Response of Coral Reefs to Global Warming

7

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Abstract

The atmospheric CO_2 crossed over 400 ppm and we must prepare for a "+2 °C world" during this century. Coral reefs are directly related to each scenario of global warming: increase in CO_2 results in ocean acidification and suppresses calcification, rise in sea surface temperature leads to severe bleaching, and sea level rise causes submergence of coral reefs and atoll islands. They are the most sensitive ecosystem and act as an early warning system to examine and predict response of ecosystem to the global warming. Records of bleaching events and SST for the last 17 years in the northwest Pacific show that 2 °C SST rise would induce severe bleaching of coral reefs. Reduction of ocean surface water pH by 0.3 would cause shift from hard coral to non-calcifying macroalgae or soft coral populations in coral reefs. Submergence of coral reefs by sea level rise of up to one meter results in a loss of their breakwater function and in atoll islands submergence of national land. "+2 °C world" is the threshold to maintain coral reefs. Factors of global warming and responses of coral reefs are coupled to form feedback loops, which enhance or stabilize the changes within a system.

Keywords

Coral reef • Global warming • Ocean acidification • Sea level rise

7.1 Introduction: Coral Reefs in "+2 °C World"

In June 2013, atmospheric CO_2 concentration crossed over 400 ppm as a daily average for the first time after a steady rise during the monitoring at Mauna Loa since 1958 (Monastersky 2013). This level is the highest even for the last a few million years. Before the Industrial Revolution, it never reached 300 ppm, and this increase of CO_2 has induced +0.85 °C global average temperature increase, +0.19 m sea level rise, and 0.1 unit pH decrease through the twentieth century as reviewed by the latest Fifth Assessment Report of Intergovernmental Panel on Climate Change (IPCC AR5: http://www.ipcc.ch/).

For the future projection, AR5 adopted four Representative Concentration Pathways (RCPs) with prescribed CO_2 concentrations reaching 421 ppm (RCP2.6: the digit indicates total radiative forcing in year 2100 relative to year 1750 in Wm^{-2}), 538 ppm (RCP4.5), 670 ppm (RCP6.0), and 936 ppm (RCP8.5) (Moss et al. 2010). RCP2.6 scenario requires that we tackle to reduce CO_2 emission at once, and RCP8.5 scenario represents that we continue to rely on fossil fuels for our energy. If we do not adopt reduction of CO_2 emission at once (RCP2.6), global surface temperature rise at the end of the twenty-first century is likely to exceed 1.5 °C relative to 1850–1900 (Fig. 7.1a). Most researchers studying global change are afraid that

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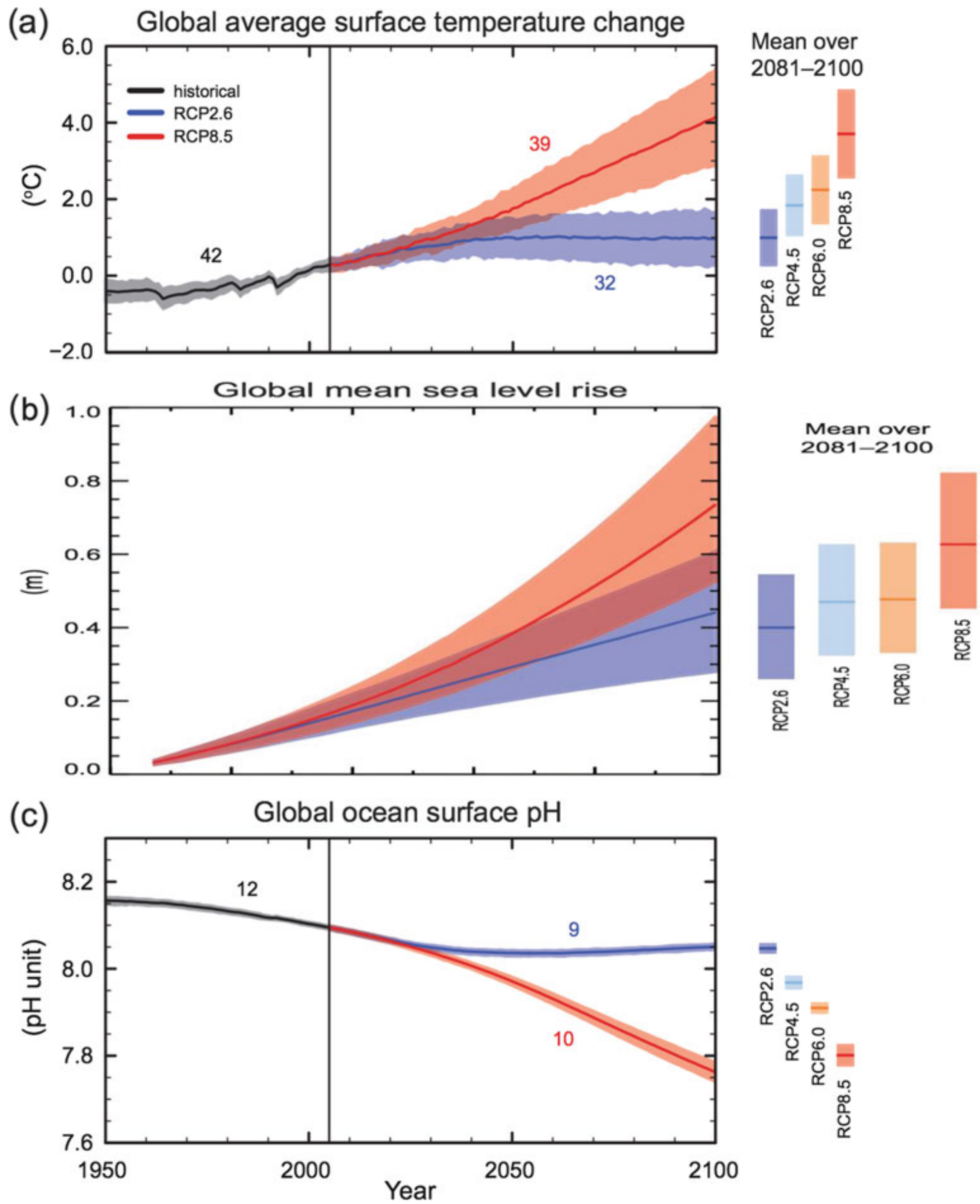

Fig. 7.1 Simulated time series from 1950 to 2100 relative to 1986–2005 for (**a**) change in global annual mean surface temperature, (**b**) global mean sea level rise, and (**c**) global mean ocean surface pH (AR5 of IPCC). Projections and uncertainty (*shading*) are shown for scenarios RCP2.6 (*blue*) and RCP8.5 (*red*)

"+2 °C world" would be inevitable and that we may face to "+4 °C world" as an extreme case (RCP8.5). The rise of sea level to be a worst case of +1 m by the end of this century (Fig. 7.1b) and surface ocean pH would decrease by 0.1–0.4 (Fig. 7.1c) units accompanying with CO_2 increase known as ocean acidification.

Ecosystem on the globe adapts to the present climate, and human activities are tied to the present ecosystem and climate. So the global climate change may collapse the ecosystem and human activities, which may not keep up with the rapid change. However, the global change so far is still small as compared with natural variability to extract its effect apparently, and we just project the probable scenario of response of ecosystem to the future global changes. The worldwide coral reef bleaching event in 1997–1998 gathered the attention not only from coral reef scientists but also from researchers in general interested in global change. The bleaching, loss of symbiotic algae from the host corals resulting in their mass mortality, was induced by ocean surface thermal anomalies 1–4 °C higher than normal years. It was the first event showing ecosystem-scale response to global warming. Before that event, coral reef researchers themselves had regarded local human impact as the main stressor to coral reefs, and global climate change would become the serious issue some time during the twenty-first century. After the bleaching event, they changed the mind and have now regarded global as well as local environmental change would evenly bring serious impact to coral reefs (Wilkinson 2002).

Coral reefs are directly related not only to warming but also to the other factors of the global warming scenario (Fig. 7.2). Coral reefs are the largest site of calcium

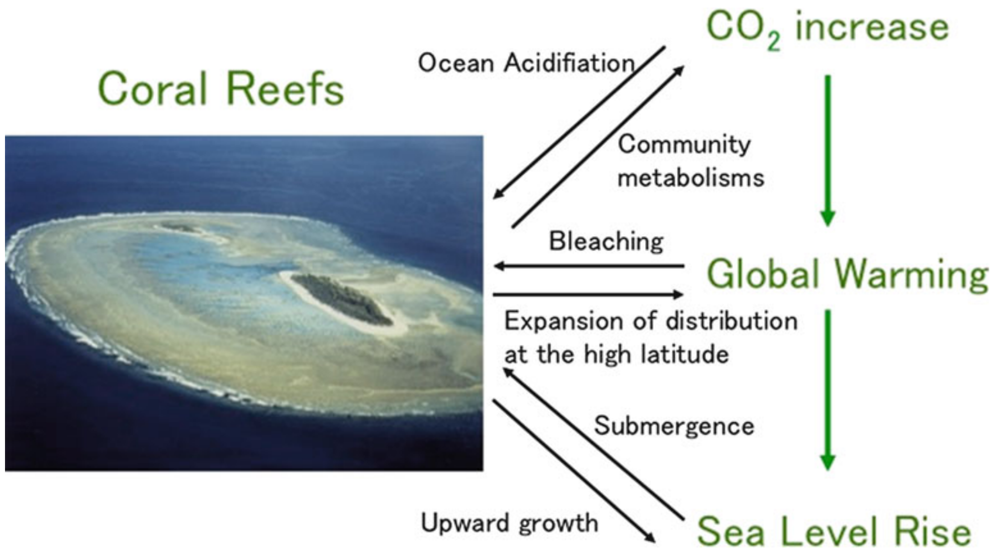

Fig. 7.2 Responses of coral reefs to global warming

carbonate production, which would be suppressed by the ocean acidification. The rise in sea surface temperature would cause more frequent and severe coral reef bleaching. Sea level rise would lead to submergence of coral reefs and loss of its function as a natural breakwater and habitat for the highest diversity of lives in the ocean.

Hoegh-Guldberg et al. (2007) inferred that density and diversity of corals are likely to decline under a global warming scenario of 450–500 ppm CO_2 and +2 °C temperature rise from preindustrial level, and macroalgae would be dominated over a few corals under a scenario of CO_2 >500 ppm and +3 °C thermal stress. The threshold CO_2 concentration of 450 ppm with +2 °C thermal stress for the decline of coral reef ecosystem has been reconfirmed by the later reviews on response of coral reefs to the global warming scenario (Veron et al. 2009; Hoegh-Guldberg and Bruno 2010). This threshold value corresponds to a moderate future scenario of the IPCC projection (RCP4.5 or 6.0) of "+2 °C world." Silverman et al. (2009) suggested a threshold of 550 ppm for coral reefs to erode rather than grow by acidification and surface ocean warming. These reviews predict the decline of coral reefs by the combined stresses of high SST and low pH. On the other hand, Frieler et al. (2013) claimed that only a thermal stress of +2 °C would be enough for two-thirds of world coral reefs to be subject to long-term degradation.

However, responses of coral reefs are not straightforward but will return feedback reactions against the change. Increase in CO_2 would also enhance dissolution of calcium carbonate sediments as well as photosynthesis, both of which act to reduce CO_2 concentration at least in coral reef water. Global warming would also expand the habitat of corals along the margin of their distribution. Coral reefs have a potential to catch up with rising sea level. Moreover, corals may adapt to the future ocean acidification and/or rise in SST.

We need to understand complicated responses of coral reefs to the global warming. By now, the signatures of the global warming are not so large (−0.1 pH unit ocean acidification, +0.85 °C temperature, and +0.19 m sea level rise by IPCC AR5). Coral reefs have already been affected by and responded to the global warming. Coral reefs are the most sensitive ecosystem and act as an early warning system to examine and predict response of ecosystem to the global warming. Analysis of the early signatures is effective to predict the future changes in coral reef response to the global warming.

7.2 Global Warming

7.2.1 Threshold Temperatures for Bleaching

Since the worldwide bleaching event in 1997–1998 (Wilkinson et al. 1999), fortunately no such global event has occurred. However, specific region of coral reefs suffered from regional scale higher than normal temperature resulting in regional-scale bleaching event. Field experience and laboratory experiment showed that thermal stress of 1–2 °C higher than the usual summer maximum can cause mass coral bleaching (Jokiel and Coles 1990). Small increases in SST (0.5–1.5 °C) over several weeks or large increase (3–4 °C) over a few days will lead to bleaching (Glynn 1993; Baker et al. 2008). Thus, the accumulation of thermal stress should determine the threshold for coral bleaching.

The National Oceanic and Atmospheric Administration (NOAA), USA, has monitored world sea surface temperature (SST) by satellite and released near-real-time anomalously high SST regions as coral bleaching HotSpots charts with 1° longitude × 1° latitude grid since 1997. The HotSpots anomalies are summed to estimate a degree heating week (DHW) to predict bleaching. DHW is the accumulation of the anomalies exceeding the maximum of the monthly mean SST for a given region over a rolling 12 weeks (Liu et al. 2003, 2006). Only anomalous values ≥1 °C are accumulated on an assumption that less than 1 °C SST anomaly is insufficient to cause visible stress on corals. Two DHW are equivalent to 2 weeks of anomalous temperature staying at 1 °C or 1 week of anomalous SST at 2 °C and so forth. Empirically, DHW values of 4.0 °C would cause bleaching, and as DHW values reached 8.0 °C, widespread bleaching is likely and some mortality is expected.

Kayanne (submitted) validated the DHW as threshold values for mass coral bleaching by the observed bleaching events in eight islands in the northwest Pacific: Kushimoto, Kochi, Amami Oshima, Okinawa Island, Ishigaki Island, Ogasawara Islands, Guam, and Palau (Fig. 7.3). In these localities coral bleaching events were observed in detail and recorded at least since 1998. Occurrence of the bleaching events is differed in year location by location and thus effective to test their correlation with temperature anomalies in these localities.

In Shiraho Reef, southeast coast of Ishigaki Island, a 15-year survey along fixed transect revealed time-series change in coral cover in response to thermal stresses (Harii et al. 2014). Coral population at Shiraho Reef decreased to a half after the 1998 bleaching, but recovered dramatically by 2000 (Kayanne et al. 2002). Coral coverage increased until 2003 after damage by 1998 bleaching, but then decreased by 2009 mostly due to a decline in branching *Montipora* (Fig. 7.4; Harii et al. 2014). The decline between 2003 and 2009 is explained by the bleaching event in 2007 (Dadhich et al. 2012) and mechanical destruction by large typhoons from 2004 to 2007. The bleaching event in 2007 was observed widely around Ishigaki Island; 60 % of acropoid corals died by the bleaching in Sekisei Lagoon, south of Ishigaki Island (Nojima and Okamoto 2008). In Sekisei Lagoon, moderate-scale bleaching was also reported in 2001 and 2003, but it was not observed in Shiraho Reef.

In Amami Oshima, island-scale bleaching was reported to occur in 1998 and 2001 (http://www.coremoc.go.jp/375). In Okinawa Island, two thermally induced bleaching events were recorded also in 1998 and 2001 (van Woesik et al. 2011). Bleaching events were also recorded in 1980, 1983, 1986, 1991, 1994, 1995, 1996, and 2003 in Okinawa (Nakano 2004). In Ogasawara Islands, widespread bleaching had not been observed since 1973 including 1998 (http://www.coremoc.go.jp), and it was the first event identified in September 2003 (Yoneyama et al. 2008). Guam was also escaped from bleaching in 1998. Since 1970, only two large-scale bleaching events have been recorded in 1994 and 1996, both of which did not appear to be associated with high SST (Paulay and Benayahu 1999; Porter et al. 2005). In Palau, severe bleaching occurred in 1998, but the coral cover recovered less than a decade later. However, in 2010 Palau experienced another thermal stress bleaching event (van Woesik et al. 2012).

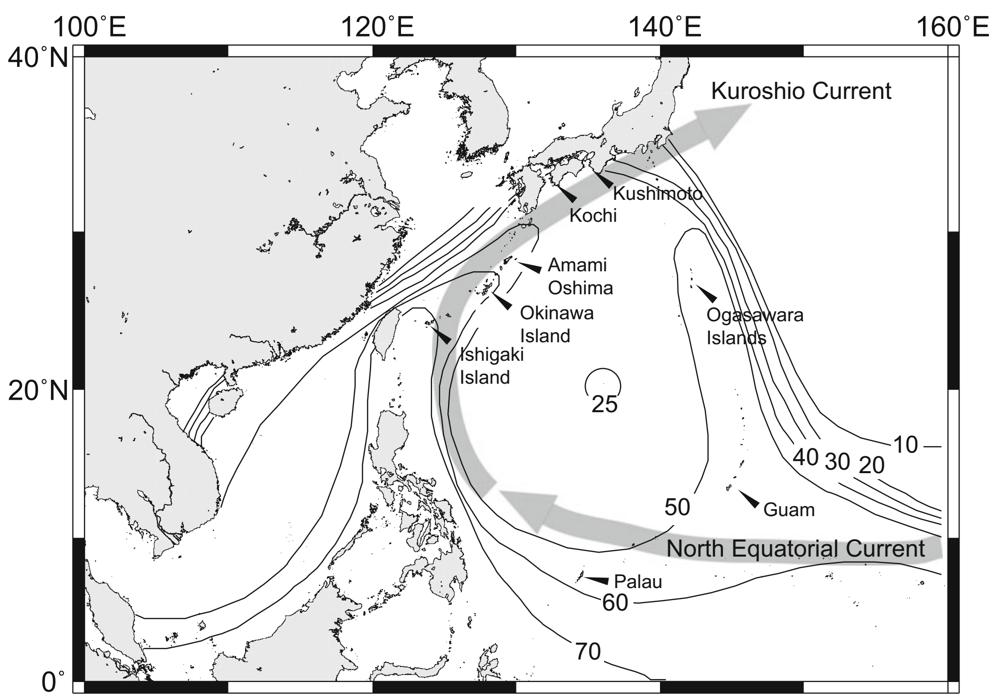

Fig. 7.3 Locality map for examining relation between bleaching events and SST anomalies. Isolines show number of coral genera

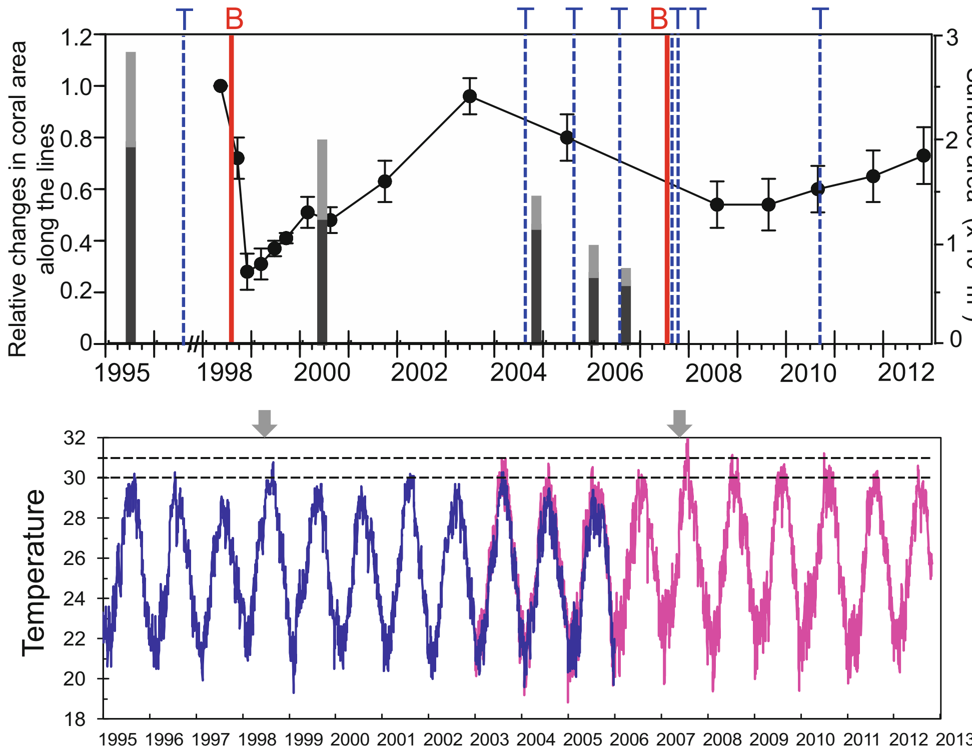

Fig. 7.4 (**a**) Time-series changes in total net area of six dominant coral genera/species along five transect lines from 1998 to 2012. The bars show surface area ($\times 10^3$ m^2) of coral coverage from 50 % to 100 % (*black bars*) and from 5 to 50 % (*gray bars*) in Shiraho Reef from 1995 to 2006 by aerial photographs. *B* bleaching events (*red lines*), *T* typhoons (*blue line*). (**b**) Changes in sea surface temperature from 1998 to 2012 at Ishigaki Port (*blue line*) and Shiraho Reef (*pink line*) (From Harii et al. (2014) with permission of Inter Research)

The observed bleaching events in the eight localities are examined retrospectively in relation to the satellite-based DHW (Kayanne, submitted). In general, DHW provides reasonable threshold for bleaching: DHW of >8 °C induced severe bleaching events. However, in some cases DHW less than 4 °C induced local bleaching events, which might be resulted from local heating event on shallow reef flats (Ishigaki Island in 2007 and several cases in Okinawa before 1996) or bleaching which was not resulted from thermal stresses (Guam in 1994 and 1996 and several cases in Okinawa before 1996).

DHW of >8 °C corresponds to 1-month averaged anomaly of >2 °C, which thermal environment should be easily attained by "+2 °C world" under the global warming. Therefore, unless we tackle with the global warming at once, coral reefs would suffer from severe bleaching every year, and we cannot sustain healthy reefs to the next century, unless they adapt to the thermal stress.

7.2.2 Poleward Range Expansion of Corals

Degradation of corals by thermally induced bleaching has obtained attention for tropical areas. On the other hand, more favorable condition would be expanded to the higher latitudes, and poleward shift in species distribution may occur. Average range shifts have been reported as 6.1 km/decade for terrestrial communities (Parmesan and Yohe 2003), induced by shift of isotherm on land with a velocity of 27.3 km/decade (Burrows et al. 2011). Meta-analysis of response of marine organisms to recent climate change revealed a mean rate of poleward expansion at the leading range edge of marine species was 72.0 ± 13.5 km/decade with faster rate for mobile pelagic organisms (Poloczanska et al. 2013).

Japan coast, along which coral fauna distributes accompanying with strong constraint of SST gradient (Veron and Minchin 1992; Sugihara et al. 2009), provides a unique site to monitor poleward shift of coastal fauna by warming. Yamano et al. (2011) analyzed 80 years of coral fauna records along Japan coast from 29°N to 35°N and found most major coral species showed poleward range expansion with a speed of 140 km/decade since the 1930s. Four major coral species categories (*Acropora hyacinthus*, *A. muricata*, *A. pruinosa*, *and A. solitaryensis*) showed poleward range expansions since the 1930s, whereas no species demonstrated southward range shrinkage. The expansion speed is higher than terrestrial or average marine fauna, which is explained by relatively larger increase in SST (+1.5 °C) along the mainland Japan coast and high dispersal potential of coral larvae delivered by the strong Kuroshio Current.

Model study also showed that coral habitats are projected to expand northward by several hundred kilometers by the end of this century (Yara et al. 2011). However, the northern expansion of coral distribution may be limited by southward shift of the isoline of carbonate saturation state of Ωaragonite = 3, as a limit for tropical coral habitat (Yara et al. 2012). The southern habitat will be suffering from more frequent bleaching, and the model simulation projected that coral habitat will disappear at the end of the twenty-first century under the scenario of "business as usual scenario" corresponding to RCP8.5.

7.3 Ocean Acidification

Anthropogenic increases in CO_2 cause ocean acidification, declining calcium carbonate saturation states ($\Omega = [Ca^{2+}] \times [CO_3^{2-}]/K_{sp}$), and reduced coral reef calcification (red arrows in Fig. 7.5). The effect of ocean acidification to marine calcifiers has been examined by increasing number of CO_2-enrichment experiments in laboratory, which are conducted only for a short time period (days to weeks) under fixed conditions. However, natural environment is changing its physical and chemical conditions daily, seasonally, and inter-annually. As the number of experiments grows, variation of responses to increasing CO_2 has become obvious (Doney et al. 2009). In a high CO_2 experiment conducted under near-natural environment, calcification rate of *Acropora digitifera* did not decrease with increase in CO_2 (Takahashi and Kurihara 2013). Moreover, organisms interact with each other and with physical environment. The relationship between calcification rate and CO_2 is most likely more variable than previously speculated.

Laboratory experiment cannot predict which organisms would replace the present dominant species (in the case of coral reefs, corals). Most projected community changes due to ocean acidification describe transitions from hard coral to non-calcifying macroalgal communities with an analogy from state shift of coral reefs by local stresses (Hoegh-Guldberg et al. 2007). Other organisms have received less attention, despite the biotic diversity of coral reef communities. Therefore, we need to shift our view not only from laboratory but also to actual fields.

In shallow coral reef flats, we observed a large diurnal variation for physical and chemical parameters. In Shiraho Reef, Ishigaki Island, Ryukyu Islands, during daytime dissolved inorganic carbon (DIC) decreases by 400 μmol kg^{-1} by calcification and photosynthesis, total alkalinity (TA) decreases by 100 μmol kg^{-1}, and CO_2 decreases by photosynthesis over calcification (Kayanne et al. 2005). The change in carbonate chemistry showed a large spatial variation by heterogeneity in community metabolisms and hydrodynamics on the reef flat (Watanabe et al. 2013). During nighttime, DIC increases by photosynthesis, and TA shows almost stable values, but in some cases TA shows a slight increase by nighttime dissolution, which was observed when the saturation state of aragonite (Ω_{arag}) in water of 2.5–3.8. It has been known that Mg-calcite with Mg concentration between 8 and 12 mol% as formed by foraminifera, sea urchin, and coralline algae dissolves more readily than aragonite or calcite (Plummer and Mackenzie 1974; Morse et al. 2006). The coral reef flat sediments contain much high Mg-calcite formed by foraminifera and calcareous algae.

Yamamoto et al. (2012) conducted a dissolution experiment and found that foraminifera tests and calcareous algae formed by high Mg-calcite start to dissolve at $\Omega_{arag} = 3.0$. Yamamoto et al. (2015) further explored the sediment-water interface on a calcareous sand in Shiraho Reef and found that Ω_{arag} in sediment pore water deeper than 5 mm had a constant value of 3.0, which equals the saturation

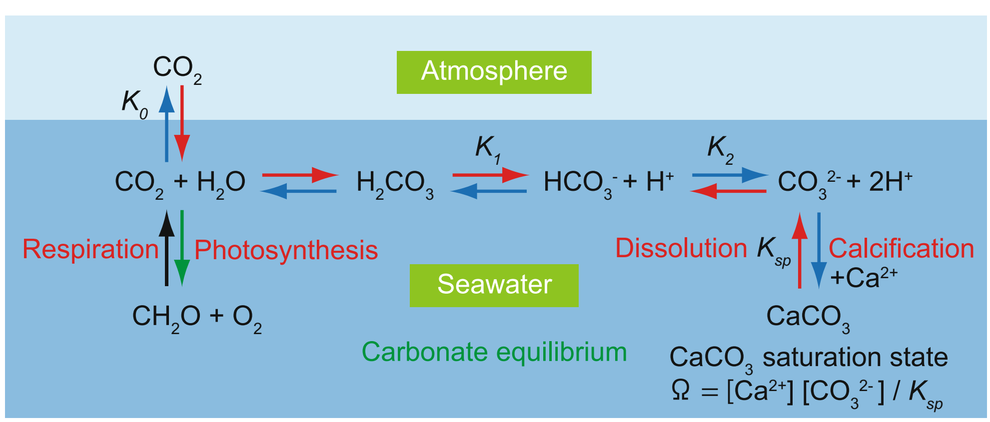

Fig. 7.5 Schematic diagram of ocean carbonate system

threshold of foraminifera. In the sediment pore water, CO_2 released by organic respiration is neutralized by inorganic Mg-calcite dissolution to keep constant saturation state. In the surface sediment, Ω_{arag} and TA had gradients, resulting in a constant TA flux into the water column, which indicates dissolution of Mg-calcite sediment. Dissolution may act as a buffer against increasing CO_2 within sandy areas of coral reefs.

To evaluate acidification impact on ecosystems, natural CO_2 seeps have now been attracted much interest. The first such site was reported from Ischia Island off Italy, Mediterranean Sea (Hall-Spencer et al. 2008). At this site, along gradients of normal pH (8.1–8.2) to lowered pH (mean 7.8–7.9, minimum 7.4–7.5), typical rocky shore communities with abundant calcareous organisms shifted to communities lacking scleractinian corals with significant reduction in sea urchin and coralline algal abundance and dominance of sea grass. The second one, the first from coral reefs, was reported from Milne Bay, Papua New Guinea (Fabricius et al. 2011). At this site, with declining pH from 8.1 to 7.8, coral diversity, recruitment, and the abundance of structural complex framework builders were reduced and the abundance of macroalgae increased, but pH did not affect the abundance of hard corals. Another in situ study of coral reef communities in Mexico also demonstrated that lowered pH derived from high-alkalinity groundwater decreased coral diversity (Crook et al. 2012). These sites suggested that coral community may shift to non-calcifying macroalgae or sea grass by lowered pH of 7.8 (=800 ppm CO_2).

Another CO_2 seep site from coral reefs was reported from Iwotorishima Island, an uninhabited volcanic island in the Ryukyu Islands, Japan (Inoue et al. 2013). Hard corals are restricted to non-acidified low-pCO_2 (225 ppm, pH 8.3) zones, dense populations of the soft coral *Sarcophyton elegans* dominate medium-pCO_2 (831 ppm, pH 7.8) zones, and both hard and soft corals are absent from the highest-pCO_2 (1465 ppm, pH 7.6) zones. Culture experiment confirmed the benefited effect of medium-level pCO_2 to *S. elegans* by enhancing photosynthesis while no effect on light calcification. These results suggest that reef communities may shift from hard coral to soft corals under pCO_2 of 550–970 ppm and challenge the survival of hard corals.

7.4 Sea level Rise

7.4.1 Response of Coral Reef Crest

Coral reefs typically have a shallow reef flat and a reef slope to its seaward. In many cases, a rise, called the reef crest, exists on the seaward edge of the reef flat, which acts as a natural breakwater to separate the reef flat from the open ocean. The reef flat and coastal area behind is protected from ocean waves and swells by the reef crest. Coral reef surfaces caught up with the sea level after its stabilization from 7000 to 4000 years ago with some interruption by environmental deterioration (Hamanaka et al. 2012). The first part of the reef to reach sea level was the reef crest with a vertical accumulation rate of 0.1–0.4 m/100 years (Kayanne 1992) or up to 0.5 m/100 years (Hongo 2012). Some fast-growing corals such as branching *Acropora* can add up to several meters/100 years (Montaggioni 2005), but they are sheltered or shallow water species deeper than 3–5 m, and they cannot construct the reef crest to reach sea surface in the turbulent water conditions of breakwater.

Species-level investigation of Holocene coral reef facies in the northwest Pacific reefs revealed that the robust framework of the reef crest consists of a few species of coral: corymbose and tabular *Acropora* (*A. digitifera*, *A. hyacinthus*, and *A. robusta*/*A. abrotanoides*) and *Isopora palifera* (Hongo and Kayanne 2010, 2011; Hongo 2012). These corals distribute over a present reef edge to an upper reef slope, which is the growth frontier of the present reef formation. Therefore, the corymbose and tabular *Acropora* have a potential to maintain coral reef landforms to catch up with the rising sea level with a rate of 0.5 m/100 years at its maximum (Fig. 7.6). If sea level rise in this century tracks the medium scenario (RCP4.5 or RCP6.0), surface of the present reef crest would be able to catch up with the sea level to maintain its function of breakwater.

However, these key species are most vulnerable to thermal stresses and impact of typhoons (Hongo and Yamano 2013; Harii et al. 2014). For instance, super typhoons, which are projected to occur more frequently by the global warming, will dislodge *A. digitifera*, one of the key coral species (Hongo et al. 2012). Increasing both stresses will degrade the potential of the key species to form a rigid framework to catch up with the rising sea level.

7.4.2 Response of Atoll Islands

Atoll islands are areas of low, flat land, and the sustainability of habitable land in such environments is sensitive to even slight changes in sea level. In the tropical Pacific, a high sea stand of 1–2 m above present level was widely observed from 2000 to 4000 years before present, and many atoll islands were formed during the subsequent relative fall in sea level on the reef flat which caught up with this sea level (Schofield 1977; McLean and Woodroffe 1994; Woodroffe et al. 1999; Kayanne et al. 2011).

In Majuro Atoll, central Pacific, sea level reached high stand of 1.1 m above present mean sea level around 4000 years ago, and coral reef had been formed to catch up

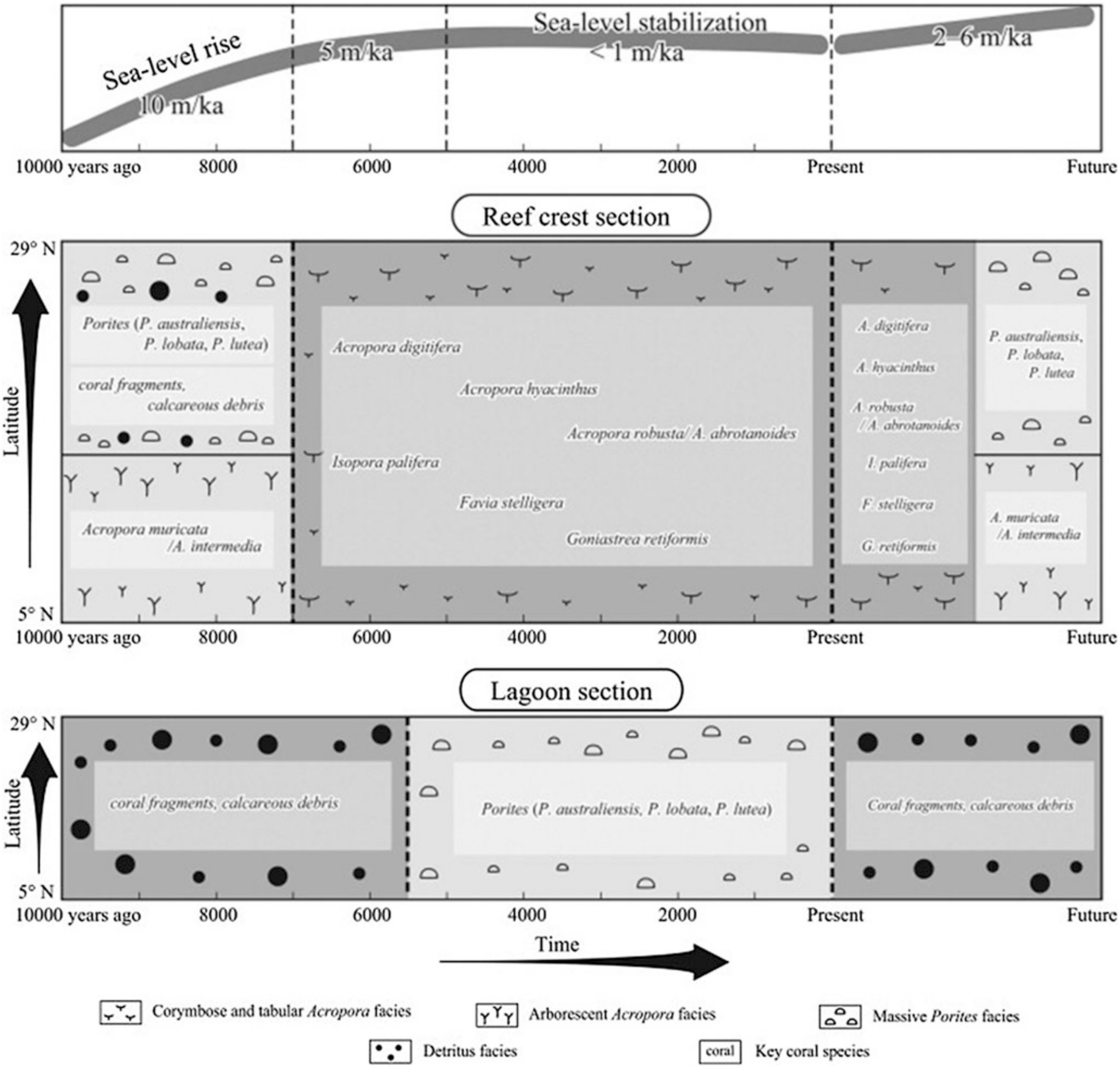

Fig. 7.6 Temporal and spatial patterns of sedimentary facies and key coral species in the Northwest Pacific (Hongo 2012). During the period of rapid sea level rise (10 m/ka) between 10,000 and 7000 years ago, arborescent *Acropora* (*A. muricata*/*A. intermedia*) and massive *Porites* were the dominant contributors to reef growth in tropical and subtropical regions, respectively. During the period of slower sea level rise (5 m/ka) between 7000 and 5000 years ago, the key species were completely replaced by *A. digitifera*, *A. hyacinthus*, *A. robusta*/*A. abrotanoides*, and *Isopora palifera* from corymbose and tabular *Acropora* facies. These coral species contributed to reef crest formation during the period of sea level stabilization to the present. The key coral species of the corymbose and tabular *Acropora* facies is expected to contribute to reef crest formation in response to future sea level rise at a rate of 2–6 m/ka (From Hongo (2012) with permission of Elsevier)

with this level (Fig. 7.7a). Then a fall of sea level occurred 2000 years ago, and an island consisting of coral gravel and foraminifera sand above high water level was formed within 100 years. The emergence of the island was followed by human settlement almost at once (Fig. 7.7b) (Kayanne et al. 2011). The narrow atoll islands have been continuously settled for the past 2000 years since the pioneering people migrated to colonize the bare island, which landscape has been modified by the settlers since colonization, with particular rapid change in recent years (Yamaguchi et al. 2009).

Fongafale Island, the capital of Tuvalu, inundated during spring high tide, which has been reported to be possibly

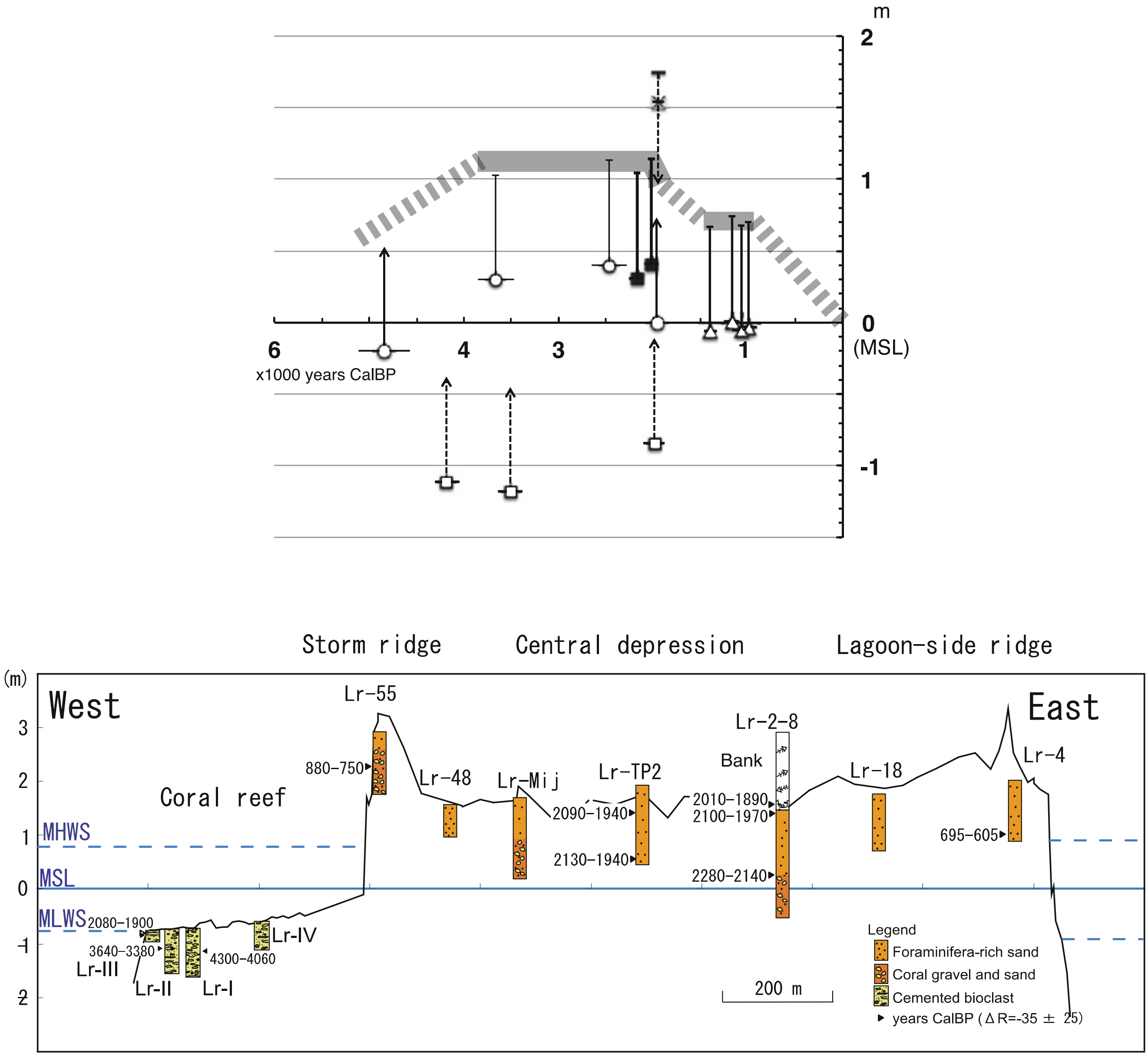

Fig. 7.7 Holocene sea level change and cross section of Laura Island, Majuro Atoll (From Kayanne et al. Rapid settlement of Majuro Atoll, central Pacific, following its emergence at 2000 years CalBP. Copyright © 2011 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc)

related to sea level rise, since local people claim that they never had experienced such inundation before (Patel 2006). However, historical maps, aerial photos, and satellite images revealed that the inundation is resulted from expansion of residential area into low swampland in the course of population increase since the independence of Tuvalu in 1978 (Yamano et al. 2007).

Moreover, ecosystem degradation by human impact reduced the foraminifera sand production in the capital island of Majuro (Osawa et al. 2010) and Tuvalu (Fujita et al. 2013). The sand transportation along the coast was blocked by artificial constructions such as a causeway, piers, and dredges. Therefore, environmental problems in atoll islands at present are not as simple as submergence by sea level rise but more complex mainly induced by local human impacts in the course of population increase (Fig. 7.8). However, these local issues increased vulnerability of atoll islands against projected future sea level rise up to 1 m by

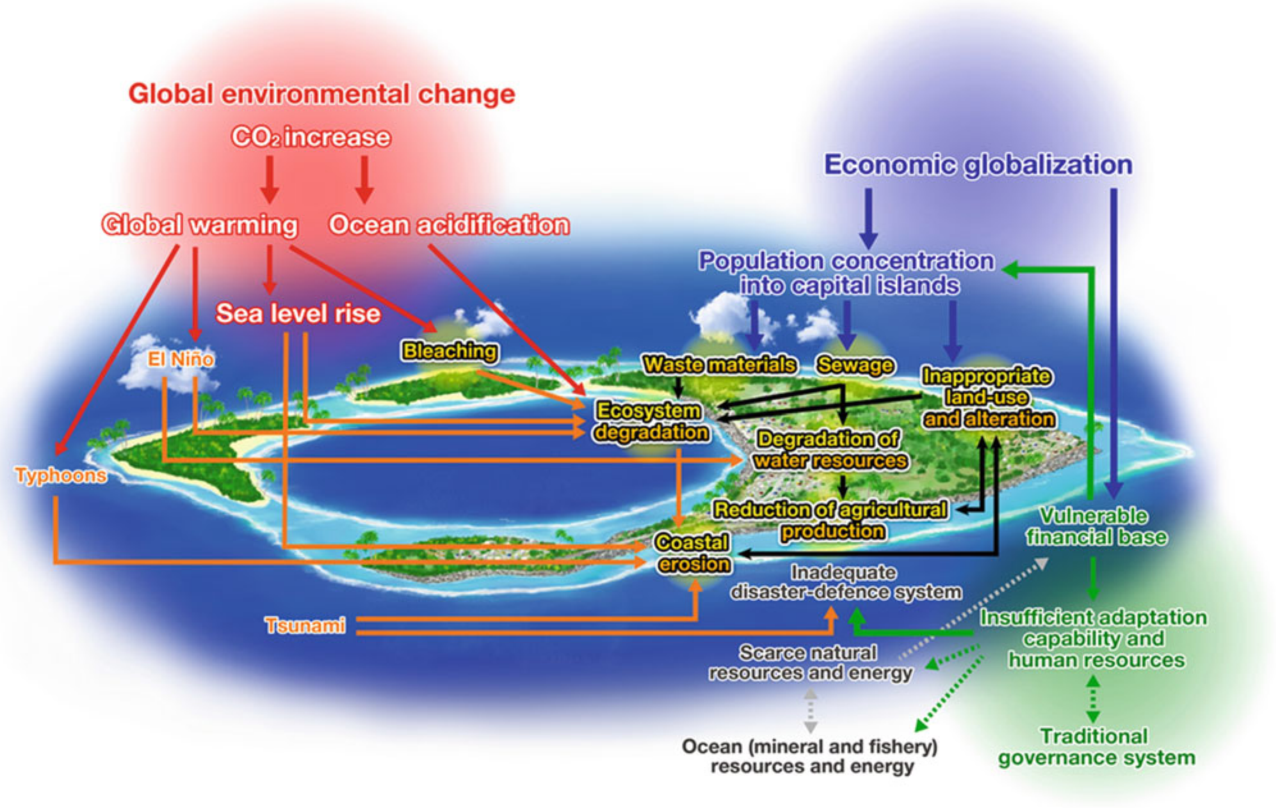

Fig. 7.8 Combined threats to atoll islands

the end of this century. Thus, to sustain atoll island against sea level rise, rehabilitation of natural island formation process is most important.

7.5 Management and Conservation of Coral Reefs in the "+2 °C World"

7.5.1 Future Scenario

Table 7.1 summarizes the future scenarios of the global warming relative to the preindustrial level, roughly approximating the RCP scenarios of AR5, IPCC. We have already emitted 370 GtC by fossil fuel burning and atmospheric CO_2 concentration reached 400 ppm. The averaged temperature has increased 0.8 °C, pH has decreased by 0.1 unit to 8.1, and sea level has risen by 0.2 m from preindustrial time. If we tackle with the global warming by reducing fossil fuel emission and by increasing CO_2 sink at once, the CO_2 concentration will be stabilized at 420 ppm, and there will be an increase of temperature at 1.5 °C (+1 °C world in Table 5.2) in the twenty-first century. The pH level will not reduce below 8.0, but sea level will show relatively large increase with a time lag to heat large volume of the ocean water and to melt glaciers. In the "+1 °C world," corals will be able to survive, but severe bleaching will occur every 5 years (Frieler et al. 2013). Ocean acidification will not affect most of the coral reefs, and they will be able to sustain coral reef landform with their reef crest keeping up with the rising sea level with 0.6 m/100 years. However, sustainability of coral reefs will be achieved only by healthy corals, and if humans would increase local pressure and degrade the reef health, they cannot sustain its landforms.

Under the condition of "+2 °C world," more probable scenario as we have shown no signature of reducing CO_2 emission by now, the future of coral reefs is more pessimistic. Severe bleaching would occur every year, and coral reef calcification would be reduced to become net dissolution below pH 8.0 unit. Reef crest cannot keep up with the rising sea level of 0.7 m, because the rate exceeds the potential vertical accumulation rate of coral reef top together with degradation of key coral species by warming and acidification. The coral population would shift from hard corals to macroalgae or soft corals, both of which have no function of reef landform formation.

Table 7.1 Approximate scenarios of the global warming by year 2100 relative to preindustrial time (year 1850)

		Cumulative CO_2 emission	Atmospheric CO_2 concentration	Average temperature	pH	Sea level (ultimate rise)	Corresponding RCP by IPCC
		GtC	ppm	°C		m	
Preindustrial		–	300	–	8.2	–	
Present		370	400	+0.8	8.1	+0.2	
In 2100	+1 °C world	650	420	+1.5	8.0	+0.6 (+1–2?)	RCP2.6
	+2 °C world	1000–1500	550–700	+2–+3	8.0–7.9	+0.7 (+2–4?)	RCP4.5, 6.0
	+4 °C world	2000	900	+4	7.8	+0.8 (+5–9?)	RCP8.5

In any cases, "+2 °C world" is the threshold to maintain coral reefs with their meaningful coverage of living corals. It might be possible for corals to adapt to the increasing SST and decreasing pH, yet it is susceptible that they adapt to the change within such a short time of 100 years. Under the worst scenario of "+4 °C world," no corals will be able to survive and present reef will be covered by macroalgae, which will be submerged by high rate of sea level rise in the centuries to come.

Each factor of the global warming would give a stress, and they combine to give a synergistic effect. Corals are more susceptible to bleaching by a combined effect of high SST and low pH (Anthony et al. 2008). If coral coverage and calcification rate would decrease by bleaching and ocean acidification, respectively, function of coral reefs to form a rigid structure to keep up with sea level rise would be lost.

7.5.2 Feedback Loops

Relation between the global warming scenario and coral reefs is schematically shown in Fig. 7.9. Solid line represents a positive coupling, in which an increase (decrease) in one component leads to an increase (decrease) in the linked component. When CO_2 increases, SST increases and sea level increases. Global warming scenario is linked by a series of positive couplings. In contrast, dashed line represents a negative coupling, in which an increase (decrease) in one component leads to a decrease (increase) in the linked component. As CO_2 increases, calcification decreases by the ocean acidification; and as SST increases, photosynthesis decreases by bleaching (Kayanne et al. 2005).

In some cases, link of the positive and negative couplings returned to the same component to form a positive or negative feedback loops. As CO_2 increases and as a result SST increases, photosynthetic production decreases leading to loss of fixation capacity of CO_2. This is the positive feedback loop as increase in CO_2 enhances its increase within the loop. On the other hand, as CO_2 increases, calcification decreases, which then buffers increase in CO_2, acting as a negative feedback loop. Increase in CO_2 enhances photosynthesis and fixes more CO_2 to counteracts its increase, which also acts as a negative feedback loop. All these loops are rather small to feedback to global environmental change, but would act to change coral reef carbonate chemistry (Fig. 7.5) (Anthony et al. 2011; Kleypas et al. 2011). Negative feedback loops act to stabilize reef water chemistry and buffer the increase of CO_2.

These feedback loops between the global environmental change and coral reefs are added to local human stresses such as eutrophication, effluent of silt, and over-fishing. These local stresses generally favor macroalgae dominance over corals and then degrade the coral reef landform formation processes. The system with feedback loops may sometimes trigger phase shift in which dramatic and irreversible state change occurs at a threshold point of stresses outside the system (Scheffer et al. 2001). Phase shift from coral-dominated to macroalgal-dominated reefs is regarded as one of the representative cases of ecosystem phase shift and has been modeled mainly between coral and macroalgal cover (Hoegh-Guldberg et al. 2007; Mumby et al. 2007). The increase or decrease of all the components can be reversed within the same positive or negative feedback loops. The decreasing trend of coral cover within a positive feedback loop can be reversed to increase its cover within the same positive feedback. The degradation of coral is not "negative" feedback as was misinterpreted in Mumby and Steneck (2008) and Mumby (2009).

7.5.3 Management and Conservation

Reduction of local stresses must firstly be achieved to conserve coral reefs against global environmental changes. If reef degradation was enhanced by a positive feedback loop, efforts to turn at least one component should be conducted to

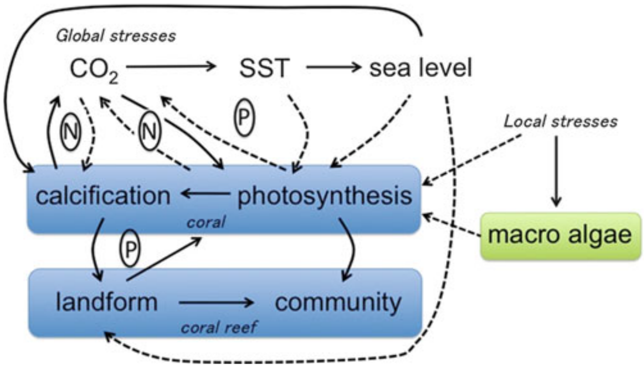

Fig. 7.9 Feedback loops between global stresses and coral and coral reefs. *Solid lines*: positive couplings; *dashed lines*: negative couplings. P and N denote positive and negative feedbacks, respectively

reverse it into reef rehabilitation: decrease macroalgal cover, reduction of local stresses or enhance coral metabolisms.

Magnitudes of effects of global warming and ocean acidification are varied geographically. Reef sites with higher rate of exchange with the ocean water or sheltered from warm surface water in relatively deep water must be prioritized to conserve and to remove local stresses.

Mass culture of corals must also be taken into consideration (Nakamura et al. 2011). In juvenile culture process, corals and symbiotic algae which are more tolerant to stresses should be challenged. In transplantation of juvenile corals, appropriate species must be transplanted at appropriate habitat. To maintain reef structure, the key coral species must be planted in the edge of reef crest. Removal of local stresses is prerequisite.

Adaptation of corals to global stresses (higher SST and lower pH) was not discussed in this chapter, though increasing number of studies have confirmed the evidence. However, it is susceptible that corals can keep up to adapt the enhanced rates of the changes in this century.

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