1A. GLOBAL CLIMATE CHANGE AND CORAL REEFS: RISING TEMPERATURES, ACIDIFICATION AND THE NEED FOR RESILIENT REEFS

C. MARK EAKIN, JOAN KLEYPAS, AND OVE HOEGH-GULDBERG

SUMMARY

- Coral reefs, both tropical and deep cold water, are global centres of biodiversity that are being damaged by a combination of direct human impacts and global climate change;
- The major climate change threats are increasing sea temperatures and increasing ocean acidity from rising atmospheric concentrations of carbon dioxide (CO_2), as well as a predicted increase in storms;
- Higher than normal sea surface temperatures stress corals and cause coral bleaching, frequently with large scale mortality. Bleaching is the loss of algal symbionts and a reduction in the coral's energy producing systems; severe stress often results in coral mortality or reduces reproduction and their ability to stave off infectious disease;
- Increasing concentrations of CO_2 lower the pH of seawater (ocean acidification) with a coincident decrease in the concentration of carbonate ions. This reduces the capacity of corals and other calcifying organisms to make calcium carbonate skeletons. Ocean acidification also may increase the susceptibility of corals to bleaching during thermal stress.
- These threats, combined with local factors such as declining water quality and overfishing, are reducing coral reef resilience to environmental change, changing reef structure coral abundance and community composition;
- The result will be a loss of biodiversity through the destruction of the habitats of other organisms;
- Action to conserve reefs is now urgent and must include: strong policies to reduce greenhouse gas emissions; effective management of local stresses; and research to improve conservation and restoration efforts. Only through such concerted action will corals survive the next two centuries as temperatures continue to rise.

ENVIRONMENTAL CHANGES FROM CLIMATE CHANGE

Coral reefs are the world's most diverse marine ecosystems and are critical for the livelihoods of millions of people who depend on them. Despite this, the health of many coral reefs has declined for decades due to many local stresses; now climate change has the potential to devastate coral reefs around the world. Warming temperatures and ocean acidification are already affecting coral reefs, causing frequent bleaching events and slowing the formation of coral skeletons. We can avoid catastrophic damage to coral reefs but to do so means we must reduce both climate change and local threats. All available evidence suggests that time is running out and that soon conditions on the planet will be so severe that coral reefs will no longer thrive.

There is strong international consensus that the world is experiencing global climate change, that the rate of climate change is increasing, and that much of the change is due to human release of greenhouse gases. Before the industrial revolution, the atmosphere contained about 280 parts per million (ppm) of CO_2; today it is 35% higher (>380 ppm) and the increase in CO_2 continues to accelerate faster than predicted.

Sadly, coral reefs are among the first major marine ecosystems in the world to be seriously damaged by global climate change. The most recent (4th) Intergovernmental Panel on Climate Change (IPCC) assessment states "Corals are vulnerable to thermal stress and have low adaptive capacity. Increases in sea surface temperature of about 1–3°C are projected to result in more frequent coral bleaching events and widespread mortality, unless there is thermal adaptation or acclimatization by corals." The IPCC listed the following changes as pertinent to coral reefs:

- Rising sea surface temperatures;
- Increasing concentrations of CO_2 in seawater;
- Sea level rise;
- Possible shifting of ocean currents;
- Associated rises in UV concentrations; and
- Increases in hurricanes and cyclonic storms.

Here we focus on the first two. We are highly confident that the increases in human-caused greenhouse gases in the atmosphere over the last century have caused most of the 0.7°C (1.3°F) rise in the average global temperature of the surface ocean, and the 0.5°C (0.9°F) rise in tropical coral reef water temperatures. The ocean absorbs between one-quarter and one-third of the CO_2 that is added to the atmosphere each year resulting in 'ocean acidification' from carbonic acid made by increasing concentrations of dissolved CO_2 in seawater. Average global ocean pH has already dropped from around 8.2 to 8.1.

There is strong international consensus that climate change and ocean acidification are already affecting shallow water corals and their symbiosis with dinoflagellate algae. There are vast areas of deep-sea corals that are also being affected; these largely unknown complex ecosystems provide major fish habitat, but are now considered at particular risk to ocean acidification (see p. 30). This chapter focuses on two major questions: 'How are temperature increases and ocean acidification acting together to threaten coral reefs?' and 'How can we help coral reefs survive during climate change?'

RISING SEA SURFACE TEMPERATURES AND CORAL BLEACHING

Increasing sea surface temperatures (SSTs) in tropical/subtropical waters have moved reef-building corals 0.5°C closer to their upper thermal limits. Natural temperature variability can now push corals into temperatures that cause bleaching more readily than in the past. When SSTs exceed the summer maximum by more than 1°C for 4 weeks or more under clear tropical skies, corals bleach by expelling their symbiotic algae, revealing either the pale pastel colours of coral pigments or the brilliant white skeleton. If warmer conditions persist corals could die in large numbers. We now know that high temperatures speed up the normal photosynthetic process in the symbiotic zooxanthellae beyond their capacity to repair damage to photosynthetic systems. This produces toxic free oxygen radicals causing corals to eject the algae, losing their major source of energy. Even if corals survive, the stress increases the incidence of coral diseases and reduces corals' ability to reproduce. Disease was the final cause of much of the coral death after the 2005 Caribbean bleaching event.

Widespread and severe coral bleaching events already are becoming more common. Another 1°C rise is almost certain by the end of this century even if all greenhouse gas emissions stopped today: even this will make coral bleaching more frequent and severe. The potential of a 4°C rise could make bleaching an annual event: this will not provide sufficient time for coral reefs to recover between bleaching episodes. Under scenarios of a 2°C rise or more, coral dominated reefs are expected to largely disappear from many shallow coastal regions of the world.

Why most genetic adaptation probably will not work: A core assumption in the predictions of rapid reef decline is that genetic change in corals and their symbiotic algae will be insufficient to keep pace with climate change. Coral thermal stress thresholds have been relatively stable over 20 years with no measurable shift upwards. However, bleaching and mortality are increasing, indicating that stress thresholds are not changing rapidly enough to prevent bleaching.

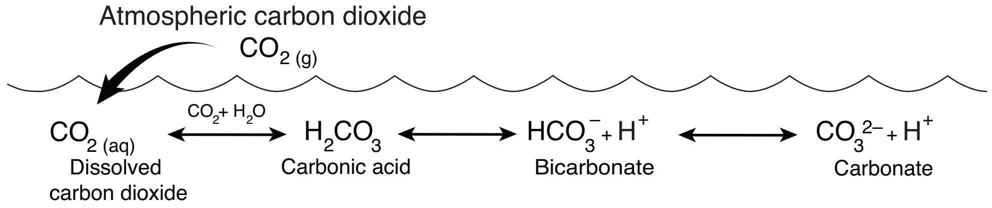
An alternative hypothesis is that corals, via their symbiont zooxanthellae, may evolve rapidly by acquiring more thermally tolerant symbionts within a few decades. This would make corals more thermally tolerant and keep pace with rapid climate change. But this would require an adaptation at a rate of at least 0.2–0.4°C per decade and there is no evidence that corals can change their symbiotic relationships or develop temperature tolerance so quickly. No lasting changes have been observed in coral-zooxanthellae partnerships before and after major bleaching events. On-going research now seeks to enhance the coral acclimation/adaptation potential. While such an approach could enhance conservation, it remains untested. Another option for adaptation is 'Darwinian' selection to act on reef corals. Unfortunately, this natural selection process has culled many of the more sensitive coral species, leading to a loss of biodiversity and functional redundancy.

The 2007 IPCC Report predicts that climate changes will continue for hundreds of years, with increases in greenhouse gas emissions. Current predictions are that corals will not adapt to warmer water without stabilization or a decrease in greenhouse gas emissions. The best case scenario is that low emission technologies and removal of CO_2 from the atmosphere may stabilize global temperatures at 2°C above the present; however, coral populations will initially decrease with the loss of temperature sensitive species, hopefully to be replaced by more temperature resistant ones. Even this will cause the probable extinction of many corals and other species that depend on coral reefs for habitat and food. Current predictions are for concentrations of CO_2 of 500–600 ppm, thereby increasing temperatures by 2–6°C and jeopardizing most of the important ecological services provided to the estimated 500 million people that depend partially or wholly on coral reefs for their daily food and resources.

INCREASING CONCENTRATIONS OF CO_2 IN SEAWATER

Ocean uptake of CO_2 from the atmosphere reduces the severity of the greenhouse effect and climate change (and the temperatures that cause coral bleaching). Unfortunately, increased CO_2 alters the chemistry of seawater and lowers the pH (a lower pH means more acidic via a higher concentration of hydrogen ions). CO_2 levels in the surface ocean are expected to reach double pre-industrial levels within 40–50 years, and seawater pH will decrease by another 0.2 units. We have already seen a reduction in globally-averaged pH of the surface ocean of 0.1 pH units. This change in pH may seem small, but it is significant because:

- pH is measured on a logarithmic scale — a 0.1 decrease in pH is a 30% increase in ocean acidity;
- Surface ocean pH is already at its lowest in 800 000 years, and probably more than 20 million years;
- The speed of this change is likely to outstrip the ability of many organisms to adapt;
- Acidification interacts with other factors such as sea temperature rise and storm intensity to produce much larger impacts than each factor acting alone.



Preindustrial versus doubled preindustrial CO2 concentrations

$CO_{2\,(g)}$ ppmv	$CO_{2\,(aq)} + H_2CO_3$ µmol kg^{-1}	HCO_3^- µmol kg^{-1}	CO_3^{2-} µmol Kg^{-1}	pH
280	8	1635	272	8.11
560	16	1867	177	7.93

This diagram illustrates what will happen to ocean chemistry as more CO_2 dissolves in seawater. When CO_2 concentrations in the atmosphere effectively double from pre-industrial levels, there will be an increase in dissolved bicarbonate and a decrease in the available carbonate in sea water. Thus it will become more difficult and energy consuming for coral reef animals and plants to make skeletons.

The significance of these changes: Biological processes can be directly impacted by ocean acidification because of changes in pH, or by changes in the concentrations of dissolved carbon dioxide, bicarbonate ion or carbonate ion. Virtually every major biological function (photosynthesis, respiration rate, growth rate, calcification rate, nitrogen-fixation rate, reproduction, and recruitment) can be affected by these chemical changes. Dissolved CO_2 and bicarbonate are used in photosynthesis, thus seagrasses and some marine algae may benefit from CO_2 increases. The decrease in the carbonate ion concentration, however, will reduce the ability of many organisms to form calcium carbonate ($CaCO_3$) skeletons. The effects on shell and skeleton growth are the best studied of these responses. The calcification rates of almost all tropical and cold-water corals are likely to decrease by 20–50% by 2050. Under extreme conditions, some species lose their skeletons completely and are transformed into colonial anemone-like animals. Even if such 'naked' corals survive, they will not build reefs or provide the services of current coral reefs. Evidence now suggests that coral growth rates have already decreased by 15%, although it is unclear how much of this is due to ocean acidification versus temperature increases and other factors. Reduced calcification can either slow coral growth, making them less able to compete for space, or weaken coral skeletons increasing their vulnerability to erosion, storm damage and predation.

Crustose coralline algae (CCA) are also important reef calcifiers that appear to be particularly vulnerable to ocean acidification. CCA are abundant carbonate producers on many reefs, form the structural crust on reef flats, and attract settlement of new coral recruits. CCA secrete a form of calcium carbonate that is more easily dissolved than corals and experiments show that CCA growth rates and recruitment success will be greatly reduced under the ocean acidification conditions expected by 2100.

The responses in other groups, such as echinoderms and molluscs, will be mixed with some species responding poorly to ocean acidification, others showing little to no response, and some even increasing calcification, possibly at the expense of muscle mass. The varied responses reflect differences in the mineralogy and structure of the calcium carbonate, the biological process of calcification, and the evolutionary history of an organism. The net effects of ocean acidification on coral reefs are difficult to assess within these diverse communities, although a study of a natural CO_2 seep in the Mediterranean showed a dramatic decrease in calcifying organisms near the seeps, while seagrasses and invasive algae thrived.

Coral reef ecosystems are unique because the excess production of calcium carbonate builds reef structure – the very basis of a coral reef habitat. As calcification declines and dissolution rises, the balance between reef growth and reef destruction will also change. Reefs with a low surplus of carbonate production, such as those at high latitudes or upwelling regions, may shift from net reef building to net reef loss within a few decades and will no longer keep up with rising sea levels. Coral reefs that grow in waters naturally high in CO_2 (e.g. eastern Pacific) are less cemented, less developed, and suffer higher erosion rates than other reefs, suggesting that all coral reefs in the future will be structurally less robust as the oceans acidify. Even worse, recent laboratory work shows that the temperature threshold for bleaching is lowered as seawater CO_2 increases. This means that rising atmospheric CO_2 may cause coral bleaching in two ways — via ocean acidification as well as from tropical sea warming.

ACTIONS REQUIRED TO LIMIT CLIMATE CHANGE IMPACTS

The loss of corals, and hence the framework of coral reefs that support thousands of other species, will result in considerable reduction of the goods and services provided by reefs, and reduce biodiversity through many local or total extinctions. For example, some corallivorous (coral eating) fish species may be lost, while herbivores may increase as algal food increases.

Many papers at the 2008 11th International Coral Reef Symposium (see p.43) focused on the combined harmful impacts of climate change, water quality, and fishing, with calls for simultaneous action to reduce all three threats. Coral reefs have flourished for millions of years. To help them survive the next few centuries, we must take three actions:

1. It is imperative that everyone reduce greenhouse gas emissions to prevent atmospheric CO_2 concentrations from exceeding 450–500 ppm. This target will be difficult to achieve without technological breakthroughs; nevertheless, temperatures will continue to rise and impact coral growth. Without concerted and immediate international actions we risk long lasting destruction of coral reefs.
2. Reefs will persist longer under the climate change stresses if their resilience is maintained. Resilience buys important time for recovery from the inevitable ecological shocks from climate change. Thus, declining water quality, harmful fishing, and habitat destruction, must be reduced through effective management. This is the job for local resource managers working in concert with the international community.
3. Increased investment in research on reef restoration and in methods to enhance the natural resilience in corals is necessary, including drastic measures such as cooling or shading high value reefs during bleaching events.

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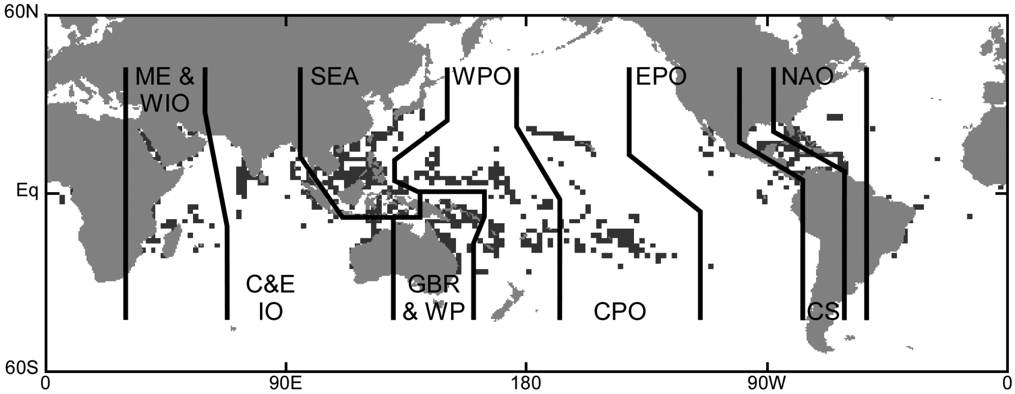
1B. GLOBAL CLIMATE CHANGE AND CORAL REEFS: REEF TEMPERATURE PERSPECTIVES COVERING THE LAST CENTURY

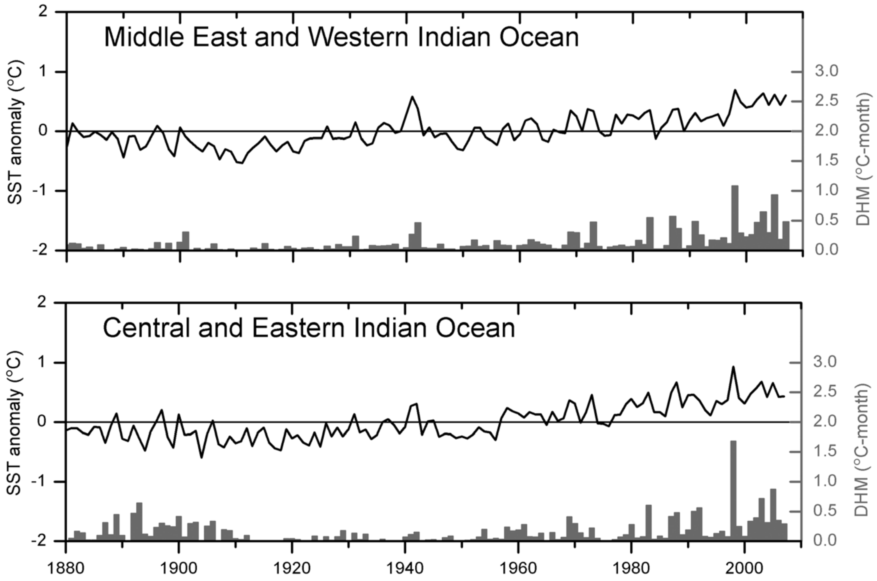
SCOTT HERON, WILLIAM SKIRVING, MARK EAKIN

Temperatures and thermal stress at reef locations around the globe have generally increased over the past 128 years with regional trends in the range of 0.24–0.59°C per century. For most coral reef regions the levels of thermal stress are unprecedented within the last two decades. While satellite monitoring of the waters surrounding coral reefs has provided an accurate and timely measure of current and recent conditions, these have been put into a century-long context using long-term water temperature data collected by passing ships and buoy-mounted instruments. This gives an insight into how climate has been changing over the last century and affecting coral reef ecosystems around the world.

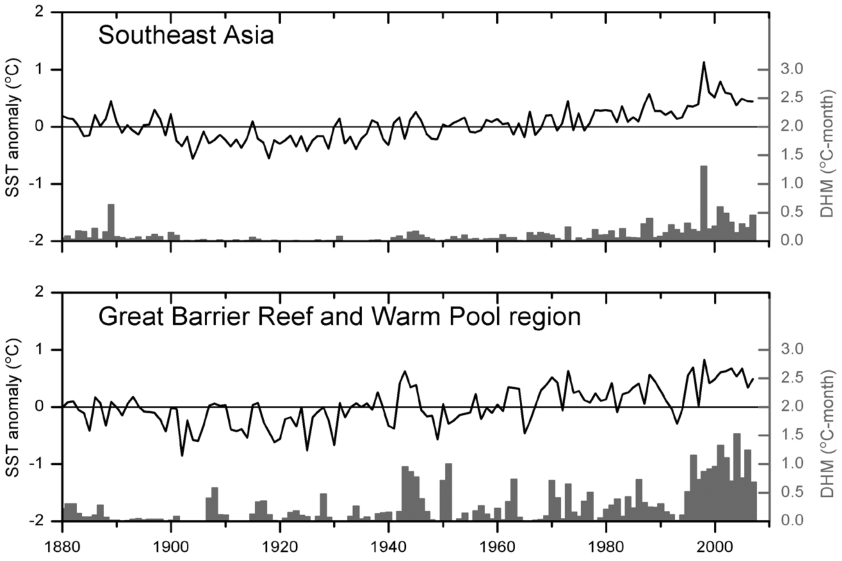


This map shows global reef locations (squares) and 9 regional groups used to investigate long-term temperature patterns. Regional groups are (from left): Middle East and Western Indian Ocean; Central and Eastern Indian Ocean; Southeast Asia; Great Barrier Reef and Warm Pool; Western Pacific Ocean; Central Pacific Ocean; Eastern Pacific Ocean; Caribbean Sea; and North Atlantic Ocean.

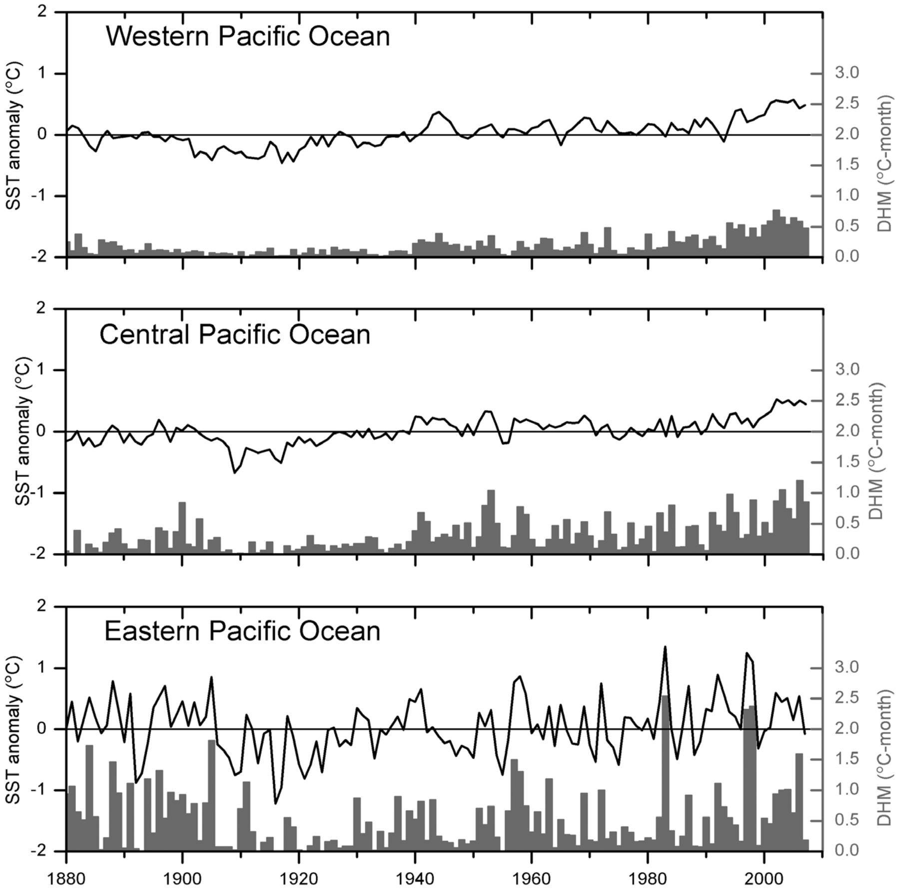
Methods: The Extended Reconstructed SST (ERSST) version 3 dataset was produced by mapping in situ observations (ship measurements and buoy data from 1854 to the present) and satellite SST (since 1985) onto a 2°× 2° grid at monthly resolution using statistical techniques. Measurements prior to 1880 were extremely sparse, with increasing errors; thus this analysis starts from 1880. The biggest issue with using this dataset is the spatial resolution mismatch between the scale of conditions on individual coral reefs (kilometres) to the pixel-size of the ERSST analyses (~200 km). To make sure that the ERSST data are relevant to reef locations, they were compared with an established satellite temperature dataset. NOAA Coral Reef Watch (CRW) monitors thermal conditions at reef locations around the world using satellite data. These products are produced in near real-time at 0.5° (~50 × 50 km) resolution, twice each week, and are based on night-time SST values. The SST product is not an average of temperature across each 0.5° pixel but uses only the warmest 9 km region. This helps to avoid clouds and provides a stable measurement to monitor thermal stress around coral reefs. The 0.5° SSTs are used to make the Degree Heating Week (DHW) index, which combines the magnitude and duration of summertime thermal stress experienced by ocean ecosystems. CRW has also constructed a dataset for 1985–2006 that mimics the methods for the near real-time data, based on data from the NOAA/NASA AVHRR Oceans Pathfinder Program (PFSST). This dataset was used to validate the ERSST data. Comparisons were made between ERSST and PFSST data from reef-containing pixels for the period of overlap between the datasets, 1985–2006. The datasets were evaluated for each pixel-pairing to determine if there was a significant linear correlation between the broad-scale (ERSST) and reef-specific (PFSST) values. Of 711 ERSST reef pixels, 101 were excluded due to poor linear correlation with PFSST values ($R^2 < 0.50$) or because they spanned two distinct water masses. Based on similar pixel-relationships with PFSST data, ERSST data were grouped into 9 regional groups. For each remaining reef pixel, monthly climatologies were created by averaging ERSST values for the period 1901–2000 and SST anomalies calculated. Monthly anomalies were averaged across regional groups and for each year to show the regional trends in temperatures. To examine the accumulated thermal stress, a DHM index was calculated, following previous long-term studies. For this study, positive anomalies of SST, as compared with the warmest month's temperature, were calculated and averaged across each regional group for each month. These values were then accumulated across a three-month window, mimicking the accumulation of DHW over 12 weeks. Rather than look at a specific threshold in DHM values, relative patterns through time were used to give context to recent levels of stress within each region.



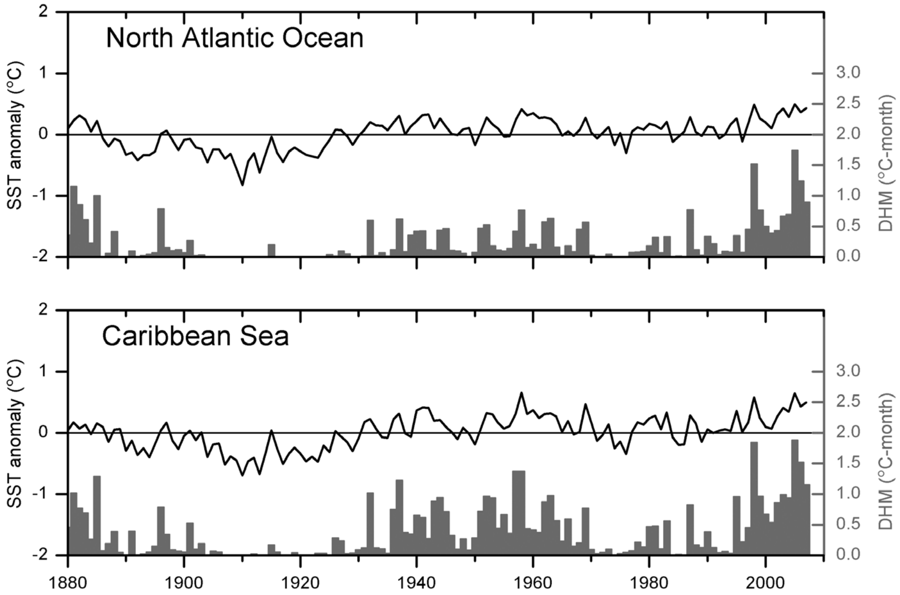
Sea surface temperature anomalies (SSTA) around reefs in the Indian Ocean (IO) region have increased through the 20th century by 0.50°C/century in Middle East and Western IO and by 0.59°C/century in Central and Eastern IO, with higher variability in the latter region (methods below). The temperature change in the Central and Eastern IO was faster than that of any other region. Throughout the IO, the highest anomaly occurred in 1998 and corresponded to the highest accumulated thermal stress (Degree-Heating-Months or DHM; defined below); 1998 was the El Niño year when widespread coral bleaching occurred across the entire Indian Ocean. The next two highest DHM values were in 2003 and 2005 for both regions, which typifies the steady increase in DHM through the 1900s. The Middle East and Western IO regions experienced a significant warm anomaly during the early 1940s, comparable to the highest SSTA observed in recent years, however, the accumulated thermal stress was considerably lower indicating that summer temperatures were not extreme. There was also a period in the late 1800s where thermal stress accumulated in the Central and Eastern IO despite having cooler than average annual SSTA values. This suggests that there was significant intra-annual variability within each of these years including unusually warm summers. A rapid rise from a cool winter into the warm summer temperatures, as likely occurred during the late 1800s, may have caused considerable stress in this region, however, temperature data prior to 1910 are sparse and therefore may not be reliable.



Reef locations in South-east Asia have also experienced increased temperatures during the last 80–90 years at a rate of 0.44°C/century with relatively small variability. This gradual rise correlates with a pattern of accumulating thermal stress that coincides with increased observations of bleaching. The year 1998 stands out for this region in both the SSTA and DHM, consistent with the most extensive bleaching. In contrast, there has been no particular stand-out year for the Great Barrier Reef and Warm Pool region but both temperature and accumulated thermal stress have been high since 1995. This recent episode of increased DHM may be related to a phase shift of the Pacific Decadal Oscillation (PDO) which has a periodicity of 50–60 years. The high variability of reef temperatures in this region is probably related to phases of El Niño and La Niña, however, there is still a general increase in thermal stress associated with the trend in SSTA values of 0.52°C/century. Coral bleaching was observed on parts of the Great Barrier Reef in 1998, 2002 and 2006.



The smallest temperature variability of all the regions was shown by reefs in the Western and Central Pacific Ocean (PO) with increasing trends in temperature of 0.40 and 0.35°C/century, respectively. Accumulated thermal stress increased slightly in both regions, however, the change in DHM levels appears to have remained fairly small. The consistency of DHM values since 1995, particularly in the Western PO, supports the suggestion of PDO influence. The Eastern PO shows much higher variability in temperature, characteristic of locations strongly influenced by El Niño-La Niña variations. The Eastern Pacific had the lowest increasing trend (0.24 °C/century). El Niño-Southern Oscillation events of 1982–1983 and 1997–1998 stand out in the SSTA and DHM traces. Levels of accumulated thermal stress are also highly variable throughout the record; corals that have lived through such variations may be well equipped to survive future stress events predicted with continued climate change. However, species diversity in the Eastern PO is low relative to more-stable regions. The highest bleaching and mortality in this region occurred in 1983 and was quite severe at many sites.



A feature of North Atlantic Ocean and Caribbean Sea records is the 65–70 year cycle of both temperature and thermal stress. The Atlantic Multi-decadal Oscillation (AMO) has a period of 65–70 years and clearly influences the pattern of temperatures on Atlantic and Caribbean reefs. This oscillating pattern is superimposed over the increasing temperature trends of 0.36 and 0.37°C/century for the North Atlantic Ocean and Caribbean Sea respectively. Although these are independent factors, when the warm phase of the oscillation is added to the steady increase in sea surface temperatures there is potential for serious consequences to coral reef ecosystems. The extensive and devastating bleaching during 2005 likely provides a foretaste of future bleaching events which could overwhelm many reefs in these regions.

Conclusions

Water temperatures over the past century have risen on coral reefs in all global regions. The largest increases have been in the Indian Ocean, symbolised by the massive coral bleaching there in 1998. Thermal stress records show a high degree of correlation with widespread and severe coral bleaching observed on coral reefs around the world in recent years. Moreover, with predictions of continued warming, the outlook for corals around the world is one of repeated large-scale bleaching events. The question that remains is how successfully corals and reef ecosystems can acclimate and adapt to these future warm conditions.

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