

REVIEW PAPER

Climate change and tropical marine agriculture

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Abstract

The coral reef ecosystem forms part of a 'seascape' that includes land-based ecosystems such as mangroves and forests, and ideally should form a complete system for conservation and management. Aquaculture, including artisanal fishing for fish and invertebrates, shrimp farming, and seaweed farming, is a major part of the farming and gleaning practices of many tropical communities, particularly on small islands, and depends upon the integrity of the reefs. Climate change is making major impacts on these communities, not least through global warming and high CO₂ concentrations. Corals grow within very narrow limits of temperature, provide livelihoods for millions of people in tropical areas, and are under serious threat from a variety of environmental and climate extremes. Corals survive and grow through a symbiotic relationship with photosynthetic algae: zooxanthellae. Such systems apply highly co-operative regulation to minimize the fluctuation of metabolite concentration profiles in the face of transient perturbations. This review will discuss research on how climate influences reef ecosystems, and how science can lead to conservation actions, with benefits for the human populations reliant on the reefs for their survival.

Key words: Bleaching, capacity building, climate, coral reefs, global warming, robustness.

Introduction

Coral reefs, found predominantly between the tropics of Carpicorn and Cancer, provide an environment in which one-third of all marine fish species and many thousands of other species are found, and from which 6 million tons of fish are caught annually. This not only provides an income to national and international fishing fleets, but also for local communities, which, in addition, rely on the local fish stocks to provide nutritional sustenance. The reefs also act as barriers to wave action and storms by reducing the incident wave energy through wave reflection, dissipation, and shoaling, protecting the land and an estimated half a billion people who live within 100 km of reefs. The coral reef ecosystem forms part of a 'seascape' that includes land-based ecosystems such as mangroves, and ideally should form a complete system for conservation and management (Mumby and Steneck, 2008).

This review will concentrate on the effects of climate change on tropical marine agriculture and aquaculture that is associated with scleractinian (reef-building) corals. It will also cover the potential for capacity building to improve integrated coastal zone management.

Climate and climate change

The growth and subsistence of corals depend on many variables, including temperature, irradiance, calcium carbonate saturation, turbidity, sedimentation, salinity, pH, and nutrients. These variables influence the physiological processes of photosynthesis and calcification as well as coral survival, and, as a result, coral reefs occur only in selected areas of the world's oceans, largely between the Tropics of Cancer and Capricorn. Meteorological processes can alter these variables, and Fig. 1 summarizes their influences on global and synoptic scales on coral requirements for growth and survival (Walker, 2005; Crabbe *et al.*, 2008a). Coral reefs are currently under severe threat from climate change (Lough, 2008), as well as from many other anthropogenic influences, such as pollution and overfishing (Mumby *et al.*, 2007; Crabbe *et al.*, 2008b).

Climate processes and extremes can influence the physiological processes responsible for the growth of coral reef colonies. In a number of empirical models for coral growth,

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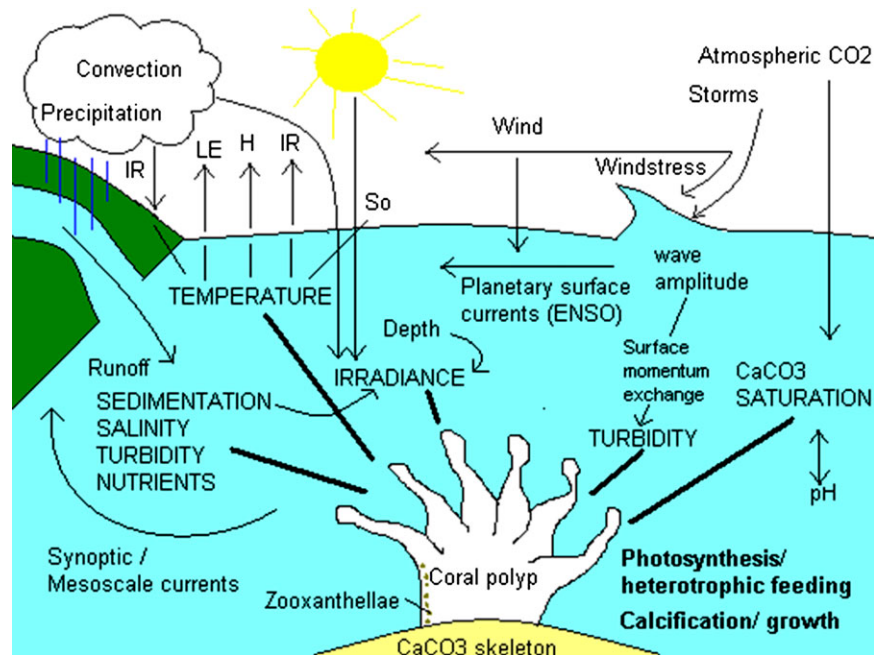


Fig. 1. Schematic diagram summarizing key meteorological processes and coral requirements controlling calcification, photosynthesis, and survival (adapted from Crabbe *et al.*, 2008a and reproduced by kind permission of Cambridge University Press). Abbreviations: ENSO, El Niño-southern oscillation; IR, irradiance; H, heat; So, insolation; LE, light energy.

small changes in temperature and rates of temperature change can significantly influence coral colony growth rates (Crabbe, 2007). There is a need to continue to develop models of how non-steady-state processes such as global warming and climate change will affect coral reefs, and on whether corals or their symbiont algae will evolve to keep pace with the climate and environmental changes. Our recent work shows that highly co-operative metabolic regulation can assure robustness in biological systems under changing environmental conditions (Luo *et al.*, 2009).

Tropical marine agriculture and aquaculture

Agriculture and fisheries in the tropics are often associated with coral reef ecosystems on islands, and depends upon the integrity of the coral reefs. The latest IPCC report concluded: 'It is very likely that subsistence and commercial agriculture on small islands will be adversely affected by climate change (high confidence)' (Mimura *et al.*, 2007). The effects of climate change include sea-level rise, coastal flooding, changes in saline concentration, and ocean acidification.

Local food production is vital to tropical islands, and a report by the FAO Commission in 1998 found that some countries' dependence on plant genetic resources ranged from 91% in Comoros to 37% in Vanuatu (Ximena, 1998). Fisheries contribute significantly to GDP in many tropical countries and islands. Climate change will exacerbate other anthropogenic stressors such as over-fishing (McLean *et al.*, 2001; Graham *et al.*, 2006). Nutrients released from intensive mariculture and fish hatcheries may not necessarily lead to the demise of coral reefs (Alvarez-Lajonchere *et al.*,

2007), as has been commonly presumed (Bongiorni *et al.*, 2003).

Attracted by the demand for shrimp in the developed countries, shrimp aquaculture has expanded rapidly, mainly in the subtropical and tropical lowlands of America and Asia. The use of mangroves and halophytes as biofilters of shrimp pond effluents offers an attractive tool for reducing the impact in those regions where mangrove wetlands and appropriate conditions for halophyte plantations exist (Paez-Osuna, 2001; Bhaskar and Sachindra, 2006).

Seaweed farming is often depicted as a sustainable form of aquaculture, but suspected habitat alterations and the spread of algae outside farms has given rise to speculation on the actual degree of sustainability. In parts of Indonesia such farming has probably been a factor in the decline of coral reef cover (Tun *et al.*, 2008). The risk of ecosystem-level changes in large-scale and uncontrolled farm enterprises warrants a holistic and integrated coastal management approach which considers all aspects of the tropical seascape, including human societies and natural resource use (Costa *et al.*, 2006; Eklof *et al.*, 2006; Lewis *et al.*, 2007).

Tropical sensitivity to climate change

In the 1990s, it was becoming clear that climate change would have a major influence in the tropics, and cause deleterious changes to agricultures in those areas. In 1993, Rosenweig and Hillel stated: 'While agriculture in some temperate regions may benefit from global climate change, tropical and subtropical regions may suffer. ...Understanding the potential impacts of climate change is a prerequisite to developing societal responses' (Rosenweig and Hillel,

1993). Even earlier, in 1991, Roy and Connell published their work on atolls, and stated: 'The combination of rising sea level and increased storminess that is expected to accompany changes in global climate due to the greenhouse effect may well have severe impacts on low-lying coral islands in tropical oceans. ...The economic and social viability of atoll island states in the future is therefore doubtful; their people may become the first environmental refugees of the greenhouse era' (Roy and Connell, 1991).

Traditional ideas of intra-seasonal and inter-annual climatic variability in the Western Indian Ocean, dominated by the mean cycle of seasonally reversing monsoon winds, are being replaced by a more complex picture, comprising air-sea interactions and feedbacks; atmosphere-ocean dynamics operating over intra-annual to inter-decadal time-scales; and climatological and oceanographic boundary condition changes at centennial to millennial time-scales. These forcings, which are mediated by the orography of East Africa and the Asian continent and by seafloor topography (most notably in this area by the banks and shoals of the Mascarene Plateau which interrupts the westward-flowing South Equatorial Current), determine fluxes of water, nutrients and biogeochemical constituents, the essential controls on ocean and shallow-sea productivity and ecosystem health (Meza and Wilks, 2003; Spencer *et al.*, 2005).

Irradiance

Diurnal and seasonal changes in radiation are predictable and large-scale shifts are not likely to occur over the next century (Kleypas *et al.*, 1999a, b). However, the future changes in the level of irradiance on coral reefs are hard to predict, because the effects of cloud cover and water transparency cannot be predicted at the global scale (Guinotte *et al.*, 2003). In addition, the mesoscale effects of cloudiness and storms, which can reduce surface irradiance and also increase turbidity and phytoplankton blooms, are highly unpredictable (Brown, 1997).

Sea level change

Sea-level is predicted to rise by 0.11–0.77 m over the next 100 years. This rise will increase the depth of the water column above a coral reef and the level of irradiance will also decrease. The stability of the sea level for the last few thousand years has led to reefs growing up to a point where they are limited by the level of the sea, therefore an increase in sea level may be beneficial to some reefs allowing an increase in upward growth (Buddmeier *et al.*, 2004). Fast-growing corals such as members of the genus *Acropora* which add up to 20 cm per year to their branch tips should not have any problem keeping up the changing sea level (Done, 1999). However, slower growing species of corals, such as *Porites*, are likely to be drowned as the predicted sea level rise rate of 0.95 cm per year overtakes the upwards

growth rate of around 1 cm per year (Lough and Barnes, 2000). An increase in sea-level rise could also lead to increased erosion of shorelines resulting in a higher level of sedimentation and a lower level of irradiance.

Atmospheric CO₂

Corals grow by the deposition of a calcium carbonate skeleton (calcification) in the form of aragonite by combining calcium ions with carbonate ions. The concentration of calcium ions in sea water is much higher than the concentration of the carbonate ion, therefore the rate of calcification is controlled by the saturation state of carbonate ions in the sea water (Kleypas *et al.*, 1999a). The saturation state of calcium carbonate is determined by the concentration of CO₂, which dissolves in water to form an acidic solution consisting of three species of inorganic carbon; carbonic acid: H₂CO₃, bicarbonate ion: HCO₃⁻, and carbonate ion: CO₃²⁻.

The more CO₂ dissolved in the water, the more readily the calcium carbonate will dissolve. CO₂ is more soluble in cold pressurized water and less soluble in warm non-pressurized water. Therefore the concentration of CO₂ is smaller in shallow tropical waters, which reduces the solubility of the calcium carbonate, allowing corals to precipitate calcium carbonate skeletons in these conditions.

Dissolved CO₂ also affects the pH of water. An increase in CO₂ causes a decrease in pH. As corals use the carbonate ion to form their skeletons, a decrease in the levels of carbonate ion will lead to a reduction in the calcification rate, less carbonate accumulation on average, and probably lower extension rates or weaker skeletons in some corals. The result of this would be a reduction in the ability of the coral to compete for space and to withstand erosion (Guinotte *et al.*, 2003).

Kleypas *et al.* (1999a) have calculated from predictions of future atmospheric CO₂ levels that the surface waters of the extra-tropics may well reach a level of undersaturation in the future. The tropical and warmest subtropical waters are unlikely to become undersaturated. However, even though the waters are likely to remain supersaturated, the degree of supersaturation affects the rate of coral calcification. Feely *et al.* (2004) have shown that even when the saturation state of calcium carbonate is greater than one (supersaturated) the calcification rates of all calcifying organisms, including corals, decrease in a response to a decreasing saturation state.

Coral bleaching

Coral bleaching is caused by the loss of the zooxanthellae by the coral. Most of the pigmentation within corals is within the zooxanthellae, and so when they are lost the coral appears white, or bleached, due to the white calcium carbonate coral skeleton showing through the translucent living tissue. Bleaching occurs when the coral is exposed to

prolonged above-normal temperatures, resulting in additional energy demands on the coral, depleted reserves, and reduced biomass. Under these circumstances the coral is unable to house the zooxanthellae and so becomes bleached (Muller-Parker and D'Elia, 1997). The effect of high temperature can be aggravated by high levels of irradiance; Gleason and Wellington (1993) report that corals tend to bleach on their upper, most sunlit surfaces first. However, the absence of mass bleaching events occurring in the presence of high UV radiation intensity and normal temperatures indicates that high UV radiation is not a primary factor in causing mass bleaching (Hoegh-Guldberg, 1999).

Corals can die as a result of bleaching, although they may partially or fully recover from bleaching events (Lough, 2000). Bleaching causes a decrease in the growth rate of corals, and the time taken for a coral to recover from a bleaching event may take several years or decades. If the frequency of bleaching increases then the capacity for coral reefs to recover is diminished (Done, 1999).

Bleaching tends to occur in regions where high temperatures are the norm (Muller-Parker and D'Elia, 1997). There have been six major episodes of coral bleaching since 1979 affecting reefs in every part of the world. The 1998 event was the largest, killing an estimated 16% of the world's corals (Hughes *et al.*, 2003). There are virtually no reports of coral bleaching prior to 1979. The lack of reports may be due to the increase of reef observers since then, but it is more likely that there were little or no bleaching events, since neither tourist resorts at the time or indigenous fishers are aware of any events occurring before this time (Hoegh-Guldberg, 1999).

Sea surface temperatures in all regions have been increasing over the past 20 years (McLean *et al.*, 2001). This increase has brought corals up to their upper thermal limit (Hoegh-Guldberg, 1999), and, as a result, bleaching occurs when there are higher than normal sea temperatures such as during an El Niño-southern oscillation (ENSO) event. There is no single bleaching threshold for all locations, times, and species, but most bleaching events occur when the temperature is at least 1 °C higher than seasonal maximum temperatures (Winter *et al.*, 1998; Hughes *et al.*, 2003).

Projected sea temperatures and bleaching events

Within the narrow temperature range for coral growth, corals can respond to rate of temperature change as well as to temperature *per se* (Crabbe, 2008). The number of times that corals will be bleached in the future has been estimated (Hoegh-Guldberg, 1999). The key assumption that reef-building corals and their zooxanthellae are unable to adapt fast enough or acclimatize to sporadic thermal stress, was made. All model runs indicated that the frequency of bleaching events is set to rise rapidly, with the rate being highest in the Caribbean, South East Asia, and the Great Barrier Reef, and the slowest in the Central Pacific. The

frequency of bleaching events were predicted to become annual in most oceans by 2040, and the Caribbean and South East Asia will reach this point by 2020, being triggered by seasonal changes in sea water temperature rather than by El Niño events.

There is some evidence that corals can adapt to climate change. Corals can contain different clades of zooxanthellae. Baker *et al.* (2004) studied corals in Panama, the Persian (Arabian) Gulf, and the Western Indian Ocean, following the 1997–1998 El Niño-southern oscillation bleaching event, and compared these to corals in areas which were relatively unaffected by the El Niño-southern oscillation. The surviving corals were found to contain a higher percentage of zooxanthellae of the genus *Symbiodinium* in clade D than the unaffected corals. For example 62% of coral colonies in Panama had clade D symbionts compared to just 1.5% of colonies in the Red Sea (which was relatively unaffected by ENSO and does not experience such high seasonal temperatures). This suggested that clade D *Symbiodinium* were more thermally tolerant than other clades.

Rowan (2004) found similar responses to Baker *et al.* (2004), where *Symbiodinium* clade D was found to be more resistant to high temperatures than clade C. Rowan (2004) proposed that corals may be able to adapt to global warming by recombination with temperature-resistant zooxanthellae.

It seems unlikely that bleaching is a way of corals adapting to climate change by the expulsion of susceptible zooxanthellae in order to take up more resistant ones. Rather as Hughes *et al.* (2003) have argued, bleaching is a stress response often followed by high mortality, reduced growth rates, and lower fecundity.

Capacity building to improve science and management

Capacity building, the enhancement of the skills of people and the capacity of institutions in resource management through education and training (Wescott, 2002), is the assistance which is provided to the governments of developing countries, organizations, and people, which need to develop certain skills or competencies or which need to create appropriate policies and institutions in order to function effectively. Capacity building is a long-term process; the transfer of this knowledge must be done in a manner which will ensure its longevity and sustainability. (Definition from: *Femmes Africa Solidarité (FAS)*, a women's non-governmental organization (NGO) working to engender the peace process in Africa.)

Capacity building by engagement has been used in many communities where there are inherent and long-standing challenges to sustainability (Wescott, 2002; Crabbe, 2006), for example, in Marine Protected Areas (MPAs) (Chircop, 1998), and indigenous community-based conservation (Mutandwa and Gadzirayi, 2007; Tai, 2007). While many, if not all, capacity-building programmes involve building

competencies and empowerment in local communities, few involve policy-makers or government officials (Mequanent and Taylor, 2007). Therefore a capacity-building exercise was undertaken around MPAs in Belize which involved both local NGO community workers and a government fisheries officer, so that community engagement could be directly interfaced with fisheries operations and policy (Crabbe *et al.*, 2009a). New ideas were produced to improve organization, management, education, support, and policy development in MPAs in Southern Belize. In addition, it was suggested that MPAs need to share regulation, enforcement, and conservation, underpinned by scientific research. Our study reinforced the idea that co-operative research improves capacity building and encourages innovative approaches to management, as has been found in north-eastern USA and north-western Europe (Johnson and Van Densen, 2007). Our approach is part of a complex relationship (Gray and Hatchard, 2008) linking an ecosystem-based approach to fisheries management involving forests, mangroves, and reefs with comprehensive stakeholder participation. It is important for communities to consider coral reefs as integral to land environments. Resorts and deforestation have major effects on mangroves and corals. Communities and governments need to be educated to consider a holistic environmental view when undertaking major land or marine policies (Crabbe, 2006; Crabbe *et al.*, 2009b). The environment needs to be seen as part of the solution, and not as part of the problem.

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