; Wie et al., 2021). In contrast, investigations into ocean extremes represent a developing field, with only recent studies delving into these phenomena, both global distribution and trends (Zhang & Wang, 2019). Consequently, understanding the development of extreme hydrological, physical, and biological features during the past few decades, such as SST, low salinity, and phytoplankton biomass, is still uncertain (Lee, Park et al., 2023).

The rising SST trend not only impacts coral reefs globally but also negatively influences the coral reefs in East Asia, particularly evident through coral bleaching (Liu, 2020; Sully et al., 2019; Van et al., 2022). A serious hazard from rising sea temperatures is the potential for coral bleaching events, which can degrade the irreplaceable coral reef ecosystem, home to various marine animals (Sully et al., 2019). Given the crucial role that elevated sea temperatures play as the primary cause of mass coral bleaching, future projections indicate that the frequency and extent of bleaching events are anticipated to intensify as the SST continues to rise, posing an increasing threat to coral reefs worldwide (Liu, 2020; Sully et al., 2019; Van et al., 2022). Scleractinian corals also can be found in temperate regions, although they do not generally form a coral reef; in poleward, warm current-affected countries like Korea and Japan, corals have spread at higher latitudes (Lee et al., 2022; Sugihara et al., 2014).

Understanding how ocean circulation changes in a warming climate is a critical yet insufficiently elucidated aspect of scientific research (Peng et al., 2022). The complex ocean circulation system is pivotal in transporting heat and nutrients, significantly influencing marine ecosystem responses to greenhouse warming (Moore et al., 2018). Although previous research has mostly concentrated on the effects of changing winds on the upper ocean circulation, there are still many unknowns surrounding the anticipated changes in air circulation (Liu et al., 2023; Wie et al., 2021). The escalating SST, particularly on the upper surface, contributes to ocean stratification and hinders vertical circulation, transforming the upper surface into a vital heat storage location and source (Wie et al., 2021). Interestingly, less research has been done on how higher SST affects ocean circulation. However, increased SST can potentially exacerbate the surface subtropical gyre in a warmer climate and significantly change the SST (Peng et al., 2022). Understanding the larger effects of climate change on marine ecosystems and climate dynamics depends on understanding the intricate interplay between ocean circulation and temperature fluctuations (Jung et al., 2014; Moore et al., 2018; Wie et al., 2021). Increasing surface warming and sea ice loss lead to considerable nutrient trapping in the sea, according to a climate simulation extended to the year 2300. With a net transfer to the deep sea, this trapping causes a redistribution of nutrients on a global scale. Decreases of 24% and 41% in primary output and carbon export, respectively, are predicted by 2300 due to surface nutrient reductions north of 30°S (Moore et al., 2018).

According to research examining the relationship between marine biodiversity and climate change, a net gain in overall species richness is typically the result of slow changes in species composition. Such modifications directly impact the distribution (Serisawa et al., 2004), phenology, and physiology of organisms (Hong et al., 2021). Furthermore, by changing biotic interactions, climate change can significantly negatively affect populations, community structure, and ecosystem functions (Vergés et al., 2014). The generation of new biotic interactions as range-shifted species introduce themselves to native communities (Vieira et al., 2016), the elimination of current interactions when species leave their native ranges (Serisawa et al., 2004), or the modification of crucial behavioural, physiological, or other traits that mediate species interactions are all examples of indirect effects. In tropical locations, warming temperatures contribute to species loss and a decline in diversity, while temperate regions experience species turnover and, in some cases, net diversity increases as oceans warm. Observations in polar environments indicate declining trends in ice-dependent species due to the impacts of global warming (Cheung et al., 2009; Moore et al., 2018; Worm & Lotze, 2016). In East Asia, many studies highlight that, to date, the most compelling evidence for climate-driven changes in species distribution and diversity comes from long-term fish and plankton monitoring data (Kang et al., 2012), with an increasing number of studies investigating other groups, such as corals (Denis et al., 2015; Lee et al., 2022; Sugihara et al., 2014), and macroalgae (Vieira et al., 2016), to gain deeper insights into the impacts of climate change on their distribution and diversity in marine ecosystems.

Monitoring marine biodiversity on a global scale and understanding the distribution of invasive species is crucial for detecting changes in marine ecosystems. Environmental DNA (eDNA) has gained widespread popularity in the monitoring field and has experienced rapid advancements, particularly in the surveillance of aquatic invasive species (Vallejo et al., 2019). Recent developments in eDNA analysis, which extracts extra-organism DNA from various environmental samples, have made it possible to gather highly sensitive data about the diversity of fish in aquatic ecosystems in a less time-consuming, non-invasive, and cost-effective manner. Due to its benefits, eDNA has become a viable tool for biomonitoring, replacing or enhancing established techniques such as net sampling (Kawakami et al., 2023).

2.3. Effects on fish

Studies have investigated latitudinal shifts in the distribution of exploited fishes in the Yellow Sea, driven by the warming trends resulting from climate change, based on circulation model projections, temperature stratification in the Korea Strait (Figure 2) is anticipated to vanish by 2030 (Jung et al., 2014). By analysing long-term fisheries data and oceanographic observations, the mechanisms and implications of the latitudinal range shift of seven commercially important fish species in response to changing environmental conditions. Empirical relationships further indicate that five of the examined ranges of fish species are expected to shift poleward by 19–71 km from the 2000s to the 2030s (Jung et al., 2014). While the mean latitude of chub mackerel has not exhibited a significant overall northward shift (the catch distribution of chub mackerel has undergone a noteworthy change from the Korea Strait to the Yellow Sea in recent years (Jung et al., 2014)). Similarly, another study found that 12 fish species were classified as "winner" species due to their potential to thrive under changing environmental conditions, while nine out of 21 fish species could face reduced habitats by the 2050s, making them potential "loser" species in their ability to adapt to climate change. The study also predicted that 20 species' habitat changes would travel northward, with an average habitat median shifting distance varied from 110 to 206.5 km (Hu et al., 2022). These findings shed light on the potential implications of global warming on marine fish distributions in East Asia.

2.4. Effects on planktons and dinoflagellates

Phytoplankton, zooplankton, and dinoflagellates play crucial roles in marine ecosystems, affecting biomass, community composition, and population dynamics via food web relationships. The changing nutrient stress levels in the marine environment can influence their abundance and distribution, ultimately leading to shifts in the marine food web (Kang, Kim et al., 2020; Kim et al., 2008; Vergés et al., 2014). As nutrient stress increases, these primary producers and consumers may experience alterations in their secondary production, potentially impacting higher trophic levels and ecosystem dynamics (Vergés et al., 2014). Understanding these intricate relationships and responses to nutrient stress is vital for comprehending the

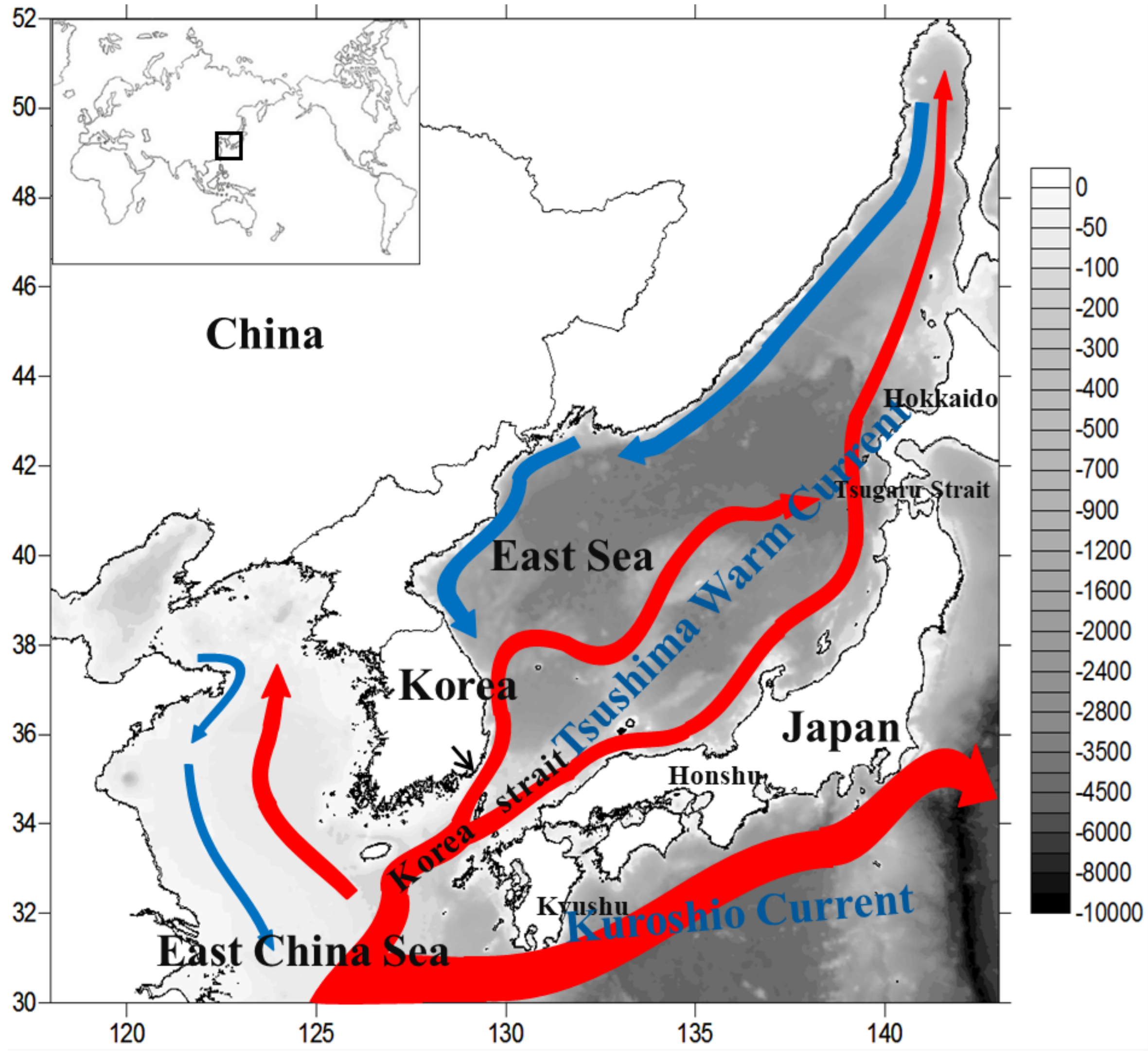

FIGURE 2. Map showing the major ocean currents in the northwest Pacific Ocean. The Kuroshio current and its branch, Tsushima warm current, are important for fisheries species in Korean waters (Cited from Jung et al., 2014).

resilience and stability of marine food webs in the face of ongoing environmental changes (Kang et al., 2012; Kang, Jang et al., 2020). The subtropical region in East Asia hosts a diverse array of tropical dinoflagellate species from the *Ornithocercus* and *Triposolenia* genera, with their populations exhibiting seasonal fluctuations, peaking in abundance during November. The direction and strength of the Jeju Warm Current (JWC), which flows into the strait, considerably impact this pattern. According to the study, these tropical dinoflagellates could be used as biological indicators to track the JWC's entry into the Jeju Strait. Furthermore, these dinoflagellates are assumed to have not yet established themselves on the coastal region of the south coast of Korea despite their constant northward advance toward the coastal areas in autumn and winter (Kim et al., 2008; Lee, Kim et al., 2023). In the Yellow Sea, long-term changes in phytoplankton and zooplankton in Jiaozhou Bay indicate an increase in warm-water plankton species, particularly dinoflagellates and gelatinous zooplankton, and a decrease in the size of the plankton community, while the overall health of Jiaozhou Bay has shown a positive upward trend (Wang et al., 2020).

2.5. Effects on corals and macroalgae

In East Asia, from Japan (Southern Kyushu and the Ryukyu arc) and up to Jeju Island in South Korea's southernmost part, this area is known as the northern limit of the range for many coral species, making it a unique site for studying the impacts of global warming on these organisms (Kang, Kim et al., 2020; Sugihara et al., 2009). The presence of a stable and thriving population of scleractinian corals (Figure 3) in the waters surrounding the sub-tropical region suggests that

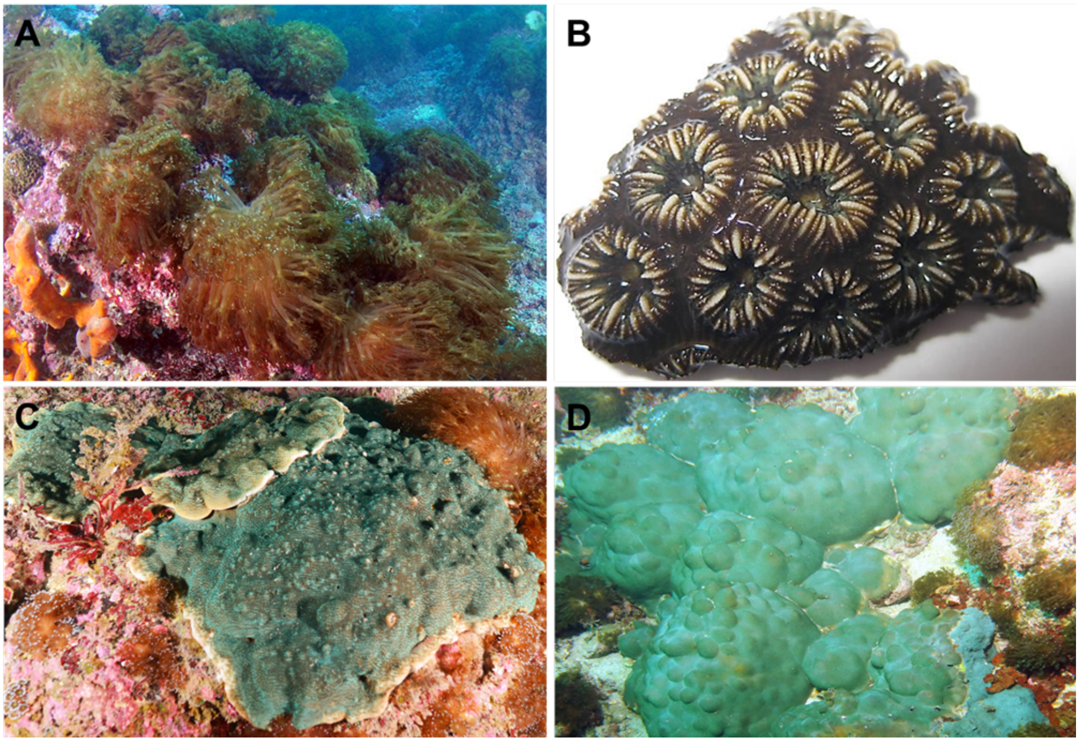

FIGURE 3. Notable scleractinian coral species are found around Jeju Island. A - *Alveopora japonica* (From northern Jeju); B - *Oulastrea crispata* (From southern Jeju); C - *Montipora millepora* (From southern Jeju); D - *Psammocora* sp. (From southern Jeju).

significant changes have occurred in the coastal ecosystem, leading to alterations in benthic composition, competition, and biodiversity (Sugihara et al., 2014; Denis et al., 2015; Vieira et al., 2016; Lee et al., 2022). Recent reports of sub-tropical fish species and new scleractinian coral species (Takatsuki et al., 2007; Denis et al., 2013; Kang, Jang et al., 2020) suggest that these coral communities have either migrated from tropical regions or expanded due to rising SST. Consequently, there has been an increase in scleractinian coral populations in the coastal benthic ecosystem (Vieira et al., 2016), leading to a shift from macroalgae to dominant coral ecosystems in some parts of Jeju Island (Figure 4) (Denis et al., 2015; Vieira et al., 2016; Kim & Kang, 2022). Remarkably, the northern coast of Jeju has reported up to 75% coverage of scleractinian corals, despite being considered marginal and unable to form reefs at high latitudes (Vieira et al., 2016). Additionally, when keystone species disappear, new species may be introduced from tropical locations, leading to further changes. Studies have shown that these changes have affected the benthic community dynamics in Korea, with the dominant coral species, *Alveopora japonica* experiencing high densities in some locations (Denis et al., 2013, 2015; Vieira et al., 2016). Increased abundance of *A. japonica* may contribute to the decline of brown macroalgae in Jeju Island. Anecdotal evidence has shown that until the 1980s, brown macroalgae were dominant in shallow subtidal rocky bottoms in Jeju, playing a vital ecological and economic role (Kang et al., 2012; Vieira et al., 2016). In the past few decades, high-latitude macroalgal communities, including Jeju, have suffered decimation due to temperature and other factors, leading to barren grounds with predominantly coralline algae covering the rocks and facilitating a coral takeover in numerous locations (Vieira et al., 2016; Lee et al., 2022).

Tropical coral reefs experienced the most severe bleaching event, highlighting their vulnerability to natural and human-induced disturbances. Rising SST poses an urgent global threat, triggering coral bleaching and potentially leading to widespread coral mortality (Kim et al., 2022; Nakamura et al., 2022). Following mass bleaching events, there was a significant reduction in spawning rates, ranging from 65% to 90%, in the subsequent period. The impact of bleaching on coral reproductive behaviour was profound, with many coral colonies experiencing disruptions in their normal reproductive cycles (Nakamura et al., 2022). In the temperate region,

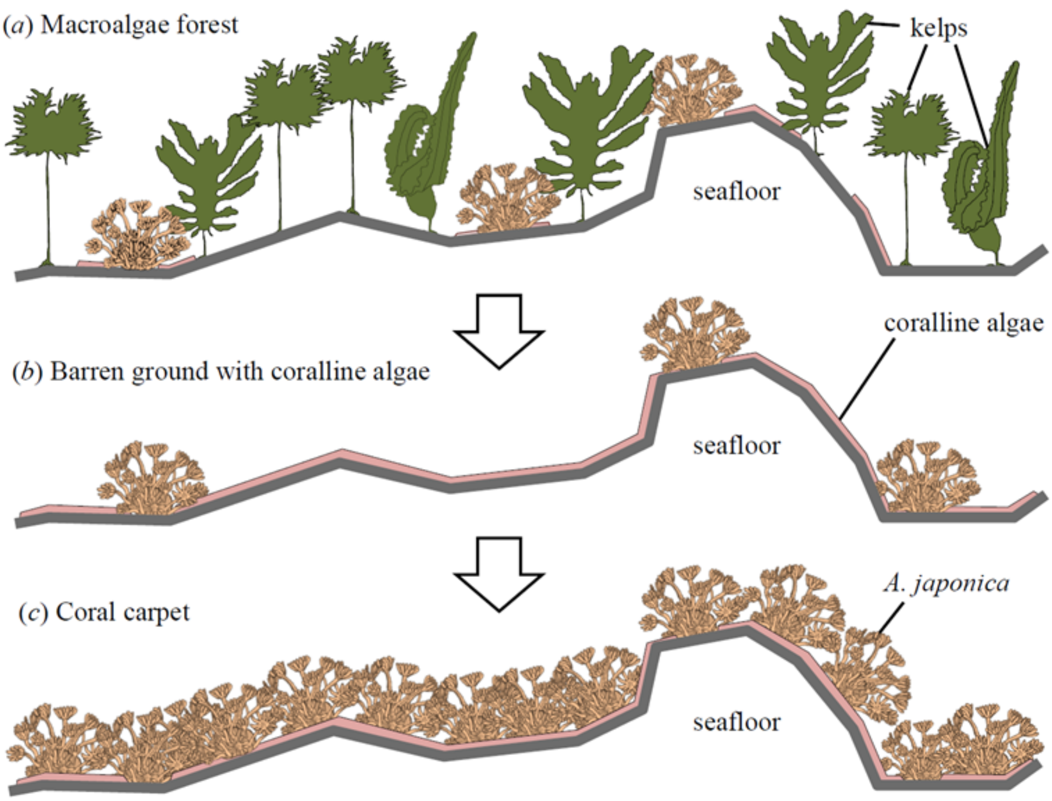

FIGURE 4. In Jeju Island, Korea, a regime shift from (a) macroalgal-dominated to (c) coral-dominated assemblages, with an intermediate (b) barren ground phase, is depicted in the schematic representation (Adapted from Vieira et al., 2016).

a recent study conducted a photographic assessment to evaluate the impact of a bleaching event on coral colonies. The results revealed that the bleaching affected 91% to 96% of the colonies, coinciding with higher summer temperatures, which likely significantly triggered the widespread bleaching (Kim et al., 2022). The high percentage of affected colonies highlights the severity of the bleaching and raises concerns about the resilience and recovery of the coral populations in the region (Gonzales et al., 2019; Van et al., 2022).

3. CONCLUSION

The impact of global warming in the East Asia region has been significant on marine biodiversity, with rising SST causing major changes. Global warming exerts a multifaceted effect on marine ecosystems, influencing various aspects such as temperature, rainfall patterns, extreme weather events, and ocean circulation. Such alterations can directly affect the physiology, distribution, and phenology of marine organisms. Furthermore, by interfering with biotic interactions, climate change has the potential to have indirect consequences that might have a considerable impact on populations, community makeup, and ecosystem functioning. The aforementioned indirect effects can take many different forms, including the emergence of new biotic interactions when species move into uncharted areas, the elimination of interactions as species move outside of their traditional ranges, or changes in important behavioural, physiological, or other traits that control species interactions. These complex interactions highlight the need for a comprehensive understanding of the cascading effects of climate change on marine biodiversity and ecosystem dynamics. Therefore, it is crucial to expand the scope to encompass a broader range of marine ecosystems and implement long-term monitoring of key indicators, thereby enabling the tracking of changes in species populations, including shifts in distribution, abundance, and size structure; in addition, efforts must be strengthened to detect and respond promptly to the spread of non-indigenous species.

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