

Effect of Climate Change on Coral Mortality

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Abstract

Coral reefs are among the most biologically diverse and economically valuable marine ecosystems, supporting nearly one-third of marine fish species and providing essential ecosystem services such as fisheries, coastal protection, and biodiversity maintenance. However, coral reefs are increasingly threatened by climate change-induced ocean warming, ocean acidification, and anthropogenic disturbances, including pollution and overfishing. Coral bleaching, a stress response resulting from the breakdown of the symbiotic relationship between corals and zooxanthellae (*Symbiodinium spp.*), has emerged as one of the most significant causes of coral mortality worldwide. Elevated sea surface temperature (SST), often combined with high irradiance, disrupts photosynthesis in symbiotic algae, leading to oxidative stress, reactive oxygen species (ROS) production, and eventual expulsion of symbionts from coral tissues. This review examines the ecological role of coral reefs, environmental factors affecting coral survival, and the mechanisms underlying coral bleaching. It highlights the importance of coral–algal symbiosis, the role of zooxanthellae in nutrient exchange and calcification, and the influence of thermal stress, ultraviolet radiation, and photoinhibition on coral physiology. Mass bleaching events since the 1980s show the increasing frequency and severity of bleaching under global warming. Some reefs exhibit resilience and adaptive potential, projections indicate that increasing SST and ocean acidification may lead to annual bleaching events in many regions within the coming decades, threatening long-term reef persistence. Therefore, strengthened conservation strategies, climate mitigation efforts, and targeted management of resilient reef systems are urgently required to safeguard coral reef ecosystems and their ecological and socioeconomic functions.

Keywords: *DHW; Oxidative Stress; Resilience; ROS; Symbiotic Algae*

Introduction

Coral reefs are one of the most threatened marine ecosystems because of different factors, including high and destructive fishing, sedimentation pollution and climate change. It has been predicted that seawater temperature will rise further and cause coral death in the next few decades. Elevated temperatures interacting with other physicochemical, biological and anthropogenic factors is the root cause of stress in the coral community and its bleaching. It has been predicted that seawater temperature will increase further and cause coral death in the next few decades. Elevated temperature in association with other physicochemical, biological and anthropogenic factors is the root cause of mortality and bleaching in coral communities (McClanahan *et al.*, 2007).

Climate change also includes rising sea surface temperatures, and global warming poses a major threat to coral communities due to the increased frequency and intensity of coral bleaching events. The continuous warming of oceans is intensifying marine heatwaves, increasing their frequency and duration, and creating stressful conditions that make coral bleaching more frequent and severe (Yu-Long & Chun-Zai, 2026). Thermal stress is one of the major causes of coral bleaching. An analysis of coral bleaching in 81 countries during the period 1998–2017 showed that bleaching is most common in areas where thermal stress events are more frequent and intense. Reefs exposed to high variability in in-sea surface temperature (SST) anomalies showed less bleaching, indicating increased thermal tolerance. Coral bleaching is one of the greatest current threats to reef ecosystems worldwide and occurs when water temperatures exceed the

thermal tolerance of corals (Rivera-Sosa *et al.*, 2025). The highest levels of coral bleaching have been observed in tropical mid-latitudes, approximately 15°–20° north and south, rather than near the equator, despite similar levels of thermal stress. Bleaching started at about 0.50°C higher SSTs than earlier, causing loss of heat-sensitive corals, resulting in higher thermal thresholds in remaining coral populations (Sully *et al.*, 2019).

Coral reefs emit marine biogenic aerosols (sulfur compounds), which play a major role in local climate and influence ocean albedo and cloud formation. Coral reefs are a major source of local biogenic aerosols. A study reveals that beyond the critical thermal stress threshold, corals can no longer influence atmospheric properties. Above this tipping point, corals become vulnerable and undergo mass bleaching. Under this condition, corals can't release aerosols. So, sea surface temperature increase plays an important role in coral bleaching and local climate.

Corals contain a symbiotic alga, and at the time of bleaching, they lose these algae (zooxanthellae), which is responsible for most coral pigmentation. Thermal bleaching occurs due to prolonged exposure to abnormal temperatures, leading to reduced coral biomass. Significant coral mortality has happened in the last 17 years, which are recurrent local, regional, and global bleaching events. The most widespread and severe bleaching occurred during 1997-98, when coral reefs of more than 42 countries were affected by massive coral mortality. The countries that were affected were southern Japan, Sri Lanka, the Maldives, India, Kenya, Tanzania, the Seychelles and other sites in the Indo-Pacific (Fitt *et al.*, 2001).

In this review article, I will search for the root causes of coral mortality and bleaching.

Role of Coral Reefs in the Ecosystem:

Coral reefs are mainly found between the tropics of Capricorn and Cancer and support nearly one-third of all marine fish species as well as thousands of marine organisms. They are ecologically and economically valuable, providing about 6 million tons of fish each year. These resources support both international fishing industries and local coastal communities that depend on reef fish for food and livelihood. In addition to that, coral reefs act as a natural barrier against waves and storms by reducing wave energy through reflection and dissipation, thereby protecting coastal land and nearly half a million people living within 100 km of the reef system (Crabbe, 2008).

Several Environmental Factors Which Influence Coral Survival:

Temperature, light intensity, calcium carbonate saturation, turbidity, sedimentation, salinity, pH and nutrient availability influence the growth and survival of corals. These factors regulate key physiological processes such as photosynthesis and calcification, which limit coral reefs to particular regions of the world oceans. Currently, coral reefs face serious threats from climate change as well as human activities like pollution and overfishing (Crabbe, 2008).

What Is Coral Bleaching?

Most of the color in corals comes from symbiotic algae called zooxanthellae that live within their tissues. Coral bleaching occurs when corals lose these algae. Thermal bleaching happens when corals lose these algae. Coral bleaching occurs when corals lose these algae. Thermal bleaching happens when corals are exposed to temperatures that remain above or below normal for long periods, such temperature stress increases the corals' energy requirements, depletes stored reserves and reduces overall biomass (Crabbe, 2008).

Bleaching can lead to coral death, although some corals may recover, either partially or completely. The process also shows coral growth, recovery from bleaching of coral reefs declines significantly. This trend has been observed during several natural bleaching events, including those in 1983-1984, 1998 and 2005.

Scientists have created mathematical models that examine coevolution to understand how corals might develop resistance to bleaching under rising temperatures (Crabbe, 2008).

Coral-Algal Symbiosis

Corals may adapt to rising temperatures by forming symbioses with more heat-tolerant *Symbiodinium sp.*, although the extent of this adaptation remains debated. Understanding future thermal stress on coral reefs and the level of adaptation required to prevent frequent bleaching is important for both coral reef conservation and global climate policy.

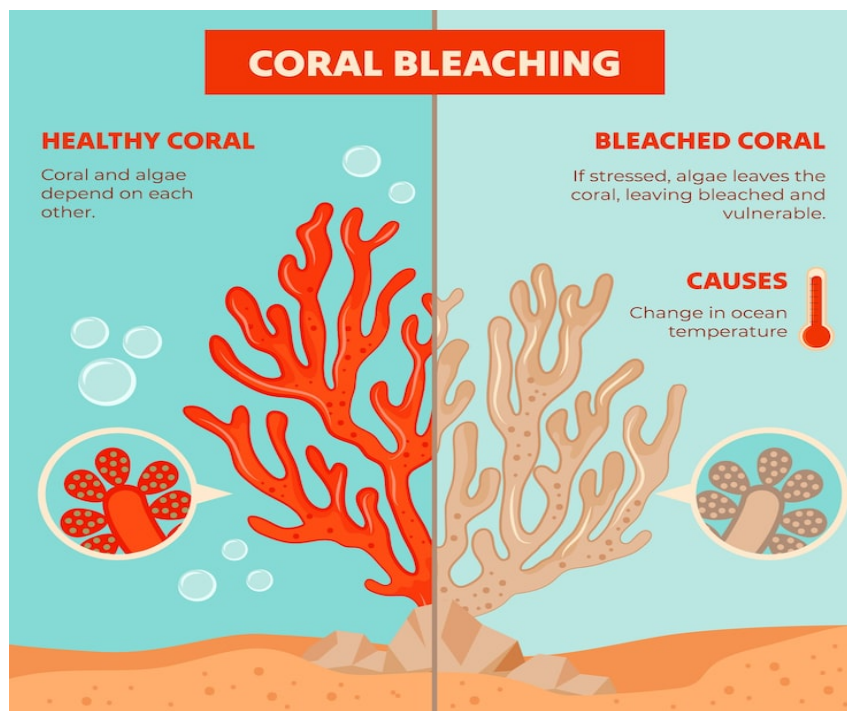


Figure 1: Healthy Vs Bleached Coral

Bleaching Prediction System

The bleaching prediction system developed by NOAA Coral Reef Watch uses satellite data to monitor unusually warm ocean temperatures and measure thermal stress through Degree Heating Weeks (DHW), which effectively predicts coral bleaching events. These real-time warnings are widely used by scientists and marine managers. Historical satellite data from NOAA Coral Reef Watch and global reef maps help to develop methods to project coral bleaching from climate model outputs and forecast the future of mass bleaching under different emission scenarios, as well as the level of increased thermal tolerance needed for coral survival (Donner *et al.*, 2005).

Flexibility of Coral Algal Symbiosis

The flexibility of symbiosis enables the corals to gradually improve their resistance to thermal stress and assist in the recovery of coral cover following bleaching events. Some species of *Symbiodinium* possess higher temperature tolerance, which helps explain why certain corals are able to survive mass bleaching or persist in warmer environments. Corals can acquire a variety of *Symbiodinium* types during their early life stages and may reorganize these symbiotic associations over time in response to thermal stress. They may also obtain different *Symbiodinium* from the surrounding environment when stressed. In some coral communities, shifts towards more heat-tolerant *Symbiodinium* after bleaching have been observed,

suggesting a potential mechanism for adaptation to climate change. However, clear evidence of corals switching completely to entirely new symbiotic partnerships is still lacking (Donner *et al.*, 2005).

Mass Coral Bleaching

Unprecedented mass coral bleaching events associated with increased sea surface temperatures and global warming have been occurring since the 1980s, including three pantropical episodes in 1998, 2010 and 2015-2016. As a result of marine heatwaves or thermal stress, the coral-algal symbiotic relationship with *Symbiodinium spp.* is disrupted, leading to the loss of coral pigmentation. Bleaching causes significant physiological stress to corals and when it persists for extended periods, it often results in high mortality rates. A study indicates that bleaching events are individual disturbances to reefs and focuses on three recurrent bleaching events over the past 18 years along the 2,300 km length of the Great Barrier Reef (Hughes *et al.*, 2017).

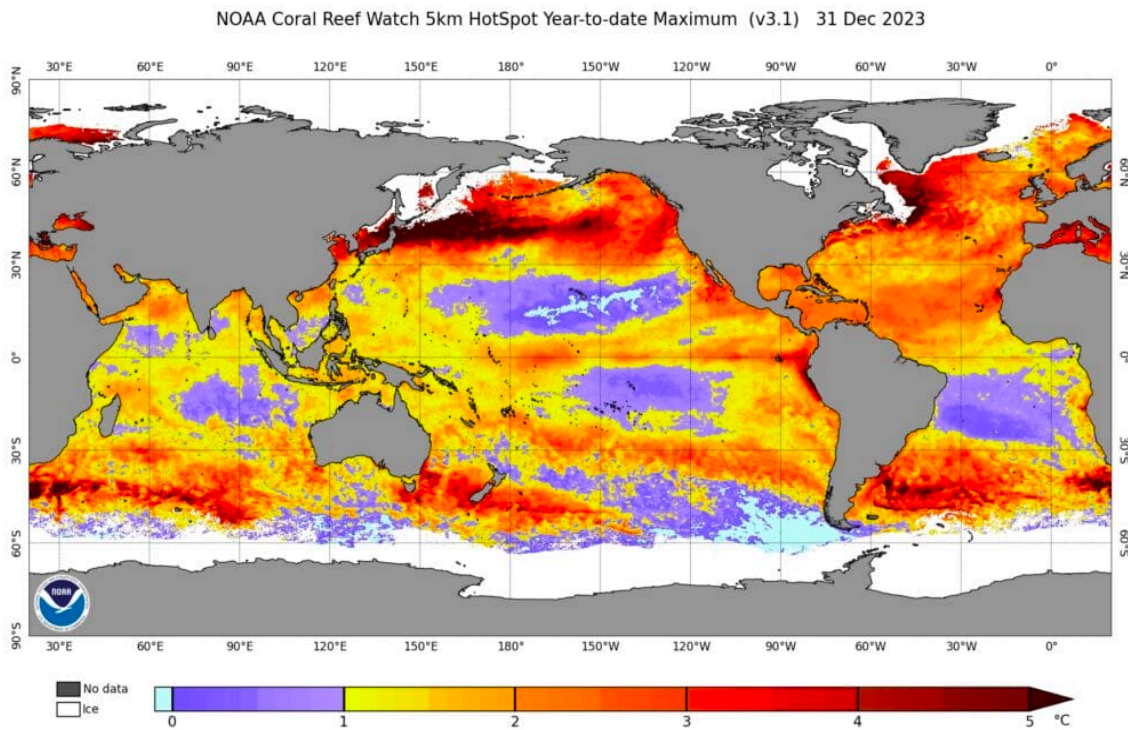


Figure 2: Bleaching Hotspots (Map)

Resistance and Adaptation to Bleaching

Severe bleaching occurred widely across the Great Barrier Reef, regardless of the water quality or protection level. In addition, reefs that experienced bleaching in 1998 or 2002 did not show reduced bleaching in 2016, suggesting that past exposure did not provide significant acclimation or adaptation, likely because the 2016 heat stress was extremely severe. Severe bleaching can affect even very old corals, while milder bleaching is selective, with some resistant species (winners) surviving better than susceptible ones (losers). Fast-growing corals can recover in 10-15 years, but long-lived corals take decades to replace once they die. As the global temperature continues to rise, the long recovery periods are unlikely, meaning coral community structure in the north Great Barrier Reef may shift permanently (Hughes *et al.*, 2017).

Role of Zooxanthellae

Zooxanthellae photosynthesize and live inside the coral host, providing 95% of their photosynthetic production to it. The algae provide amino acids, sugar, complex carbohydrates and small peptides across

the host-symbiont barrier. In return, corals supply the zooxanthellae with their crucial plant nutrients (ammonia and phosphate) from their waste metabolic products, which is very crucial for the survival of these primary producers in marine water.

Photosynthetic oxygen evolution and a loss of variable fluorescence have been reported in cultured zooxanthellae when exposed to temperatures of 34-36°C. The same algae within Caribbean corals are exposed to 32° and 34°C. These studies indicated that corals and these algae, when exposed to heat, caused a malfunction of light reactions. High light intensities will lead to over-reduction of the light reactions and the production of harmful products, like oxygen-free radicals. Temperatures of the tropical seas have increased in the last 100 years; coral cores of the central Pacific confirm this. A 1-2°C sea temperature increase happened due to enhanced concentrations of atmospheric greenhouse gases like CO₂. The emission scenario was specified by the IPCC (Intergovernmental Panel on Climate Change 1992). Greenhouse gases like CFCs and HCFCs will be doubled in the year 2100 (Hoegh-Guildberg, 1999).

Short-wavelength radiation, especially ultraviolet radiation (UVR, 290–400 nm), significantly affects the distribution and physiology of marine organisms, including corals and dinoflagellates. UVR can cause harmful effects, reducing growth rates, chlorophyll content, carbon:nitrogen ratios, photosynthetic oxygen production and the activity of the enzyme Rubisco in these symbionts. Similar negative impacts occur when the dinoflagellates live within the coral tissues. To cope with UVR stress, both corals (hosts) and their symbionts have evolved mycosporine-like amino acids (natural sunscreen compounds that absorb UV radiation) and antioxidant systems that neutralize harmful reactive oxygen species (Hoegh-Guildberg, 1999).

Adaptive Bleaching Hypothesis

It proposes that corals survive stress by replacing sensitive zooxanthellae with more heat-tolerant types, but it lacks strong evidence. There is no direct observation of corals actively switching symbionts during stress. Coral bleaching has a strong impact on coral survival after increasing death rates significantly. The extent of mortality varies on the severity of the bleaching event. In mild cases, coral death may be very slow. In case of severe bleaching events, mortality can reach nearly 100%, as observed in Indonesia and during the 1982-83 eastern Pacific event. In other regions, such as the central and western Pacific (1991 and 1994), coral mortality has ranged between 30 and 50%. Mortality among family-specific staghorn corals (Acroporidae) is the worst affected. Bleaching affected all the colonies of *Acropora hyacinthus* and *A. gemmifera*, and 70% - 80% were dead 5 weeks after the onset of bleaching. The indication of severity of the 1998 bleaching event on the Great Barrier Reef, where corals of 700 years died (Hoegh-Guildberg, 1999).

Different Areas Affected by Coral Bleaching

Projections of sea surface temperature (SST) indicate that coral bleaching events are likely to increase rapidly in frequency. The greatest rise is expected in the Caribbean, Southeast Asia, and the Great Barrier Reef, whereas the Central Pacific is predicted to experience comparatively fewer events. It is anticipated that bleaching may occur every year in most ocean regions by about 2040, with the Caribbean and Southeast Asia potentially reaching annual bleaching conditions by 2020. These bleaching episodes are caused by seasonal increases in seawater temperatures rather than by El Niño events. The results suggest that there is about a 50% likelihood that SST will become high enough to cause coral bleaching by around 2030 in areas such as Comoros and Chagos in the Indian Ocean. The National Oceanic and Atmospheric Administration operates the NOAA Coral Reef Watch program. This system provides satellite-based monitoring and alert services for coral bleaching through online platforms (Crabbe, 2008).

Coral Reefs Produces Aerosol Helps in Cloud Formation

Mass coral bleaching events are becoming increased conditions, and photosystems of symbiotic algae are frequently singular across the Great Barrier Reef (GBR), indicating that continuous ocean warming is surpassing the natural protective capacity of corals. When SST and light intensity rise beyond the physiological tolerance of corals, their stress defense mechanisms begin to fail. Under such stressful conditions, photosystems of symbiotic algae (Zooxanthellae) produce a high amount of Reactive Oxygen species (ROS), which are harmful to coral cells. To counteract this oxidative stress, corals activate their antioxidant defense system. This response increases the intracellular consumption of dimethylsulfopropionate (DMSP), a compound that normally breaks down to produce dimethylsulfide (DMS), an important aerosol precursor gas. Due to high SST and irradiance, a reduction in DMS emission could leave significant climate consequences. Lower DMS emissions may reduce the formation of cloud condensation nuclei (CCN) and low-level clouds (LLC). With fewer clouds reflecting sunlight. So more solar radiation reaches the ocean surface, increasing irradiance and further raising SST. This process can intensify coral stress and create a positive feedback loop, where warming leads to reduced cloud formation (Jackson *et al.*, 2018).

Coral Reef Resilience

Corals that have acclimatized or adapted to thermal stress are more tolerant to high temperatures and radiation, resulting in lower bleaching levels. However, this increased tolerance may lead to the loss of coral species that are less capable of coping with environmental fluctuations. To understand coral reef resilience, researchers have increasingly studied stressed or marginal reef environments. Although such reefs are often less productive and less diverse, they can provide valuable insights into coral resistance. Researchers have increasingly studied stressed or marginal reef environments. More important for conservation and management are reefs that maintain high coral cover, species diversity, and ecological functioning despite disturbances. Reefs in Tanzania, the Comoros, and possibly northern Madagascar show these characteristics, maintaining high coral cover and diversity even after extreme disturbances, making them important priorities for future research and management (McClanahan *et al.*, 2007).

Photoinhibition causes bleaching of symbiotic algae are of two types:

1. Chronic Photoinhibition

- Chronic photoinhibition refers to irreversible photodamage in the photosynthetic system of symbiotic algae, which occurs when the biochemical pathway responsible for synthesis or repair of photosystem components malfunctions.
- The damage can lead to the death of individual algal cells.
- The damaged symbionts are eventually expelled from the coral host through processes such as exocytosis or host cell detachment

2. Dynamic Photoinhibition

- It is a reversible photostress response of algae. Where light energy is diverted away from photosynthesis through nonphotochemical quenching.
- One protective mechanism is the xanthophyll cycle, which redirects excess photons away from photosystem II, especially during midday high-light conditions in shallow-water corals.
- This helps prevent damage to the photosynthetic system, which can also be measured by PAM fluorometry and may act as a protective precursor to chronic photoinhibition.

Putnam and colleagues (2017) suggested that during coral bleaching, the symbiotic algae play a relatively passive role. The algae remain inside host digestive cells that are shed from the coral's gastrodermal layer. Laboratory study indicates that coral hosts are more heat tolerant than symbiotic dinoflagellates (less heat tolerant) (Fitt *et al.*, 2001).

Little work has been done on sensitive indicators of temperature stress in corals and their symbiotic algae, such as induction of heat shock proteins. Such stress proteins are known to confer an ability upon cells to survive previously lethal temperatures, and their induction has been found on exposure of corals to elevated temperatures in the Caribbean genus *Montastrea* sp. (Fitt *et al.*, 2001).

Oxidative Stress and Oxygen Radical Formation

Oxidative stress caused by oxygen radicals in coral-algal symbiotic systems both under normal conditions and during light and temperature stress. Reactive oxygen species such as superoxide and hydrogen peroxide are usually detected indirectly by measuring antioxidant enzymes like superoxide dismutase, catalase, and ascorbate peroxidase, which help remove these harmful molecules (Fitt *et al.*, 2001). Under high temperature and light, chloroplast membranes in symbiotic algae having high levels of unsaturated fatty acids become vulnerable to oxidative damage. The damage can be measured through lipid peroxidation (Fitt *et al.*, 2001).

Coral Disease

Increased temperature can weaken corals and reduce their resistance to pathogens, making them more susceptible to opportunistic diseases. Studies indicate that coral diseases have increased in number and severity, especially in the Caribbean, suggesting that corals are currently experiencing higher physiological stress than in the past several thousand years.

Many coral diseases peak at the end of the warmest season, when coral tissues are thinner and symbiotic algae (Zooxanthellae) densities are lowest, which likely reduces coral resilience (Fitt *et al.*, 2001).

Temperature Stress Caused Decreased Coral Reproduction

Elevated seawater temperature not only causes coral mortality but also significantly reduces their reproductive capacity. Studies following the 1998 bleaching event at Heron Island showed that many bleached coral species (e.g., *Symphyllia*, *Montipora*, *Acropora humilis*, *Favia gonisiastrea*, *Platygyra daedalea*) produced no eggs at all, while others (e.g., *Acropora aspera*, *A. palifera*, *A. pulchra*, *Montipora digitata*) had significantly fewer eggs compared to unbleached corals.

Even after recovering their symbiotic algae (Zooxanthellae), bleached corals often failed to spawn during normal reproductive periods. This indicates that the effects of bleaching persist beyond visible recovery (Hoegh-Guildberg, 1999).

Climate Change Affects Coral Calcification Process

- Photosynthetic activity of zooxanthellae provides them energy for calcification.
- Reduced photosynthesis: during stress or bleaching, corals show reduced growth and calcification. This weakens their ability to compete for space with organisms like microalgae.
- Shift in reef communities: Reduced coral performance can lead to long-term ecological changes, where coral-dominated reefs shift to microalgae-dominated communities, found in the Caribbean and eastern Pacific (Hoegh-Guildberg, 1999).

Discussion

Faster increases in SST are associated with higher levels of bleaching. Global climate models project that SST will increase approximately 0.0270°C/year between 1990 and 2090, which is nearly twice the rate (0.0150°C/year) observed during the previous three decades. If ocean temperatures continue to rise more rapidly, a greater number of reef locations are expected to experience bleaching events (Sully *et al.*, 2019). Studies indicated that equatorial coral reefs show greater resilience to episodes of extreme heat. Because corals in these regions are constantly exposed to variable temperatures, they may develop greater

tolerance to thermal stress. As a result, these regions are considered important priorities for conservation, since those reefs located there are more likely to persist under future climatic conditions (Sully *et al.*, 2019).

Bleaching event in 2016, which was one of the most severe bleaching events ever recorded and was associated with extremely high SST and a strong El Niño. Approximately 93% of reefs within the GBR were highly affected, which resulted in a loss of about two-thirds of corals in the northern Great Barrier Reef and 29% of shallow water corals across the entire reef system. Bleaching was most severe in northern GBR, while central GBR showed moderate impacts (Jackson *et al.*, 2018).

The bleaching event from January to March in 2002 caused moderate to severe bleaching of 41% of offshore reefs and 72% of inshore reefs across the Great Barrier Reef (Jackson *et al.*, 2018).

Elevated temperature combined with high levels of light or irradiance can intensify bleaching. However, ultraviolet radiation is not considered the main cause of large-scale bleaching events. Seasurface temperature analyses show that the warmest parts of the WPWP have warmed less than other tropical ocean areas, suggesting the presence of natural “thermostat” mechanisms that help limit temperature increase beyond certain thresholds (Crabbe, 2008).

Rising sea surface temperatures have been widely predicted to cause significant coral mortality in the coming decades. Elevated temperatures, combined with other physicochemical, biological and human-induced factors, are regarded as the main cause of coral bleaching (McClanahan *et al.*, 2007).

Their study contributes to existing knowledge by analyzing the spatial patterns of temperature variation and the recent increase in temperature within East African coastal current systems between 1951 and 2002. It also examines how that temperature patterns may be linked to spatial differences in coral mortality observed after the 1998 El Niño Southern Oscillation (ENSO) event.

Bleaching event in 2005: In which, after a thermal hotspot developed in the Southern Indian Ocean in January 2005, coral bleaching surveys were carried out in April 2005 on eight reefs along the Kenyan coast, shortly after sea surface temperature reached its peak. Bleaching was characterized as loss of normal coral coloration and estimated by examining color intensity among randomly selected coral colonies. Each colony was categorized into one of six bleaching conditions: 1) unbleached with normal coloration 2) pale or lighter-than-normal color 3) 0-20% of the surface is bleached and 4) 20-50% is bleached 5) 50-80% bleached 6) 80-100% bleached. A difference is observed in bleaching because different genetic types of symbiotic algae may exist within the corals. These symbionts can vary in their environmental tolerance and light absorption capacity (McClanahan *et al.*, 2007).

The 1998 coral bleaching event had a strong impact on coral cover, with reefs that originally had high coral cover experiencing the greatest damage. The reefs were dominated by branching and encrusting corals, which possess thin tissues, rapid growth rates and high sensitivity to thermal stress, making them more vulnerable to bleaching.

The 1998 coral bleaching event had a strong impact on coral cover, with reefs that originally had high coral cover experiencing the greatest damage. The reefs were dominated by branching and encrusting corals, which possess thin tissues, rapid growth rates and high sensitivity to thermal stress, making them more vulnerable to bleaching. During typical warm years, seasonal increases in seawater temperatures often cause bleaching in susceptible coral species, but they recover within a few months. During 1997-98 even more heat-resistant coral forms were affected. Mortality was particularly high among fast-growing corals, while slower-growing and more resistant types survived better (McClanahan *et al.*, 2007).

It has been suggested that corals can gradually acclimate or adapt to temperature changes, while the other proposes that corals have rigid thermal thresholds (around 310°C) beyond which bleaching and mortality occur regardless of past exposure (García *et al.*, 2024). Different models agree that reefs in stable, cooler water with few temperature anomalies have the greatest chance of surviving climate change. Scientists are

focusing on identifying reefs that can maintain high coral cover, biodiversity, and ecological functioning. This interest is linked to the concept of resilience, which refers to the ability of ecosystems to recover and regenerate after major disturbances such as coral bleaching. Consequently, resilience has become an important focus in ecological and resource management research aiming to understand and protect reef systems that are better able to withstand environmental stress.

A bleaching survey conducted in 2005 suggests that many reefs in Tanzania demonstrate strong resistance to bleaching, rapid recovery following bleaching events and the ability to sustain high coral cover and species diversity. The 2005 bleaching survey also enabled an analysis of reef community structure, revealing that Tanzanian reefs are among the most diverse in the Indian Ocean. Their generic diversity is comparable to that reported from the Maldives. These findings are also consistent with observations of high species diversity in the region (McClanahan *et al.*, 2007).

Mass coral bleaching events associated with increased sea surface temperatures and global warming have been occurring since the 1980s, including three pantropical episodes in 1998, 2010 and 2015-2016. As a result of marine heatwaves, or thermal stress, which disrupts the symbiotic relationship between corals and their algal partners, *Symbiodinium spp.* Resulting in the loss of coral pigmentation. Bleaching causes significant physiological stress to corals when it persists for extended periods, resulting in high mortality rates (Thirukanthan *et al.*, 2023).

A study indicates that bleaching events are individual disturbances to reefs and focuses on three recurrent bleaching events over the past 18 years along the 2,300 km length of the Great Barrier Reef. Repeated bleaching events have increased in frequency, with the proportion of affected reefs rising from 43% in 1998 to 56% in 2002 and 85% in 2016, indicating a growing loss of potential refuges for coral reefs (Hughes *et al.*, 2017).

Research on the coral *Montastraea annularis* shows how multiple environmental stressors, such as increased temperature and salinity, affect coral physiology. Scientists created a physiological response surface to illustrate the combined effects of different stressors on coral net photosynthesis. Seasonal changes in sea temperature and solar radiation also influence coral tissues and their symbiotic dinoflagellates (Zooxanthellae). The highest symbiont density and pigmentation usually occur during cooler seasons with lower solar radiation, while the lowest densities occur at the end of the warmest season (Hughes *et al.*, 2017).

Coral tissues can only accommodate a limited number of symbiotic dinoflagellates (Zooxanthellae). This means that the population size of these symbionts is physiologically constrained by the amount of host tissue. Therefore, the density of symbionts is directly related to the amount of coral tissue, although different corals may contain different symbiont densities. Environmental factors such as temperature, solar radiation and nutrient availability can cause changes in these stable densities (Fitt *et al.*, 2001).

The ongoing global decline of coral reefs has prompted the development of several strategies aimed at reducing the warming impacts of greenhouse gases (GHGs). One proposed approach involves the artificial release of sea spray or sulfate particles into the atmosphere to imitate natural biogenic aerosols, thereby increasing the local ocean albedo above coral reef regions. Model simulations suggest that injecting 5 Tg of SO₂ annually over Caribbean coral reefs could lower sea surface temperature (SST), reduce solar irradiance, and limit sea-level rise, resulting in almost no predicted coral bleaching events over the next 50 years.

However, applying this method to extensive reef systems such as the Great Barrier Reef (GBR) would likely be costly and inefficient over the long term. Despite these limitations, such interventions may become necessary to safeguard particularly vulnerable or high-value coral reef ecosystems as ocean warming continues (Jackson *et al.*, 2018).

Elevated temperature causes reduced reproduction in corals and as a result reduced production of larvae (reproductive propagules) leads to slower population recovery, making reefs more vulnerable over time. If bleaching events continue frequently as predicted for the coming decades many surviving corals may fail to reproduce altogether, severely threatening the long-term stability and regeneration of coral reef ecosystems (Hoegh- Guildberg, 1999).

Higher temperature enhances bacterial attachment to coral tissue; the pathogen colonizes the coral. It releases extracellular substances that inhibit photosynthesis in symbiotic algae. This causes loss of algal pigments and algal cell lysis, leading to coral bleaching and eventual coral death (Fitt *et al.*, 2001).

In the coral *Oculina Patagonica*, bleaching incidence increases at the end of the warm season. At higher temperatures, the bacterium *Vibrio* AH-1 becomes more virulent. Laboratory studies showed that bacteria grown at 25°C strongly adhere to coral tissues; at 16°C little or no adhesion occurs. It indicates that sea temperatures activate bacterial adhesion genes, enabling infection (Fitt *et al.*, 2001).

Short wavelength radiation, especially ultraviolet radiation, especially UVR (290-400nm), significantly affects the distribution and physiology of marine organisms including corals and their dinoflagellates (Torregiani & Lesser, 2007). UVR can cause harmful effects, such as reducing growth rates, chlorophyll content, Carbon: Nitrogen ratios, photosynthetic oxygen production and the activity of the enzyme Rubisco in these symbionts.

To cope with UVR stress, both corals (hosts) and their symbionts have evolved protective mechanisms, which include the production of mycosporine-like amino acids (natural sunscreen compounds that absorb UV radiation) and antioxidant systems that neutralize harmful reactive oxygen species (Hoegh-Guildberg, 1999).

Climatic factors like ocean acidification cause seawater acidity and reduce carbonate concentration. Lower aragonite saturation rate, which is essential for coral skeleton and decline of calcification rate (calcification reduced by 14-30% by 2050), affecting reef-building capacity.

Conclusion

Coral bleaching has already caused severe and widespread damage to coral populations worldwide and will continue to affect coral reefs in the next few decades. To prevent further degradation of coral reefs, urgent global action to reduce carbon emissions is essential. Without significant effort to limit climate change, a continued rise in ocean temperature will lead to further declines in coral reefs. Current evidence indicates that corals and their symbiotic zooxanthellae cannot adapt or acclimate quickly enough to cope with rapid ocean warming. Continued coral mortality will likely lead to shifts in coral distribution, disrupting reef structure and function.

As corals and zooxanthellae are fundamental to reef ecosystems, these changes will have serious ecological and economic consequences globally by the mid to late 21st century. However, these impacts are still not fully assessed and require urgent research. Climate change can shift coral community structure by favoring more heat-tolerant species while reducing or eliminating sensitive ones. Even under moderate greenhouse gas scenarios (like IS92a), rising sea temperatures are expected to severely impact coral reefs within the next 20–30 years. By around 2040, most reefs will likely experience near-annual bleaching events, exceeding the severity of the 1998 event. Protecting coral reefs, including heavily managed systems like the Great Barrier Reef, requires urgent and rapid global action to reduce climate change and global warming.

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