The Threat of Climate Change to Coral Reefs

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Abstract

Coral reefs are the "rainforests" of the oceans, containing the highest diversity of marine organisms. They are highly productive and of great value for populations in tropical coastal areas. All around the world, warm-water coral reefs have experienced large-scale degradation. The greatest threat to their long-term sustainability is climate change and there is increasing evidence that global climate change is having direct impacts on coral reefs. These ecosystems are very sensitive to changes in their physical environment. That is why coral bleaching, resulting from climate-induced elevated sea surface temperatures, is a major threat. Bleaching is the loss by the coral animal of their symbiotic algae, affecting biological functions and possibly leading to coral mortality. Mass bleaching events have resulted in catastrophic loss of coral cover in many areas. The number of bleaching records worldwide has clearly increased during the last decades. The other serious threat of climate change is ocean acidification. The oceans absorbed 25% of the atmospheric carbon dioxide derived from human activities between the years of 2000-2006, leading to a decrease in seawater pH and a reduction of available carbonate in seawater. Corals depend upon carbonate ions for skeletal growth and the present decline has lead to reduced calcification of corals, resulting in decreased growth and skeletal density. Calcification is an important determinant of the health of reef ecosystems since many species depend on the structure provided by the coral skeletons.

Climate change models and estimations suggest that coral bleaching events will increase in frequency and severity due to global warming. Atmospheric carbon dioxide concentrations are increasing, making the ocean more acidic. Predictions show that within the next 50 years, tropical coral reefs will be unable to calcify because carbonate saturation may drop below those required to sustain coral reef accretion. Acidification and bleaching together with direct human pressures, such as pollution and overfishing, are very likely to drive ecosystems toward domination by non-coral communities if climate change continues. It is therefore important to implement conservation strategies that help coral reefs maintain their ecological resilience. By removing other threats to coral reefs, such as direct human pressure, coral health will improve and increase ecosystem resilience. Control of these secondary stress factors may help coral reefs survive climate change. Investments in further research of climate change impacts on coral reefs, more collaboration and improved conservation strategies would help increase the coral reef's ability to survive.

Sammanfattning

Korallrev är "den marina världens regnskogar" och de är ett av världens mest artrika och produktiva ekosystem. Korallreven är av stor betydelse för befolkningen i tropiska havsområden. Varmvattenkoraller utsätts idag för storskaliga nedbrytningar och det största hotet mot deras existens anses vara klimatförändringar. Antropogena utsläpp av koldioxid i atmosfären har inneburit en ökning av jordens medeltemperatur vilket även innebär ökad ytvattentemperatur. Koraller är mycket känsliga för förändringar i den fysiska miljön. Korallblekning är en process som uppstår när ytvattentemperaturen ökar och är ett stort hot mot koraller. Blekning innebär att koralldjuret stöter bort sin symbiotiska alg den är beroende av för överlevnad. De biologiska funktionerna påverkas och korallen kan dö. Flera olika episoder av massblekning de senaste årtiondena har resulterat i stora förluster av korallrev världen över. Det andra stora klimathotet är försurning i haven. Detta beror på att haven absorberar koldioxid från atmosfären. 25 % av antropogena utsläpp mellan år 2000-2006 togs upp av haven, vilket har lett till en pH- sänkning i haven. Detta innebär också att karbonatjoner, som koraller är beroende av för att bilda sitt skelett, i ytvattnet minskar. Försurningen i haven har redan lett till en minskad tillväxt hos korallrev och kalkavlagringen är även viktig för hela ekosystemets funktion eftersom många arter är beroende av korallrevens skyddande skelett.

Klimatmodeller och uppskattningar visar att det i framtiden är mycket troligt att blekning av koraller kommer öka i frekvens och svårighetsgrad eftersom temperaturökningen fortsätter. Koldioxidkoncentrationen i atmosfären ökar konstant, vilket innebär en fortsatt försurning som försvårar korallers tillväxt. Om klimatförändringen pågår i denna takt är det mycket troligt att blekning och försurning i kombination med andra hot, som till exempel föroreningar och utfiskning, på sikt hotar korallrevens existens som vi känner till dem idag. Korallerna kan komma att ersättas av andra organismer som snabbväxande alger. Det är därför viktigt att implementera hållbara skötselstrategier. Att minska stressfaktorer som utfiskning och föroreningar hjälper till att öka korallernas kapacitet att bättre klara av klimatförändringar, vilket kallas ekologisk resiliens. Investeringar i fortsatt forskning i klimatproblematiken och hur korallreven påverkas av denna, utökat samarbete samt förbättrade skötselstrategier skulle öka korallrevens chans att överleva.

Nyckelord: Geografi, Naturgeografi, Klimatförändring, Korallrev, Blekning, Försurning, Ekologisk resiliens, Skötselstrategier,

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Cover Picture: A Blue Starfish (*Linckia laevigata*) resting on hard *Acropora* coral. Lighthouse, Ribbon Reefs in the Great Barrier Reef (Ling, 2004).

1 Introduction

1.1 Background

Coral reefs are often called the rainforests of the marine world. They are highly productive, rich in species but also very vulnerable to future degradation (Bryany et al., 1998). They cover a mere 0.1% of the ocean surface, yet they are one of the most valuable ecosystems on earth because of their biodiversity and economic and environmental services they provide to a large population. Last year, 2008, was declared the "International Year of the Reef" to emphasise the need for urgent action to conserve coral reefs. At the same time, the Global Coral Reef Monitoring Network (GCRMN) released their "Status of Coral Reefs of the World: 2008" report, stating that current rates of climate change pose the greatest threat to the long-term sustainability of coral reefs. There are natural threats to coral reefs like storms, plagues, diseases, earthquakes, volcanoes and tsunamis. However, coral reefs generally recover from those disturbances. Coral reef degradation often originates from human activities by growing human populations in coastal areas where there is no effective management of the resources. Destructive fishing damages reefs directly and overfishing removes herbivores that keep competing macroalgae in check. Poor land management, agriculture, deforestation and industry make toxic chemicals, nutrients, pollutants, pesticides and excess sediments to end up in coral waters through runoff. This leads to several deleterious effects such as poisoning, eutrophication and smothering of marine environments (Côté and Reynolds, 2006).

This review will focus on threats to coral reefs caused by climate change, especially elevated sea surface temperatures and increasing carbon dioxide (CO_2) levels in the atmosphere. There is increasing evidence that global climate change is having direct impacts on coral reefs, and these ecosystems are particularly sensitive to climate-induced changes in the physical environment (Baker et al., 2008). According to the Intergovernmental Panel on Climate Change (IPCC), global warming and associated increases in sea surface temperatures are projected to be very likely in the coming decades. It is clear that global atmospheric CO_2 concentrations have increased as a result of human activities since 1750, primarily due to fossil fuel use and land use change (IPCC, 2007*b*). The concentration of CO_2 in the atmosphere now exceeds 380 ppm compared to pre-industrial levels of 280 ppm (Lüthi et al., 2008) and rising CO_2 levels are changing global climate. Both elevated sea surface temperatures and increased CO_2 concentrations affect coral reefs and pose the greatest threats caused by climate change.

1.2 Aim

The aim of this review is to bring clarity about the different types of problems climate change most certainly will pose to the world's coral reefs. How do climate change factors affect coral reefs and what are the biological and chemical mechanisms involved? How has climate change affected coral reefs already and what do scientists predict in the future? Since the International Coral Reef Initiative (ICRI) was conceived at the UN Conference in Barbados in 1994 to recognise the problems facing coral reefs, many studies have focused on the pressure that humans place on coral reefs through pollution, mining, overfishing and coastal development. The climate change issue has recently gained attention as a very serious threat to coral reefs and therefore, this subject contain new research areas with many interesting scientific studies and results to investigate.

Modern coral reefs that have been built up during the last 10,000 years are very sensitive to small changes in the environment. The current rate of climate change is worrying because corals may not be able to adapt to these changes. Because of the great value of these fascinating ecosystems, I would like to raise awareness to the importance of conserving coral reefs. What is being done and what kind of conservation strategies could be implemented to increase coral reef survival?

2 Coral Reef Ecosystems

Coral reefs are some of the most diverse and valuable ecosystems on Earth. This marine environment supports more species per unit area than any other in the ocean, including approximately 4,000 species of fish, 800 species of hard corals and hundreds of other species. However, experts have barely begun to record all the species found in these habitats. Scientists estimate there may be another 1 to 8 million undiscovered species of organisms living in and around reefs (Reaka-Kudla et al., 1997).

2.1 Biology of Coral Reefs

Despite the poor nutrient waters they live in, coral reefs create a highly productive and very efficient ecosystem and support an extremely biodiverse community of marine life. They grow over geologic time and are composed of calcium carbonate secreted by tiny soft-bodied-animals called coral polyps, classified in the phylum *Cnidaria* and the class *Anthozoa*. The structures are ancient even by geological standards and the oldest species of corals are over 450 million years old (UN, 2009). A single coral animal, the polyp, has a tube-shaped body with a mouth surrounded by tentacles. The polyps divide themselves and grow into colonies all held together in one rigid calcareous skeleton connected by living tissue. The skeleton is secreted by the polyps in thin plates or layers, which accumulate over thousands of years. Millions of polyps grow on top of the limestone remains of former colonies to create reefs that eventually reach surface waters. They remain attached to the seafloor and become so large that only storms disturb them naturally (OCEAN, 2009).

The coral polyps feed during the night by stretching out their tentacles. The tentacles have small stinging cells, which can shoot poison spears into the zooplanktons, or even small fish, that pass by. However, the main sources of food to corals are microalgae, zooxanthellae, which are small plants that live in large numbers within the tissues of the
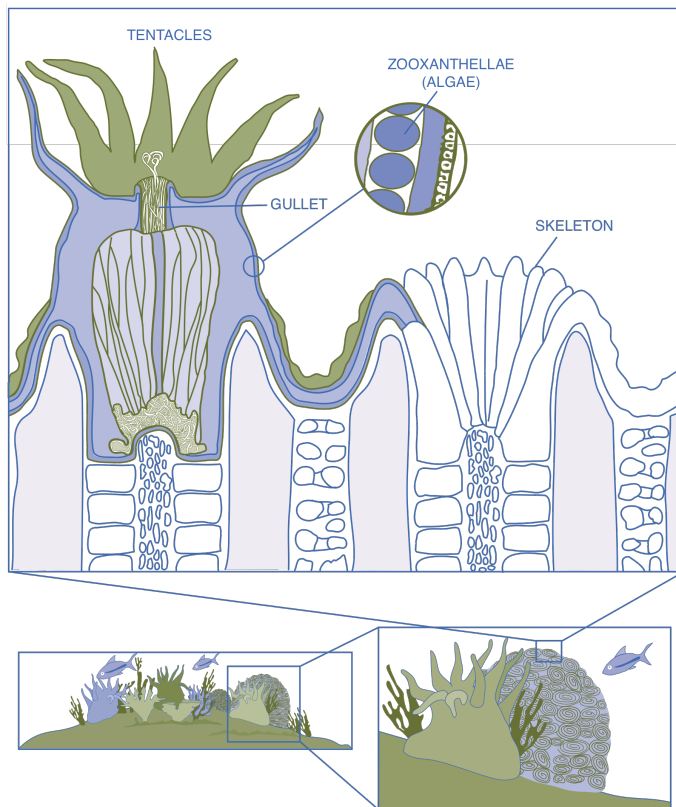

Figure 1: Cross-section diagram of a polyp and the skeleton of a typical reef-building coral, illustrating the presence of symbiotic microalgae (zooxanthellae). The organism is colonial, with many polyps connected in a single living surface above the limestone skeleton. From Buddemeier et al. (2004)

coral animals. Many coral polyps and a larger number of algae form a single living entity (Figure 1), and it is the photosynthetic pigments of the algae that give the coral its colour. In the *hermatypic* corals, the kind that contain and depend upon zooxanthellae, the polyp and the alga form a symbiotic relationship that benefits both partners. The corals get food from the plant photosynthesis and the microalgae benefit from nutrients released as waste by the corals. The algae also obtain protection in a stable environment that the coral skeletons provide. They both also have complementary effects on CO_2 exchange that is believed to account for the rapid rates of skeletal growth (Buddemeier et al., 2004). This growth of calcium carbonate (limestone) skeleton is a very energy demanding process, which is why the reef-building corals are very dependent on the energy it obtains from the algae. If the corals loose their algae or if they are shielded from sunlight, the skeleton growth stops. On a sunny day, the rate of growth can be twice as large than on a cloudy day (Lang, 2008).

Corals can reproduce both sexually and asexually. In asexual reproduction, genetically identical polyps are produced to allow growth of the colony by either budding, where a new polyp grows from an adult, or by division, where two polyps are formed each as large as the original. Sexual reproduction is predominant and 75% of the hermatypic corals release gametes (eggs and sperm) into the water to spread colonies over large distances, called "broadcast spawn". The other corals release sperm but harbour the eggs called "brooding". The eggs and sperm fuse during fertilization to form a larvum called planula that drift in surface waters usually a few days before it swims back and attach itself to a colony where the larva grows into a coral polyp. Eventually it becomes a coral head by asexual budding and growth creating new polyps (Lang, 2008).

2.2 Distribution of Coral Reefs

The most favourable conditions to growth of coral reefs exist in tropical or near-tropical surface waters (OCEAN, 2009). The reef organisms are dependent on heat and sunlight and prefer waters no deeper than 20 m and water temperatures from 22–28°C. Such conditions are normally found on the eastern side of the continents, where most of the reefs in the world are found. Surface ocean currents generated by wind belts control the sea surface temperatures of the world's larger oceans. Westerly winds from the poles brings cold water from the poles along the west coasts of the continents, while easterly winds transport the heated waters to the continent's east costs. Because of this circulation, coral reefs are generally situated on the eastern side of the continents (Figure 2). Coral reefs are also found in cold waters along coasts in temperate oceans at a depth of 60-1400 m. Organisms that are not in symbiosis and not dependent on heat or sunlight build up these reefs, but the focus in this review is on warm-water corals, and especially *scleractinians* (stony corals) with a hard calcareous skeleton that contain and depend upon zooxanthellae and are known as "reef-builders" in shallow tropical waters.

Coral reefs take different forms defined as the following: *Fringing reefs* consists of a flat reef area directly attached to a shore. A *barrier reef* lies several kilometres offshore separated by a lagoon or channel. *Atolls* are like circular barrier reefs without a central landmass and instead enclose a shallow lagoon. Finally, there are *patch reefs*, which form irregular tablelike or pinnacle features (OCEAN, 2009).
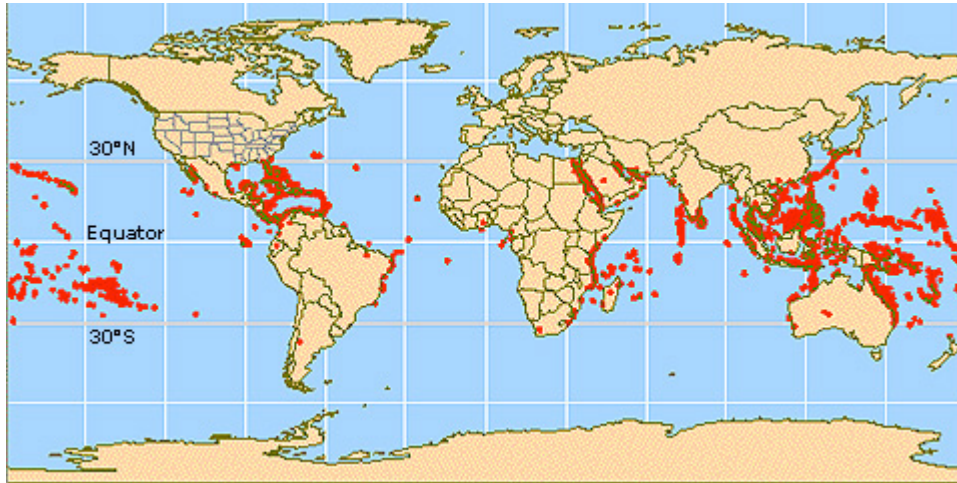
Figure 2: The distribution of tropical and subtropical coral reefs in the world (NOAA, 2005).

2.3 The Great Barrier Reef

Many examples and studies in this review come from the Great Barrier Reef in Australia. The Great Barrier Reef was selected as a World Heritage Site in 1981. It has also been labelled by CNN (the Cable News Network) as one of the 7 natural wonders of the underwater world. The reef stretches 2000 km along the east coast and it is known for its biodiversity with 400 types of corals, 1500 species of fish and 4000 types of molluscs, shells and squids. Long records of climatic and reef condition data exist and this marine park managed by the Great Barrier Reef Marine Park Authority (GBRMPA) is therefore a good location to study. The coral reefs are threatened by climate change, pollution, poor water quality, diseases, severe storms and development, but the park is also one of the world's most protected reef regions. The resources to manage this site sustainably exist and the strategy is to maintain biodiversity and support the ecosystem's resilience to make it survive through climate change (GBRMPA, 2007).

2.4 Importance and Value

Coral reefs provide food, jobs, income, and protection to billions of people worldwide. An acknowledged estimation show that reef habitats provide resources and services worth $375 billion each year (Costanza et al., 1997), an astonishing figure for an environment that covers less than 1% of the Earth's surface. Resources include fish and seafood that are especially important to the world's poor in developing regions who depend on reef species for food. Healthy reefs also contribute to local economies through their recreational value attracting scuba divers and snorkelers, but they also add value to the tourism product through associated images of exoticism and beauty. Tourism is an attractive industry for many developing countries with reef resources. Since long-haul travel is becoming cheaper and more accessible, previously remote areas are becoming available for tourists.

Other benefits from coral reefs include that they buffer nearby shorelines from wave action and storms, preventing erosion and protecting harbours, fisheries and properties. In recent years, chemicals within reef species have gained attention as sources of new medicines to possibly cure cancer and other diseases (Bryany et al., 1998).

3 Climate Change Effect on Coral Reefs

While coral reefs are subject to a wide range of anthropogenic and natural disturbances, climate change is rapidly emerging as the single greatest threat to these ecosystems (Hughes et al., 2003). Several climate change factors may threaten coral reefs. Those include sea-level rise, excessive rainfall, weakening or strengthening of ocean currents and also storms that possibly will become more frequent or severe. But the two greatest threats to coral reefs and their long-term sustainability are elevated sea surface temperature and increased CO_2 uptake in the ocean. Increased temperatures are responsible for a process called coral bleaching and increasing atmospheric CO_2 changes the pH in the water, leading to damage or even total collapse of coral reef ecosystems. Expert opinions from 96 countries show that 19% of the original area of coral reefs is already lost with no immediate prospect of recovery, much due to coral bleaching but also direct human pressures (Wilkinson, 2008).

3.1 Coral Reef Bleaching

3.1.1 Background and Definition

Expressed as a global average, surface temperatures have increased by about 0.74°C between 1906 and 2005 (IPCC, 2007*a*). The ocean's heat capacity is 1000 times larger than the atmosphere, and the ocean absorb the heat added to the climate system. The oceans are warming and over the period 1961 to 2003, global ocean temperatures has risen by 0.10 °C from the surface to a depth of 700 m (IPCC, 2007*b*). Scientists are highly confident that human-caused greenhouse gas emissions in the atmosphere have caused most of the rise in tropical coral reef water temperatures (Wilkinson, 2008).

Coral bleaching is the term used to describe the loss by the coral polyp of all or some of their symbiotic algae (Van Open and Lough, 2009). Since the photosynthetic pigments that the algae contain are lost, the white calcium carbonate skeleton becomes visible through the now transparent tissue of the polyp where the algae used to live. The coral looses its colour and appear white or *bleached*. It is the photosynthetic machinery in the algae that is damaged by environmental extremes, resulting in overproduction of oxygen radicals. This leads to cellular damage in the algae and possibly also the host, the coral polyp, and can then lead to the expulsion of the algae (Baker et al., 2008). A coral may recover from a bleaching event, but in other cases, it may die. The term *coral mortality*, which is used to describe the loss (deaths) of corals in percentages, should be distinct from bleaching where there is a chance of coral recovery.

3.1.2 Bleaching Events

Coral bleaching is not a new phenomenon or one that exist only because of global warming. Bleaching is a result of a range of environmental stresses such as for example low salinity, pollution or unusually low or high water temperatures. In the past, bleaching was observed only in small areas or patches of reef due to local stresses, but now, bleaching is clearly related to global warming and the effect is an increase in frequency of large-scale mass coral bleaching events where entire reefs are affected (Van Open and Lough, 2009). Worst-case scenario is a total colony collapse. Over the past three decades, bleaching has been reported from nearly every region that contain coral reefs, and none of the world's tropical or subtropical reefs appear safe (Baker et al., 2008).

The first report of bleaching due to thermal stress was recorded in 1931 in the Great Barrier Reef during a summer of high temperatures. Many corals died but some were observed to have lost their zooxanthellae and turned white. Later, these corals got their colour back and it was clear that they have started to recover their algae populations. Since the early 1980s, the number of coral reef bleaching reports has increased dramatically and the single most important factor driving coral bleaching is the increasing frequency of high temperature anomalies, which correlates well with mass bleaching events (Baker et al., 2008). Figure 4 shows the correlation between SST anomalies and the percentage of coral reef bleaching in the Caribbean between 1983 and 2000 (McWilliams et al., 2005). The solid circles represent years with mass bleaching events and as seen in the figure, these occurred at regional SST anomalies of 0.2°C and above. Corals are especially sensitive to temperature anomalies, because reef corals and zooaxanthelle organisms live close to their thermal tolerance limits.
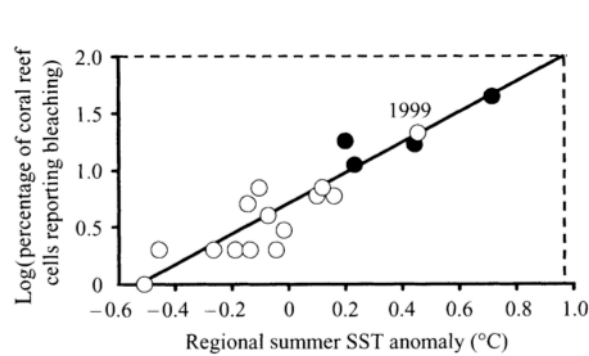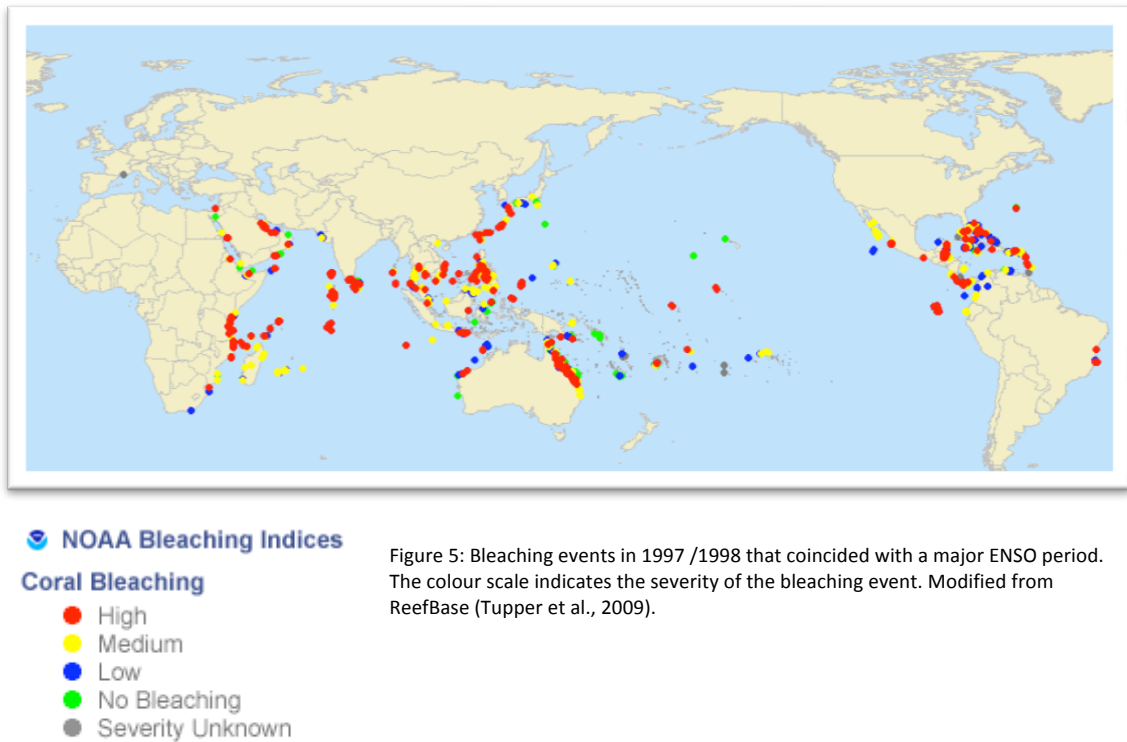
Figure 4: The relationship between regional SST anomalies and the percentage 1° lat/long cells bleaching occurrence recorded during August-October in the Caribbean between 1983 and 2000. Each data point represent one year and solid circles represent mass bleaching events. From McWilliams et al. (2005).

Van Open and Lough (2009) have compiled global data of bleaching and present the most comprehensive record available on a global level. The results provide bleaching frequency and periodicity for the past three decades. Four periods (1983, 1987, 1998 and 2005) can be called global bleaching events in terms of frequency, intensity and the number of countries affected. The results clearly show an increase in the number of bleaching reports during this time with a major increase in the past decade after the 1998 event. The most severe and spatially extensive period of bleaching so far was in 1997/1998. This period coincided with a major El Niño-Southern Oscillation (ENSO) event, which is a phenomenon where the atmospheric pressure fluctuates between the Indian-Australasian and South American regions. It causes a wide range of climatic and oceanic changes in the Pacific, affecting rainfall, wind patterns and sea surface temperature. The 1997-1998 El Niño event, coinciding with what was then the warmest year on record, resulted in a worldwide bleaching event (Van Open and Lough, 2009). Figure 5 shows the severity and locations of the documented bleaching events in 1997/1998. 15% of the world's reefs died and many reefs suffered over 90% bleaching. The damage was greatest in the Indian Ocean, Western Pacific and the Caribbean (Wilkinson, 2008). ENSO do not alone cause bleaching events but they increase the possibility of anomalously high SSTs. 2005 was another devastating year for coral reefs. It was the hottest year in the Northern Hemisphere since 1998 and resulted in massive coral bleaching throughout the Caribbean. In the U.S Virgin Islands, there was a 51.5% loss of live hard coral cover and in several places like Cayman Islands and Barbados, more than 50% of coral colonies bleached. The coral mortality was up to 20% on Barbados (Wilkinson, 2008).

NOAA Bleaching Indices

Coral Bleaching
- High (red)
- Medium (yellow)
- Low (blue)
- No Bleaching (green)
- Severity Unknown (grey)

Figure 5: Bleaching events in 1997 /1998 that coincided with a major ENSO period. The colour scale indicates the severity of the bleaching event. Modified from ReefBase (Tupper et al., 2009).

But how much heat is needed and over how long time? Temperature anomaly, the distance covered, length and timing are all important factors in causing bleaching. Several different "bleaching thresholds" have been developed where the original idea is that upper and lower temperature thresholds exist which result in physiological stress when exceeded (Baker et al., 2008). It is still debated today exactly how theses should be defined, whether they need to be exceeded only once or repeatedly and for how much or how long. To be able to forecast and hindcast bleaching episodes, monthly mean sea temperatures above a local threshold and also cumulative heatstress have been used. One of the earliest indexes was Degree Heating Month (DHM), defined as the cumulative sum of anomailies more than 1°C above long-term monthly averages. This index is now used to identify ocean "hotspots" used as a part of NOAA's (National Oceanic and Atmospheric Administration) Coral Reef Watch program, explained further in section 3.1.3. Manzello et al. (2007) investigated bleaching in the Florida Keys to evaluate if it was short-term temperature stress, cumulative temperature stress or temperature variability that predicted the onset of bleaching best. They found that the maximum monthly SST and the number of days spent above a threshold of 30.5°C were the most significant conditions.

An index used by NOAA in the Coral Reef Watch program is Degree Heating Weeks (DHW). It is a cumulative measurement of the intensity and duration of thermal stress expressed in °C-weeks. DHW accumulates "hotspots" greater than 1°C over a 12-week period, showing how stressful conditions have been in the last three months. DHWs over 4 °C-weeks have been shown to cause coral bleaching and values over 8°C may cause severe bleaching and also mortality (NOOA, 2008). The graph in Figure 6 show the latest data from NOAA's Coral Reef Watch program from Davies Reef in Australia. The solid dark-blue line show the sea surface temperature (SST) time series. No line is present for DHW since during this time period, DHW values did not exceed zero. Several "bleaching watch" warnings were still issued in summertime since the "hotspot" criteria was fulfilled with SST exceeding the solid light-blue line (threshold SST). The five colour-coded bleaching alert categories are defined using levels of DHW and "hotspots".
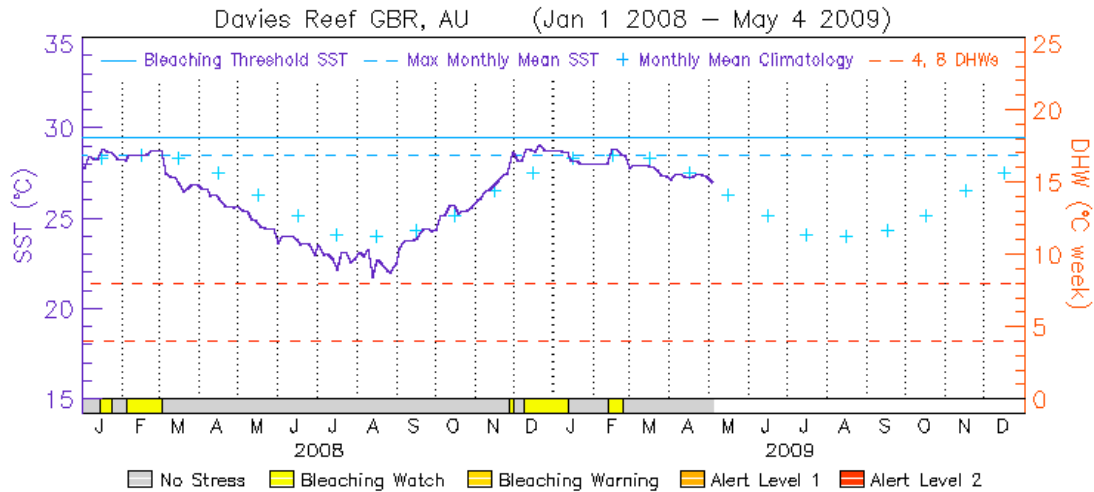
Figure 6: Time-series data of SST (solid dark-blue line) and DHW from NOOAs Coral Reef Watch program. The thermal condition is colour coded and plotted below the time series in five bleaching alert categories (NOAA Coral Reef Watch, 2009)

DHW have been rather successful in predicting bleaching events, but studies have shown that they cannot predict all of them, especially the milder ones. Also, globally applied algorithms may contain errors (Van Open and Lough, 2009). The best predictor of bleaching appears to be a combination of acute and cumulative temperature stress. The history of temperature variability also increases accuracy (Baker et al., 2008).

3.1.3 Detecting and Monitoring Bleaching Events

Coral bleaching has become a widespread phenomenon and it is important to quantify the scale of these events, which is challenging. Underwater detailed observation as well as remote continuous observation is needed to ensure that near total loss of corals do not pass by unnoticed, and to be able to understand this global threat. Fine-scale observations may clarify patterns of survival and recovery and help us understand the mechanisms, and to determine management responses.

At the broadest scale there is a need to observe coral bleaching worldwide. Satellite sensors and aerial photography can be used for this purpose. Bleached corals have a very distinct spectral signature compared to healthy corals (Baker et al., 2008). This means that the possibilities for detection and monitoring are good, but there are some difficulties. Spatial resolution is crucial because coral reefs are complex with many types of substrate types. Large pixel sizes lead to more mixed spectral signatures, since many different substrate signals beside the coral one may be included. Another problem is that the bleaching signature is very similar to that of sand. However, many studies have shown that bleaching is detectable at certain levels. Commonly used remote platforms for reef mapping are Landsat, SPOT and IKONOS that allow coverage of large areas and provide data relatively cheap (Van Open and Lough, 2009). The temporal resolution is also important since corals can change from bleached to recovered in only a few weeks, and dead corals could also be overgrown by algae quickly. Since cloud cover is frequent in the tropics a return of 2 weeks could be insufficient to detect a bleaching event (Van Open and Lough, 2009). Aerial photography has fine resolution and great capacity to be used for bleaching observation, but it might be hard to access remote areas and the method is also expensive. The conclusion is that bleaching detection is still not possible at regional to

global scales and the search for satisfactory remote-sensing tools continues. However, remote sensing has proven to be a very useful tool in other areas relating to coral reefs. For example, Geographic Information Systems (GIS) and remote sensing tools can help evaluate the effects of management strategies on marine habitats, described in section 4.2.

Spatially low resolution data is used as indicators of bleaching likelihood. The SST data used in the Coral Reef Watch program mentioned in section 3.1.2 is derived from night-time only SST records at low resolution (50 km). NOAA generates data from the Advanced Very High Resolution Radiometer (AVHRR) where SST measures are gathered twice weekly. These are then used to generate "hotspots" and DHWs that are used for predicting bleaching events. (Van Open and Lough, 2009).

Field-based observation by scientists and trained volunteers provide the basis for most assessments of how much corals have bleached, and where. During a bleaching event, the colour of the corals fades gradually (Van Open and Lough, 2009). Colour scales are used for the description of bleaching status and have been successful in field studies using towed observers and video cameras (Baker et al., 2008). A colour reference card is commonly used to describe the degree of paling. An organisation called Coral Watch, in collaboration with the University of Queensland in Australia, has recently developed a method of monitoring coral health. Anyone from scientists to tourist divers can help collect data. The method uses simple colour charts based on the actual colours of bleached and healthy corals with variation in brightness representing different stages of bleaching or recovery. The colour of the coral is matched with one of the colours in the coral health card and then recorded on the Coral Watch website data sheet along with coral type and site information. Every reef investigated has its own specifics method to select corals to obtain good accuracy. Methods used include random selection, using a quadrant or transect, and repeated measurement of individually marked colonies over time. Once the data is submitted a graph is produced representing the overall health of the monitored site. This program makes it possible for scientists to compare the condition of a reef over time, and also to compare many different reefs (CoralWatch, 2009).

3.1.4 Short- and Long term Ecological Effects

The immediate effects of bleaching and mortality of reef corals are numerous. Species that live in close association with these hosts such as crustaceans and fish are forced to emigrate with increased risk of predation. Corals are also more susceptible to diseases as bleaching weakens them. Further more, due to reduced photosynthesis, tissue growth, regeneration and calcification rates decline during bleaching events. Field experiments in the Caribbean have shown that bleached corals regenerate tissue more slowly than unbleached corals, even though its highly variable between species of corals (Baker et al., 2008). Bleaching has consequences for many other biological functions. More specifically, zooxanthellae have been estimated to provide 30% of the total nitrogen and 91% of the carbon needs of the coral polyp. The changes in biogeochemical composition after bleaching include reductions in protein, lipid, amino-acids and carotenoid concentrations of coral tissue (Van Open and Lough, 2009). Coral mortality is, just like tissue regeneration, highly variable both between affected taxa and also among bleaching events. Large colonies often suffer partial mortality while small colonies may suffer absolute mortality. Mortality rates might be low following mild bleaching events where temperate anomalies are minor. Conversely, severe bleaching events may result in 100% mortality, which nearly happened in the Galapagos Islands in 1982-83. An El Niño bleaching event resulted in a 97% coral mortality (Baker et al., 2008). Scleractinians, the

stony corals, are among the organisms that are most affected by bleaching. In Figure 7, common species of stony corals are shown both in a healthy and bleached state.
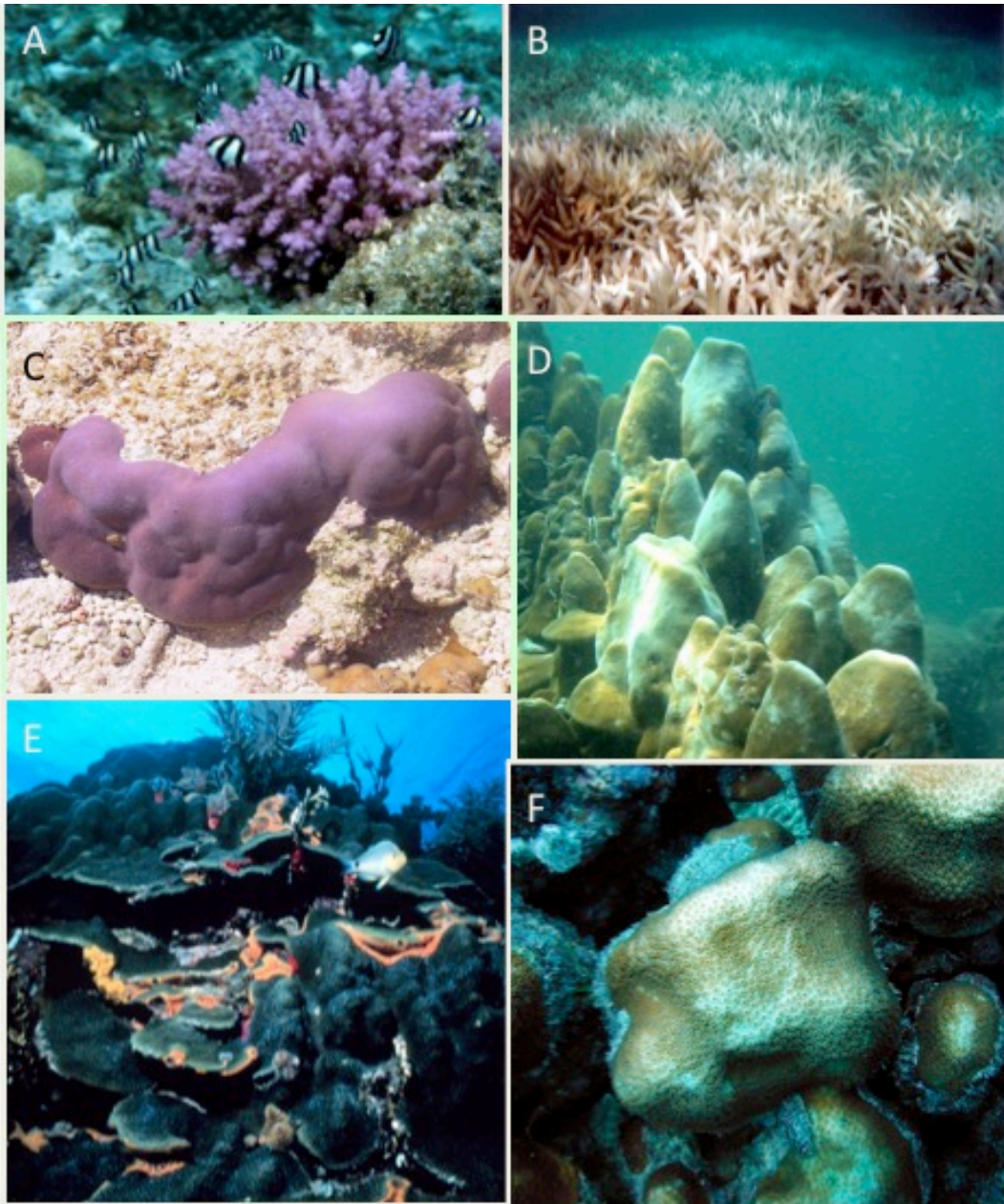

Figure 7: Healthy and bleached scleractinian (stony) corals. **A)** Healthy *Acropora sp.* (Branching coral) in American Samoa (Cornish, 2002). **B)** Bleached *Acropora sp.* (Branching coral) in the Great Keppel Island, Australia (Lotton, 2002). **C)** Healthy *Porites sp.* (Finger coral) colony in Fiji (Oliver, 2001). **D)** Bleached *Porites sp.* (Finger coral) in Malaysia (Marine Park Unit Department of Fisheries, Malaysia, 2002). **E)** Healthy *Montastraea sp.* (Boulder star coral) in Florida Keys (Harrigan, 2007). **F)** Bleached *Montastraea sp.* (Boulder star coral) in Florida Keys (UNCV, 2004).

The longer term effects of bleaching include reduction in coral reproduction and recruitment, changes in structure and in algal symbiont communities and also bioerosion. Reproduction of corals has proven to be compromised during and after bleaching, where reproduction is interrupted or compromised and corals may not be able to produce gametes or to spawn. For example, during the 1998 bleaching event, most reef flat corals that bleached at Heron Island in the Great Barrier Reef showed a reduction in percent

fertile polyps and number of eggs per polyp (Ward et al., 2000) . Bleaching events may cause changes in coral community structure. Scleractinian corals with branching colony morphologies generally suffer higher rates of mortality than massive species with a cover of hard crust. The hypothesis is that these massive corals transfer water more efficiently, therefore removing the damaging cellular toxins. Massive species of *Porites*, with the common name finger coral, are often among the survivors and is considered quite bleaching resistant, while *Acropora*, branching coral, is considered sensitive. In the Caribbean, coral communities are undergoing changes in community structure. Areas where frame-builders such as *Acropora* and *Montastraea* were the most abundant corals are now being dominated by non-frame-builders such as *Porites* (Coelho and Manfrino, 2007).

Corals may also have capacity to change their symbiotic algae. There are eight different variants or "clade" of zooxanthellae. Many corals appear to harbour a specific clade of algae, but with environmental change, changes in symbiont type can occur. These different clades of symbionts may demonstrate different physiological tolerances (Van Open and Lough, 2009). It is therefore possible that corals could increase their thermal tolerance by changing symbiont and possibly avoid bleaching. Another longer-term effect of bleaching is bioerosion, which is the biological breakdown of limestone skeletons and reef framework by for example borers such as bacteria, worms and sponges and also fishes. Calcification rates in healthy reefs and hence the build-up (reef accretion) normally exceed bioerosion, but coral mortality due to bleaching could result in loss of reef structure framework (Baker et al., 2008). An example of what this process can mean comes from Panama, where a reef that had depositing $CaCO_3$ is now eroding with a vertical loss of 6 mm/year. This reversal is due to 50% coral mortality after the 1982 bleaching event (Côté and Reynolds, 2006). The removal of reef material can have the same effect as a sea-level rise, leading to drowning of reefs.

3.1.5 Recovery

Currently, no detailed global analysis exist of coral recovery from bleaching, but Wilkinson's (2008) report stated that 40% of the reefs that were seriously damaged by bleaching in 1998 had recovered or were recovering well. Baker et al. (2008) summarized available recovery research and found that the rate of recovery among sites was variable. In some cases, the rate was high enough to be detected within 2 years, but in other locations, recovery was absent for over 20 years. Among the dominant recruiting taxa where recovery was observed included *Acropora* and branching *Porites*. The global analysis shows that corals that reproduce as "broadcasters", such as *Porites*, are the predominating recovering corals in most regions. Reefs can recover both asexually and sexually. Sexual recruitment can occur from deep surviving populations. The reason for that "broadcast spawners" are more successful in regenerating than "brooders" is that their larvae tend to spend more time in the water column, therefore having higher dispersion potential with increased capacity to colonize. While recruitment is important, the status of the reef framework is as important for the recovery process. If bioerosion occur, the recruitment substrate can collapse and kill newly settled corals (Baker et al., 2008).

3.1.6 Predicted Trends of Coral Bleaching

Global Climate Models (GCMs) that simulate the response of the earth to emissions of greenhouse gases are the basis for predictions of coral bleaching. The models used in the latest IPCC report predict that the planet could warm by 2-4°C by 2100, depending on

which scenario that is used for the prediction (IPCC, 2007*b*). SSTs from these models are the most reliable information available to predict the thermal conditions that coral reefs will be influenced by in the future. Early predictions of bleaching frequency and intensity by scientists derived from GCMs and bleaching thresholds concluded that bleaching events were likely to become common worldwide by 2020 (Hoegh-Guldberg, 1999). After this, there have been surprisingly few studies to update these results. Donner et al., (2005) presented the first comprehensive global study of future bleaching under climate change. They used "business as usual" climate scenarios from IPCC and bleaching prediction algorithms from NOAA's Coral Reef Watch program. The result shows that the majority of the reefs in the world are at risk of annual bleaching by 2050, if an increase in thermal tolerance by 0.2-1.0°C per decade does not occur. Several other studies confirm the result of Hoegh-Guldberg (1999) across emission scenarios (Van Open and Lough 2009) and state that coral bleaching will be a severe threat to continued coral survival (Baker et al., 2008).

3.2 Ocean Acidification

The concentration of CO_2 in the atmosphere now exceeds 380 ppm, compared to pre-industrial levels of 280 ppm. The current concentration is higher than experienced on Earth for at least the past 800,000 years as determined from ice cores (Lüthi et al., 2008). The oceans have the ability to absorb atmospheric CO_2, thus reducing the severity of the greenhouse effect and climate change. However, CO_2 alters the chemistry of seawater, leading to ocean acidification.

3.2.1 The Chemistry Behind Ocean Acidification

The ocean's uptake of CO_2 alters the chemistry of the water and lowers the pH, meaning that the oceans get more acidic via a higher concentration of hydrogen ions (H^+). The sea surface is generally basic with a pH above 7. Approximately 25% of the emitted anthropogenic CO_2 entered the oceans between the years of 2000 and 2006 (Canadell et al., 2007). The increased atmospheric CO_2 drives this greenhouse gas into the oceans. In seawater, CO_2 dissolves in water and much of it immediately forms carbonic acid (H_2CO_3), which then split into a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+), (Equation 1).

$$CO_2 + H_2O \Leftrightarrow H_2CO_3 \Leftrightarrow H^+ + HCO_3^- \qquad \text{(Eq. 1)}$$
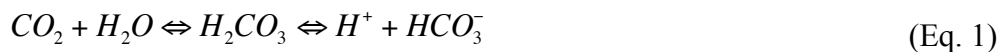
Bicarbonate can itself split to release another hydrogen ion and form a carbonate ion (CO_3^{2-}), (Equation 2).

$$HCO_3^- \Leftrightarrow H^+ + CO_3^{2-} \qquad \text{(Eq. 2)}$$

A carbonate ion can then be combined with a calcium ion (Ca^{2+}) to form calcium carbonate ($CaCO_3$), the basic building blocks for the skeleton of corals (Equation 3).

$$Ca^{2+} + CO_3^{2-} \Leftrightarrow CaCO_3 \qquad \text{(Eq. 3)}$$

Plenty of calcium ions are available in seawater as a result of weathering of rocks. Carbonate ions exist in saturation in most of the ocean. However, as atmospheric CO_2 concentrations increase, the equilibriums that exist in the equations above are changed. In

the reaction in Equation 2, the equilibrium is such that currently most of the carbon is in the form of HCO_3^- and little in form of CO_3^{2-}. As additional CO_2 dissolves in seawater, it adds to the concentration of HCO_3^- and H^+ (Equation 1). The equilibrium between HCO_3^- and CO_3^{2-} is then affected with a net flow to the left, since the equilibrium already is strongly biased to the left. The concentration of CO_3^{2-} is then reduced. In summary, new CO_2 that dissolves in seawater makes the concentration of carbonate ions decrease in the surface ocean, which in turn mean that corals get difficulties to form their skeletons (Denny, 2008). The pH of surface seawaters has decreased by about 0.1 since the beginning of the industrial revolution. This decrease is significant because pH is measured on a logarithmic scale, which means that a 0.1 decrease in pH is a 30% increase in ocean acidity. It is predicted that CO_2 levels in the atmosphere rise 150-250% by the year 2100 (IPCC, 2007*b*). Figure 8 illustrates what will happen to ocean chemistry when CO_2 levels in the atmosphere rise to doubled pre-industrial values.

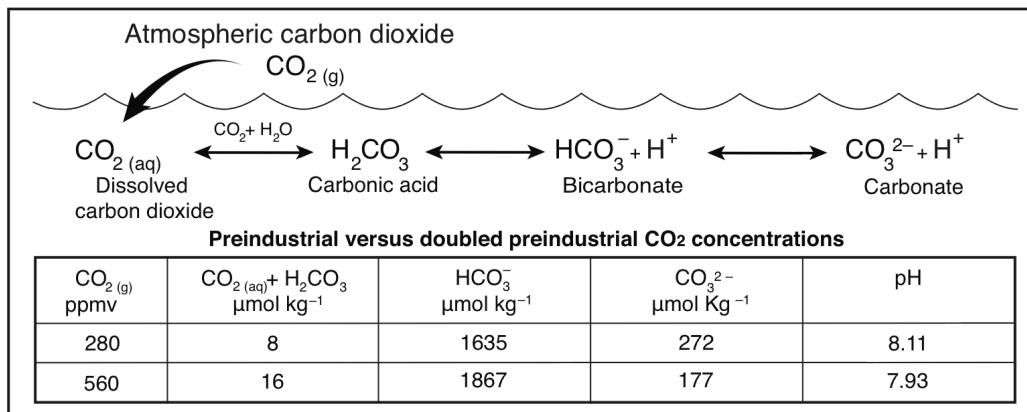| Preindustrial versus doubled preindustrial CO₂ concentrations				
$CO_{2\,(g)}$ ppmv	$CO_{2\,(aq)} + H_2CO_3$ µmol kg^{-1}	HCO_3^- µmol kg^{-1}	CO_3^{2-} µmol Kg^{-1}	pH
280	8	1635	272	8.11
560	16	1867	177	7.93

Figure 8: Changes in ocean chemistry as more CO₂ dissolves in seawater. When atmospheric CO₂ doubles from pre-industrial values, there will be an increase in dissolved bicarbonate and a decrease in the available carbonate in seawater. Carbonate is essential for coral reefs to make skeletons. From Wilkinson (2008).

There will be an increase in dissolved bicarbonate and a decrease in carbonate in seawater. The seawater pH will decrease by another 0.2 units and fall below eight. The changes in pH and the ocean chemistry directly affect biological processes. For example, CO_2 and bicarbonate are used in photosynthesis. Therefore, seagrasses and macroalgae may benefit from the increases. Conversely, it will become more difficult for coral reef animals and plants to form skeletons since available carbonate is reduced (Wilkinson, 2008).

3.2.2 Coral Calcification

Marine organisms use carbonate to produce shells or skeletons of the minerals calcite and aragonite consisting of calcium carbonate ($CaCO_3$). Fine needles of aragonite or crystals of calcite help to cement the reef components together. Aragonite, found in corals precipitated within the narrow space between the tissue and previously deposited skeleton, is twice as soluble as calcite, found in for example crustaceans. Under ideal conditions, a single coral can grow 10 cm per year. However, entire coral reefs have much slower vertical growth rate. Under periods of fast growth, the rate is 9-15 meters in 1000 years (0.9-1.5 cm per year). Today's coral reefs are not a result of constant growth, because the sea level has varied greatly during the latest ice ages, drowning or drying reefs, which make coral growth impossible and the reefs are defined as fossil reefs. Between these extreme periods, sea level returns to normal and coral polyps can recolonize the fossil reefs. In general, vertical growth is often stopped by the sea level. That is why today's coral reefs grow sideways (Lang, 2008). Coral calcification rates vary greatly in response

to changes in pH and aragonite saturation state (Doney et al., 2009). Figure 9 show scleractinian corals grown in seawater of normal pH (*b*) and in highly acidic seawater (*a*). The naked anemone-like coral polyps remained healthy, but completely lost their protective skeleton.
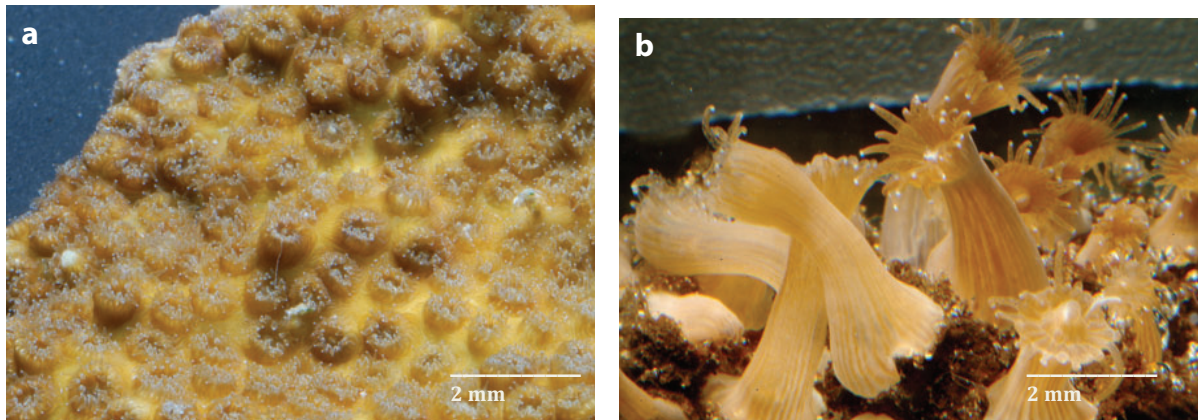

Figure 9: Photos of scleractinian corals after being maintained for 12 months in (*a*) normal seawater (pH = 8.2) and (*b*) acidified seawater (pH = 7.4). In the acidic water, the corals completely lost their skeletons. From Doney et al. (2009).

Several other experimental studies have shown that coral calcification decreases by up to 40% in growth rate because of that aragonite formation is inhibited as carbonate ion concentrations decrease (Hoegh-Guldberg et al., 2007). A recent study by De'ath et al. (2009) that investigated skeleton records of *Porites* corals from the Great Barrier Reef shows that coral calcification has declined by 14.2% since 1990, also suggesting that such a severe and sudden decline has not appeared in at least the past 400 years. The theory behind the decline is that increasing temperature stress and a declining saturation state of seawater aragonite may affect the ability of the corals to deposit calcium carbonate. Coral calcification is an important determinant of the health of reef ecosystems and many species depend on the protective structure provided by the coral skeletons. Overall, acidification impacts processes so fundamental to the structure and function of marine ecosystems so that any changes could have serious consequences for the future oceans (Doney et al., 2009).

The surface ocean today is saturated with calcium carbonate including the mineral forms such as aragonite. Below the saturated zone starts an undersaturated zone at varying depths depending on location. In the saturated zone, there is still enough calcium and carbonate ions for organisms to build skeleton, but in the colder and deeper undersaturated zone, the water dissolve these minerals. Because of increasing CO_2, the saturation zone has shifted towards the surface by 50-200 meters compared to pre-industrial positions (Doney, 2006). This means that the saturated zone is growing smaller. Before the industrial revolution, nearly all shallow tropical water coral reefs had an aragonite saturation over 3.25, which is the minimum value that coral reefs are associated with today. Figure 10 show changes in aragonite saturation ($\Omega_{aragonite}$) predicted to occur as atmospheric CO_2 concentrations increase. These estimations were made using the lower range of IPCC emission scenarios. Shallow water coral reefs are shown as pink dots in the figure. The areas with the minimum value of aragonite saturation (blue regions) decrease rapidly as CO_2 increases. It is suggested that within the next 50 years, tropical coral reefs will be unable to calcify because aragonite saturation may drop below those required to sustain coral reef accretion. Changes in ocean acidification will vary among regions. As seen in the figure, the Great Barrier Reef and the Caribbean sea are at risk of reaching low

aragonite saturations more rapidly than other areas, such as the central Pacific (Hoegh-Guldberg et al., 2007).
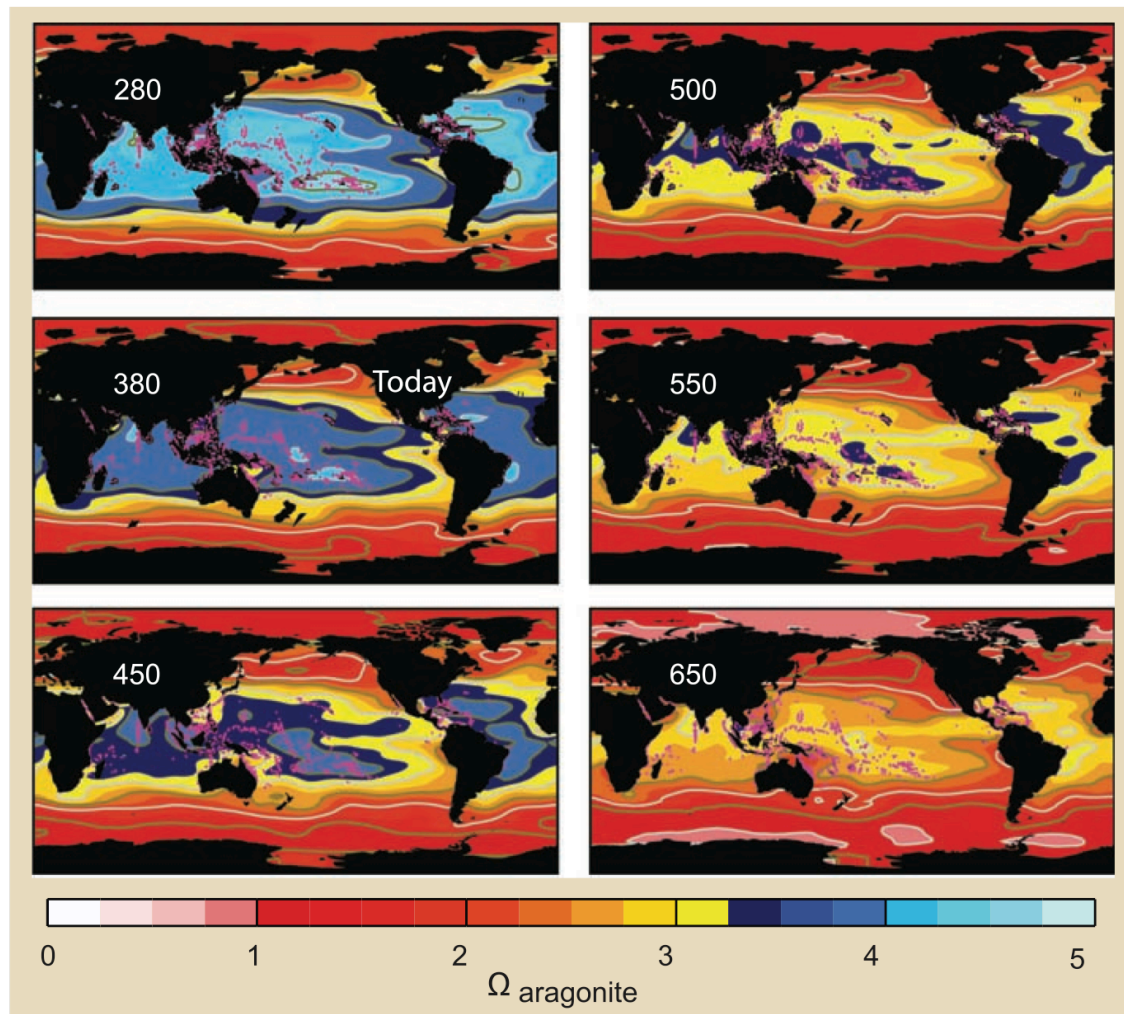

Figure 10: Changes in aragonite saturation ($\Omega_{aragonite}$) predicted to occur as atmospheric CO_2 (ppm) increases, shown as numbers in white. Shallow-water coral reef locations are shown as pink dots. Before the industrial revolution (280 ppm) nearly all shallow water reefs had $\Omega_{aragonite}$ > 3.25 (blue regions), which is the minimum value that coral reefs are associated with today. The number of coral reefs with the minimum saturation value decreases rapidly as atmospheric CO_2 increase. From Hoegh-Guldberg et al. (2007).

3.2.3 Evidence From the Past

Fossil records may provide some clues to the presence of calcified organisms in the past. The scleractinian (stony) corals evolved in the early Triassic period 250 million years ago and replaced the rugose corals that went extinct in the Permian-Triassic mass extinction event. The scleractinian corals ability to produce large quantities of calcium carbonate has contributed to their evolutionary success (Doney et al., 2009). Geological studies show a gap in the fossil record of scleractinian corals later in the early Triassic when atmospheric CO_2 concentrations increased dramatically to reach values five times larger than today. Scleractinian corals later appeared in the mid-Triassic and lived during much higher CO_2 levels than present, but no evidence exist that they lived in seawater with low carbonate saturation. It is the rapid increase in atmospheric CO_2 and not its absolute values that are responsible for the altered chemistry and carbon saturation of seawater. Therefore, the

current rate of increasing CO_2 is worrying, because modern corals may not have the capacity to adapt fast enough to these changes (Hoegh-Guldberg et al., 2007).

Another way of looking into the past is to reconstruct past conditions. Evidence of changes in ocean chemistry is preserved in geochemical records in the long-lived carbonate skeleton of corals. In a study by Wei et al. (2009), a 200 year old boron isotopic record from a *Porites* coral in the Great Barrier Reef could be used to reconstruct changes in seaweater pH since the industrial era. The results reflect variations in seawater pH and the changes in the carbon composition of surface waters due to fossil fuel burning. There is a general trend of ocean acidification with pH decreasing by 0.2-0.3 units from 1940 to the present day. Correlations of isotopic carbon and isotopic boron during this period indicate that the increasing acidification is the result of enhanced dissolution of CO_2 in surface seawater from the rapidly increasing atmospheric CO_2 concentrations, mainly from fossil fuel emissions.

Hoegh-Guldberg et al. (2007) also reconstructed past conditions by using global atmospheric CO_2 concentrations and temperature data from the Vostok Ice Core to explore the ocean temperature and carbonate-ion concentration seen today relative to the recent past for a typical low-latitude sea with a temperature of 25°C during the past 420 000 years. The results in figure 11 show a cluster of points between warmer interglacial periods with lower carbonate concentrations to cooler glacial periods with higher carbonate concentrations. The conditions today (point A in the figure) are significantly shifted to the right of the cluster, with carbonate concentrations lower than any other time during the past 420 000 years, during which most existing marine organisms evolved. The thresholds for major changes to coral reef communities are indicated in the figure for thermal stress (+2°C), carbonate-ion concentrations (200μmol/kg) and atmospheric CO_2 (480 ppm).
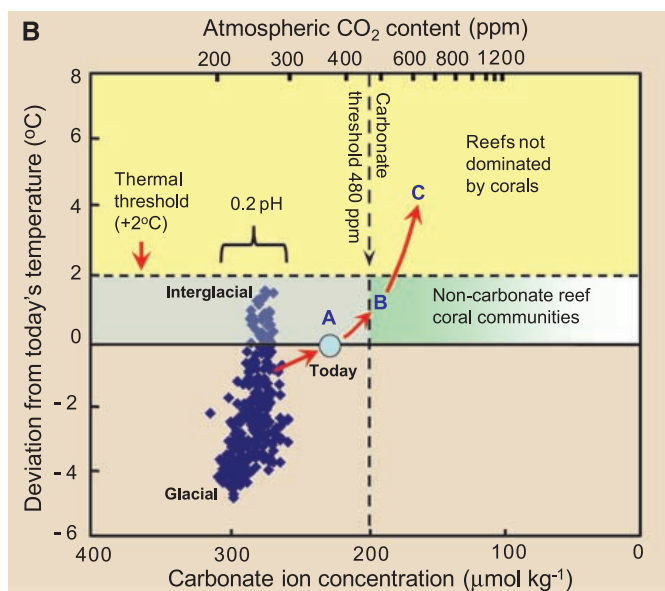

Figure 11: Atmospheric CO_2, temperature and carbonate ion-concentrations reconstructed for the past 420,000 years. The thresholds for thermal stress and carbonate-ion concentrations are indicated. Point B and C represent future coral reef scenarios. From Hoegh-Guldberg et al. (2007).

Leading scientists in the subject agree that calcifying species, such as coral reefs, will be severely affected by declining carbonate saturation (Orr et al., 2005; Hoegh-Guldberg et al., 2007). But what implications does this acidification mean for coral reefs? Reef-building corals may show several different responses to reduced calcification. The most direct response is a decrease in extension (the linear growth). In the calcification study by De'ath et al. (2009) mentioned above, where colonies of *Porites* corals from the Great Barrier Reef were investigated, the decline in calcification by 14.2% is pre-dominately because linear growth has declined by 13.3%. This makes them less able to compete for space.

Another response is reduced skeletal density, a way for corals to maintain their physical extension rate, but brittle skeletons are at greater risk for storm damage, erosion and predation. If rate of erosion exceed calcification, habitat quality and diversity will be reduced. Last, if corals invest greater energy in calcification, they may maintain both skeletal growth and density under reduced carbonate saturation. However, the disadvantage of this is that resources are diverted from other processes such as reproduction (Hoegh-Guldberg et al., 2007).

3.2.4 Future Predictions of Ecological Structures

Point B and C in figure 11 represent two different future coral reef scenarios projected by Hoegh-Guldberg et al. (2007). They have taken into account the local threats to coral reefs such as water quality and overexploitation that may produce feedbacks together with climate change. At present conditions (point A), coral reefs will continue to change but remain dominated by corals and accrete carbonate in most current locations of coral reefs, if conditions are stabilized at the present atmospheric CO_2 concentration of approximately 380 ppm. However, as CO_2 increases, coral community structure will change and some areas will become more dominated by thermally tolerant massive *Porites*, and other areas may become dominated by sensitive but rapidly colonising corals such as *Acropora*. Point B represents a scenario with current rate of CO_2 increase. Carbonate-ion concentrations will then drop below 200μmol/kg and reef erosion will exceed calcification at CO_2 concentration of 500 ppm. As seen in the figure, point B is then inside the area for when conditions exists so that non-carbonate reef coral communities dominate. The density and diversity of corals are likely to decline as well as the very pH sensitive coralline algae that act as key substrate for corals. The conclusion is that the loss of corals makes space for the settlement of macroalgae. Since macroalgae compete for space, light and also produce compounds that prevent settlement by competitors, coral recruitment and growth is inhibited. Macroalgae can then form stable communities that are resistant to a possible return of coral domination. Increases in CO_2 above 500 ppm (point C) will push carbonate far below the threshold and also exceed the thermal threshold for coral bleaching. These changes will reduce coral ecosystems to collapsed frameworks with few calcareous corals. Examples of the ecological structures anticipated for scenario B and C are seen in figure 12 (Hoegh-Guldberg et al., 2007).
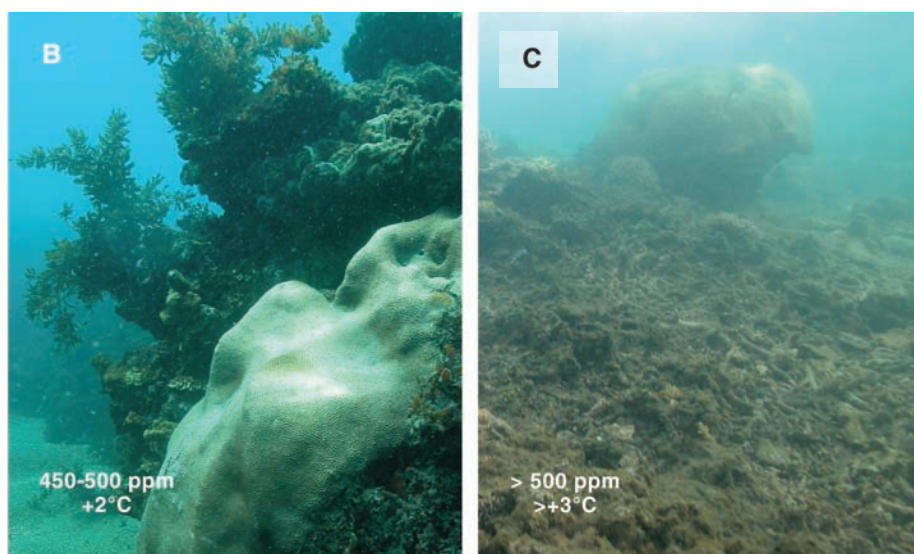

Figure 12: Examples of reef structures from the Great Barrier Reef for the ecological structures anticipated for coral reef scenarios B and C. **B**) Mixed algal and coral communities around St. Bees Island, Mackay. **C**) Collapsed frameworks at a reef slope around the Low isles near Port Douglas. From Hoegh-Guldberg et al. (2007).

Acidification and bleaching may together drive coral ecosystems toward domination by non-coral and macroalgae communities. This theory of a combined effect of acidification and bleaching on reefs that enhance all harmful feedbacks is purely theoretical. However, it has found support in recent laboratory work. By using a tank experimental system, CO_2 levels were manipulated to simulate doubling and three- to four time increases relative to present day levels, under both cool and warm scenarios. The results show that high CO_2 is a bleaching agent for corals under high irradiance, acting in combination with warming to lower thermal bleaching thresholds (Wei et al., 2009). This means that increasing CO_2 levels may cause coral bleaching via both ocean acidification and tropical sea warming.

4 Conservation Strategies

4.1 Observation and Management

No continuous coral reef datasets covering satellite and instrumental observations for decades or centuries exist. However, good data is available at various temporal and spatial scales (Van Open and Lough, 2009). NOAA and ReefBase (the official database of the GCMRN) both provide databases and online Geographic Information Systems (GIS) containing information on the location, status, threats, monitoring, and management of coral reefs around the world. The GCRMN (Global Reef Monitoring Network) represents many organisations around the world that collaborate to improve research, management, sustainable use and conservation of coral reefs. They have stated a number of recommendations to conserve coral reefs. The greatest threat to long-term sustainability of coral reefs, climate change, must be combated. The GCRMN request that "the world community, through their governments, agencies, NGOs, academic institutions and especially business establishments, collaborate to urgently reduce the current rate of emissions of greenhouse gases through reductions in energy use and the development of sustainable energy generating mechanisms or trading systems, and develop technologies to remove these gases, especially CO_2, from the atmosphere, to ensure that coral reefs will thrive in the next century" (Wilkinson, 2008). Raven et al. (2005) conclude that in addition to climate change, ocean acidification is a powerful reason for reducing global CO_2 emissions.

Herbivory is a vital part of the ecological balance of coral reefs. Fishes and sea urchins graze on algae, which are competitively superior to corals. Without grazing of algae, coral reefs become smothered, overgrown and dominated by macroalgae, resulting in coral mortality. This was the result in the Caribbean in the 1980's when the long-spined sea urchin, *Diadema antillarum*, was almost completely eliminated by disease (Hoegh-Guldberg et al., 2007). Therefore, it is vital to facilitate grazing by fish and herbivores by improved management through for example setting of catch limits. Another important management strategy is the idea of maintaining ecological resilience. By removing the second major threat to reefs, direct human pressure, coral health will improve and increase ecosystem resilience. Control of the secondary stress factors such as pollution, overfishing and sedimentation may help coral reefs survive climate change (Baker et al., 2008).

4.2 Marine Protected Areas

Marine Protected Areas (MPAs) are considered as the best strategy to conserve coral reef habitat and biodiversity. The Great Barrier Reef Marine Park that was established in 1975 is a good example. In 2004, the park was re-zoned to increase the no-take area, which

means that no fishing or disturbances such as anchoring or removal of material is allowed. Especially no-take marine reserves have resulted in positive ecological effects (Wilkinson, 2008). A study from Mexico provides proof on the effectiveness of marine reserves. Rioja-Nieto and Sheppard (2008) evaluated the effects of management strategies on the marine habitats in one of Mexico's most important MPA, the Cozumel Reefs National Park. They compared benthic habitat structure between the MPA and an unmanaged bordering region by using aerial photography and satellite images. The aim was to see whether management of an MPA for some time is having any useful effect on the landscape ecology. The satellite images were used to classify the habitats into 15 different marine habitats, consisting of for example fringing reefs, patch reefs and mixed coral on hard substrate. Habitat fragmentation (breaking up of habitat into isolated patches) and β-diversity (a measure of biodiversity) of benthic marine habitats were then measured and compared between the MPA and the unmanaged region, which have similar physical features. The comparison of diversity showed significant results. The value in the managed region was higher than in the unmanaged one, which suggests that management is having a marked effect. High β-diversity generally implies a high habitat complexity, which is a measure of the ecosystem function and biodiversity (Harborne et al. 2006). The fragmentation result was less clear. Fragmentation (habitat patchiness) is usually caused by anchoring, but in the managed region were anchoring is forbidden, great fragmentation still occurred. The reason for this is probably that the park has a high visitor number of snorkel and scuba divers, which tend to cause physical damage of the structures with their fins (Rioja-Nieto and Sheppard, 2008).

The Great Barrier Reef was until recently the only large existing MPA. In 2002, the World Summit on Sustainable Development (WSSD) and the United Nations (UN) General Assembly endorsed a target to significantly reduce the rate of biodiversity loss in general by 2010. For coral reefs, the WSSD suggested to establish networks of MPAs surrounding 20% of marine resources by 2012. New initiatives in coral reef conservation have been created since then. In 2006, two large MPAs focussed on coral reefs were declared in the Pacific. The Coral Triangle Initiative formed in 2006 to reduce biodiversity loss and set up networks of MPAs. The countries involved, which have the world's highest biodiversity coral reefs, are Indonesia, Phillipines, Malaysia, Papau New Guinea, the Solomon Islands and Timor Leste. The budget of conserving these marine resources consists of $300 million from governments, UN agencies and NGOs (Non Governmental Organizations) (Wilkinson, 2008).

4.3 Direct Intervention Strategies

Strategies and mitigations against climate change to reduce mortality over smaller areas include direct intervention strategies. To artificially shade sections of reefs, a shadecloth could be used to reduce irradiance that work in combination with high temperature to cause bleaching. Solar powered sprinkler devices that operate under bleaching conditions may also be an alternative. These could scatter and reflect sunlight as well as increase evaporative cooling. Artificial upwelling devices to bring cool, nutrient-rich deep water to the surface and mitigate bleaching by reducing thermal stress have also been proposed. All of these strategies are challenging to implement and require manipulation, but they may be of future conservation interest and attempts to run experiments are underway in the Great Barrier Reef (Baker et al., 2008).

4.4 Future Predictions and Reefs at Risk

Future predictions and warning systems may help to identify areas most likely to be affected by coral bleaching or reduced calcification. NOAA's Coral Reef Watch program for example includes a warning system for coral bleaching. Actions to mitigate the effects could then be implemented. But predictions about the future of coral reefs are difficult since several stresses and climate factors affect reefs. Predictions about the future of coral reefs out to 40 years from now by the GCRMN in the "Status of Coral Reefs of the World: 2008" report are made on a "business as usual" assumption, meaning that there will be no improvements in management and does not consider the looming threats posed by global climate change. The assessments and predictions are based on monitoring data and on future human stresses, without considering the threats of global climate change. Observed trends over the last century, demographic increases in human population pressures and assessments of current management actions are considered. The result show that 15% of the world's coral reefs are at a critical state under threat of joining the already lost category (which is 19%) within the next 10-20 years. The most threatened regions are Eastern Africa, South Asia and the wider Caribbean. 20% of the world's reefs are under threat of loss in 20-40 years. Finally, 46% of the reefs are considered to be at low risk. They are either stable or recovering and are not threatened by high levels of human stress. These reefs are considered well managed and include the Great Barrier Reef, Bermuda, Cuba and the Flower Garden Banks. Or, they are remote from landmasses and human disturbance such as the Red Sea, the Maldives, Papau New Guinea and small atolls in the Pacific Ocean (Wilkinson, 2008).

5 Discussion

The studies cited in this review all agree that climate change is a major threat to warm-water coral reefs. Extinctions of any coral species have not yet occurred, but bioerosion and loss of live coral cover and framework have all been observed. Considering bleaching, there are speculations that both frequency and severity of bleaching events have increased due to climate change, but it is certain that the number of bleaching events has clearly increased. The online database "ReefBase" provides the most comprehensive coral bleaching records but the analysis of these by Van Open and Lough (2009) presented a number of problems. Records of severity were quite subjective and some records of bleaching turned out to be duplicates of other records of the same event. Also, the number of reports may also be a result of increased numbers of observers with an interest in bleaching. No data exist on this reporting effect, and it can be assumed that the number of observers have increased over the past decades as field-based observations have increased and the attention from media on the deterioration of coral reefs has grown. Despite these problems, the authors behind this compiled record of bleaching believe the analysis is cautious and conservative. At least in the Great Barrier Reef and much of the Caribbean, the level of scientific monitoring and research and the effort to report all bleaching events have been ongoing since 1983.

The newly discovered threat of ocean acidification should be taken seriously. Not only corals, but also all calcifying organisms are threatened as carbonate saturation in seawater declines. These organisms are important for the formation and function of ecosystem, food webs and productivity of the world's oceans (De'ath et al., 2009). Especially high-latitude surface waters that are already naturally low in calcium and carbonate ion concentration will be the first to have under saturated waters. The saturated zone in these areas might

even disappear completely by 2050 (Orr et al., 2005). However, coral reefs might be the most sensitive ecosystem since they require such specific environmental conditions and have slow adaptation rates, discussed further below. Coral reefs might in the future be structurally less robust because they become less cemented, less developed and suffer higher erosion rates as the oceans acidify. Therefore, they may no longer be able to keep up with rising sea levels (Wilkinson, 2008).

Oceans play an important role in the Earth's climate system and the global carbon cycle. The oceans both release and absorb CO_2, but currently draw down more than they release. These systems are highly complex with many interactions and feedbacks between changes in the state of the oceans and changes in the global climate and atmospheric chemistry. However, the change in ocean chemistry will reduce the capacity to absorb atmospheric CO_2, which mean that more CO_2 will stay in the atmosphere and therefore affect global warming (Raven, 2005). Even if the uptake of CO_2 in the oceans then will be reduced, it will take tens of thousands of years for ocean chemistry to return to a condition similar to that of 200 years ago. It is the poor mixing of the water throughout the oceans that delay the process. Ocean sediments could otherwise neutralize the acidified surface seawaters (Raven, 2005). More research is needed in this area to fully understand the processes. A reduction in CO_2 emissions into the atmosphere seems to be the only practical way to minimize the risk of long-term changes in the oceans.

Some might argue that if coral reefs no longer can live in tropical areas, they can migrate to higher latitudes with more favourable temperatures, but it must be remembered that this is highly dependant on substrate availability. Today's coral reefs have accumulated slowly during the last 10,000 years and the modern reef communities live on top of very old limestone accumulations (Buddemeier et al., 2004). It all starts with coral polyps that begin to grow on an area with stable ground, such as on a dead old coral reef. With time, coarse sediments start to accumulate in cracks. The sediments contain calcium carbonate and derive from coral fragments and shells and skeletons from dead organisms. Coralline algae start to grow on the sediments and when they deposit calcium carbonate as calcite, they act in cementing the reef together. A new and living reef has been created (Lang, 2008). Therefore, just because adequate temperatures may exist at slightly higher latitudes, it is not possible for warm-water coral reefs to start to grow anywhere. Furthermore, warm-water coral reefs exist within a narrow environmental envelope where temperature, light and aragonite saturations must be adequate. This makes these ecosystems highly sensitive to environmental changes. Adaptation to warmer temperatures and lower carbonate saturation might not be possible. Shifts in symbiont communities that are more resistant to bleaching have been demonstrated (Baker et al. 2008), but if this adaptation will enhance coral survival in this era of climate change have not been widely investigated and remains to be fully determined. Further more, stony corals have long generation times and low genetic diversity, resulting in slow rates of adaptation (Baker et al., 2008).

The future predictions of both coral bleaching and ocean acidification raise serious concern, but it should be said that climate models deal with large-scale atmospheric and oceanic processes, which are highly complex with many parameters and feedback loops that are difficult to quantify. Global Climate Models (GCMs) have coarse spatial resolution with limited ability to project future ocean temperatures. Upwelling of cooler deep waters or heating of shallow waters are processes that these systems cannot represent. Further, models are not so reliable in representing the natural variability of

climate. The El Niño-Southern Oscillation, which is linked to mass coral bleaching is an example of such natural variability (Van Open and Lough, 2009). However, GCMs show that if CO_2 emissions were stopped today, there would still be a warming of 0.3-0.9°C by the end of the 21st century (IPCC, 2007*b*). This is due to the long residence time of CO_2 in the atmosphere. Therefore, a certain warming is expected to occur because of past emissions. Some have argued that the predictions of future CO_2 levels should be revised sharply upwards (Canadell et al., 2007). Rummukainen and Källén (2009) summarize the climate science results that have been published since the latest IPCC report in 2007. They conclude that new research in many respects confirm earlier results about climate change and human influence. Some of the effects of the continued global warming are even more severe than previously thought. Future climate warming can be larger than previously estimated.

The assessment of reefs at risk by the GCRMN does not consider any future threat of climate change and still, 15% of the world's reefs are considered to be at high risk of being lost within 10-20 years. The Great Barrier Reef for example is considered at low risk of future degradation when considering future human local stressors, but the area is likely to attain risky levels of aragonite saturation more rapidly than others (Hoegh-Guldberg et al., 2007). The combined threat of continued warming and ocean acidification due to climate change is alarming. Bleaching has proven to reduce coral reproduction and growth. Ocean acidification also weakens corals with decreased growth and reduced skeletal density. All of this in conjunction with other factors such as bioerosion may lead to domination by non-coral communities that compete for space. A field study of corals in waters near natural subsurface volcanic CO_2 vents showed that under high CO_2 and low pH, scleractinian corals were absent (Doney et al., 2009). The vent areas, that are naturally high in CO_2, were instead dominated by seagrasses with an increased number of non-native invasive species. In the future, macroalgae may dominate in some areas and phytoplankton blooms may be more frequent in other. Blooms may appear because of water quality decline, as climate change may be responsible for drying of catchments and causing episodic heavy rainfall that transports nutrients and sediments into coastal areas (Hoegh-Guldberg et al., 2007).

While corals have potential to recover from bleaching, coral calcification has consistently been shown to decrease with decreasing pH and does not recover as long as the conditions of acidity persist (Doney et al., 2009). Moreover, sea urchins that similar to corals also have a skeleton of calcium carbonate, are also they sensitive to acidification. Reduced shell growth, fertilization success, development rates and larval size have all been observed in sea urchins (Doney et al., 2009). As described in section 4.1, these herbivores have an important role in the ecological balance of coral reefs. All of the processes discussed above point to dominance by non-coral communities in the future if nothing changes. At least, coral reefs as we know them today would be extremely rare.

The socio-economic effects of climate change could be significant, because the damage to reef ecosystems and the fisheries and recreation industries that depend on them could amount to large economic losses (Raven, 2005). There is a need for further research and also improved management strategies. Research has focussed on understanding the mechanism of coral bleaching, but population ecological studies of corals are lacking (Baird et al., 2009). Exactly why the alga is expelled is still a mystery and research has concentrated more on the onset of bleaching rather than recovery (Baker et al., 2008). The potential for marine organisms to adapt to higher CO_2 and broader consequences for

marine ecosystems are not well known. The present understanding of acidification impacts on marine organisms is largely derived from short-term laboratory studies. The response of single organisms, populations and communities to realistic gradual changes is essentially unknown and is high priority for future research (Doney et al., 2009). Collaboration between geologists, ecologists, marine scientists and climatologists is needed. Combined ecological and physical models may help in estimating the ability of reefs to adapt to warmer temperatures, rising CO_2 and other local stressors such as overfishing (Van Open and Lough, 2009). Investment in research on reef restoration and in methods to enhance the natural resilience in corals would help us understand how to increase coral reef survival. Finally, there is also a need for guidance and support to the growing coastal populations who depend on and are trying to make a living by exploiting coral reefs. Legislative basis that enables management are often lacking and there is also difficulties in enforcing centralised fishery management rules and regulations (Wittingham et al., 2003). Destructive fishing methods are still a problem in many areas. These include deep-water trawling and by using dynamite. Poisons like cyanide are used to stun and capture live fish, which kills polyps and degrade their habitats. There is a need for further guidance, collaboration and funding from governments and NGOs to help in establishing more initiatives and networks for coral reef conservation, with strategies that will benefit both marine resources and local populations.

6 Conclusion

Climate change is emerging as the single greatest threat to coral reefs. The aim of this study was to review research covering this subject that recently has gained much attention, and to clarify the different mechanisms behind the issue. It can be concluded that the existing observations of coral bleaching confirm that severe bleaching events have occurred at global scales on four occasions and that the events correlate with elevated sea surface temperatures. The number of bleaching records has clearly increased during the last decades. The immediate and longer term negative effects of bleaching and mortality for coral reefs are numerous. Rising CO_2 emissions into the atmosphere is taken up by the oceans and alters ocean chemistry, leading to acidification. This in turn affects coral calcification, an important determinant of the health of coral reef ecosystems. The ability of corals to deposit calcium carbonate has declined and is likely to have several consequences such as weakening of coral skeletons and reef structures. 19% of the world's coral reefs are estimated as already lost and model outputs show that bleaching and acidification will be a severe threat to continued coral survival. The current rate of increasing CO_2 is worrying, because modern coral reef may not have the ability to adapt to these changes and together with direct human pressures, this may drive coral ecosystems toward domination by non-coral communities. Actions to conserve reefs are urgent and must include polices to reduce CO_2 emissions. Further research is needed to fully understand this highly complex subject. Investments and collaboration in order to include more coral reef areas in MPA networks and to also improve other management strategies would help to protect coral reef ecosystems and increase their ability to survive.

7 Acknowledgements

8 References

Baird, A.H., Bhagooli, R., and Ralph, P.J. (2009) Coral bleaching: the role of the host. *Trends in Ecology & Evolution* 24, p. 16-21.

Baker, A.C., Glynn, P.W., and Riegl, B. (2008) Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook: *Estuarine, Coastal and Shelf Science* 80, p. 435-471.

Bryany, D., Bureke, L., McManus, J., and Spalding, M. (1998) Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs: Washington, D.C, USA, World Resources Institute.

Buddemeier, R.W., Kleypas, J.A., and Aronson, R.B. (2004) Coral reefs & Global climate change - Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems: Arlington, USA, Pew Center on Global Climate Change.

Canadell J.G., Le Quéré, C., Raupach M.R., Field C.B., Buitenhuis E.T., Ciais, P., Conway T.J., Gillett N.P., Houghton, R.A., and Marland, G. (2007) Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proceedings of the National Academy of Sciences of the United States of America* 104, p. 18866-18870.

Coelho, V.R., and Manfrino, C. (2007) Coral community decline at a remote Caribbean island: marine no-take reserves are not enough. *Aquatic Conservation: Marine and Freshwater Ecosystems* 17, p. 666-685.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., and van den Belt, M. (1997) The value of the world's ecosystem services and natural capital. *Nature* 387, p. 253-260.

Côté, I.M., and Reynolds, J.D. (2006) Coral reef conservation. Cambridge University Press.

De'ath, G., Lough Janice, M., and Fabricius K.E. (2009) Declining Coral Calcification on the Great Barrier Reef. *Science* (New York) 323, p. 116-119.

Denny, M. (2008) How the ocean works : an introduction to oceanography. Princeton University Press.

Doney, S.C. (2006) The Dangers of Ocean Acidification. *Scientific American*, p. 58-65.

Doney, S.C., Fabry, V.J., Feely, R.A., and Kleypas, J.A. (2009) Ocean Acidification: The other CO_2 Problem. *Annual Review of Marine Science* 1. p. 169–92.

Harborne, A.R., Mumby, P.J., Zychaluk, K., Hedley, J.D., and Blackwell, P.G. (2006) Modelling the beta diversity of coral reefs. *Ecology* 87(11):2871-81.

Hoegh-Guldberg, O. (1999) Climate change, coral bleaching and the future of the world's coral reefs. *Marine And Freshwater Research 50*, p. 839-866.

Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., and Hatziolos, M.E. (2007) Coral Reefs Under Rapid Climate Change and Ocean Acidification. *Science* (New York) 318, p. 1737-1742.

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Palumbi, S.R., Pandolfi, J.M., Rosen, B., and Roughgarden, J. (2003) Climate Change, Human Impacts, and the Resilience of Coral Reefs. *Science* 301, p. 929-933.

IPCC, 2007a, Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the

Intergovernmental Panel on Climate Change. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

IPCC, 2007b, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.M., Siegenthaler, U., Raynaud, D., Jouzel, J, Fischer, H., Kawamura, K., and Stocker, T.F. (2008) High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature* 453, p. 379-382.

Manzello, D.P., Berkelmans, R., and Hendee, J.C. (2007) Coral bleaching indices and thresholds for the Florida Reef Tract, Bahamas, and St. Croix, US Virgin Islands. *Marine Pollution Bulletin* 54, p. 1923-1931.

McWilliams, J.P., Jennifer, A.G., William, J.S., and Andrew, R.W. (2005) Accelerating Impacts of Temperature-Induced Coral Bleaching in the Caribbean. *Ecology* 86, p. 2055-2060.

Orr, J., C. , Fabry, V., J., Aumont, O., Laurent, B., Doney, S., C. , Feely, R., A. , Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R., M. , Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R., G. , Plattner, G.-K., Rodgers, K., B. , Sabine, C., L. , Sarmiento, J., L. , Schlitzer, R., Slater, R., D. , Totterdell, I., J. , Weirig, M.-F., Yamanaka, Y., and Yool, A. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms: *Nature* (London) 437, p. 681-686.

Raven, J., K. Caldeira, H. Elderfield, O. Hoegh-Guldberg, P. Liss, U. Riebesell, J. Shepherd, C. Turley and A. Watson. (2005) Ocean acidification due to increasing atmospheric carbon dioxide. *London: Royal Society* 57.

Reaka-Kudla, M., L., Don, E.W., and Edward, O.W. (1997), Biodiversity II. Understanding and Protecting Our Biological Resources. *Science* 275, p. 175-175.

Rioja-Nieto, R., and Sheppard, C. (2008) Effects of management strategies on the landscape ecology of a Marine Protected Area. *Ocean & Coastal Management* 51, 397-404

Rummukainen, M., and Källén, E. (2009) Ny klimatvetenskap 2006–2009. Regeringskansliet, Kommissionen för hållbar utveckling.

Van Open, M.J.H., and Lough, J.M. (2009) Coral bleaching : patterns, processes, causes and consequences. Berlin, Springer.

Ward, S., Harrison, P., and Hoegh-Guldberg, O. (2000) Coral bleaching reduces reproduction of scleractinian corals and increases susceptibility to future stress. *Proceedings of the 9th International Coral Reef Symposium* 2, p. 1123-1128.

Wei, G., McCulloch, M.T., Mortimer, G., Deng, W., and Xie, L. (2009) Evidence for ocean acidification in the Great Barrier Reef of Australia. *Geochemica et Cosmochimica Acta* 73, p. 2332-2346.

Wilkinson, C.R (2008) Status of coral reefs of the world: 2008. Townsville, Australia, Global Coral Reef Monitoring Network and Reef and Rainforest Research Centre, pp. 296.

World Wide Web

CoralWatch (2009), Retrieved May 8, 2009 from: http://www.coralwatch.org/default.aspx

GBRMPA (2009) Commonwealth of Australia: The Great Barrier Reef Marine Park Authority. Retrieved May 15, 2009 from: http://www.gbrmpa.gov.au/

Lang, O. (2008). Gothenburg University. Retrieved March 17, 2009 from: http://www.korallrev.se

NOAA (2008) NOAA's Coral Reef Watch, Retrieved May 4, 2009 from http://coralreefwatch.noaa.gov/satellite/methodology/methodology.html#hotspot.

OCEAN (2009). In Encyclopædia Britannica. Retrieved April 6, 2009, from Encyclopædia Britannica Online: http://search.eb.com.ludwig.lub.lu.se/eb/article-67168

UN (2009) UN Atlas of the Oceans. Retrieved May 15, 2009 from: http://www.oceansatlas.org/servlet/CDSServlet?status=ND0xMjcyNSY2PWVuJj MzPSomMzc9a29z

Wittingham, E., Campbell, J., and Townsley, P. (2003) Poverty and reefs: a global overview. Retrieved May 28, 2009 from: http://www.reefbase.org/key_topics/poverty_and_reefs.aspx

Online Sources - Figures

Cover picture

Ling, R. (2004) Retrieved April 10, 2009 from: http://www.rling.com.

Figure 2

NOAA (2005) Retrieved May 15, 2009 from: http://oceanservice.noaa.gov/education/kits/corals/media/supp_coral05a.html

Figure 5

Tupper, M., Tewfik, A., Tan, M.K., Tan, S.L., The, L.H., Radius, M.J., Abdullah, S., (2009) ReefBase: A Global Information System on Coral Reefs [Online]. Retrieved April 6, 2009 from: http://www.reefbase.org

Figure 6

NOAA Coral Reef Watch (2009) Retrieved May 4, 2009 from: http://coralreefwatch.noaa.gov/satellite/current/sst_series_daviesreef_cur.html

Figure 7

A) Cornish, A. (2002) Retrieved May 14, 2009 from: http://www.reefbase.org/resource_center/photos.aspx.

B) Lotton, G. (2002) Retrieved May 14, 2009 from: http://www.reefbase.org/resource_center/photos.aspx.

C) Oliver, J. (2001) Retrieved May 14, 2009 from: http://www.reefbase.org/resource_center/photos.aspx.

D) Marine Park Unit Department of Fisheries, Malaysia, (2002) Retrieved May 14, 2009 from: http://www.reefbase.org/resource_center/photos.aspx.

E) Harrigan, W. (2007) Retrieved May 14, 2009 from: http://www.photolib.noaa.gov/htmls/reef2553.htm.

F) University of North Carolina at Wilmington, (UNCW). (2004) Retrieved May 14, 2009 from: http://people.uncw.edu/millers/images/Image%20Database/Flora%20and %20Fauna/Coral%20diseases/Montastraea_bleaching3.jpg.

8 Glossary

Anthozoa - A class of marine organisms in the phylum *Cnidaria* including the soft, horny, stony, and black corals, the sea pens, and the sea anemones.

Anthropogenic CO$_2$ - Excess carbon dioxide added to ocean and atmosphere from human fossil fuel combustion and deforestation.

Aragonite - A relatively soluble mineral form of calcium carbonate found in coral and a variety of invertebrates and algae.

Benthic zone - The ecological region at the lowest level of a body of water such as an ocean or a lake, including the sediment surface and some sub-surface layers.

β-diversity - A measure of biodiversity by comparing the species diversity between ecosystems or along environmental gradients. Involves comparing the number of taxa that are unique to each ecosystem. It is *the rate* of change in species composition across habitats or communities and gives a quantitative measure of diversity of communities that experience changing environments.

Calcium carbonate - A colorless or white crystalline compound, $CaCO_3$, occurring naturally as chalk, limestone, marble, and other forms.

Calcification - A biological process that uses dissolved ions to form calcium carbonate minerals for shells and skeletal components.

Cnidaria - Any of various invertebrate animals of the phylum *Cnidaria*, characterized by a radially symmetrical body with a saclike internal cavity, and including the jellyfishes, hydras, sea anemones, and corals.

Coral bleaching - The whitening of diverse invertebrate taxa, results from the loss of symbiotic zooxantheallae and/or a reduction in photosynthetic pigment concentrations in zooxanthellae residing within scleractinian corals.

DHW - Degree Heating Weeks. A cumulative measurement of the intensity and duration of thermal stress expressed in °C-weeks.

Ecological resilience - The amount of disturbance that an ecosystem could withstand without changing self-organized processes and structures

El Niño-Southern Oscillation - A global coupled ocean-atmosphere phenomenon. The Pacific Ocean signatures, El Niño and La Niña are important temperature fluctuations in surface waters of the tropical Eastern Pacific Ocean.

Eutrophication - A process in which the supply of plant nutrients in an aquatic ecosystem is increased. While the process of eutrophication is a natural one, it has been accelerated by human activities, resulting in an accelerated growth of plants, producing overcrowding.

Global Climate Model - Also known as a **general circulation model**; describes climate behavior by integrating a variety of fluid-dynamical, chemical, or even biological equations.

Hermatypic - Reef-building corals that depend upon zooxanthellae for survival.

Limestone - A common sedimentary rock consisting mostly of calcium carbonate, $CaCO_3$.

MPA - Marine Protected Area; any area of the intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment.

Ocean acidification - The decrease in the pH of the Earth's oceans, caused by their uptake of anthropogenic carbon dioxide from the atmosphere.

pH - An index of acidity/alkalinity of a solution, being an expression of concentration of hydrogen ions.

Polyp - A sessile cnidarian individual having a hollow, cylindrical body attached at one end, with a mouth surrounded by tentacles at the free end; may be solitary (hydra) or colonial (coral).

ppm - Parts per million; Ratio to determine the molecular presence of a particular substance per million parts in relation to others.

Remote Sensing - The gathering and recording of information about the earth's surface by methods which do not involve actual contact with the surface. Remote sensing techniques include photography, infra-red imagery, and radar from aircraft, satellites, and spacecraft.

Saturation state - Thermodynamic condition of seawater that describes the degree of supersaturation or undersaturation with respect to the particular phase of the $CaCO_3$ mineral.

Scleractinia - also called **stony corals**, are exclusively marine animals; they are very similar to sea anemones but generate a hard skeleton. Much of the framework of coral reefs is formed by scleractinians.

Zooxanthellae - Any of various symbiotic yellow-green or yellow–brown algae in the cytoplasm of certain marine invertebrates.

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