



Assessing the Impact of Climate Change on Marine Biodiversity: A Study of Coral Reef Ecosystems

Muhammad Umair^{1*}, Sadia Saleem², Abdul Jabbar³

¹Faculty of Environmental Sciences, University of Agriculture, Dera Ismail Khan-29050, Pakistan

²Department of Physiology and Biochemistry, Cholistan University of Veterinary and Animal Sciences Bahawalpur

³Environmental Sciences, COMSATS University Islamabad, Vehari Campus, Punjab, Pakistan

*Corresponding Author Email: mumairk536@gmail.com

Article Information

Article History

Received: July 09, 2024
Revised: August 18, 2024
Accepted: September 12, 2024
Available Online: December 31, 2024

Keywords:

Climate change, Ocean
Acidification, Mass Coral
Bleaching, Declining
Calcification Erosion

Abstract

Human activities through fossil fuel combustion combined with deforestation and modified land management practices have induced substantial alterations in atmospheric greenhouse gas contents, especially carbon dioxide and methane emissions. These alterations triggered by heat stress together with ocean acidification and falling carbonate ion levels caused both global warming and ocean acidification thus becoming major threats to coral reef ecosystems. Observational evidence shows that increasing coral bleaching events and reduced calcification rates together with numerous subtle but essential ecological and physiological changes affect coral reefs. Scientists make a prediction of coral reef ecosystems becoming rare worldwide during this century because reef-building corals and other species show no signs of adapting to these environmental changes. Many experts believe that preventing dire outcomes for coral reefs will be possible through proper control of atmospheric carbon dioxide rise along with local pressure reduction including overfishing and declining water quality. Coral reefs maintain vital importance for the survival of millions of people which requires immediate adoption of protective measures. It has been concluded that the current ocean acidification rate together with temperature increase patterns threaten coral reef ecosystems to a significant degree. The ongoing atmospheric CO₂ concentration trends will enable coral reefs to exceed their critical carbonate ion requirements while surpassing their temperature tolerance thresholds within short periods. The situation is predicted to become more severe for tropical and subtropical coastal areas due to expected increases in storm strength and rainfall intensity and sea-level rise. Under these circumstances coral reefs will experience dramatic shrinkage in their size distribution along with corals becoming extremely rare reef-dwelling animals within tropical and subtropical regions. Multiple species that depend on reef-building corals and carbonate structure creation will face extinction due to these circumstances. Research does not show sufficient signs of coral-dinoflagellate symbiosis to match the swift modifications in human-generated environmental changes.

INTRODUCTION

Science confirms that massive increases in atmospheric carbon dioxide alongside greenhouse gas emissions during the Industrial Era have led to major Earth environmental modifications which establish climate change as the top ecological and financial and societal matter for our present time (IPCC 2007). The modifications show two to three orders of magnitude speedier rate than the previous 740,000 years' glacial-interglacial phases (Petit et al. 1999; Augustin et al. 2004; Hansson et al. 2006). Scientific evidence shows that biological systems are changing throughout the planet (Walther et al. 2002). The rapid human-induced climate change demands knowledge of ecosystem responses across Earth through studies of coral reef ecosystems. The authors evaluate existing knowledge about these developments in this chapter before presenting various projections about significant maritime changes including coral reef alteration throughout upcoming decades and centuries. The world community needs to take urgent actions to stabilize carbon dioxide levels at current values or reduce them further because humanity faces the probable loss of fundamental ecosystems.

LITERATURE REVIEW

The Coral Reef Environment

Environmental conditions that set the locations for coral reefs offer significant insights about future evolutionary patterns of these ecosystems during rapid environmental changes. Deeper portions of this textbook have established that coral reefs exist in tropical and subtropical shallow waters exposed to sunlight. Coral reefs located in these areas absorb large amounts of sunlight that gets transformed into organic energy which the environment uses or helps with calcification processes (Muscatine 1990). The coral reefs exist within an equal distance of 30° degrees latitude north and south of the equator (Kleypas et al. 1999a). The northern and southern regions enforce the complete disappearance of carbonate reefs and the negative shift from reef growth and ultimately force calcification rates below erosion speed. The rate of coral colony development on rocky and sandy substrates remains slow because their skeletal material disappears after death. Therefore, coral colonies do not play any role in reef formation on such surfaces. The combination of calcium carbonate deposition at low latitudes exceeds both biological and physical destructive mechanisms so the reef framework steadily grows. The biodiversity examined under this structure contains millions of animal, plant, fungal and protist species which receive insufficient research attention (Reaka-Kudla 1997).

Kleypas et al. (1999a) provided the initial systematic study which examined the environmental criteria that led to carbonate coral reef ecosystem development. Scientists analyzed over 1,000 coral reef sites globally to determine that coral reefs exist only when temperature and salinity levels along with nutrient and aragonite saturation and light availability (depth and turbidity) are specific. The environmental elements which formed coral reef development also existed during present times are presented in Table 1. The multiple elements function in unbreakable proportion regarding coral reef dispersion while no individual factor can independently limit their distribution. The key attribute of this distribution style reveals that too many of these circumstances will create physical distress that leads to mortality. The research found in Chapter 23 shows that coral colonies get bleached after a specific temperature change in a specific geographic area (Hoegh-Guldberg 1999). The processes of reef calcification will not match up with physical and

biological damage until carbonate ion levels drop beneath 200 mmol per kg of water, which is the essential threshold for aragonite saturation (Table 1) (Guinotte et al. 2003 ; Hoegh-Guldberg et al. 2007).

Variable	Minimum	Maximum	Mean	Standard Deviation
Temperature (°C)				
Average	21	29.5	27.6	1.1
Minimum	16	28.2	24.8	1.8
Maximum	24.7	34.4	30.2	0.6
Salinity (ppt)				
Minimum	23.3	40	34.3	1.2
Maximum	31.2	41.8	35.3	0.9
Nutrients (μmol L⁻¹)				
Nitrate	0	3.34	0.25	0.28
Phosphate	0	0.54	0.13	0.08
Aragonite Saturation (Ω_{arag})				
Average	3.28	4.06	3.83	0.09
Maximum depth of light penetration (m)				
Average	-9	-81	-53	13.5
Minimum	-7	-72	-40	13.5
Maximum	-10	-91	-65	13.4

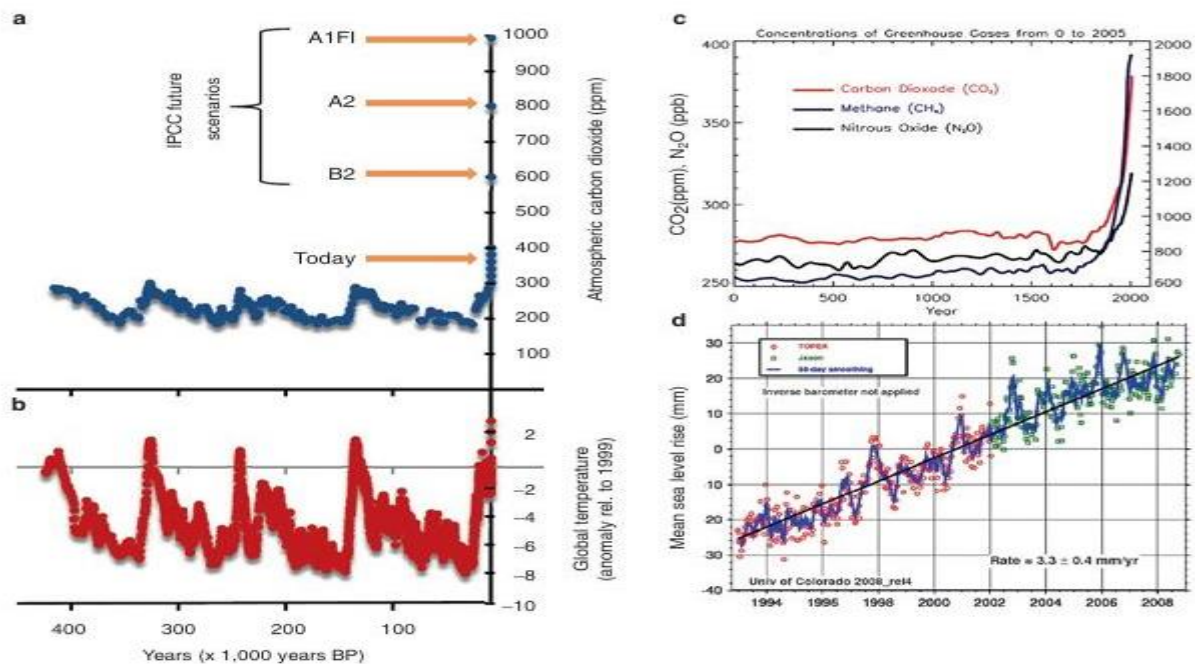


Fig 1. The Impact of Climate Change on Coral Reef Ecosystem

The planet experiences modifications through natural changes alongside human-caused changes as Exhibit 1 illustrates. The atmospheric carbon dioxide patterns revealed themselves through 420,000 years of data (Petit et al. 1999). Three main IPCC Fourth Assessment Report scenarios and current atmospheric concentrations are displayed through arrows (IPCC 2007). Temperature anomalies can be calculated using isotopic tracers relative to year 1999. Data has been collected about primary greenhouse gas alterations throughout the past two millennia (IPCC 2007). Sea level data is

measured by satellite altimeters which are sourced from the University of Colorado's Colorado Centre for Astrodynamics.

Changes to Tropical/Sub-tropical Oceans

Rising atmospheric concentrations of greenhouse gases caused the worldwide ocean temperatures to rise 0.74°C and the average sea level height to increase 17 cm during the twentieth century according to IPCC 2007. While CO₂ creates immediate temperature increases it enters ocean waters because seas absorb it and the compound reacts with salt solutions to form diluted carbonic acid. When carbonic acid dissolves into smaller protons the new protons transform carbonate ions into bicarbonate ions. Water pH within typical coral reef habitat environments undergoes a 0.1 unit decrease because of acid-base reactions that produce a 26% elevation of hydrogen ions while normal carbonate ion content decreases to approximately 30 mmol kg⁻¹ water based on Hoegh-Guldberg et al. (2007). Coral reefs maintain the ability to adapt to environmentally distinct temperature and carbonate ion concentration and pH patterns by evaluating current ocean changes since the Industrial Revolution against their historical evolutionary record spanning 420,000 years (Fig. 1a). The ocean temperature rose very quickly along with carbonate ion concentrations. The pace which humans have moved under glacial cycle shifts during the past century is equivalent to the change that takes place naturally in around 20,000 to 40,000 years according to (Petit et al. 1999; Augustin et al. 2004). The advancement of atmospheric CO₂ beyond 450 parts per million will trigger carbonate ion concentrations supporting coral reefs to decrease toward equatorial regions. The migration and/or evolutionary requirements of biological organisms exceed the time frame needed for adjustment thus creating major problems for reef-dwelling species.

IMPACTS ON CORAL REEFS

Impacts of Thermal Stress

Among the first documented cases of biological damage from human-driven fast climate change we have coral reefs. The latest scientific records show that "mass coral bleaching" became documented for the first time in literature during the early 1980s. In the early 1980s Panama together with Florida and other Caribbean territories experienced widespread "mass" coral bleaching events (Glynn 1983; Lessios et al. 1983; Glynn 1996) that transformed extensive reef coral populations white within weeks. Environmental stress causes coral tissue bleaching through the loss of either their dinoflagellates (Symbiodinium) cells or their essential pigments. The combination of elevated temperature levels plus increased irradiance serves among numerous elements responsible for mass coral bleaching based on the research summary by Hoegh-Guldberg (1999). The link between massive coral bleaching incidents and the "equatorial doldrums" combination of hot water temperatures and stable conditions became apparent in the late 1980s although researchers lacked an explanation for the sudden coral reef outbreaks. Mass coral bleaching and mortality causes the death of coral reefs as their death can spread over thousands of square kilometres within a few weeks (Hoegh-Guldberg et al., 2007). Scientists have identified warm ocean temperatures as the reason behind coral diseases (see Chapter 23).

IMPACTS OF OCEAN ACIDIFICATION

Kleypas together with his colleagues identified that ocean acidification from rising atmospheric CO₂ amounts posed a substantial risk to coral reefs apart from rising ocean temperatures. The scientific community now recognizes ocean acidification as "ocean acidification" (Caldeira and Wickett 2003) to represent a major danger to marine calcifying creatures including coral reefs. Growth of CO₂ in saltwater from increasing atmospheric CO₂ amounts leads to ocean acidification (Figure 4). Ocean water produces carbonic acid as CO₂ interacts with water molecules. Upon carbonic acid breakdown the proton separates to create carbonate ion and bicarbonate ion pairs. The main crystalline form of calcium carbonate crystals used to represent carbonate ion concentrations in reef-building corals as well as other marine calcifying organisms is aragonite seawater saturation. A doubling of atmospheric CO₂ levels could decrease the formation capability of coral calcium carbonate skeletons along with other marine calcifying organisms by up to 40% based on the research found in Kleypas et al. 1999b.

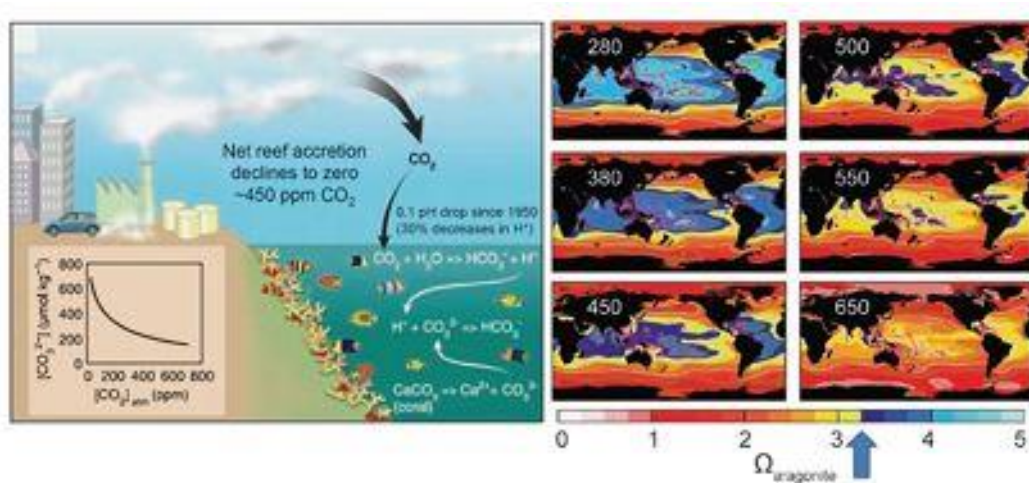


Fig 2

The image in Figure 2 shows underwater structures affected by ocean acidification. A visual representation shows the connection of human-made atmospheric carbon dioxide to tropical and subtropical ocean acidification. Reef corals together with calcareous red algae face reduced carbon dioxide availability because increased ocean acidification from elevated atmospheric carbon dioxide levels lowers ocean carbonate ion (CO_3^{2-}) concentrations. The inset shows a standard relationship between ocean carbonate ion levels and atmospheric carbon dioxide measurements. (b) Aragonite saturation constant (white numbers inside each panel) as a function of location and atmospheric carbon dioxide concentration. The aragonite solubility product (calcium carbonate deposition material used by corals and other species to build skeletons) obtains its saturation constant value by dividing the calcium ion and carbonate ion product through their concentrations. The blue arrows in the chart indicate the aragonite saturation constant which maintains values below its threshold that coral reefs primarily do not develop. The pink dots displayed in Figure 1 indicate carbonate coral reef system locations which are approved for use by Science and originated from Hoegh-Guldberg et al. 2007.

Other Factors Associated with Climate Change

Research has confirmed that increased Earth greenhouse effects generate various environmental impacts beyond water temperature and acidity changes. Most scientists agree that coral reefs will survive sea level increases unharmed according to IPCC 2007 and Rahmstorf 2007. The sustainable existence of some coral reef populations faces potential threats from small sea level fluctuations because other parameters including water temperature and acidity cause actual

harm to coral development. The sea level alterations from collapsing Greenland and West Antarctic ice sheets will worsen the current issue (Ridley et al. 2005; Gregory and Huybrechts 2006; Hansen 2007). Lower lighting conditions within coral reefs will occur as a consequence leading to reef ecosystem deterioration (Gregory and Huybrechts 2006; Steig et al. 2009). Coral reef futures face potential negative effects due to two environmental variables which include changes in storm conditions and drought patterns. Droughts already affect multiple worldwide regions leading to severe drying conditions while destabilizing sediments and increasing river basin runoff particularly at coastal Queensland near the Great Barrier Reef location. The projected drought together with more intense rainfall events will cause substantial increases in sediment and nutrient flow throughout the upcoming decades into the next century in these basins. Sediments and nutrients maintain their essential role in reef health deterioration since they limit coral reef growth in different global areas. Climate change will modify various essential components of coral reefs beyond those already studied. The cyclonic hydrological patterns modify coastal cloud numbers which subsequently affects the UV and photosynthetic radiation distribution. According to Mumby et al. (2001) sea conditions in French Polynesia during 1998 demonstrated how extreme cloud cover compensated for heat alterations. The pattern and strength of reef links can change due to impulsive ocean current variations which result from ocean circulation fluctuations. The fundamental question in this research field focuses on the interactions between all involved elements. The research of Anthony et al. (2008) reveals that ocean acidification amplifies thermal stress and results in substantial reductions of coral bleaching thermal limits during thermal stress events in acidified ocean conditions. Understanding global change development requires understanding local-global interactions while this understanding provides coral reef managers the potential to address climate change effects. Sustaining sufficient grazing levels on coral reefs during the period of greenhouse gas stabilization efforts might be essential to acquire necessary time for climate intervention. Reductions in fish grazing could harm bleached coral reefs in their ability to recover according to Hughes et al. (2003).

Ecosystem Responses and Outcomes

Baskett et al. (2009) suggest that based on most studies about coral population responses to climate change mortality will increase and growth rates will decline so corals on reefs will decrease substantially. Coral habitat formation benefits several located species because declining reef-building coral populations along with structural changes influence near-reef environments. Climate change addresses the reef species population in general but produces noticeable changes to coral reef fish demographics and others in certain select populations (Przeslawski et al. 2008). Research studies performed on fish populations on coral reefs with extensive bleaching events along with crown-of-thorns starfish (*Acanthaster planci*) population outbreaks show climate change triggers substantial modifications in the distributions of numerous reef-dwelling animals (Wilson et al. 2006; Graham et al. 2007; Pratchett et al. 2008; Wilson et al. 2008). According to Wilson et al. (2006) who analyzed 17 disturbance studies conducted throughout ten years researchers discovered that 62% of fish species displayed population decline over three years and lost more than 10% of coral cover. Researchers studying fish populations in coral-declining reefs found that species which depend on physical corals for feeding or coastal adhesive use are the first to become extinct (Wilson et al. 2006; Graham et al. 2007; Pratchett et al. 2008). When fish eat epiphytic algal matrix (EAM) or invertebrates there are mixed changes within their populations where some population size remains stable while others show minor increases. Research should focus on understanding how climate change affects coral and calcareous algae capability to protect important fish habitat structure because this understanding is critical for conservation. Fishes experience direct impacts because of changes in water temperature and

pH levels as do all other organisms. Research conducted by Munday et al. (2008) alongside Portner and Farrell (2008) indicates that these observed changes produce major health issues among coral reef fish by affecting their response systems and key variables combined.

The Role of Acclimation and Adaptation in Altering Projections of the State of Coral Reefs Under Climate Change

Life responds to change through multiple basic behavioral patterns. Natural selection leads populations to experience genetic changes that increase tolerant genetic profiles within the population while simultaneously improving physiological efficiency for modified environmental conditions ("adapt"; refer to Chapters 8 and 24). Sexual reproduction enables the introduction of new capabilities which originate from mutated genes or combinations of genes. When new genetic abilities enter populations through migration processes it may cause genetic alterations in these species' groups. The speed at which present climate change initiated by human activities affects these systems plays a critical role in determining how various species will evolve. Climate change rates in the past million years during ice age transitions moved at speeds which were significantly lower than the present rapid climate changes. Research demonstrates that ice age transition processes produced major alterations to ecosystem structures whereas their slower rates of change make them equally concerning to the Earth's health (Mayewski et al., 2004). Understanding stress threshold evolution permits scientists to forecast future transformations in coral ecosystems throughout both the short and long term. The changes in tolerance thresholds have been investigated by numerous scientists regarding their effect on coral populations under changing sea temperatures (Hoegh-Guldberg 1999; Done et al. 2003; Hughes et al. 2003; Donner et al. 2005). The required improvement in coral heat tolerance needs to reach between 0.2-1.0 degrees Celsius every decade to stop the scenario described by Hoegh-Guldberg (1999) according to Donner et al. (2005). Annual changes in sea temperature do not show enough evidence of coral adaptations to thermal thresholds over a 30-year observation period. Available evidence provides competing indications regarding the speed with which corals and their associated symbionts might adapt. The development of reef-building corals proceeds at a slow rate since their extended life cycles correlate with low genetic diversity among groups. Scientists agree that coral ecosystems now include fewer species while demonstrating greater resistance (Hoegh-Guldberg and Salvat 1995; Marshall and Baird 2000). The process of natural selection uses population fitness optima to choose sensitive coral community members for elimination (Maynard et al. 2008).

CONCLUSIONS AND FUTURE DIRECTIONS

The current ocean acidification rate together with temperature increase patterns threaten coral reef ecosystems to a significant degree. The ongoing atmospheric CO₂ concentration trends will enable coral reefs to exceed their critical carbonate ion requirements while surpassing their temperature tolerance thresholds within short periods. The situation is predicted to become more severe for tropical and subtropical coastal areas due to expected increases in storm strength and rainfall intensity and sea-level rise. Under these circumstances coral reefs will experience dramatic shrinkage in their size distribution along with corals becoming extremely rare reef-dwelling animals within tropical and subtropical regions. Multiple species that depend on reef-building corals and carbonate structure creation will face extinction due to these circumstances. Research does not show sufficient signs of coral-dinoflagellate symbiosis to match the swift modifications in human-generated environmental changes. The intense risk exposure of coral reefs requires governments

throughout the world to make immediate CO₂ emission reductions while directed support for developing nations to mitigate their local environmental stressors. The necessary requirements enable coral reef ecosystems to experience better prospects of surviving next century's harsh environmental stressors.

REFERENCES

- Anthony KR, Kline DI, Diaz-Pulido G, Dove S, Hoegh-Guldberg O (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proc Natl Acad Sci U S A* 105: 17442–17446
- Augustin L, Barbante C, Barnes PRF, Barnola JM, Bigler M, Castellano E, Cattani O, Chappellaz J, Dahl-Jensen D, Delmonte B et al (2004) Eight glacial cycles from an Antarctic ice core. *Nature* 429:623–628
- Baker AC (2001) Reef corals bleach to survive change. *Nature* 411:765–766
- Baker AC (2004) Symbiont diversity on coral reefs and its relationship to bleaching resistance and resilience. In: Rosenberg E, Loya Y (eds) *Coral health and disease*. Springer, Berlin, p 488
- Baker AC, Romanski AM (2007) Multiple symbiotic partnerships are common in scleractinian corals, but not in octocorals: comment on Goulet (2006). *Mar Ecol Prog Ser* 335:237–242
- Baskett M, Gaines S, Nisbet R (2009) Symbiont diversity may help coral reefs survive moderate climate change. *Ecol Appl* 19:3–17
- Bruno JF, Selig ER (2007a) Regional decline of coral cover in the IndoPacific: timing, extent, and subregional comparisons. *PLoS ONE* 2(8):e711
- Buddemeier RW, Fautin DG (1993) Coral bleaching as an adaptive mechanism. *Bioscience* 43:320–326
- Caldeira K, Wickett ME (2003) Anthropogenic carbon and ocean pH. *Nature* 425:365
- Cressey D (2007) Arctic melt opens Northwest passage. *Nature* 449:267–267
- De'ath G, Lough JM, Fabricius KE (2009) Declining coral calcification on the Great Barrier Reef. *Science* 323:116–119
- Derocher AE, Lunn NJ, Stirling I (2004) Polar bears in a warming climate. *Integr Comp Biol* 44:163–176
- Done T, Whetton P, Jones R, Berkelmans R, Lough J, Skirving W, Wooldridge S (2003) Global climate change and coral bleaching on the Great Barrier Reef. *State of Queensland Greenhouse Taskforce, Department of Natural Resources and Mines, Brisbane, p 54*
- Donner SD, Skirving WJ, Little CM, Oppenheimer M, Hoegh-Guldberg O (2005) Global assessment of coral bleaching and required rates of adaptation under climate change. *Glob Change Biol* 11:2251–2265
- Donner SD, Knutson TR, Oppenheimer M (2007) Model-based assessment of the role of human-induced climate change in the 2005 Caribbean coral bleaching event. *Proc Natl Acad Sci U S A* 104:5483–5488
- Dove S (2004) Scleractinian corals with photoprotective host pigments are hypersensitive to thermal bleaching. *Mar Ecol Prog Ser* 272:99–116
- Emanuel K (2005) Increasing destructiveness of tropical cyclones over the past 30 years. *Nature* 436:686–688
- Glynn PW (1983) Extensive bleaching and death of reef corals on the Pacific coast of Panama. *Environ Conserv* 10:149–154
- Glynn PW (1996) Coral reef bleaching: Facts, hypotheses and implications. *Global Change Biol* 2:495–509
- Glynn PW, D'Croz L (1990) Experimental-evidence for high-temperature stress as the cause of el-nino-coincident coral mortality. *Coral Reefs* 8:181–191