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Global change and coral reefs: impacts on reefs, economies and human cultures

CLIVE R. WILKINSON
Australian Institute of Marine Science, PMB no. 3, Townsville MC, 4810 Australia

Abstract

Coral reefs have reconstituted themselves after previous large sea-level variations, and climate changes. For the past 6000 years of unusually stable sea-level, reefs have grown without serious interruptions. During recent decades, however, new stresses threaten localized devastation of many reefs. A new period of global climate change is occurring, stimulated by anthropogenic increases in greenhouse gases. Coral reefs will cope well with predicted sea-level rises of 4.5 cm per decade, but reef islands will not. Higher sea levels will provide corals with greater room for growth across reef flats, but there are no foreseeable mechanisms for reef island growth to keep pace with sea-level rise, therefore many low islands may ultimately become uninhabitable.

Climate change will introduce localized variations in weather patterns, but changes to individual reefs cannot be predicted. Reefs on average should cope well with regional climate change, as they have coped with similar previous fluctuations. Air temperature increases of 0.2–0.3 °C/decade will induce slower increases in sea-surface temperatures, which may cause localized, or regional increases in coral bleaching. Changes in rainfall will impact on reefs near land masses. Likewise, increased storms and variations in El Niño Southern Oscillation (ENSO) may stress some reefs, but not others.

The greatest impact of climate change will be a synergistic enhancement of direct anthropogenic stresses (excessive sediment and pollution from the land; over-fishing, especially via destructive methods; mining of coral rock and sand; and engineering modifications), which currently cause most damage to coral reefs. Many of the world's reefs have been degraded and more will be damaged as anthropogenic impacts increase under the 'demophoric' increases in population (demos) and economic (phoric) activity. This biotic and habitat loss will result in severe economic and social losses. Reefs, however, have considerable recovery powers and losses can be minimized by effective management of direct human impacts and reducing indirect threats of global climate change.

Keywords: coral reefs, economies, fisheries, global change, pollution, tourism

Introduction

Recently, increasing attention has been focused on how global change is adversely affecting coral reefs. The worst-case scenario presented in 1992 at the 7th International Coral Reef Symposium in Guam, indicated possible losses of up to 70% of the world's reefs in four decades, if rectifying management was not undertaken (Wilkinson 1993). Anthropogenic activities are the major factors behind changes in coral reef structures and productivity (Gomez 1988; Kinsey 1988; Grigg & Dollar 1990; Buddemeier 1993). All this spawned the International Coral Reef Initiative (ICRI) in 1994 and other international co-operative actions to seek solutions for this apparent decline (Crosby *et al.* 1995).

My theme emphasizes how 'global change' is affecting the interactions between coral reefs and the peoples associated with them. Reefs are currently being severely damaged by anthropogenic stresses (Wilkinson 1993) and global climate change poses new threats. The prospect of synergism between these two introduces significantly greater problems for people who live on reefs or use the resources.

A Global Coral Reef Task Team, sponsored by IOC–UNEP-ASPEI–IUCN (Intergovernmental Oceanographic Commission, United Nations Environment Programme, Association of South Pacific Environmental Institutions,

Correspondence: fax +61/77-72-5852

Table 1. Demographic data on countries and states with large areas of coral reefs. Many of these have high rates of population growth (Growth rate %), but low levels of GNP (Gross National Product) per capita (in US$). Many smaller Pacific Island states have little export income and rely on external aid, shown as negative Balance per capita (except for Nauru which is a net exporter of phosphate fertiliser).

Country/Territory	Atoll population ×1000	Total population ×1000	Growth rate %	Population density per km^2	Coastline length km	GNP per capita	Balance per capita
Atoll Islands (predominantly)							
Kiribati	72	80	2.1	108	1143	720	–215
Maldives	240	240	3.7	800	644	820	
Marshall Is	52	52	3.4	255		1000	
Tokelau	2	2	1.5	180			
Tuvalu	11	11	2.4	392	24	450	–335
Mixed Atoll and High Island							
Comoros Archipelago	1	521	3.5	229	340	520	
Cook Is	1	18	5.3	71	120	2600	–2120
Fed States Micronesia	16	102	4.0	144		905	
Fiji	3	796	1.5	44	1129	2140	–207
French Polynesia	15	210	2.8	56	2525	13030	–2940
Palau	0.1	15	0.7	31		1020	
Samoa U.S.	1	53	2.7	234		4400	–1240
Samoa W		200	2.2	71		980	–340
Seychelles	1	80	1.6	230	491	6370	
Tonga	0.5	105	0.8	146	419	1610	–450
Wallis & Futuna		18	2.3	55			
Small to Medium Islands with Reefs							
Bahamas		274	1.9	27	3542	11750	
Barbados		273	0.9	63	97	6240	
Dominica		88	1.6	77	148	2440	
Dominican Rep.		7680	2.2	159	1288	1080	
Grenada		97	2.0	301	121	2410	
Guam		145	2.2	247		8140	
Haiti		6997	2.0	254	1177	370	
Indonesia		194950	1.8	108	54711	730	
Jamaica		2540	1.2	235	1022	1380	
Japan		125900	0.4	332	13685	31540	
Madagascar		13450	3.2	23	4828	240	
Mauritius		1140	1.2	616	177	2980	
Nauru		10	2.3	480		20000	+5924
New Caledonia		180	1.0	9	2254	11000	–480
Niue		2	–5.3	10	64		
Papua New Guinea		4270	2.3	9	5152	1120	–23
Philippines		67600	2.5	227	22542	830	
Puerto Rico		3815	0.9	424		7020	
Singapore		2905	1.1	4762	193	19310	
Solomon Is		370	3.6	13	5313	750	–106
Sri Lanka		17905	1.3	277	1340	600	
Trinidad & Tobago		1364	1.4	266	362	3760	
Vanuatu		200	2.4	51	5828	1230	–285
Continental Land with Substantial Reefs							
Australia		18010	1.4	2	25760	17050	
Belize		208	2.4	9	386	2240	

Table 1. *Cont.*

Country/Territory	Atoll population ×1000	Total population ×1000	Growth rate %	Population density per km^2	Coastline length km	GNP per capita	Balance per capita
Columbia		34929	1.9	34	2414	1400	
Costa Rica		3350	2.3	66	1290	2160	
Cuba		11010	0.9	100	3735	1000	
Djibouti		441	2.9	22		780	
Eritrea		3500	2.7	48	1094	120	
Honduras		5806	3.2	52	820	580	
India		920310	2.1	310	12700	330	
Kenya		27685	3.6	49	536	340	
Malaysia		19640	2.6	60	4675	3160	
Nicaragua		4260	3.4	36	910	460	
Oman		1519	3.8	8	2092	6120	
Panama		2660	1.9	35	2490	2580	
Saudi Arabia		17500	3.8	8	2510	7820	
Somalia		8235	2.4	13	3025	120	
Sudan		29250	2.9	12	853	450	
Tanzania		28200	3.7	32	1424	100	
Thailand		59825	1.4	117	3219	2040	
Venezuela		21280	2.6	24	2800	2730	
Vietnam		70990	2.2	218	3444	215	
Yemen (Rep.)		13812	3.5	26	1906	520	

Data from Table 3.1 in Wilkinson & Buddemeier (1994), with additional data from World Resources Institute (1994), SBS (1995).

and the International Union for the Conservation of Nature and Natural Resources) produced a report on the effects of global climate change on coral reefs (Wilkinson & Buddemeier 1994). This paper extracts material from that report, along with new information, and includes the most recent predictions of climate change (Callander 1995).

Human societies and coral reefs

The major traditional role for coral reefs was to provide a place to live with available food and building materials (rock and sand). These traditional roles continue, with the addition of new values for reefs that can potentially provide greater wealth for developing tropical countries. Coral reefs are a major focus for recreation and tourism, the most rapidly expanding sector being ecotourism. Coastal reefs are also the recipients of land-based pollution, as it is 'cheaper' to dump wastes into rivers and the sea than treat them.

Reefs and habitation

Coral reef growth has created or expanded land masses which now host millions of people (Table 1). Approximately 350 million of the world's 5.8 billion people live on coral islands or islands with large components of coral reefs; more than 450 million live within 60 km of coral reefs, and directly or indirectly derive income and food from those reefs (World Resources Institute 1994; SBS 1995). Some of these countries have large populations, e.g. Indonesia (195 million) the Philippines (68 million), but other small independent nations like Tokelau (1700) and Niue (1600) have few people.

The islands of the Pacific were populated over a protracted period by migration 'waves': Polynesian peoples populated New Zealand, Hawaii, Tonga, Cook Islands and French Polynesia during the present interglacial period; Melanesian peoples colonized the high islands of the western Pacific (Papua New Guinea, Solomon Islands, Vanuatu and New Caledonia) as far back as 40,000 years ago; and Micronesian peoples colonized many low islands (Micronesia, Marshall Islands) during the last 2000 years of stable high sea-level.

Over the centuries, these peoples developed cultures based on the utilization of island resources, which were often finite e.g. coral reef fisheries. These island cultures introduced many 'modern' fisheries management practices e.g. restricted seasons, protection of spawning aggregations, catch limits (Johannes *et al.* 1991).

Caribbean islands were originally occupied by American Indians (tens of thousands of years ago), who were displaced by immigrants from Europe and Africa. These more recent cultures have had insufficient time to evolve sustainable management practices to conserve restricted resources, resulting in a steady decline in fishery stocks on many islands (Munro 1983).

The majority of people associated with coral reefs live in developing countries with low levels of external income, with foreign aid often being the largest component (Table 1). Currently about 60 member countries of the United Nations have coral reefs, such that their conservation has become a significant environmental issue, warranting specific mention in the 1992 UN Conference on Environment and Development (Chapter 17 of Agenda 21), and in the UN Resolution on Defence of Small Island States.

Extraction of building materials

On isolated islands, the only readily available building materials are timber, coral rocks and sand. The removal of sand and rock is potentially a sustainable activity, if the removal is maintained within the ability of the reef to produce calcium carbonate, or is harvested off the deep slopes away from living corals and the wave impacted areas. Mining of sand off reef flats, however, is likely to aggravate erosion damage to nearby islands from global sea level rise.

Most buildings in the Maldives have been constructed from coral blocks and recent mining and reclamation of the reef flat has removed that protective barrier (Brown & Dunce 1988; Kenchington 1990). These activities were largely responsible for the extensive flooding of the capital, Male, in 1987 from waves arising from a distant storm (Pernetta & Sestini 1989). Similarly, reefs in Sri Lanka, southern India and Indonesia have been dredged to depletion for limestone to manufacture cement (Brown 1986; UNEP/IUCN 1988). Similar unsustainable mining of sand has occurred in Mauritius and Fiji (UNEP/IUCN 1988).

Fisheries

Coral reef and adjacent open water fisheries originally provided the major animal protein source for most island peoples, and the basis for much cultural activity. For many Pacific island and remote Caribbean communities, coral reef seafood provided between 80 and 98% of animal protein (Pernetta & Hill 1982). Approximately 60% of animal protein for south-east Asia comes from fisheries with coral reefs providing 10–15% of this (Gomez & Chou 1994). There are ≈ 4.5 million people involved in fishing from tropical coral reefs, with ≈ 90% of these involved in subsistence fishing, but taking only about 40% of the total catch (Weber 1993, 1994). Recently, this dependence on seafood has decreased slightly with people purchasing imported food using aid money (Table 1).

Fishing remains a predominantly male occupation, with considerable status being given to the best fishermen (Johannes 1981). Most fishing was focused on adjacent reefs and labour intensive, using traditional methods of hook and line, nets, traps, spearing (mostly from the surface) and the construction of wooden or rock corrals on reef flats and in passes to lagoons. Transport was limited by the ability to sail or paddle to adjacent reefs and the risks associated with longer voyages. Thus, fish stocks were only depleted around inhabited islands, leaving extensive areas with adult populations able to provide a large pool of pelagic larvae.

More recently these limitations have been reduced or removed with the introduction of outboard motors. Moreover, the ability to spear fish and harvest other resources has greatly increased now that diving masks and rubber powered spearguns are available. For example, the virtual extinction of pearl shell in Tokelau is related to the introduction of diving masks (Toloa & Gillett 1989), and tridacnid clams are functionally extinct on many Indo-Pacific reefs (Gomez & Alcala 1988; Govan *et al.* 1988). On wealthier islands like Nauru, spearfishing with scuba has resulted in marked reductions in target fish species (Dalzell & Debao 1994).

Fish stocks on many coral reefs are showing distinct signs of over-exploitation, although there have been few long-term scientific studies (Goodyear 1988; Pauly 1989). Over-exploitation is prevalent near large centres of population in developing countries. The best example is the north coast of Jamaica, where there were warnings in 1959 of adverse consequences because of severely depleted fish stocks (Munro 1983). Two unrelated events, a hurricane and the widespread death of the predominant grazing urchin (*Diadema antillarum*), dropped coral cover from 40 to 70% to less than 5%, but over-fishing was the main reason for poor coral recovery, because there were no grazing fish or urchins to prevent algae from monopolizing all available surfaces (Hughes 1989, 1994).

Over-fishing removes ecological controls on reefs and can lead to massive phase shifts in populations, from reefs dominated by corals to dominance by macroalgae, soft corals or echinoids (Done 1992). Removal of urchin predators, particularly ballistids, has resulted in population explosions of algal grazing urchins in many centres, including Kenya (McClanahan & Obura 1995), Okinawa (Chou & Yamazato 1990), and Indonesia (CRW unpublished data). Grazing urchins, especially *Enhinometra mathei* actively undermine corals and remove newly settled corals.

There has been considerable recent emphasis on creating export fisheries in tropical waters with the use of aid money, but there are distinct signs that these fisheries may not be sustainable. While coral reefs have high gross productivity, most of the productivity on clean water coral reefs is tightly recycled back into the reef community, such that there is little available net fisheries productivity that can be harvested without damaging that reef community (Birkeland 1987).

Coral reef islands have few exploitable resources other than fisheries, and these are being overdeveloped through either foreign aid or external contracted fishing companies from Japan, Taiwan, USA. Fishing for export must return ≈ 10 times the 'return' from subsistence fishing to account for losses in poor handling and costs of equipment and fuel associated with larger vessels, packaging, transport, and marketing (Dalzell *et al.* 1996). Export fishing companies greatly undervalue the resource in contracts and employ relatively few fishermen, who take a disproportionately higher catch than subsistence fishers. Unfortunately, returns from local fishing cooperatives or external operators have been of little benefit to island economies.

Nevertheless, coral reef fisheries amount to 10–13% of the world fisheries catch of around 90 million t (metric tonnes; Munro & Williams 1985). A more specific estimate for coastal fisheries of the South Pacific is US$262 million from 108,000 t, with about 80% of this consumed locally by the families of subsistence fishers (Dalzell *et al.* 1996). Half of this comes from coral reef fisheries, with the rest being derived from pelagic species. The most valuable products are invertebrates, holothuroids (beche-de-mer), molluscs (tridacnids, trochus and pearl oyster), lobsters, crabs, along with the expansion of maricultured peneid shrimp. Of this catch, ≈ 20% is exported (about US$ 81 million).

Tuna fishing in the Pacific is larger, with landings in excess of one million t (over US$ 1000 million; Anon 1993). Although the bulk of these catches are taken from the Exclusive Economic Zones of Pacific Island States, less than 3% are caught by island fishing cooperatives and only 25% are landed in Pacific Islands; the rest is exported directly to east Asia and North America (Anon 1991).

Many island populations developed traditional management of their resources for sustainable harvest. The lack of control on commercial fishing is now resulting in localized extinctions of some species, notably tridacnid clams. There have also been severe depletions of some holothuroid and trochus species on many reefs and target fish species are rare.

Declining catches often induce subsistence fishermen to resort to more destructive methods to maintain catches. Catches by 200 fishermen from the reefs off Jakarta, Indonesia declined from 1200 t per annum in the early 80 s to less than 200 t in 1990 (Tomascik *et al.* 1994). Blast fishing increased and caused considerable damage to the reefs. Similar reductions have lead to the widespread use of dynamite and poisons throughout the Indo-Pacific and small mesh traps in Caribbean waters.

Cyanide fishing is probably the most destructive and 'efficient' mechanism of harvesting reef fishes. In the Indo-Pacific, this has expanded from small-scale aquarium fish capture, to the excessive use of cyanide to harvest reef fish (Johannes & Riepen 1995). It is now a major fishery with conservative estimates of 25,000 t of live serranids and labrids being exported each year to Hong Kong and other Chinese centres for the restaurant trade. Many remote reefs in the Philippines have been effectively stripped of plate-sized fish, with cyanide fishing now reported in eastern Indonesia, Papua New Guinea, other Pacific islands, the Maldives and Seychelles. But cyanide also kills most invertebrates, including corals, thereby diminishing chances for new fish recruitment.

The impacts of over-fishing on breeding stocks will be difficult to detect until the fisheries actually collapse (Dalzell *et al.* 1996), because the location of source reefs for coral reef larvae remain largely unknown.

Over-harvesting is threatening the survival of coral reef-associated turtles throughout the IndoPacific and Caribbean, through over-collection of eggs on nesting beaches, harvesting of adults at sea, and inadvertent harvesting during trawling (Limpus *et al.* 1993). Traditional hunting methods have been replaced by the more effficient use of outboard-powered aluminium boats. A similar pattern of over-harvesting is occurring for dugong, which often feed over seagrass beds adjacent to coral reefs.

Women and children are more involved in gleaning reef flats for molluscs, crustaceans and algae and in small-scale mariculture of algal species for food and traditional medicines. More recently, this mariculture has expanded to supply markets in Asia and Europe with algae for the production of carrageenan and alginates.

Many island peoples derived drugs and cultural items from reefs, which are now a major target for pharmaceutical companies bioprospecting for novel compounds (de Vries & Hall 1994). The high biodiversity of reefs is attractive because animals and plants employ many means, including 'chemical warfare', to survive in these crowded habitats.

Land-based pollution

A major impact on many coral reef communities is organic and inorganic pollution (summarized in Wilkinson & Buddemeier 1994). Nutrients wash out of the soil after over-grazing and clearing of forests, leach out from fertilized lands and are dumped as domestic and industrial sewage (Moss *et al.* 1992). Excess inorganic nitrogen and phosphorous favours the growth of algae over symbiotic corals: phytoplankton growth results in light shielding to the benthos; increased turf algal growth covers surfaces, thereby preventing coral recruitment; and enhanced macroalgal growth increases competition with corals and results in physical smothering.

Organic pollution, particularly from intensive animal rearing and domestic sewage, enhances the growth of filter-feeding animals (ascidians, sponges and soft corals), which either outcompete corals or result in increased bioerosion via burrowing molluscs, sponges and polychaete worms.

Such effects occurred when Kaneohe Bay, Hawaii was polluted and then reversed when the sewage was diverted out to sea (Smith *et al.* 1981).

The rate of pollution is increasing exponentially in many developing countries, with rapid 'demophoric' (Vallentyne 1972) increases in population (annual increases of 2–4%) combined with economic activity (5–15% increases in GNP; World Resources Institute 1994).

The growth of corals is limited by high concentrations of sediments, particularly near large rivers. Increased rates of tropical forest exploitation and clearing of land for agriculture and domestic use have resulted in massive increases in sediment runoff into tropical waters with coral reefs (Dubinsky & Stambler 1996). For example, the coral reefs off Singapore once grew below 10 m depth, but many now do not grow below 5m, as a result of land clearing and extensive reclamation (Chou 1991).

Coral reef tourism

Coral reefs are a major attraction for international tourists, particularly in the rapidly expanding field of ecotourism. The classical features of coral reefs — clean beaches, clear water, high biodiversity of corals and fish, and warm weather, are major factors that attract tourists from wealthier, temperate countries. Incomes from tourism are often the largest source of external earnings for islands with coral reefs, which lack other significant resources. Tourism can provide the major sustainable use for reefs, provided there is efficient management of infrastructure construction and use.

Tourism in south-east Asia has shown an annual growth in earnings between 5% (Philippines) and 50% (Indonesia) since the mid 80s, with the coastal resources being a major attractant (Wilkinson *et al.* 1994). In Thailand, tourism is the major 'export' earner with 3.4% of total GNP, evident as spectacular growth of more than 25% per year in tourist numbers at the coral reef resorts of Pattaya Bay, Phuket and Ko Samui, directly yielding US$65 million in 1991 (Sudara & Nateekanjanalarp 1992). Likewise, the economy of the Maldives is almost totally dependent on coral reef tourism, with fisheries as the next largest component, and a similar situation occurs for the Seychelles, with tourism amounting to 17% of GDP and 70% of foreign currency earnings (Shah 1995).

Tourism is the major income earner for many Pacific Island states; however, earnings are not evenly spread. Those states readily accessed by international air travel are profiting, whereas smaller or remote states are 'missing the boat'. Coral reef tourism is the primary revenue source for French Polynesia, bringing US$240 million in 1994 (up 20% on previous year) from 170,000 visitors. Tourism earns more than all other industries combined in the Cook Islands with 57,000 visitors in 1994, providing US$33 million. Likewise for Tonga, tourism is the most important industry earning US$11 million with 43,500 visitors (15,000 on cruise ships; Anon 1995).

The coral reefs and beaches of Hanauma Bay, Hawaii attract three million people per year, by far the most popular attraction in the islands (Gallagher & Lee 1995). Before restrictions were implemented, visitor numbers exceeded the stated maximum daily occupancy by six times.

In the Caribbean, tourism provides 15–30% of the GNP for many island states (total of US$8.9 billion in 1990), with divers and visitors to coral reefs comprising 20% of this (Dixon 1993). For example, reef tourism brings one million tourists each year to Florida, returning US$46.5 million at an average of $85 per m^2 of coral reef. Similarly, marine-protected areas of the Caribbean gross 10–20 times more than is spent on maintenance (Dixon 1993). The Virgin Islands National Park yielded $23.3 million in the early 80s, against $2.1 million for park expenses, and the Saba and Bonaire Marine Parks in the Netherlands Antilles yielded $1.5 million and $23.2 million, respectively, against running costs of approximately $1 million for each park.

The Great Barrier Reef (GBR) contributed US$683 million to the Australian economy in 1992. Tourism was the largest component being $505 million, commercial fishing yielded 16,000 t at $95 million, recreational boating and fishing $70 million, and research $14 million. Another $500 million was added indirectly to the regional economy because of the GBR (Drirnl 1994). Incomes from tourism are increasing markedly and appear sustainable, as the whole system is adequately managed. Some fears have been expressed whether current fishing intensity is sustainable, but the area is subject to extensive research and large areas have been set aside as replenishment reserves.

Impacts of climate change on coral reefs

There are five potential impacts or implications of global climate change on coral reefs:

• elevated concentrations of CO_2 in the atmosphere and dissolved in seawater (Kayanne 1996);

• temperature rise in the waters surrounding coral reefs (Glynn 1996);

• increases in UV radiation due to destruction of the ozone layer (Shick *et al.* 1996; Glynn 1996);

• potential impacts of climate change induced sea level rise on coral reefs; and

• changes in the frequency of storms and alterations in rain patterns and freshwater runoff.

The last two will be discussed below and the other three are discussed elsewhere in this Issue and summarized in Kinzie & Buddemeier (1996).

Climate change impacts on reef communities

Coral reefs continued to exist when sea levels dropped by over 100 m and mean temperature fell by 8 °C and then they flourished again during the warmer periods of higher sea level (reviews Buddemeier & Smith 1988; Wilkinson & Buddemeier 1994). These variations occurred with a near doubling of CO_2 concentrations and significant 'greenhouse' climate changes in rainfall, cloud cover, storms and currents. These previous rates of change probably exceed those that coral reefs are likely to experience during current 'anthropogenic' climate change (Callander 1995).

Most coral reefs kept up with 20 cm per decade sea-level rises between 14,000 and 6000 years ago (Digerfeldt & Hendry 1987). Relatively stable sea levels since then have curtailed upward reef growth, resulting in extensive reef flats in the Indo-Pacific and somewhat narrower ones in the Atlantic-Caribbean. Current predictions of sea-level rise of 4.5 cm per decade (range 1–9 cm; Wigley & Raper 1992; Callander 1995) are low compared to Holocene rates of rise. The predicted rises should be 'beneficial', permitting increased growth over the previously limited reef flats (Buddemeier & Smith 1988). The rises will cause imperceptible effects on the deeper parts of reefs (below 30 m on some reefs), which are usually limited by light attenuation caused by particulate matter in the water.

Sea-level rise will, however, have serious impacts on coral reef islands, particularly low-lying coral cays (Wilkinson & Buddemeier 1994). Rising sea water will contaminate the groundwater that currently supports much of the island vegetation and agriculture, and is also used for drinking water in dry periods (Fig. 1). Salt water intrusion will occur before increased sea levels drain seawater directly into the fresh water lens, because storm surges will push greater volumes of seawater over the islands and enter groundwater from above. Consolidated upward growth of reef flats is unlikely to be sufficient to prevent stormwater intrusion and there are no perceived mechanisms for increased reef growth to be translated into sufficient upward growth of islands to match these rates of sea-level change (Wilkinson & Buddemeier 1994).

Current climate change models suggest significant changes in weather patterns across the globe, but these models are not sufficiently precise to predict changes near a particular coral reef (Houghton *et al.* 1992; Wigley & Raper 1992). For example, it is probable that climate warming will be greater in the southern hemisphere, because higher levels of industrial and volcanic aerosols in the northern hemisphere will reduce warming there. There are predictions of wide fluctuations in rainfall, with more frequent events of high rain in some areas and more severe droughts in others (Whetton *et al.* 1993; Meehl & Washington 1993). More rain will increase sediment runoff and lower salinity in enclosed waters, thereby damaging those reefs. Clear evidence of such changes may, however, be masked by strong anthropogenic increases in runoff and sedimentation following deforestation and land clearing (Dubinsky & Stambler 1996).

As seawater temperatures rise, tropical storms may become more frequent and their range will expand towards higher latitudes (Ryan *et al.* 1992). Any significant changes in the frequency or magnitude of tropical storms will affect both the structure and growth of coral reefs (Lough 1994). Moreover, increases in tropical storm frequency and intensity will exacerbate the effects of sea-level rises on coral islands (Figure 1).

A potential effect of climate change on coral reefs could be significant alterations to oceanic currents (Weaver 1993; Chadwick-Furman 1996). Changes in currents could disrupt the continual supplies of fresh larvae for reef replenishment (as well as spreading pathogens and contaminants), thereby affecting the recovery of reefs after damage. Climate change models are insufficiently precise to provide detail on potential changes in current patterns.

The El Niño Southern Oscillation (ENSO) has implications for global weather and coral reefs. Tropical storms increase in the eastern Pacific during strong ENSO events in parallel with droughts over Indonesia. The intensity and frequency of ENSO events may increase with climate change, but there is insufficient evidence to either support or deny this speculation (Wilkinson & Buddemeier 1994).

There are few recorded extinctions of coral reef biota, possibly because of few observations and poor recording of the inherent biodiversity (Sebens 1994). It has been estimated that only 10% of reef species have been 'discovered' (Reaka-Kudla 1995). Global climate changes may exacerbate potential anthropogenic-induced extinc-

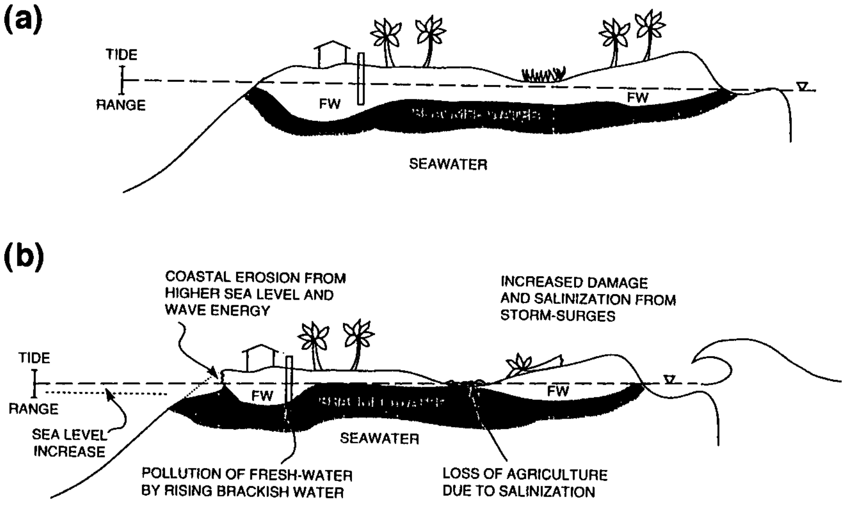

Fig. 1 Cross-section representing impacts of sea-level rises on coral reef islands, showing current situation (above) and a probable future situation at higher sea level (below).

tions, through alterations in rainfall patterns or changes in ocean currents, but such climate change signals will be difficult to detect amongst much larger signals from anthropogenic damage to reefs (Chadwick-Furman 1996; Dubinsky & Stambler 1996)

Global change synergies: impacts on humans and reefs

Impacts on reef continuities and islands

The largest threats to most coral reefs are from anthropogenic stresses, which will continue at exponential rates as populations in many tropical developing countries are predicted to double in 20–30 years (Table 1). Increases in population and economic activity will also accelerate the release of greenhouse gases, thereby increasing global climate change. While existing models of climate change do not indicate large-scale damage to coral reefs, the potential for synergism between climate change and anthropogenic damage is most alarming. For example, the natural recovery of reef communities damaged by destructive fishing or pollution may be impeded by alterations in current patterns, tropical storms, or freshwater runoff.

Sea-level rise will have serious impacts on low-lying coral islands and could render many of these uninhabitable through contamination of groundwater and increased erosion (Wilkinson & Buddemeier 1994). Any changes in rainfall patterns could further exacerbate this on some islands. The continual loss of habitable land may force migrations of peoples from coral atolls (Wilkinson & Buddemeier 1994). Such migrations may, however, provide a small benefit by reducing the direct anthropogenic impacts of pollution, sedimentation and overexploitation that are causing widespread damage to oceanic coral reefs.

Over-fishing, particularly through destructive methods (muro ami, blast, bleach, cyanide) and nets and anchors, is both reducing the breeding stock on many reefs and destroying the habitat. Thus, current anthropogenic pressures are inducing collapses in coral reef fisheries similar to those seen in most of the world's fisheries (Dalzell *et al.* 1996). The recent expansion of cyanide fishing to remote reefs (Johannes & Riepen 1995) is further reducing the supply of larvae that now recruit to the over-fished reefs close to cities and towns. Any changes in current patterns as a result of climate change could further reduce the flow of larvae between reefs and have severe consequences for many millions of peoples who depend on reef resources for food and income.

Management of over-fishing is urgently required, particularly the prevention of destructive methods. Dynamite fishing is relatively easy to detect, but cyanide fishing is silent and leaves no immediate traces. Both of these may be controlled at the point of sale, either to exporters or at intended markets (Johannes & Riepen 1995). However, a major requirement is to provide fishing families with alternative sources of food and income, through expansion of tourism and mariculture or into manufacturing industries. Control of climate changes must occur through international pressure on governments.

Impacts on tourism

The major impacts of climate change on tourism will be the eventual rendering of low-lying coral islands uninhabitable. This applies to countries like the Maldives, parts of Indonesia (Pulau Seribu off Jakarta) and some island states of the Pacific (some of the Cook islands and French Polynesia). Costs of building retaining walls and raising the height of islands will be prohibitive.

Tourism on reefs adjacent to high islands is unlikely to be seriously affected, unless resorts have been constructed too close to the water. Other aspects of global climate change should not affect tourism operations adversely, although some may be affected by changes in local weather patterns.

Of greater concern for tourist operators are the current rates of destruction of reef resources through pollution, sedimentation and over-fishing. There is a distinct loss of amenity for damaged reefs with large areas of dead coral (Kenchington 1990). This has occurred on the north coast of Jamaica, where dive magazines discourage diving tourists because there are few fish and low coral cover. Likewise, tourism to the once thriving reefs of Pattaya Bay, Thailand is now focused on other attractions. Similar situations are predicted for the developing Thai tourist centres of Phuket and Ko Samui (Sudara & Nateekarnchanalap 1988; Sudara & Yeemin 1994).

Tourist operators who encourage clean practices during construction and operation of resorts and install fish reserves, are likely to reap greater sustained benefits into the future. Thus, strategies for tourism operators to cope with global change are to reduce and manage human impacts on reef resources and ensure that all new facilities are constructed away from the shoreline, and preferably not on coral islands.

Impacts on economies

Damage to coral reefs is having direct economic impacts in developing countries through a reduction in reef fisheries and tourism numbers, particularly the diving tourists. Indirect costs will be incurred if the protective function of reefs is removed resulting in greater erosion of fragile coastlines and infrastructure. A nominal protection value of coral reefs to sandy shorelines is the cost of concrete reinforcing the barriers around Male, the Maldives, at approximately US$10 million per linear kilometre (Pernetta 1992).

The true values of coral reefs are rarely calculated. Hodgson & Dixon (1988) showed that economic returns from fishing and tourism on Palawan coral reefs, Philippines, far exceeded the value to be gained from logging the adjacent tropical forests, because of long-term sediment damage to the reefs. Similarly, Cesar (1996) calculated that losses to actual and potential tourism in Indonesia through blast and cyanide fishing exceeded the immediate economic benefits by 50 times.

Impacts on island cultures

An additional impact on global economies will be the cost of either shifting populations off affected islands or attempts at shoring up coastlines against rising sea levels (Wilkinson & Buddemeier 1994). 'Rationalist' economic analysis indicates that it is preferable to sacrifice island cultures, rather than incur greater costs of reducing global outputs of CO_2 (Adams 1993). Small Island Developing Nations have expressed totally different views to the United Nations.

It is probable that low lying coral islands will become uninhabitable with a sea-level rise of 0.5 m or less because of shoreline erosion and contamination of groundwater (Fig. 1). Current predictions are for this to occur within 100 years (Wigley & Raper 1992). Attempts at engineering solutions through the construction of artificial barriers, beach protection and replacement and reinforcement of buildings will prove largely unsuccessful and costly. Seawater will seep under bund walls, and increased storm activity will result in more seawater flowing over islands during storms. Building sea walls will exceed the budgetary resources of most island nations; wall building would cost 34% of the Maldives Gross National Product, 19% of Kiribati GNP and 14% of Tuvalu GNP (IPCC 1990).

Raising islands by dredging of sand from adjacent reef flats will prove exorbitantly expensive and increase wave erosion of shorelines. Previous suggestions of replacing the soil stripped during phosphate mining on the now wealthy Nauru and Banabas (Ocean) islands, have been discarded as impracticable.

Conclusions

The decline in coral reefs shows no consistent global pattern, although there are widespread reports of reef degradation and several cases of ecological collapse. The causes of reef damage are predominantly anthropogenic, with the effects usually being manifest close to the sources of stress. The major stresses are: excessive sedimentation arising from unwise land-use practices in the vicinity or in catchment areas; organic and inorganic pollution through runoff from agriculture and domestic and industrial activities; and over-exploitation of harvestable resources, especially fish (Gomez 1988; Kinsey 1988; Grigg & Dollar 1990; Buddemeier 1993; Wilkinson 1993). Overexploitation of fish stocks is now widespread and cyanide use is now spreading outwards to remote reefs from the central Indo-Pacific region (Johannes & Riepen 1995).

Temperature-induced coral bleaching is the only global climate change impact that may directly damage reefs (Glynn 1996). Sea-level rise poses a major threat to coral islands, and the peoples living on them, by rendering many of the islands uninhabitable. There is an urgent need to instigate planning to move affected populations to more elevated land compatible with their cultures as sea levels continue to rise. Low islands in the tropical storm belt should be affected earlier than islands around the equator. Engineering solutions based on current mechanisms are unlikely to succeed and will be exorbitantly expensive (Wilkinson & Buddemeier 1994).

The other aspects of global change (UV increases, CO_2 concentration increases, bleaching) are discussed elsewhere in this Special Issue, however, these stresses could reinforce the impacts that are occurring through anthropogenic stress. This potential complexity will require a greater level of interdisciplinary study and adaptability amongst coral reef scientists and those bodies funding coral reef research (Buddemeier 1993).

Remedial measures must be focused on reducing the impacts human populations are having on reefs and stabilize, and, where possible, reduce the input of greenhouse gases into the atmosphere. Much of this will have to be financed through the international community.

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