Assessment of Maldivian Coral Reefs in 2009 after Natural Disasters

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Male'
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Cover Photo: Marine Research Center staff members M. Shafiya and H. Hamid observing a school of Oriental Sweetlips (*Plectorhinchus vittatus)* on a training dive at 15 m along Vadoo Canyons, South Male' atoll, January 2009.

FORWARD

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List of Abbreviations, Acronyms and Place Name Spellings

AVHRR	Advanced Very High Resolution Radiometer
CoT	Crown of Thorns starfish – *Acanthaster planci*
GBR	Great Barrier Reef
IUCN	International Union for Conservation of Nature
MMS3T	mean monthly sub surface temperature
MMSST	mean monthly sea water temperature
MOFAMR	Ministry of Fisheries, Agriculture and Marine Resources
MPA	Marine Protected Areas
MRC	Marine Research Centre
NCRMS	National Coral Reef Monitoring Survey
SST	surface sea water temperature
S3T	subsurface sea water temperature

The place names spellings used in the report are based on the Ministry of Planning and National Development's *Official Atlas of the Maldives* (2008).

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Report Objectives

In this report we examine a commonly accepted suite of biological indicators of coral reef health from a geographically diverse set of lagoon, shallow Maldivian reefs from northern Haa Dhaalu to Addu atoll, south of the equator, based on field work undertaken from February – October 2009. The Marine Research Centre's (MRC) National Coral Reef Monitoring Survey (NCRMS) data set based on Reef Check survey methodology will provide an historical record, along with other outside agency studies, for assessing the recovery of Maldivian coral reefs to natural disasters in the past 12 years.

The annual sea water temperature variation for the Maldives will be discussed in the context of its relationship to geographical and seasonal variation and coral bleaching.

The status of the reefs will be broadly compared with the situation on other regional reefs that experienced bleaching.

Introduction

The Maldives is comprised of about 1192 islands with a 300 km^2 land mass and an exclusive economic zone of 859,000 km^2. Within atoll lagoon and reef areas comprise approximately 21,300 km^2. The 26 atolls (with 20 administrative atolls) lie along a north-south axis between 7^{o}06'35" N. to 0^{o}42'24" S. latitude and from 72^o 33'19" E. and 73^o 46'13" E. longitude in the central part of the Chagos – Maldives – Laccadive ridge in the central Indian Ocean. Subject to high amplitude sea level fluctuations during the Pliocene – Pleistocene with alternative periods of exposure and vertical reef growth the atolls presently rest on as much as 3 km of limestone overlying an Eocene volcanic basement (Aubert and Droxler, 1992). The islands formed 5500 - 4500 years ago (Kench, *et al*., 2005) during a period when sea level rose about 0.5 m above the reef tops.

About 193 of the islands are inhabited by native Maldivians, 93 islands have tourist resorts, and 55 islands are reserved for industrial and agricultural use. Only 33 of the inhabited islands have a land area of >1 km^2 and only three islands have an area >3 km^2. Coral reef statistics produced by the United Nation Environment Programme (UNEP) in 2003 ranked the Maldives as having the seventh largest coral reef system within its territorial boundaries. The Maldives is estimated to contain 3.14% of the total coral reef area of the world (United Nations Environmental Programme, 2003).

A wet monsoon dominates the period April to November when the winds blow from the southwest. A dry season occurs from December to March with lighter winds from the northeast (Kench, *et al*., 2006). The total population is about 299,000 people with 35% resident in the capital, Male'. About 80% of the islands have an elevation of <1 m above the mean high water mark (Ministry of Planning and National Development, 2008).

Clearly the health of the coral reefs, which are the physical basis for the Maldives, are of national strategic concern. President Nasheed called the plight of the Maldives to the world in his September 2009, address to the United Nations. He stated that failure to come to a meaningful agreement in the International Convention on Global Climate Change would be suicidal for the Maldives.

The historically low population densities in the Maldives resulted in a large area of coral reefs where the influences of humans were low. For many centuries Maldivians preferred to eat pelagic fish instead of reef fish (Sheppard and Wells, 1998) so fishing impacts on reef fish populations were slight. Mining of the reef for rocks and sand for building materials depleted many lagoons and faros of corals (Brown and Dunne, 1988) and reduced fish biomass (Dawson Shepherd, *et al*., 1992). However, human impacts on reefs are increasing. Recently, nutrients from the capital city/ island Male' (Risk, *et al*., 1994), snorkeler and diver effects (Allison, 1996) combined with shark fishing, aquarium fish and sea cucumber collection (Adam, *et al*., 1997) and harbour construction have been changing the reefs.

Although the Maldives is completely founded on the remains of living coral reefs, it has only been towards the end of the 20th century that systematic quantitative surveys of reefs, from the northern atolls to the southern most atolls were conducted by the government of the Maldives through the Marine Research Center (MRC), Ministry of Fisheries and Agriculture.

Initially, surveys were limited to individual atolls, e.g. the notable descriptive work was mainly done around the British air base at Addu atoll (Stoddart, *et al.,* 1966; Spencer-Davies, *et al.,* 1971). On the "Xaifa" expedition at Fadifolu, Rasdhoo, Ari and Addu atolls, Georg Scheer conducted some of the earliest detailed "coral sociology" studies, using the plant sociology techniques of line intercept and quadrat methods. These techniques, introduced into coral reef research by Scheer (1971; 1972; 1974), became standard for benthic reef surveys. Scheer reported coral cover ranged from 50 – 80% from his observations from Addu, Ari and Fadiffolu atolls. Along with the descriptive work of the "Xarifa" expedition (Hass, 1961; Wallace and Zahir, 2007), there were anecdotal reports of luxuriant, diverse reefs from divers dating back to the 1950s. The health and beauty of Maldivian reefs was further confirmed during the establishment of the multimillion dollar tourist industry when scores of dive schools were included in resort developments to cater to the diver seeking to "dive in one of the last paradises on earth."

Pichon and Benzoni (2007) reported that there were 248 coral species from 57 genera, although they stated that the taxonomic status of some of the earlier described species were doubtful. However, Carpenter, *et al*., (2008) considers that according to the International Union for Conservation of Nature (IUCN) Red List Categories and Criteria: 1% -10% of the total species in the Maldives are Critically Endangered and Endangered species, 10% - 20% are Critically Endangered, Endangered, and Vulnerable and 40% - 50% are threatened or near threatened. The threats are from both global climate change and local impacts.

Initial Reef Check Surveys and the 1998 Bleaching Event

Although there were previous surveys that MRC staff participated in, quantitative surveys of the coral reef community organized by MRC began in 1997 using the Reef Check coral reef monitoring protocol (Hodgson, 1999). These surveys yield a scientifically based estimate of several parameters commonly used to assess coral reef community health and resilience.

The unprecedented coral bleaching in 1997 - 1998 around the world (Wilkinson, 1998) including the Maldives, resulted in extensive mortality to scleractinian, reef building corals. During this event the living coral animals expelled their commensal living plant called zooxanthellae exposing the unpigmented coral tissue and underlying skeleton. Prior to 1998 an isolated bleaching event occurred on the three central atolls in the Maldives was reported (Wood, 1987). While the 1998 bleaching may not have been the first, it was the most intense and sustained in recent history in the Indian Ocean (Goreau, *et al*., 2000).

The NCRMS surveys clearly detail the death of live coral in Anbaraa reef, Vaavu atoll, Thuvaru reef, Meemu atoll and the high mortality of corals in Maduvvari reef, Meemu atoll (Figure 1). Prior to the bleaching event the reefs were considered luxurious at Anbaraa (Patch reef) and Maduvvari reef, with about 50 - 70% coral cover. Thuvaru reef was a moderately developed reef with less than a 30% coral cover prior to bleaching. Fast growing branching corals, such as A*cropora* spp., suffered greater mortality than slow-growing massive corals (Zahir, 2002a). Virtually all of the colonies of *Acropora* spp. in the study sites had died (Zahir, 2006). Similarly the fast growing pocilloporids were highly susceptible to bleaching. In contrast agariciids and poritids were more resilient, although they too experienced a decrease in cover (Zahir, 2006).

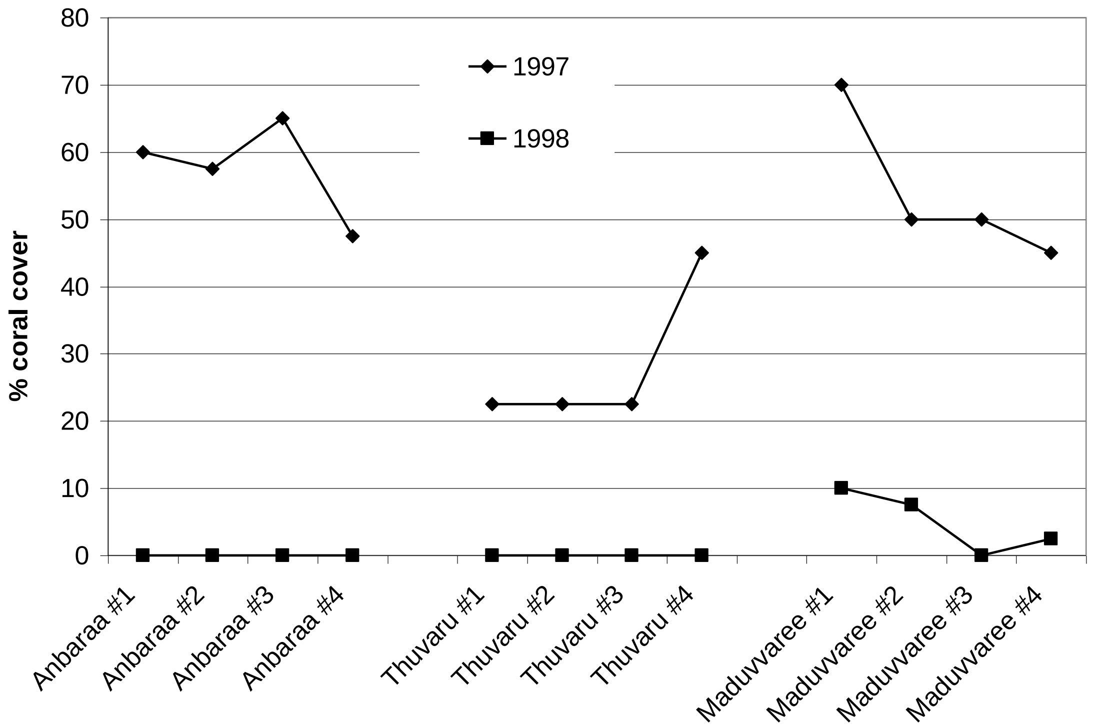

Figure 1. Comparison of NCRMS 150 m point intercept transect percent live coral cover data at three sites in 1997 before and immediately after the bleaching in April – May 1998 bleaching event (after Zahir 2002a).

Other workers found the percentage of living coral cover on several shallow reef flats declined markedly immediately after the bleaching event. Coral cover was reduced, from around 22.5 – 70% pre-bleaching to 0 – 10% post-bleaching (Allison, 1999; Clark, *et al*., 1999). The reef flat at Vabbinfaru, North Male' atoll exhibited very high mortality (Hakeem, per. com.). The luxurious reef at this site gradually became nothing but rubble / sand (Figure 2) which increased the beach erosion on the island which the resort tried to mitigate by pumping sand from the reef flat, further destabilizing natural efforts for recolonization.

Figure 2. A sea cucumber (*Holothurian atra*) lies among the rubble of the devastated reef flat (2 m) at Vabbinfaru reef, September 2009.

Tsunami Devastation

Coral reefs are critical to the Maldives as they maintain the integrity of atoll islands by providing erosion barriers and are sources of sand and rock. They are also a major attraction for the tourist industry.

In December 2004, another natural disaster impacted Maldivian coral reefs. Originating in an earthquake off the east coast of Indonesia, a tsunami struck the Maldives on 26th December 2004. In February 2005, joint Maldivian and Australian research team surveyed 124 reefs sites in seven atolls, covering about 170 km of reef margin (AusAid, 2005) looking for tsunami damage. They observed localized damage to reefs near inhabited islands from debris (from buildings and other island infrastructure) and sand that had smashed and smothered corals when it had been swept into the ocean. Some of the damage was extensive enough to alter the reef framework. They concluded that there was minor direct damage to coral reefs by the tsunami, but only observed live coral cover in the range of about 4 – 12% (Figure 3). Although the reefs were not particularly luxuriant, they were recovering from the 1998 bleaching.

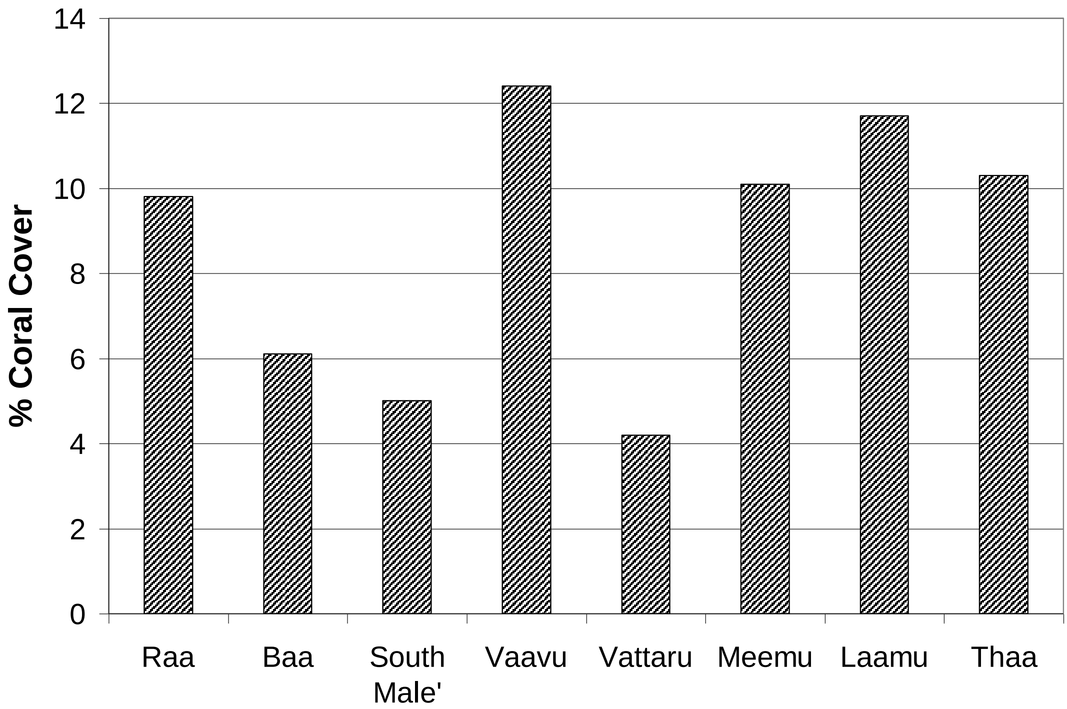

Figure 3. Percent live coral cover reported by surveys undertaken in January – February 2005, a couple months after the December 2004, tsunami (after AusAID, 2005).

The researchers considered that the 1998 coral bleaching event caused more overall damage to the reef community than the tsunami (AusAID, 2005). They found that the tsunamis did not cause significant damage to Maldivian coral reefs, but it was likely that the tsunami slowed recovery from earlier damage caused by bleaching. The damage from the tsunami was far less than the mortality resulting from the 1998 bleaching event and the on-going human damage to the reefs caused by coral rock and sand collection from reef flats and the dredge and fill operations associated with coastal development (AusAID, 2005).

The tsunamis did focus attention on the need for better management of direct human pressures and inappropriate coastal development. They note that their assessment of the condition of the reefs was hampered by the lack of comparable prior quantitative surveys that covered the length and width of the country at several depths (AusAID, 2005).

Erosion

After the 1998 bleaching event, it was postulated that waves and bioerosion would operate synergistically to dismantle the reef framework and erode the islands (Figure 4). Boring and grazing organisms might remove $CaCO_3$ faster than primary frame builders could accrete it (Zahir, 2002b) and waves would break apart the weakened live rock. As well, it was thought that a tsunami would further wash away the islands. It was hypothesized that the structural integrity of the reef would be determined by the extent and rate of these biogenic and physical processes. Should these processes exceed the very limited accretion rates of the post bleaching reefs, the reefs' framework could begin to disintegrate further exposing the islands to the forces of oceanic swells as recorded in the Seychelles (Sheppard, *et al*., 2005).

Figure 4. Trees fall into the sea as waves on Vaavu atoll sweep across the reef eroding Bodumohora Island, March 2009.

Contrary to popular perceptions of the fragility and vulnerability of atoll islands, Kench, *et al*. (2006) showed that the uninhabited islands of the Maldives were robust landforms that experienced relatively minor physical impacts from the Sumatran tsunami. Morphological and sedimentary evidence suggests that although tsunamis do generate both erosional and depositional signatures, they do not promote gross instability of islands. Tsunamis are unlikely to be important mechanisms of atoll island destruction if the sand reservoir is conserved during the tsunami (Kench, *et al*., 2006). Where the beach sand reservoir was depleted and total beach volume reduced it is uncertain if the reefal sediment production will compensate for this reduction. Without healthy coral reefs, the replenishment of the biogenetic sand necessary for the natural maintenance of these dynamic islands would not be available.

While that finding is reassuring for the long term survival for the Maldives, many resorts were constructed with the intent to provide sea side villas. Without sufficient understanding the dynamics of sand islands and their sand budget under conditions with a stressed reef, the setback are now insufficient and many resorts are under threat from erosion (Figure 5).

Figure 5. During high tide with strong westerly wind the sea washes with several meters of the villas, North Male' atoll, October 2009.

In an experiment in 2001 - 2002, Zahir (2002b) investigated bioerosion on coral blocks at two sites in North Male' atoll. He found that there was a significant difference between the sites in the intensity of bioerosion at shallow and deeper depths. However, it was unresolved whether bioerosion would damage a reef's structural integrity before it recovered. The answer to that question had to wait several more years when the reefs were resurveyed.

Natural Resilience - Recruitment

In spite of the calamities that had happened to Maldivian reefs the results from recruitment experiments were encouraging (Clark, 2000). Recruitment of juvenile corals to artificial structures 10 months after the bleaching event showed that 67% of visible (≥0.5 cm diameter) recruits were acroporids and pocilloporids and 33% were from massive families compared to 94% and 6%, respectively, in 1990–1994 (Edwards, *et al*., 2001). Although the recruitment rate had declined, the potential for restoration through natural recruitment looked promising.

Similar post-bleaching dominance of recruitment by branching corals was also seen on nearby natural reef (78% acroporids and pocilloporids; 22% massive corals) (Zahir, *et al*., 2002). Zahir *et al*. (2002) concluded that in spite of the mortality associated with the bleaching, sufficient numbers of coral colonies survived to produce "viable supplies" of planulae to recolonize the reefs. Later from the perspective of seven years after the bleaching, it appeared that the patterns and rates of coral recovery were not recruitment limited (Zahir, 2006).

Not everyone thought the reefs would recover. From their keyhole perspective at Komandoo house reef, Komandoo Island, Lhaviyani atoll, Schuhmacher *et al.* (2005) saw the slow and scattered formation of new reef structure, being outweighed by the collapse of dead protruding colonies of tabulate *Acropora* spp. Six years after the bleaching, the formerly three-dimensional structure of the reef flat and upper reef slope was a leveled field of rubble, only partly consolidated by encrusting corals. From their perspective they saw cascading deterioration of the status of the reef for the future (Schuhmacher, *et al*., 2005). Similarly, at Vabbinfaru, North Male' atoll, the once luxuriant reef flat had been reduced to rubble which has still not recovered (Hakeen, pers. comm.).

National Coral Reef Monitoring Survey Sites

As Zahir (2000) accurately observed, the expanse of reefs in the Maldives are enormous and the human and logistical resources available for monitoring them are small. Over the years MRC has done its best to assess the status of the reefs from the far north atoll of Haa Dhaalu to the southern most atoll across the equator, Addu atoll with its limited resources. The sampling design was strategic and targeted specific atolls (Figures 6a – 6f) for the following reasons:

- *Haa Dhaalu* (northern most atoll and a regional development target)
- *Male'* (central atoll with intensive tourism and other commercial activities)
- *Ari* (central atoll with intensive existing tourism development)
- *Vaavu* (south central atoll with a community-based integrated island resource management project underway).
- *Addu-Gaafu Alifu* (southern most atoll and a target for regional development with an international airport).

Within each atoll three reefs within each atoll lagoon were selected. They were chosen because they were considered to be representative of the reefs in the atoll and/or because they had been previously surveyed. Owing to the limitations associated with sampling in deeper waters and logistical issues associated with supporting divers in remote reefs, the quantitative surveys before 2009 were mainly conducted at depths less than 3 m. Surge from oceanic swells and safety considerations prohibited site selection on outer reef crests. The specific site coordinates are listed in Table 1.

Regions	Atolls	Sites	Geographic Coordinates		2009
Northern	Haa Dhaalu	Hon'daafushi	6°46.33′ N	73°07.95′ E	X
Northern	Haa Dhaalu	Finey	6°45.06′ N	73°03.56′ E	X
Northern	Haa Dhaalu	Hirimaradhoo	6°43.86′ N	73°01.31′ E	X
Central	North Malé	Boduban'dos	4°16.00′ N	73°29.12′ E	X
Central	North Malé	Udhafushi	4°18.85′ N	73°30.12′ E	X
Central	South Malé	En'boodhoofinolhu	4°07.12′ N	73°28.04′ E	X
Central	Ari	Fesdhoo	4°00.02′ N	72°00.32′ E	X
Central	Ari	Maayaafushi	4°04.94′ N	72°53.19′ E	X
Central	Ari	Velidhoo	4°11.53′ N	72°49.32′ E	X
Central	Ari	Kan'dholhudhoo	4°00.15′ N	72°52.88 ′E	X
Central	Vaavu	Anbaraa	3°26.11′ N	73°25.33′ E	X
Central	Vaavu	Vattaru	3°13.49′ N	73°26.00′ E	X
Central	Vaavu	Foththeyo	3°26.90′ N	73°45.27′ E	X
Southern	Gaafu Alifu	Koodoo	0^o43.91′ N	73^o09.29′ E	
Southern	Addu	Hithadhoo	0°35.13′ S	73°06.14′ E	X
Southern	Addu	Gan	0°41.32′ S	73°09.72′ E	X
Southern	Addu	Vilingili	0°40.45′ S	73°11.48′ E	X

Table 1. National Coral Reef Monitoring Survey sites with geographic coordinates and atoll and regional classification of the sites. Sites sampled in 2009 indicated with X. Thuvaru, Anbaraa, and Maduvvari were sampled from 1997 – 1999.

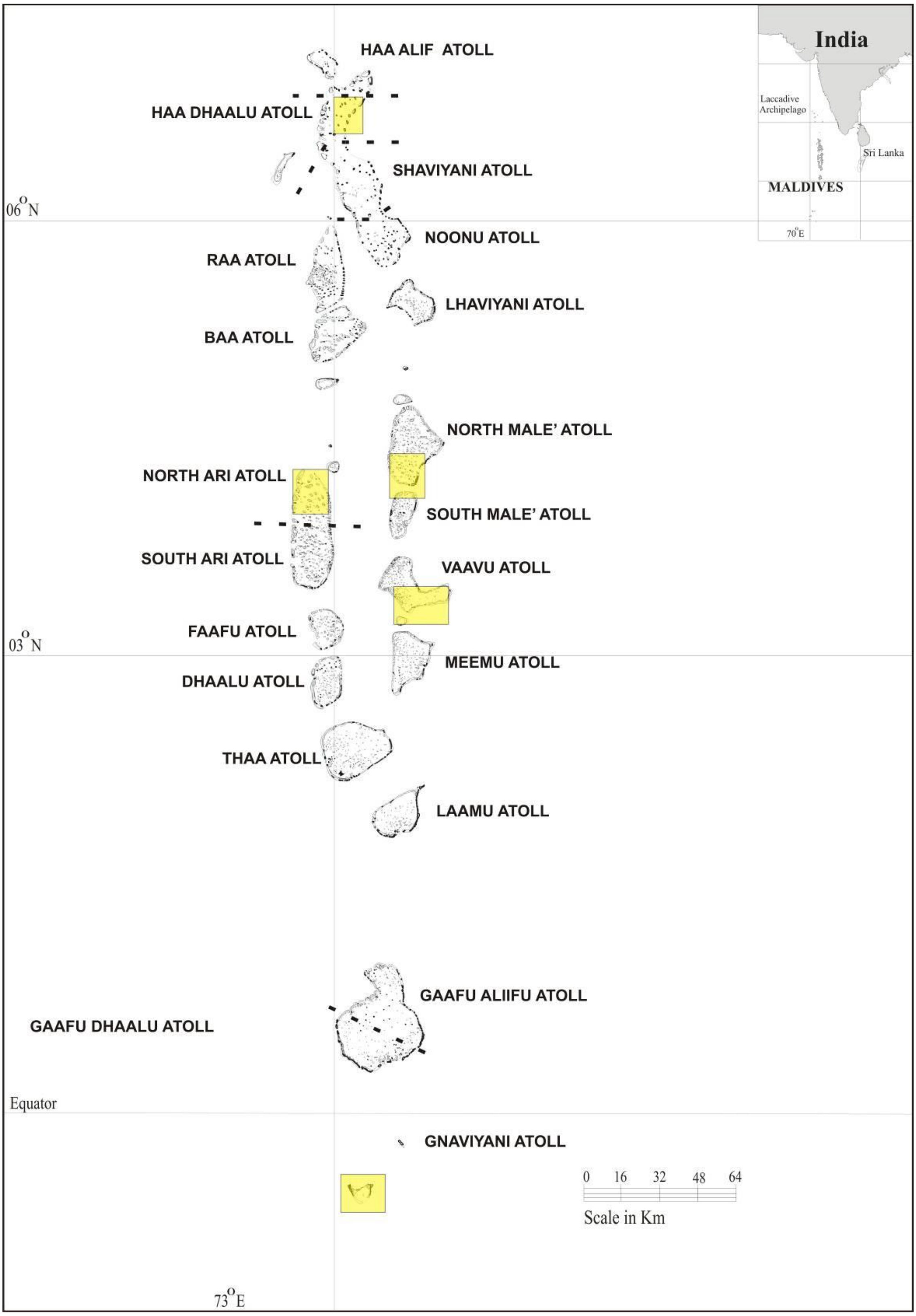

Figure 6a. Map of Maldives with colored areas showing areas with NCRMS sites sampled in 2009.

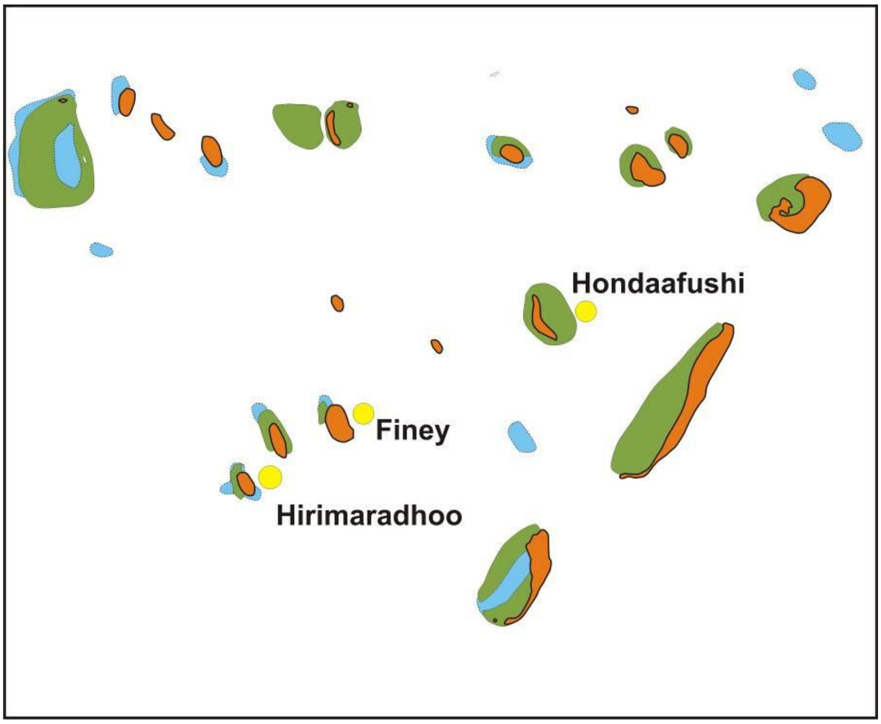

Figure 6b. Map of most northern NCRMS sites in Haa Dhaalu atoll. Orange indicates islands.

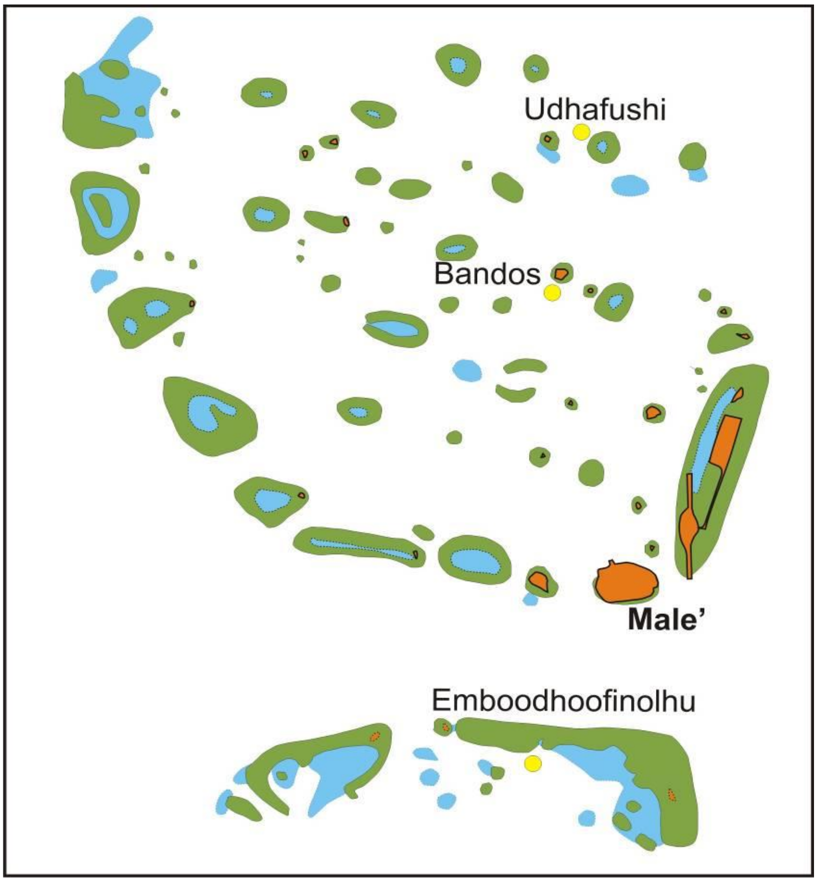

Figure 6c. Map of central NCRMS sites in North and South Male' atolls. Orange indicates islands.

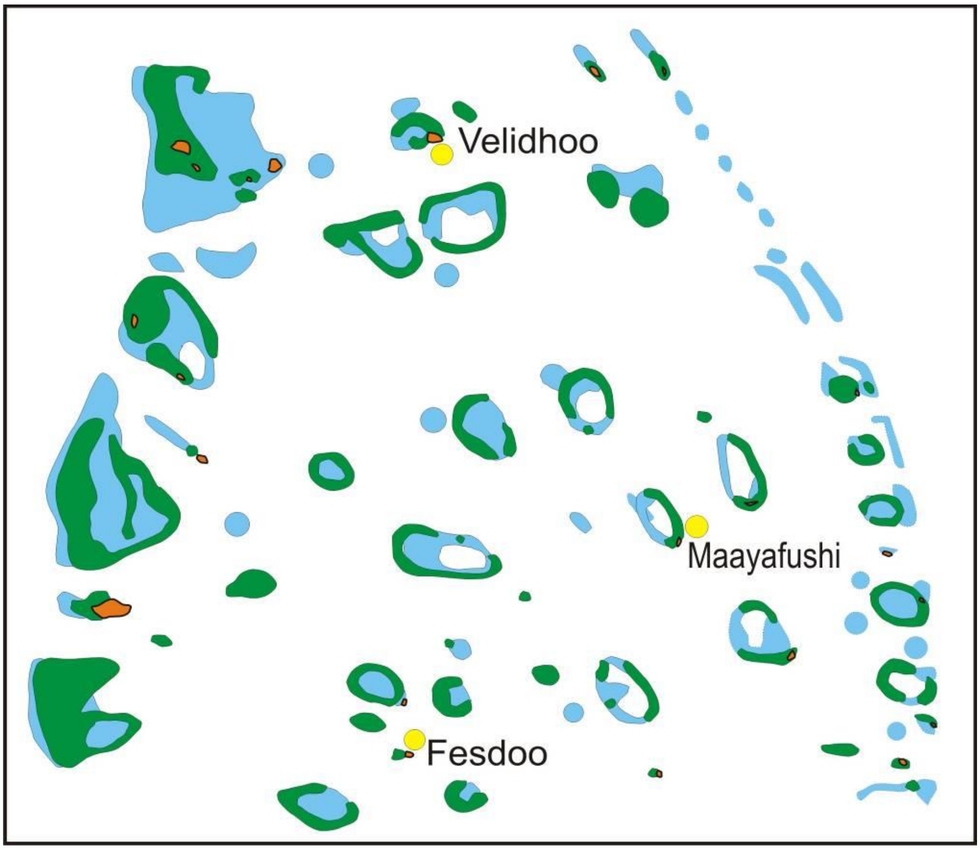

Figure 6d. Map of central NCRMS sites in Ari atoll. Orange indicates islands.

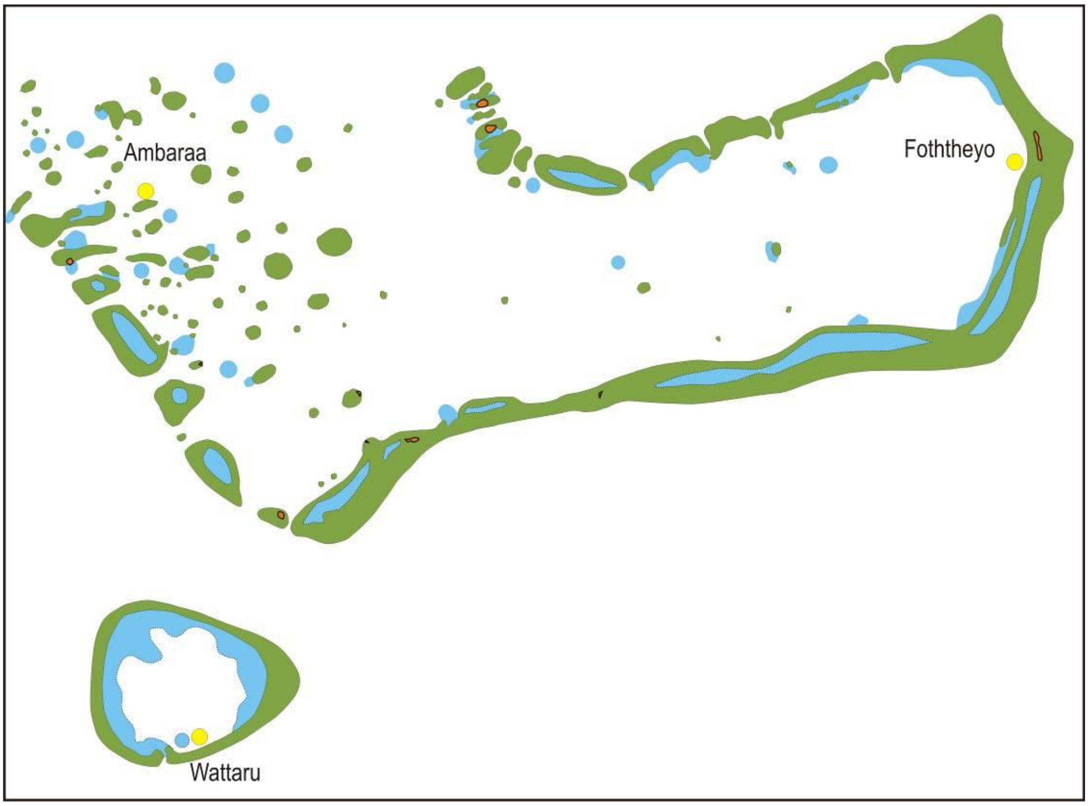

Figure 6e. Map of central NCRMS sites in Vaavu atoll.

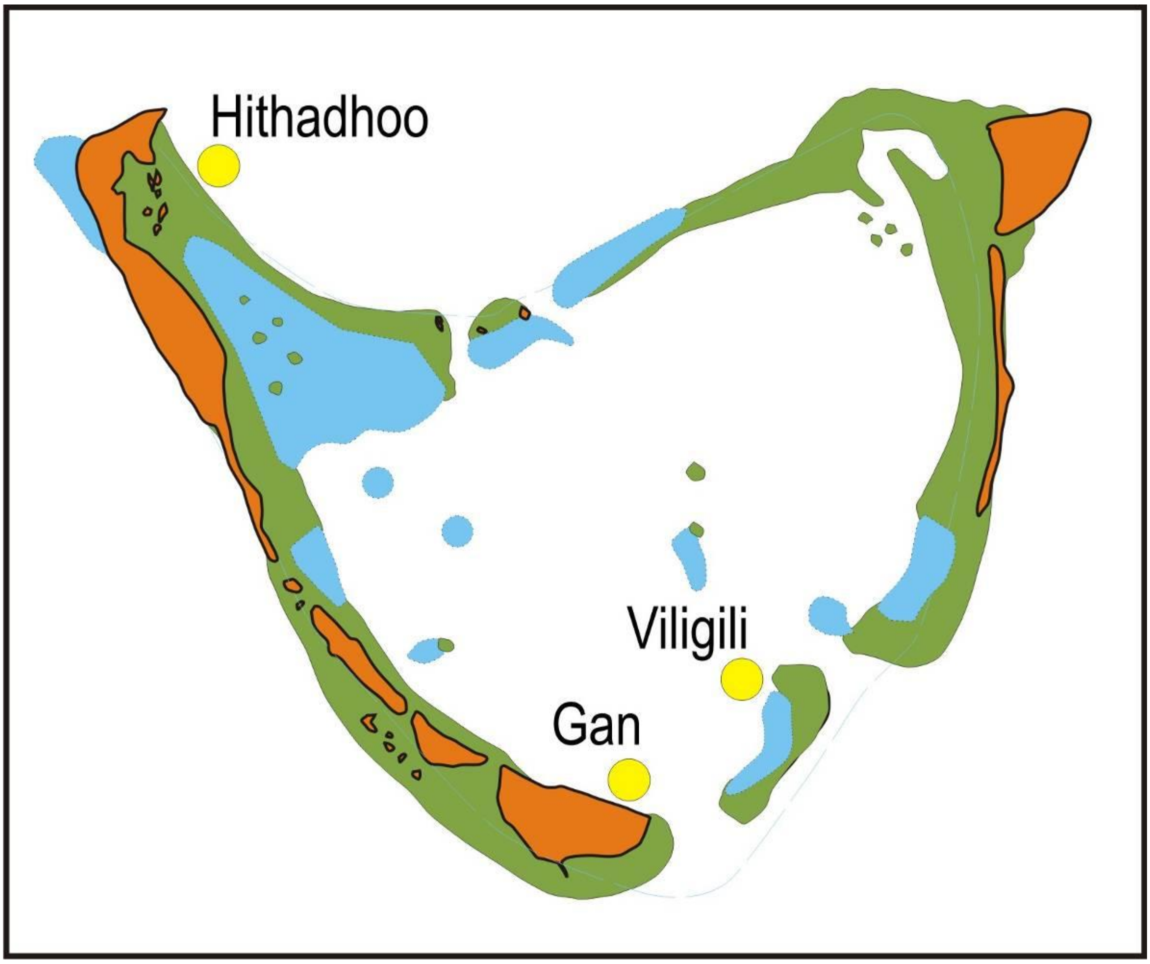

Figure 6f. Map of most southern NCRMS sites in Addu atoll. Orange indicates islands.

Survey Methods

In 2009, the NCRMS adapted the Reef Check protocol (Hodgson and Liebeler, 2002; Hodgson, *et al*., 2006) for surveying the reefs. Reef Check was designed to assess the health of coral reefs and is quite different from other monitoring protocols. It only varies slightly from the previous techniques used in the NCRMS to monitor benthic habitat. Reef Check does include a lot more parameters and is a more comprehensive technique that can be used to compare Maldivian reefs with other reefs around the world.

Since its inception, Reef Check has focused on the abundance of particular coral reef organisms that best reflect the condition of the ecosystem and that are easily recognizable to the general public. Selection of these "indicator" organisms was based on their economic and ecological value, their sensitivity to human impacts and ease of identification. Sixteen global and eight regional indicator organisms serve as specific measures of human impacts on coral reefs. These indicators include a broad spectrum of fish, invertebrates and plants that indicate human activities such as fishing, collection or pollution.

Some Reef Check categories are individual species while others are families. For example, the Napoleon humphead wrasse (*Cheilinus undulatus*) is the most sought after fish in the live food fish trade, whereas the banded coral shrimp (*Stenopus hispidus*) is collected for the aquarium trade. Both species are very distinctive organisms and are considered by Reef Check organizers excellent indicators of human predation. The Napoleon humphead wrasse has been protected in Maldivian waters since 1995 (Notice No: FA-A1/29/95/39) (24 June 1995)) and is not a good indicator in Maldivian waters. It is hypothesized that on reefs where these organisms are heavily exploited, their numbers are expected to be low compared to their abundance on unexploited reefs. The analysis of fishes will be dealt with in a subsequent report.

Reef Check teams collect four types of data:

1) a description of each reef site based on over 30 measures of environmental and socio-economic conditions and ratings of human impacts;
2) a measure of the percentage of the seabed covered by different substrate types, including live and dead coral, along four 20 m sections of a 100 m shallow reef transect;
3) invertebrate counts over four, 20 m x 5 m belts along the transect; and
4) fish counts, up to 5 m above the same belt.

Monitoring of the indicators is done along two depth contours 3 m (2 -6 m range) and 10 m (>6 – 12 m range) below sea level. Along each contour, four 20 m long line transects were surveyed using a measuring tape. The substrate under every 25 cm of the tape was recorded. Previously, three 50 m long transects were used from 1997 to 2005 and the intercept length to the nearest cm for each benthic category lying under the tape was recorded (Zahir, 2006). Transects followed the designated depth contour. Transect start and end points were separated by a 5 m space. Digital photographs were taken along the transects to document the species composition and abundance. The images will be analyzed using CPCe V3.4 software and discussed in detail in a later report.

Additionally, roving divers randomly swam along the transect line to a depth up to 30 m recording unusual animals, diseased corals, and dying corals.

Results

The mean and standard deviation of the coral cover from the two depths for each site was calculated. The mean coral cover ranged from 7.5% at Hirmaradhoo to 59.4% at Fesdhoo (Figure 7). There is a lot of variability in cover throughout the Maldives. Only four sites had a coral cover >50%: Fesdhoo, Kandholhudhoo (both Ari atoll) and Vilingili and Hithadhoo (both Addu atoll). The reefs in the narrow depth range sampled also are quite variable in there cover with the coefficient of variation ranging from 4.0% at Vilingili to over 100% at Hirmaradhoo and Maniyafushi.

In the following sections we will discuss the coral cover for each of the atolls in more detail.

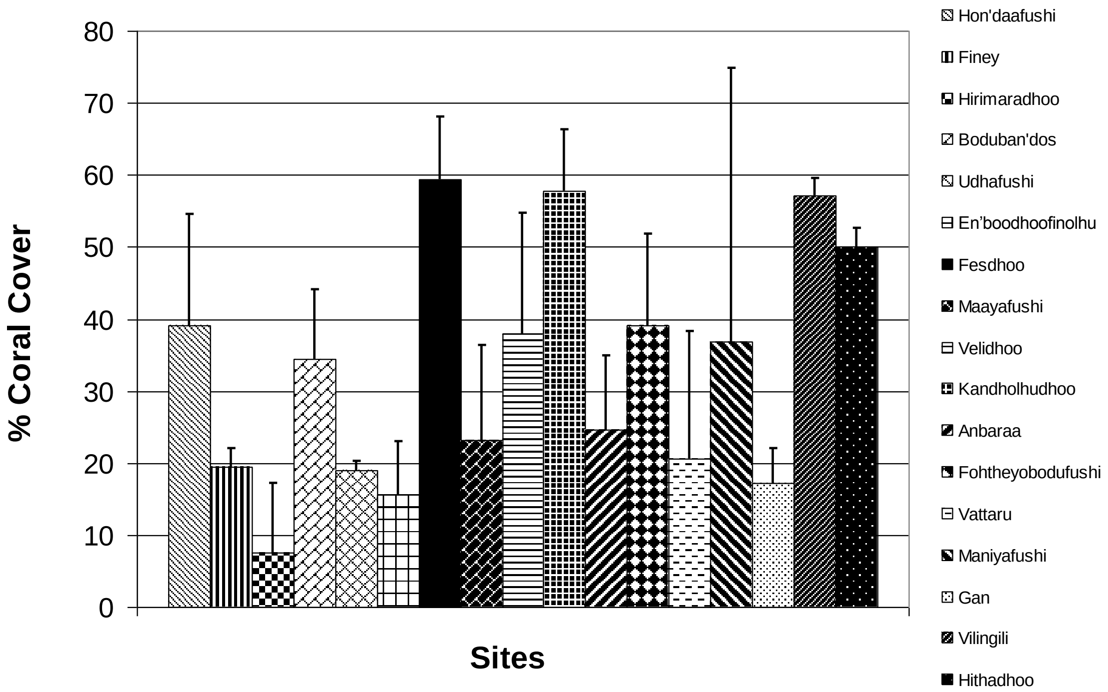

Figure 7. Mean (3 m, 10 m) percent coral cover of the 17 NCRMS sites surveyed from March to October 2009. Error bars show standard deviation. n = 8 for each site.

Haa Dhaalu Atoll

Coral cover on the northern reefs of Haa Dhaalu atoll was nearly 0% after the 1998 bleaching event (Zahir, 2000; 2006). Subsequent reef recovery was slow with coral cover only achieving 3 - 5% in 2005. However, since 2005, coral cover has been rapid. In 2009, coral cover ranged from 14% - 29% (Figure 8). This was collectively the lowest coral cover for all the atolls surveyed. The northern atolls of the Maldives are more exposed to cyclonic tropical storms than other atolls in the Maldivian chain and impacts by storms could setback recovery on northern reefs. No large storms impacted these atolls from 1998 to 2009.

At 3 m at Hirimaradhoo, the live coral cover was only 14% - lower than at Hon'daafushi and Finey (Figure 8). Over 65% of Hirimaradhoo was covered with the category "other living organisms" which was mainly the invasive corallimorpharian, *Discosoma* c.f. *rhodostoma*. The remaining 20% was non living substrate. The corallimorpharian dominated much of Hirimaradhoo reef particularly at the depths of 3 -15 m. (Figure 6). It also was dominant in many Sri Lankan reefs post bleaching (Rajasuriya and Karunarathna, 2000).

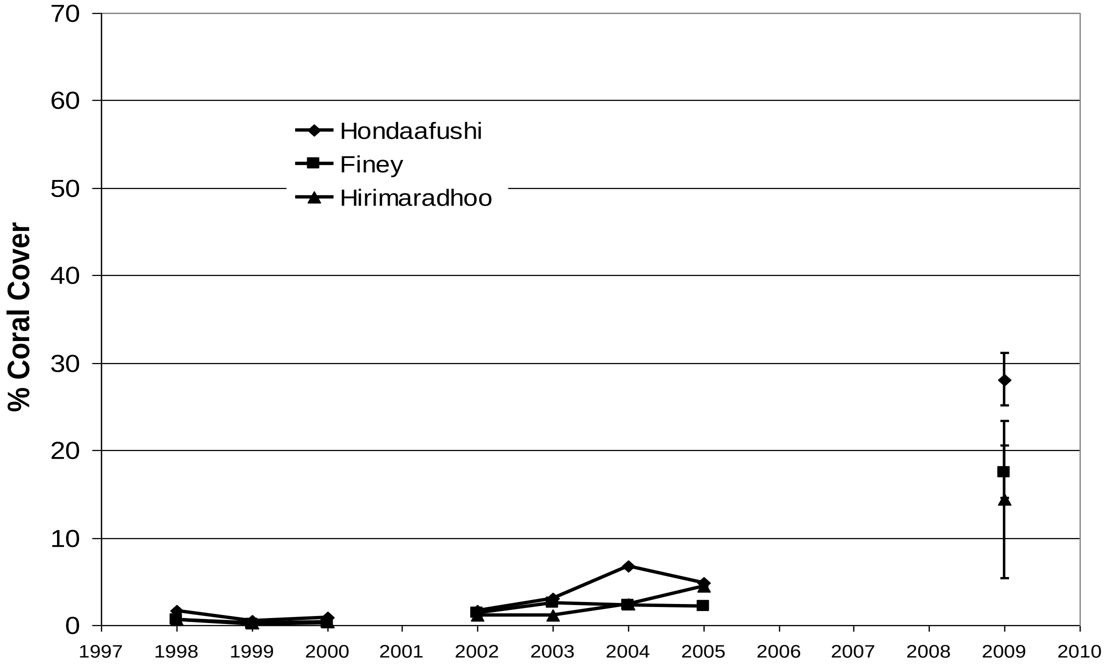

Figure 8. Percentage live coral cover at 3 m at three sites in Haa Dhaalu atoll. Error bars only included for 2009, n = 4 for each site.

Hon'daafushi and Finey had higher coral cover at 10 m than at 3 m. Hon'daafushi had a coral cover of 50% while Finey had 21% coral cover (Figure 9). At Hirimaradhoo because *Discosoma* c.f. *rhodostoma* was dominating the reef, hard coral cover was the least of the Haa Dhaalu sites with only 14% cover at 3 m and 0.6% at 10 m.

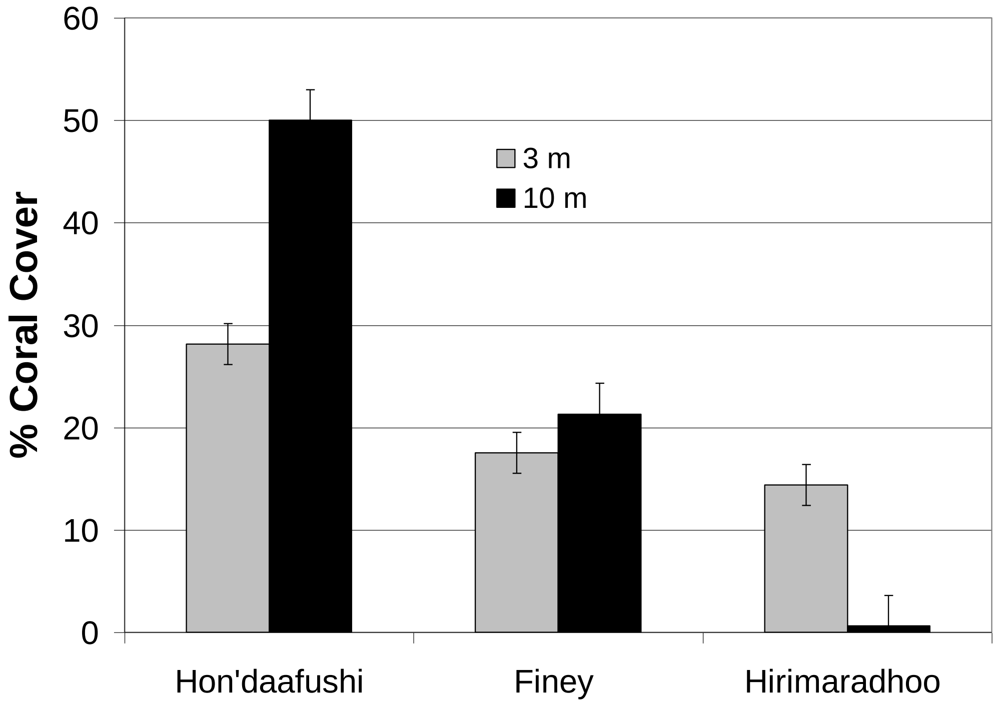

Figure 9. Comparison of % coral cover at 3 m and 10 m at three sites at Haa Dhaalu atoll, March 2009. n = 4. Standard error shown by bars.

At 10 m hard coral cover at Hirimaradhoo was <1% because corallimorphirians dominate 80% of the reef cover (Figure 10), 1% algae and non living substrate cover 18%. The cover of corallimorpharians increased from 11% in 1998 to 40% in 2005. In 2009, their cover had increased to a 65%, overgrowing coralline algae, sponges and crowding out many other taxa on the reef, and diminishing space for coral settlement. This is the only site with a documented “phase shift” from a crustose coralline algae/ coral community to a corallimorpharian community. However, large beds of corallimorphs, covering >60% of the substrate, were recorded in 2003 at Addu atoll (Ministry of the Environment, Energy and Water, 2006).

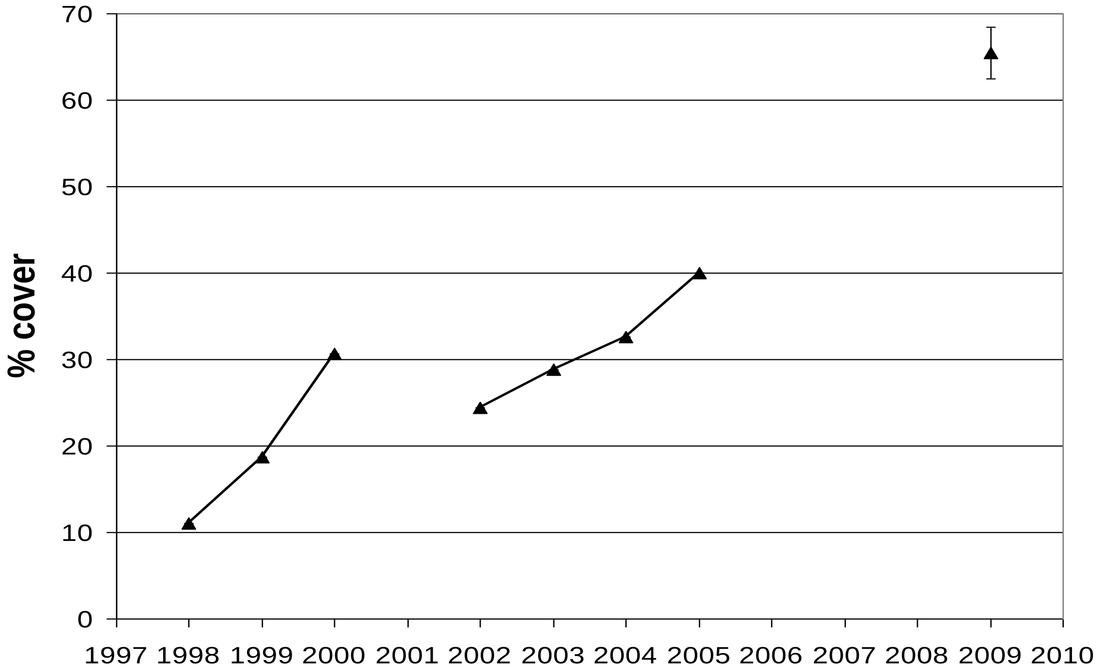

Figure 10. Percent cover of the corallimorpharian population *Discosoma* c.f. *rhodostoma* on Hirimaradhoo reef at 3 m from 1998 to 2009. Standard error bars only shown for 2009 (n = 4).

Scleractinian corals compete with each other and other sessile organisms like macroalgae for settlement space and light using a number of competitive mechanisms including direct competition. The results of interactions between corals and macroalgae depend on the specific competitive abilities of different coral and algal species. In general, there is no clear competitive dominance of one group over the other (McCook, *et al*., 2001). Subsequent to large a die-off of corals, when unchecked, fleshy macroalgae have been known to increase in biomass and cover the substrate. There has not been a documented case where the reef changed from a scleractinian dominated substrate to a corallimorpharian dominated reef.

This change in benthic cover has been term “phase shift”. The term “phase shift” was first used to describe a change to Jamaican coral reefs after a series of devastating natural events (Hughes, 1994). After Hurricane Allen in 1980 and Hurricane Gilbert in 1988, the reefs off Discovery Bay, Jamaica exhibited a dramatic decrease in coral abundance and diversity (Woodley, 1989). Live coral cover dropped to almost 0%. Wapnick, *et al*. (2004) extracted cores from the reef and found that the transition from an acroporid dominated coral reef to a macro algal dominated reef was unique on a centennial or millennial scale.

Wapnick, *et al*. (2004) considered that it was likely that the Jamaican reefs were exhibiting a community structure unique in the past several thousand years caused by extreme levels of both human and natural disturbance. Overfishing had devastated the benthic piscivorous and herbivorous fish populations. With the absence of *Diadema antillarum*, a sea urchin that had been devastated by disease, there were too few herbivores and algae covered the Jamaican reefs, drastically decreasing the amount of suitable substrate for coral planulae to settle and grow.

Healthy stocks of herbivorous fish were observed in Haa Dhaalu atoll (Figure 11). Maldivians have not intensively fished reef fish stocks, preferring to eat pelagic fish (Sheppard and Wells, 1988) leaving reef fish stocks relatively unexploited.

Figure 11. Schools of convict surgeon fish, *Acanthurus triosteges*, at 5 m, Hon'doofushi, Haa Dhaalu, March 2009.

It is uncertain what controls *D.* c.f. *rhodostoma* population dynamics at Hirimaradhoo reef. Although they are soft bodied, we have never observed fish feeding on them nor do they exhibit feeding scars. Further research is needed to understand how Maldivian reefs respond when the hard corals die and new coral recruitment is insufficient to rapidly reestablish high coral cover. Have some reefs in the Maldives always exhibited high cover of corallimorpharians or is this truly a unique "phase shift" brought about by the opening of so much bare substrate for settlement of larvae of corallimorpharians after the 1998 bleaching event?

Subsequent to the previous survey in 2005 a small channel has been constructed to assist vessels across the Hirimaradhoo reef to the beach (Figure 12). While there is an obvious alteration of the reef framework by the construction, the affects appear to be isolated to the area adjacent to the channel. It is unlikely that this relatively small reef modification is causing such a profound change to a large area of the reef in the survey transect.

Figure 12. A boat channel was constructed through the Hirimaradhoo reef after the 2005 survey.

North and South Male' Atoll

Maniyafushi

Maniyafushi is the future research station of the Marine Research Center (MRC) and had not been previously included in the National Coral Reef Monitoring program. The island is classified as an industrial island and was previously used by a fishing company which left the island in 2008. The coral reef survey by MRC was conducted in February 2009. The survey site is along the reef in front of the island's jetty. Debris tossed from the jetty litters the sea bottom including batteries, construction debris and general trash (Figure 13). It is the most littered reef we surveyed.

Figure 13. Debris tossed from Maniyafushi jetty covers part of the reef, February 2009.

The live coral cover is very high along the reef crest 63% (Figure 14). The shallow reef is dominated by acroporid and pocilliporid corals (Figure 15). Live coral cover diminishes to 24% at 12 m. At 24 m the substrate is mostly sand. The shallow reef has a much greater coral cover than at 10 m possibly because the transect at 10 m was on a reef wall. Coral growth on vertical walls is inhibited by shading and when coral branches are broken or corals are dislodged, gravity often carries them into deeper water. However, in silty environments, corals on walls are seldom smothered by sediment.

No diseased corals were observed. However, it was common to see a recently killed coral during roving dives (Figure 16). It is difficult to attribute the cause of the death, but predation is probable either by a coral eating gastropod (Figure 17), or the pin cushion starfish, *Culcita schmideliana* (Figure 18). An occasional *C. schmideliana* was observed on the reef, but never actively feeding on coral. The coral eating gastropod, *Coralliophylia* sp. is recorded from the Maldives, but the coral eating gastropod is not

Drupella cornus is not. Further effort is necessary to identify the gastropods that are eating the coral colonies.

Skeletons of the pipe organ coral, *Tubipora musica*, were scattered around the island in February 2009. The pipe organ coral is the only coral not banned from export. It is exported to India. Live colonies were not seen in any of the NCRMS surveys.

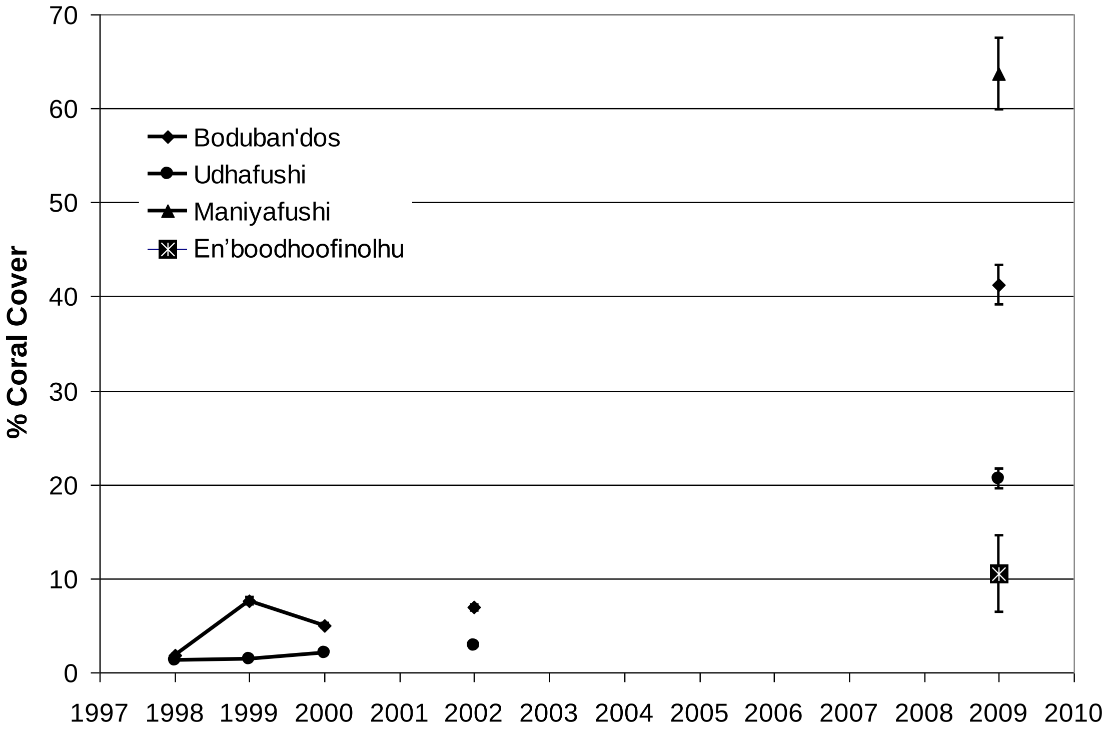

Figure 14. Percent live coral cover at 3 m at five sites in North and South Male' atoll. Standard error bars only included for 2009. n = 4 for each site.

Figure 15. M.A. Abdulla and B.L. Kojis swim past healthy *Acropora* colonies as they return from conducting a survey at Maniyafushi reef, February 2009.

Figure 16. Recently killed juvenile *Acropora* sp. coral. Possibly killed by *Culcita schmideliana* or a coral eating gastropod.

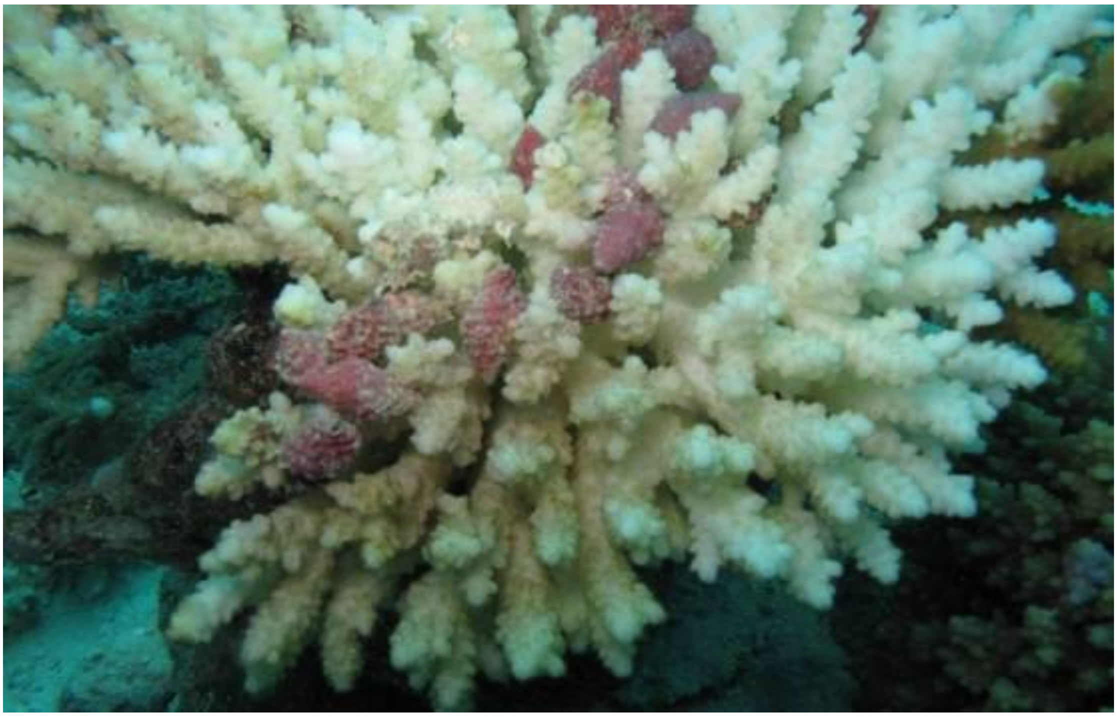

Figure 17. A swarm of coral eating snails have eaten an *Acropora* sp. colony.

Figure 18. The pin cushion starfish, *Culcita schmideliana*, on reef. This starfish eats small corals.

En'boodhoofinolhu

En'boodhoofinolhu had the lowest live coral cover in NCRMS in 2009. The reef has been used for sand mining for several decades. The sand is used in the construction industry in Male'. The mining is done from *dhonis* using divers who scoop the sand into plastic fiber bags which are then loaded on the *dhoni* and transported to Male'.

The sampling site is on the lagoon side of the reef and consequently receives the downwind sediment plume from sand mining operations. Live coral cover was low at 10.5% (Figure 14), but had risen from <3% during the period 1998 - 2002. Non living substrate (*e.g*. rock, rubble, recently killed coral and sand) accounted for >85% of the substrate. The remainder of the bottom was covered by an occasional sponge and fleshy algae.

Several *Acropora* colonies had broken branches and gaps where branches had previously existed (Figure 19). The branches at these damaged parts of the colony were either dying or dead, but the remainder of the colony appeared alive and healthy. The cause of this damage is unknown.

Boduban'dos

The coral cover at Boduban'dos after the 1998 bleaching was similar to many other reefs - a marginal 2% cover. In the years to 2002 the cover progressed at an uneven rate to 6.9%. Subsequent to the 2002 survey, construction of a harbour for the Bandos Resort occurred adjacent to the survey site. Regrettably, there was no survey immediately during the construction, or immediately after. Consequently, it is impossible to assess the effect the harbour construction had on the reef. However, despite the nearby construction the coral cover increased to 41% in September 2009. This is a remarkable recovery considering the proximity to a busy harbour with its constantly resuspended fine sediment. The recently killed coral is 1% - 2% in both the deep and shallow transects. This level is common for many of the reefs in the NCRMS in 2009. The coral community only has a few fleshy algae as the total percent of nutrient indicating algae for both transects is less than 1%.

Udhafushi

Udhafushi was the outer reef slope of a *faru* in the center of North Male' atoll. From the post bleaching coral cover of 1.3% in 1998, the site recovered slowly to 2.9% in 2002. While the percentage increase of 223% looks impressive the actual amount of additional hard coral cover is only 2.40 m over a 150 m transect. From 2002 to the survey in October 2009, the coral cover increase dramatically to 21% at 3 m and 18% at 10 m. However, the percent coral cover was still the least for North Male' atoll. Although the reef is in the center of the atoll and presumably far from oceanic swells, there was evidence of 5 m sections of the reef sliding down the reef slope.

Depth Variation

At Manyiyafushi and Boduban'dos the coral cover was greater along the shallow transects than on the deeper ones (Figure 19). The reef surveyed at 10 m at Manyiyafushi was along an east west wall which receives less direct light during periods of the year. Consequently, one would expect less coral cover. It is likely that owing to increased turbidity associated with harbour sediments the substrate at 10 m at Boduban'dos receives less light and therefore supports less coral cover. The coral cover at Udhafushi was only slightly lower at 10 m (Figure 20). Considering the variability of coral cover on the reef there was essentially no difference in cover between the two transects.

Figure 19. Damaged *Acropora* at En'boodhoofinolhu reef, South Male' atoll, at 10 m, September, 2009.

At En'boodhoofinolhu reef the coral cover was greater at 10 m than at 3 m (Figure 20). Perhaps currents help to remove some of the silt before it smothers the deeper corals or the sediment settles in the shallower water and reduces coral grow and smothers early recruits. There are no studies of current patterns from the Maldives. This is certainly a potential area for future research and help scientists to understand circulation patterns.

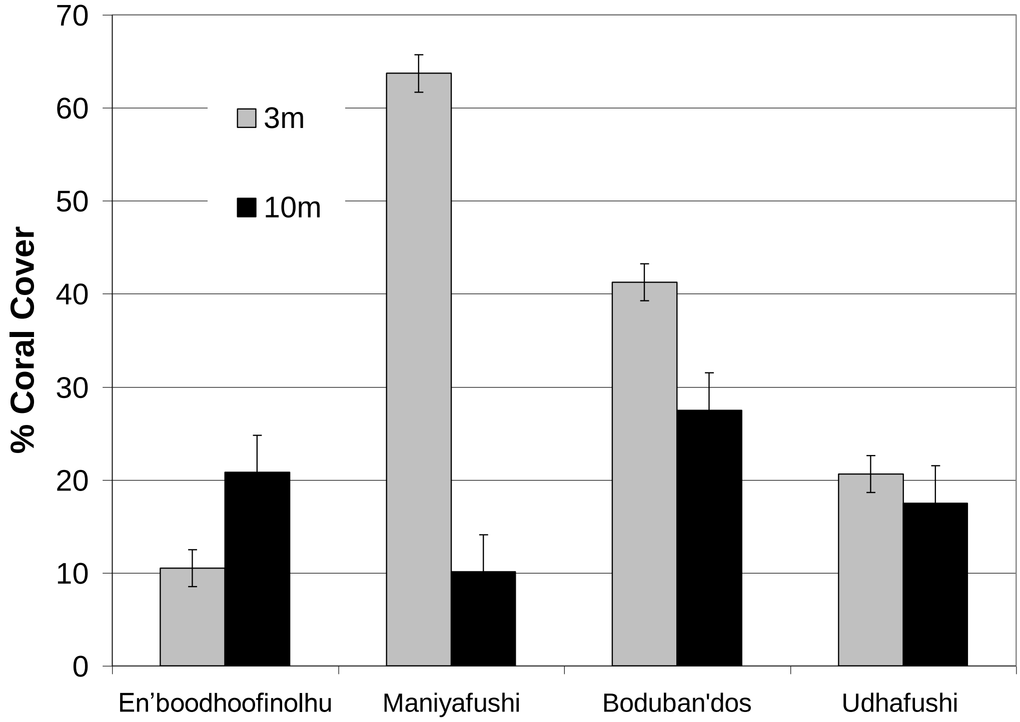

Figure 20. Comparison of % coral cover at 3 m and 10 m at one site at North Male' atoll and two sites at South Male' atoll, in 2009. n = 4 at each site and each depth. Standard error shown by bars.

Ari Atoll

Fesdhoo, Maayafushi, Velidhoo reefs

The shallow reefs of Fesdhoo, Maayafushi, Velidhoo in the NCRMS at Ari atoll exhibited exceptional resilience. In 2005, most of these reefs had coral cover less than 11% (Figure 21). Fesdhoo reef exhibited resilience throughout the survey period. After the bleaching event in 1998, it quickly recovered to 10% coral cover in 2000 and then by 2005 had over 30% coral cover. In 2009, it was among the most luxuriant reefs surveyed with about 65% coral cover. Velidhoo reef also demonstrated remarkable recovery from about 11% in 2005 to 50% in 2009. Some time after the sampling in 2005, the hotel at Maayafushi reef had expanded constructing water bungalows over the reef flat, within 100 m of the reef edge. It does not appear that the sedimentation associated with the construction of the bungalows greatly thwarted the recruitment of new corals by either smothering new recruits or covering suitable substrate with silt rendering then unsuitable for settlement. Much of the recovery in these sites is due to successful recruitment and growth of primarily acroporid colonies and to lesser extent pocilliporid colonies. Maayafushi reef also had good recovery from 6% in 2005 to 31% coral cover in 2009.

Dega *Giri*

Surveyed in 2008 by the Marine Conservation Society, Dega *giri* in Ari atoll is among the reef with the highest coral cover (68%) (Solandt and Wood, 2008) (Figure 21). The substrate was dominated by mature colonies of *Acropora* with the coral cover at the *giri* edge being the greatest (Solandt and Wood, 2008).

Surveys using a standardized protocol, such as Reef Check, from various overseas organizations are important as they contribute to the knowledge of the conditions of the vast Maldivian reef system. It is however, suggested that MRC be designated at the official Reef Check coordinator for the Maldives and that all registered Reef Check groups coordinate their efforts through MRC and provide copies of their data set to MRC. On occasion surveys by foreign researchers are undertaken and little of the knowledge gained is retained in the Maldives.

Kandholhudhoo

Kandholhudhoo reef was added to the NCRMS in 2009. With over 50% coral cover it is among the more luxuriant coral reefs in the atoll. The island has been modified to be used as a picnic island by guests from nearby resorts (Figure 22). Presumably it was chosen for that purpose because of its nice sandy beaches and diverse coral reef (Figure 23) for snorkeling and diving.

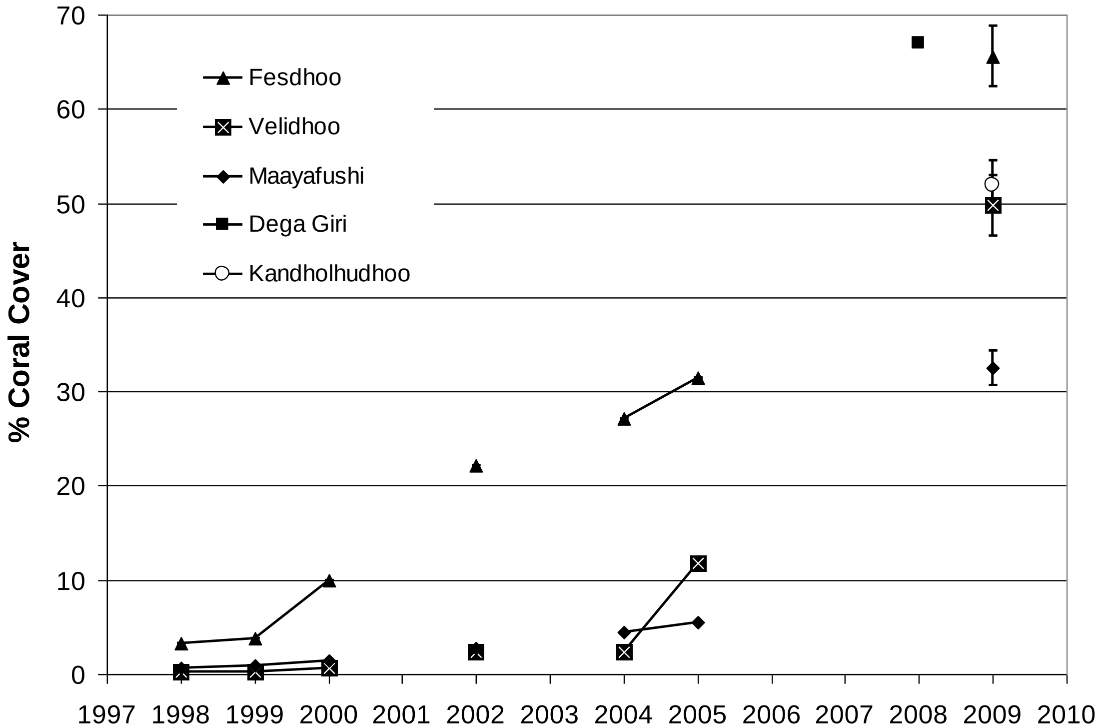

Figure 21. Percentage live coral cover at five sites in Ari atoll. Standard error bars only included for 2009. (n = 4 for each site). Dega *giri* data from Solandt and Wood (2008).

Figure 22. Kandholhudhoo is a picnic island with beautiful beaches naturally replenished by a diverse, healthy coral reef which surrounds the island. April 2009.

Figure 23. Kandholhudho reef at 7 m showing some physical damage and partial mortality to tabulate *Acropora* and intact tabulate *Acropora* colonies, March 2009.

In Fesdhoo, Maayafushi, and Velidhoo the percent coral cover was greater in the shallow water than at 10 m (Figure 24). At 10 m, Kandholhudho reef had a 64% coral cover and was as luxuriant as the shallow Fesdhoo reef. Water bungalows have been built at Fesdhoo near the survey site since the last survey and have not adversely affected the reef.

The Velidhoo reefs here had the second lowest % coral cover at both the 3 m and 10 m surveys. It is unclear why the coral cover was so low. Maayafushi had the lowest coral cover (32.5% at 3 m and 13.8% at 10 m). The presence of a sewage outflow from the resort at the Maayafushi NCRMS site at 10 m is hypothesized as a causal agent in diminishing the ability of the reef to recover. This site would be an interesting research site to assess the effects of point source pollution on a remote and relatively pristine reef.

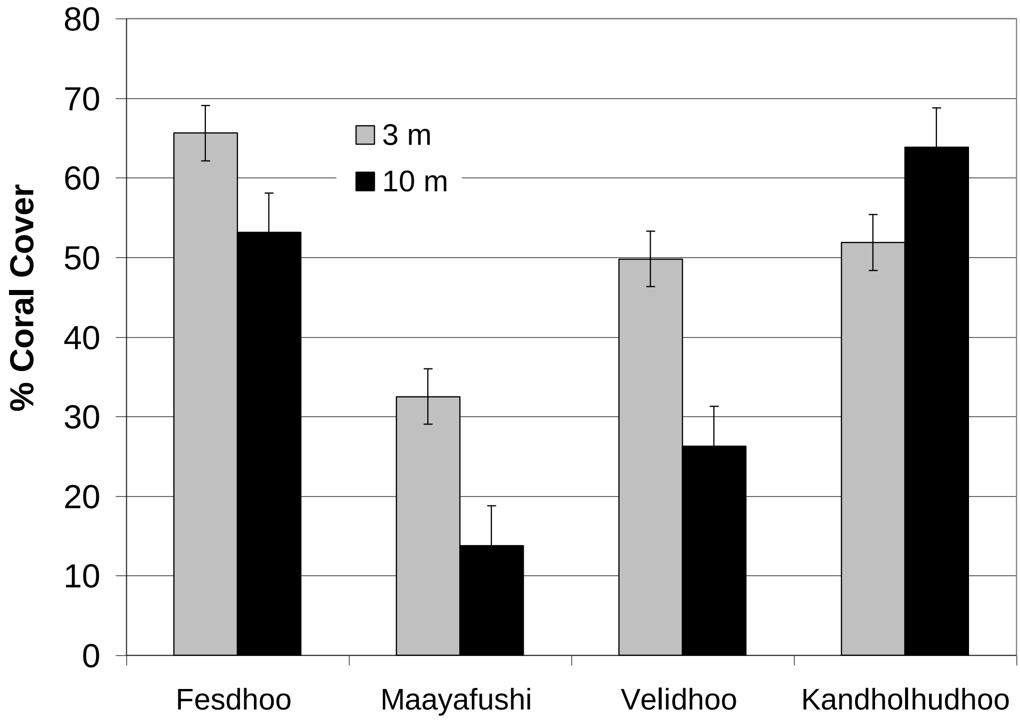

Figure 24. Comparison of % coral cover at 3 m and 10 m at four sites at Ari atoll, April 2009. n = 4 at each site and each depth. Standard error shown by bars.

Vaavu Atoll

The NCRMS established a shallow water survey site at Anbaraa in 1997, before the 1999 bleaching event. This was among the most luxuriant reefs with near 60% coral cover (Figure 25). In a resurvey of the site shortly after bleaching in 1998, the coral cover had been dramatically reduced to about 1%. The acroporids and pocilloporids had died. Only a few massive (Poritidae, Faviidae) and non branching corals (Agariciidae) remained.

In April-May 1999, McClanahan (2000) surveyed 19 sites at a depth of 1 - 30 m (mostly in the Vaavu atoll region) and noted that the benthic cover was dominated by coralline and turf algae (68%), followed by erect algae (9%), hard coral (8%), sand (7%) and other invertebrate groups <3.5%. In 1999, *Porities, Astreopora, Pavona, Favites, Fungia, Favia*, *Leptastrea*, *Coscinarea*, *Symphyllia*, *Montipora* and *Goniastrea* accounted for 45.4% of the live coral in 1999, while *Acropora* accounted for only 3.5% of the coral cover. In March 2009, *Acropora* dominated the shallow water coral community at the three NCRMS sites.

Two months after the December 2004 tsunami the reefs were resurveyed and compared to the 2004 NCRMS observations. In two of the three sites the coral cover had declined: 1) from 10.8% to 9 % at Vattaru and 2) from 4.4% at Fohtheyobodufushi to 1.8% (Zahir, *et al*., 2006). The decline in coral cover was caused by sediment deposition and smothering of the corals by sand and debris that had washed across the reef flat (Zahir, *et al*., 2006). Both sites were lagoon side reefs on the eastern side of the Maldives facing the direction of the tsunami. No effects of the tsunami were observed at Anbaraa. This is possibly because the site is located in the middle of the atoll and because the reef is not orientated to waves sweeping over the reef flat.

In 2009, the reefs of Vaavu atoll have recovered from a percent coral cover of <10% in 1999 to a coral cover of 18% - 48% in March 2009. The reef by the most eastern island in the Maldives, Fohtheyobodufushi, had the highest coral cover for the atoll 48% (Fig. 24). The island was uninhabited and was only occasionally used by fishermen and visitors from safari dive boats. On the other side of the atoll the reef at Anbaraa had increased from about 5% coral cover in 2005 to about 18%. To the south of Vaavu atoll is the small atoll of Vattaru. The reef surrounding Vattaru island is a Marine Protected Area, but is used illegally by fishermen to catch marine resources. The shallow reef coral cover had varied from 1998 to 2005 when coral cover ranged from about 2% in 1998 to 5% in 2003 before dropping to below 2% in 2005 (Figure 25). By 2009, coral cover had increased dramatically to 32%.

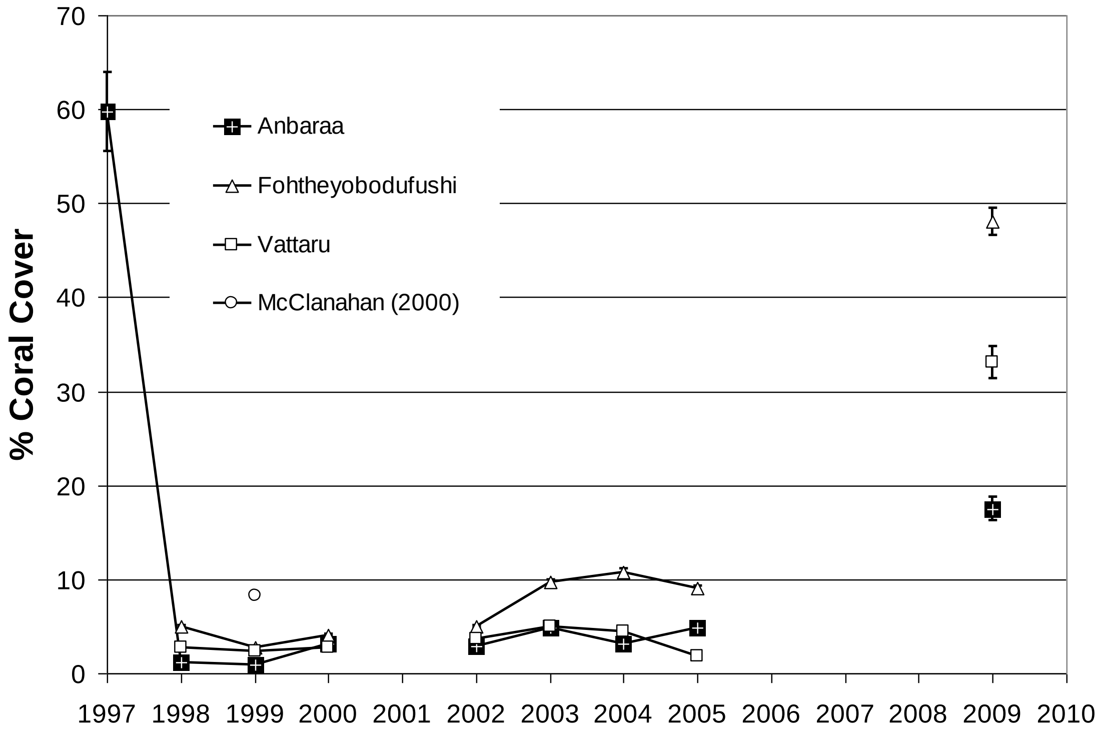

Figure 25: Percentage live coral cover at three sites in Vaavu Atoll. Standard error bars only included for 2009, n = 4 for each site and year. 1999 point represents pooled values from McClanahan (2000).

The percent coral cover was higher in shallow depths in two of the sites (Figure 26). Only at Anabarra was coral cover at 10 m greater than at 3 m. Additional abiotic data needs to be collected in order to further understand the spatial and depth variation within the atoll.

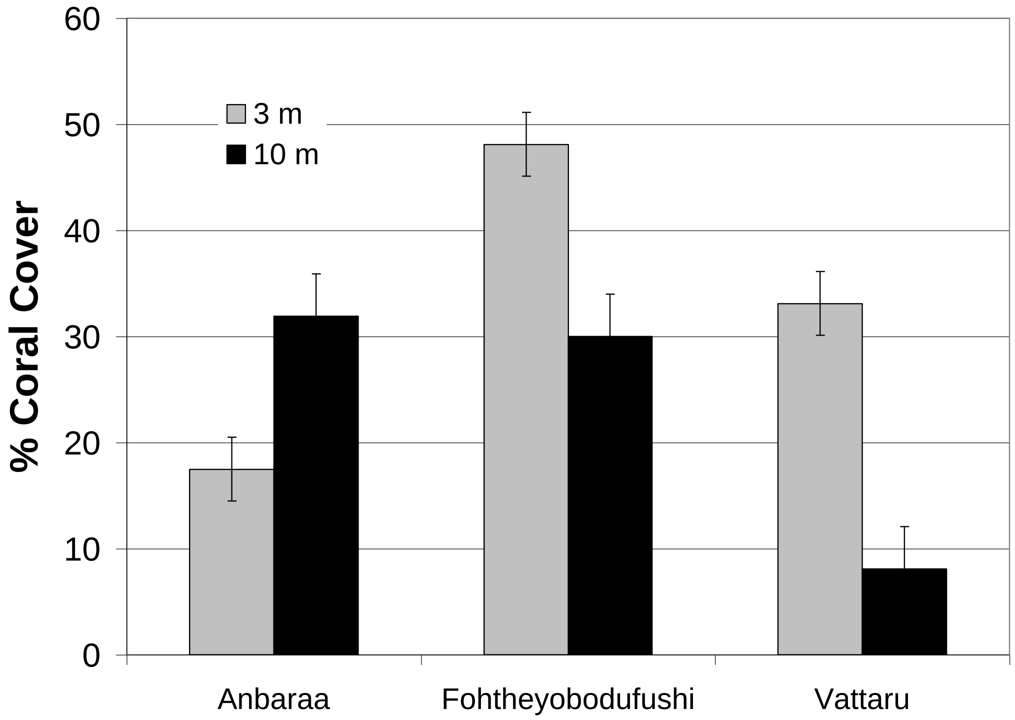

Figure 26. Comparison of percent coral cover at 3 m and 10 m at three sites at Vaavu atoll, May 2009. n = 4 at each site and depth. Standard error shown by bars.

Gaafu Alifu Atoll

The single NCRMS site in Gaafu Alifu atoll, Koodoo, was only surveyed in 1998, 1999, 2002 and 2005. By 2005, there had been a dramatic increase in coral cover from about 6% in 2002 to nearly 26% (Figure 27). The increase is attributed to a rapid growth in tabulate acroporids (Zahir, 2006).

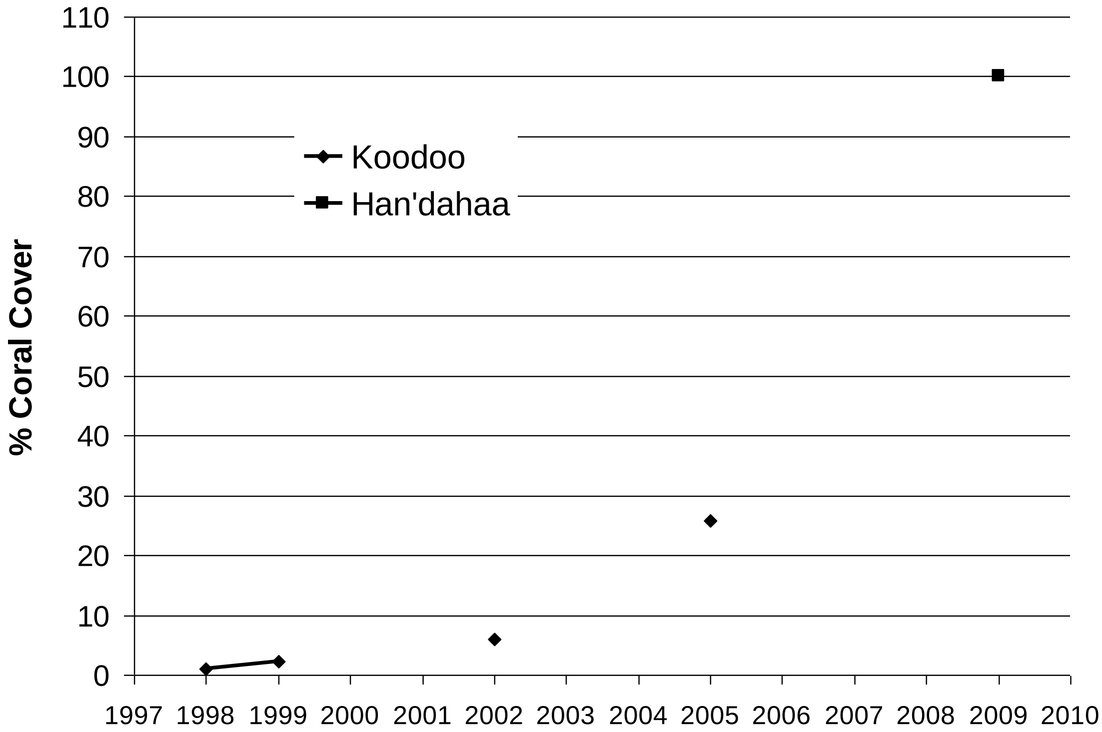

Figure 27. Percentage live coral cover at 5 m at Koodoo, and Han'dahaa in Gaafu Alifu atoll. n = 4 for Koodoo for each year. Han'dahaa based on visual estimate survey.

In September 2009, Han'dahaa reef (0° 30'19" N., 73° 27'14" E.) was inspected and coral cover estimated in a roving diver survey lasting 1 hour in depths up to 32 m. The Han'dahaa reef is has the greatest coral cover of all the reefs in the NCRMS. Large tabulate corals (*Acropora cytherea*) up to 3 m in diameter dominated the reef from 3 – 12 m. Coral cover exceeded 100% along scores of meters of reef at the 10 m depth contour (Figure 28). Large tabulate corals commonly covered other corals resulting in coral cover exceeding 100%. Even at 20 m the coral cover was about 90% (Figure 29).

This luxuriant coral reef community exists in spite of a four year construction program to build the 50 room Alila Villas Hadahaa. Great care went into the construction of the resort to preserve the natural vegetation and minimize alterations to the fringing coral reef in order to maintain the natural ambience of the island and minimize the environmental footprint of the resort. The resort was the first resort in the Maldives to adhere to the standards for EC3 Green Globe certification for 'Building, Planning and Design Standard.' Green Globe, an international benchmarking and certification program for the travel and tourism industry, is managed by EC3 Global, a subsidiary of the Australian based research body Sustainable Tourism Co-operative Research Centre (the world's largest source of tourism research). Its standards are based on the Agenda

21 principles for Sustainable Development endorsed by 182 Heads of State at the United Nations Rio Earth Summit in 1992.

In keeping with this environmental achievement the management intends to implement a long term marine monitoring program. Future monitoring programs by the resort is likely to include subsurface sea water temperature, growth of selected coral species, monitoring coral cover, stock assessment of groupers, emperors, lobsters and other reef associated indicator species. The Maldivian owners are avid scuba divers that are passionate about their desire to insure that the best management practices are applied to the island’s habitats.

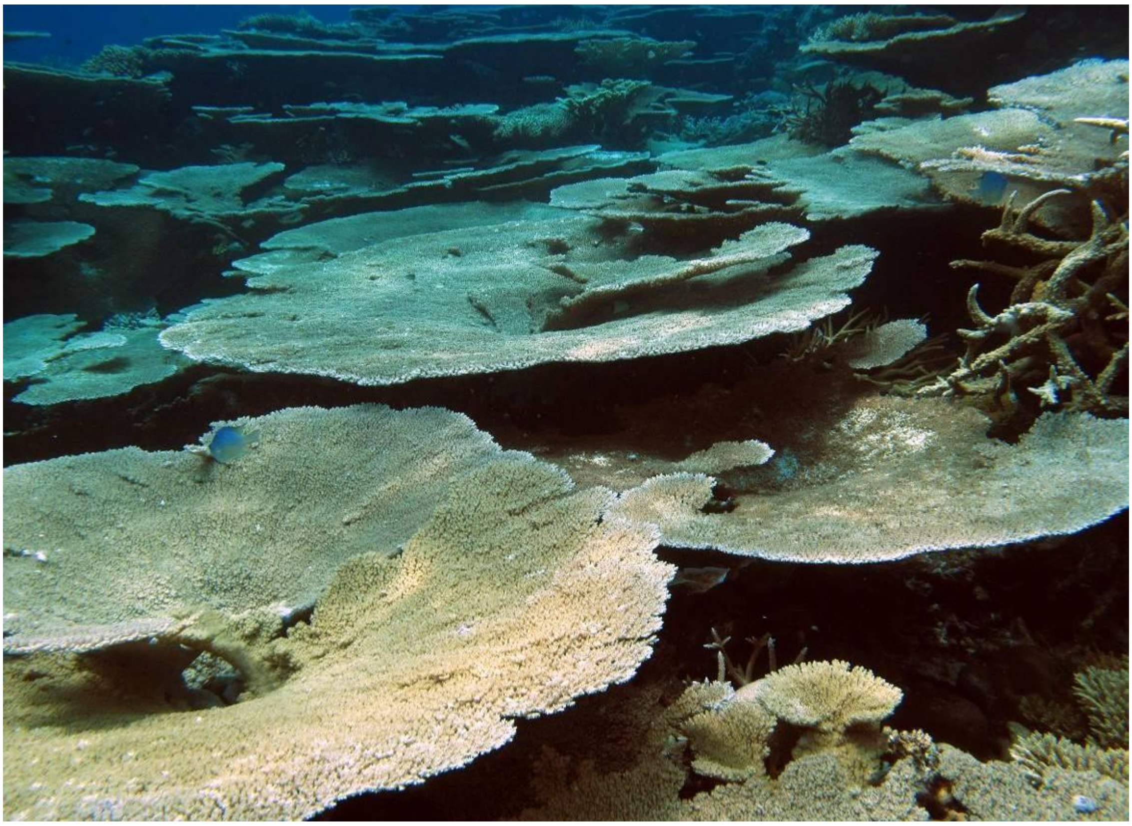

Figure 28. Over lapping of tabulate corals (*Acropora cytherea*) at 10 m at Han’dahaa, Gaafu Alifu atoll has created one of the few sites known where coral cover exceeds 100%. September 2009.

Figure 29. *Acropora* dominated the north east reef slope at 15 - 30 m, Han’dahaa, Gaafu Alifu atoll, September 2009.

While large areas of the Han’dahaa reef slope are healthy with an extremely high percent coral cover, the western reef flat showed signs of large waves several years ago. Tabulate corals over a large area away from the resort’s western loading jetty were detached and overturned. In spite of being dislodged and overturned many of the tabulate corals remained alive and some were growing in their natural horizontal shape (Figure 30).

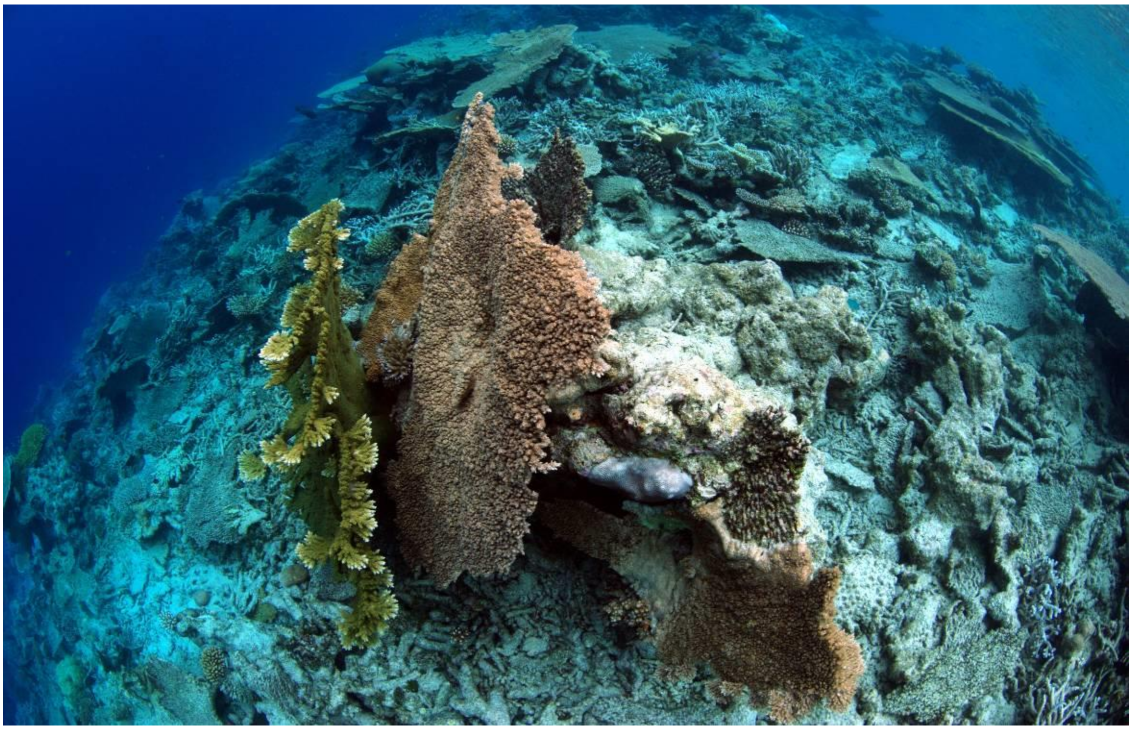

Figure 30. Dislodged and overturned *Acropora* corals on reef flat, 4 m, Han'dahaa reef, September 2009. Note corals are still alive and new horizontal growth is occurring on left coral.

During the resort construction large expanses of the western reef flat was covered by a filamentous algae (Ali, pers. comm.). By September 2009, most of the filamentous algae was gone and only a few coral appeared have died (Figure 31). The installation of *in situ* data loggers to record nutrient levels, salinity and water temperature and a terrestrial meteorological station would begin to provide the context for understanding changes to the habitat.

Figure 31. S. Ali inspects filamentous blue green algae on a tabulate coral and recently dead tabulate coral (white area) on the Han'dahaa reef flat near the desalinization plant outfall (see upper left hand corner of photo). 4 m, September 2009.

Addu Atoll

The NCRMS was conducted in May 2009, in Addu atoll (Figure 32). As with the other reefs in the Maldives, the coral reefs of Addu atoll were subjected to the 1998 bleaching event (Allison, 1999; Clark, *et al*., 1999), but had the greatest recovery of live coral cover in sites distant from anthropogenic influences. After the 1998 bleaching, the reefs at Addu atoll still had some living coral. At 5 m the Vilingili reef had about 4% coral cover in 1998 increasing to 13% in 2002. In 2009, the coral cover had increased to 55% (Figure 33) in spite of its proximity of the development of resort water bungalows and beach restoration efforts. Recently killed coral was observed (Figure 33) at Vilingili reef, but only covered 0.3% of the substrate in the two transect lines.

Figure 32. Y. Rilwan is recording substrate cover on a transect line at Vilingili reef, Addu atoll. 10 m, May 2009.

During the Vilingili survey in May 2009, the sediment plume from the resort's beach restoration occasionally clouded the shallow parts of the site. The reef has survived the 1998 bleaching better than many other reefs as there were still large colonies of the slow growing *Porites lobata* coral (Figure 35).

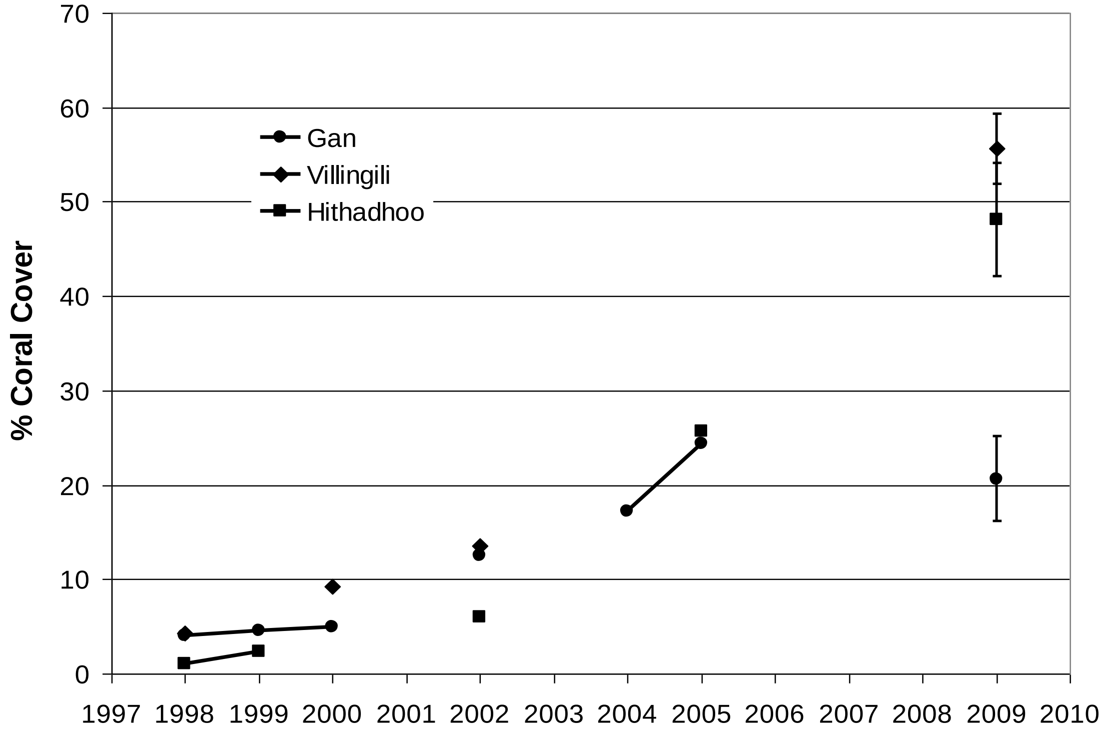

Figure 33: Percentage live coral cover at 5 m at Gan, Vilingili and Hithadhoo reef, Addu atoll. Standard error bars only included for 2009, n = 4 for each site and year.

Figure 34. Recently dead coral at Vilingili reef, Addu atoll, May 2009. Algae are beginning to grow on portions of the dead coral.

Figure 35. Large colonies of *Porites lobata* were common at Vilingili reef, May 2009.

Previous surveys of Addu atoll from 2002 - 2004 included transects at 10 m as well as shallow surveys at Gan, Vilingilli and Hithadhoo. Regrettably, there were no quantitative surveys below 5 m of these reefs immediately post bleaching, so it is difficult to assess both the damage and recovery. However, the reefs during this period had 40 – 63% coral cover (Figure 36). The Gan site is juxtaposed to a shipping jetty and in 2009 was littered with debris. Although the jetty has been there since the British used the island as a military air base, the live coral cover in 2002 was 42%. However, in the seven years from 2002 to 2009 the live coral cover dropped from 32% to 14%. Without more detailed information we are unable to determine a cause for the decline.

The other two survey sites had very good coral recovery. Vilingili reef remained within the standard error of the last survey in 2004 at nearly 60% live coral cover. Hithadho reef also remained stable with a live coral cover of 52% staying within the standard error of the previous survey. The Hithadho was a diverse healthy reef (Figure 37) that was included as a Marine Protected Area a few years ago after an intensive study of the land and marine environment (Ministry of Environment, Energy and Water, 2006).

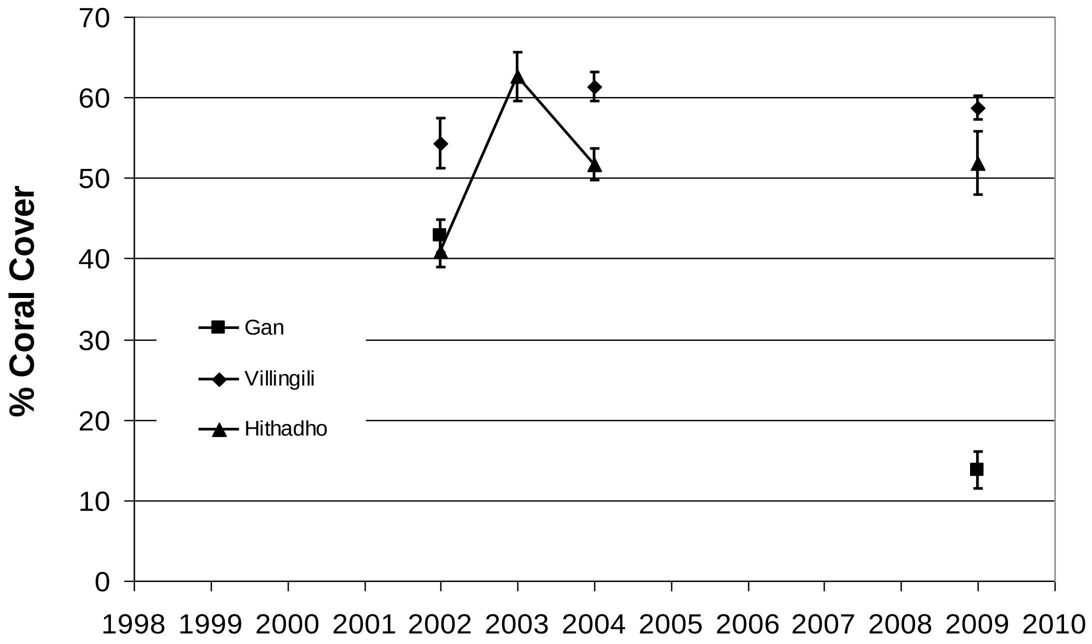

Figure 36. Percentage live coral cover at 10 m at three sites in Addu atoll, May 2009. n = 4 at each site in 2009 and n = 3 in 2002 – 2004.

Figure 37. I. Abid, a member of the MRC coral reef monitoring team conducting a survey along four 20 m transects at Hithadhoo reef, Addu atoll in May 2009.

The % coral cover at both depths at Vilingili reef and Hithadoo reef are high and not significantly different between depths (Figure 38) ($P>0.05$). The coral cover at Gan reef is much lower and there is a significant difference in coral cover with depth as previously discussed.

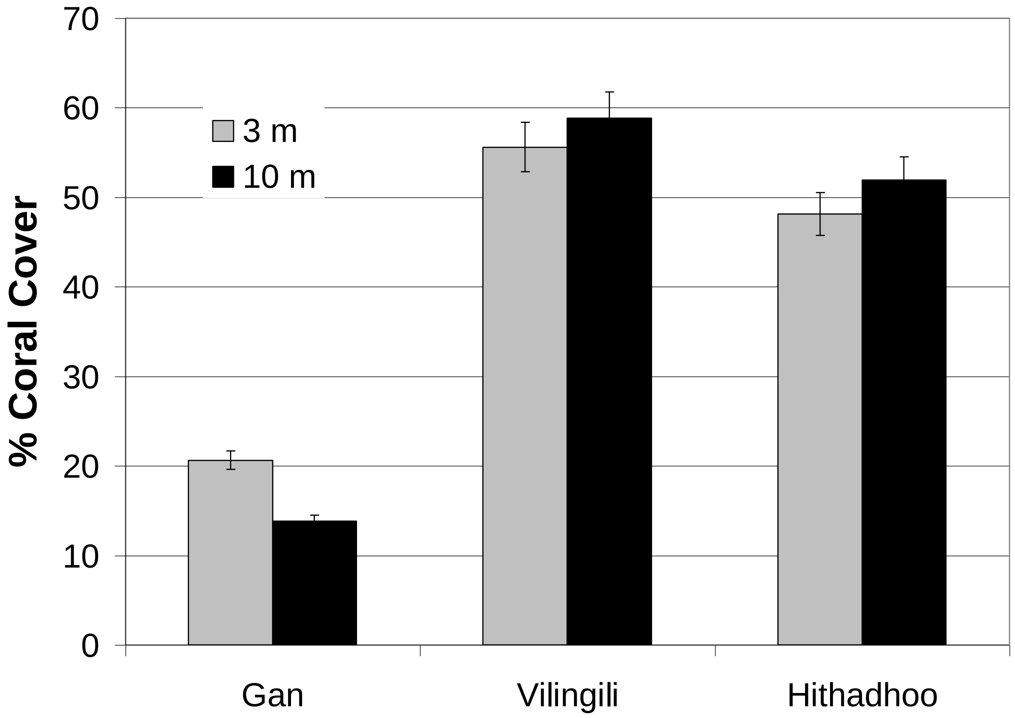

Figure 38. Comparison of % coral cover at 3 m and 10 m at three sites at Addu atoll, May 2009. n = 4 at each site and each depth. Standard error shown by bars.

During a resource assessment for the establishment of the Maldives Protected Area System Project the reefs surveyed around Addu atoll surveyed clear signs of hard coral community recovery (Ministry of Environment, Energy and Water, 2006). The recovery was dominated by Acroporidae species and a single species of Faviidae – *Echinopora*. The size of corals that recovered varied within the lagoon with the larger and subsequent old coral colonies located on the reef edge and slopes of the northern ocean side reefs. The assessment found that the area with the greatest percent live coral cover and diversity of coral included the reef where the Hithadhoo NCRMS site is.

It was recommended that this area be managed under a regime that prevents anthropogenic activities from damaging and degrading the coral populations (Ministry of Environment, Energy and Water, 2006). The assessment considered some of the major anthropogenic threats to the habitat to be:

- Pollution from human waste, petrochemicals and rubbish,
- Increased sedimentation from terrestrial degradation,
- Resource extraction, *e.g.* removal of sand, rubble and coral rock,
- Resource exploitation, *e.g.* overfishing of holothurians,
- Habitat alterations – cutting the reef to create boating channels,
- Habitat destruction – anchor damage by bait fishing vessels.

Coral Framework Status

The coralline algae / sponge association dominates much of the coral reef framework on a healthy reef. Lasagna *et al*. (2008) observed that the abundance of bare rock, sand and rubble derived from dead coral breakage was the result of the loss of 3D structure in Maldivian coral reefs and that this substrate smoothing is known to represent an impediment to coral recruitment (Loch, *et al*., 2005). This loose material can limit coral recruitment (Loch, *et al*., 2002; Lasagna, *et al*., 2006), as coral larvae preferentially settle on encrusting calcareous algae (Heyward and Negri, 1999) and frequently avoid rubble as a settlment substratum (Sheppard, *et al.*, 2002). In 1999, McClanahan (2000) observed that 11 of the 16 coral families known from the Maldives had recently recruited to the 19 reefs they surveyed. Almost the half of the recruits were Agariciidae, with Acroporidae and Pocilloporidae being rare. However, from 2001-2002 the taxonomic composition of recruits shifted from a dominance of Agariciidae in the early stages of recolonization toward a dominance of Acroporidae and Pocilloporidae (Bianchi, *et al*., 2006).

Roving diver surveys were conducted on the deeper reefs throughout the NCRMS in 2009. On many of these reefs (>20 m) *Tubastrea micranthata* was the most abundant coral. Acroporid and pocilloporid colonies were dominant in shallow waters (<10 m). Massive corals such as *Poritie*s, *Pavona* and faviids were usually small (<30 cm). These are slower growing taxa than acroporans and pocilloporids.

Colonies of *Porites* were observed with new growth on top of dead colonies (Figure 39). It is unclear whether this was regrowth of a surviving part of the original colony or new recruitment. This is certainly a question waiting for a future researcher to answer. If these colonies are survivors of the bleaching event, then it is likely that the colonies will survive future thermal increases. The comparative size of the *Porities* colonies against the other species (Figure 39) suggests that either they are survivors or early recruits to this open space.

Figure 39. Dead *Porites* colony with new colonies of *Porities, Acropora* and other species growing on it, 20 m, Magiri reef, North Male' atoll, September 2009.

It is unclear whether there has been any local extinction of coral species. Bianchi, *et al*. (2006) reports that up to 2003, no colonies of *Stylophora* or *Seriatopora*, two genera previously reported in the Maldives prior to 1998, were observed at any site. Indeed, in this survey colonies of these genera were very rare. However, H.Z. has observed both genera on the Ari atoll outer reef slopes and suggests they are slowly returning in abundance.

A couple dead colonies of *Seriatopora* were for sale at Gloria Maries, a souvenir shop, in Male' in October 2009, for Rf4000 (Rf12.75 = US$1.00). Maldivian law prohibits the export of scleractinian coral.

Only a few living remnants of *Acropora palifera* were observed post bleaching by Loch, *et al*., (2002) and by N.J.Q on the NCRMS. H.Z. has observed that *A. palifera* is common on western Ari atoll outer reefs. As well, *Millepora*, a common genus before the bleaching, was not found in surveys to 2003 (Bianchi, *et al*. (2006). Nor was it observed in 2009 in the NCRMS. In contrast, *Millepora* rapidly recruits in the Caribbean after bleaching (Kojis and Quinn, 2001).

Portions of colonies of *Porites* c.f. *lobata* and *Diploastrea heliopora* survived and grew 40 mm and 12 mm, respectively, post bleaching to March 2001 (Schuhmacher, *et al*., 2002). Perhaps the surviving remnants of these massive corals have developed a relationship with heat adapted zooxanthellae and are better adapted to increasing water temperatures. Following these colonies would yield interesting scientific information about a coral communities' adaptation to climate change.

While some habitats have recovered there are still large areas of reefs with little sign of recovery. Either the substrate is unsuitable for settling and survival or planulae are not are not being sweep past the reef. The Guraidhoo Corner reef crest (8 m), South Male' atoll (Figure 40) and Vabbinfaru reef, North Male' atoll (Figure 2) are examples of two different habitats with poor recovery. Guraidhoo Corner is at the edge of a channel with strong currents and an abundant fish community. The area is a popular dives site because of the abundance of herbivores, groupers, sharks, turtles and manta rays. Vabbinfaru reef surrounds Banyan Tree Resort which pumps sand from the reef to replenish its beach which is periodically swept away by strong waves. An informed and concerned resort management understands the importance of the reef for the physical stability of the island and for it attraction for visitors. An innovative coral restoration program is endeavoring to assist in the recovery of live coral on the reef.

Figure 40. Guraidhoo Corner, South Male' atoll is a reef subject to oceanic swells and unconsolidated corals with poor recovery. September 2009, 8 m.

While a sandy, shifting substrate may inhibit coral recruitment, for many decades Maldivians mined coral for building materials and the overall reefs seem to have survived. Historically, virtually all village homes, businesses and municipal building were constructed from coral. There were some shallow reef flats that were intensively and repeatedly mined resulting in these lagoons and *faros* being depleted of corals (Brown and Dunne, 1988). Legislation in the late 1990s recognized the environmental and economic damage of this practice and limited both the total volume and spatial extent of the coral removed. Coral mining is now regulated and specifically, coral cannot be mined on inhabited islands, resort house reefs, reef frequented by tourists, atoll rim reefs and common bait fish fishing reefs (Sluka and Miller, 1998). Many village homes now show a mixture of traditional coral and newer sand cement block construction.

The loss of complex physical structure can result in local extinctions, substantial reduction in species richness and reduced taxonomic distinctness associated with diverse productive coral reefs (Graham, *et al*., 2006). Many Maldivian atoll outer ocean facing reefs and the inner lagoon reefs (*faros*, *thila* or *giris*) do not have deep spur and groove features that characterize the Florida reef track and some southern Maldivian outer reefs. Many lagoon reefs exhibit steep slopes without major contours. In spite of the deterioration of the structural complexity of some reefs (Loch, *et al*., 2002) a large number of reefs have recovered very rapidly. At some sites there was a “tremendous increase” in hard coral cover shortly after the bleaching event (Loch, *et al*., 2002).

At a depth of 15 - 30 m caves are occasionally observed and are likely the result of erosion caused by wave action when sea level was lower during the last ice age which ended 8100 - 6500 years ago when sea level rose ~ 7 mm annually (Kench, *et al*., 2009b). These caves, formed by sea level still stands, have low light levels and consequently usually no zooxanthellate scleractinian corals. They attract low light level species such as *Tubastrea* corals, sponges, sea whips, black (Antipitherian) corals along with soldier fish and occasionally glass fish. There is no record of any surveys of these communities being conducted during or after the bleaching event. These are special communities that deserve particular consideration and monitoring.

Coral Reef Recovery in the Region

Dubai, United Arab Emirates

How have other reefs in the region recovered from the bleaching event? A decade after coral bleaching in the United Arab Emirates (UAE), one area formerly dominated by *Acropora* was dominated by faviids and poritids, with adult and juvenile composition suggesting this dominance shift is likely to persist (Burt, *et al*. 2008). Acr*opora* dominated assemblages in the UAE were observed in three of the six sites examined and coral cover (41.9 ± 2.5%) was double the coral cover immediately after the bleaching. *Porites lutea* and *Porites harrisoni* dominated communities that were negligibly impacted by the bleaching events, and the limited change in coral cover and composition in intervening years was probably from slow growth and low recruitment. Despite strong recovery of several dominant *Acropora* species, five formerly common species from this area were not observed suggesting local extinction. It was concluded that Dubai coral communities exhibit both resistance and resilience to elevated sea temperatures (Burt, *et al*., 2008).

Lakshadweep Islands, India

Closer to the Maldives in the Lakshadweep Islands, India, by 2005 the coral recovery was very site specific and was influenced by differences in post settlement survival of recruits which were driven by local water circulation patterns (Arthur, *et al*., 2006). In 2001 the coral cover ranged from 6% - 19% as the rate of recovery observed was not uniform. Recovery was greatest on the west facing reefs with very limited recovery on the east facing reefs. The reef did not experience a ‘phase shift’ to macroalgal dominated reefs. The presence of intense herbivore grazing was considered to be the most important controlling factor (Arthur, *et al*., 2006). The genera that showed the maximum increases five years after the bleaching were those with a mix of “different susceptibilities” to bleaching. Other genera that were not particularly venerable to the bleaching showed significant declines. The authors suggest that individual life history strategies, post-recruitment and circumstances greatly influence the decline and recovery of the coral communities (Arthur, *et al*., 2006).

Chagos Archipelago, Indian Ocean

To the south of the Maldives the Chagos Archipelago was particularly badly affected, suffering total or very heavy coral mortality on seaward slopes to >30 m depth with species-specific mortality extending deeper still (Sheppard, *et al*., 2002). This occurred in spite of it remoteness from direct human impacts. Hard and soft coral cover on seaward slopes before 1998 was 50% to 95%, which declined in 1998 to an average of 12%, and even to zero% at the depth of 0 – 5 m in some shallow areas (Sheppard, 1999). Initial mortality of corals was followed by a collapse of the reefs’ structural framework resulting in the loss of obligate corallivores (Spalding and Jarvis, 2002).

As in the Maldives, fleshy algal cover did not increase after the coral mortality. By 2006, coral cover was almost restored to pre-1998 levels at most shallow sites, but had recovered much less in deeper waters. Sheppard, *et al*. (2008) considers that the coral cover alone is a poor indicator of recovery because the cover was dominated by *Acropora palifera* and other corals that are largely encrusting in juvenile form, in contrast to their mature morphology, in which they have a great 3D relief structure. Spatial complexity is important to diversity and abundance within the reef community, including fishes (Graham, *et al*., 2006) and needs to be considered when assessing reef recovery.

Coral Reef Diseases

No diseased corals were recorded in the NCRMS transects. However, a disease associated with crustose coralline algae was observed, but not quantified, during roving dives (Figure 41).

Figure 41: Coralline algae being attacked by the bacterial disease, CLOD (yellow), at En'boodhoofinolhu, North Male' atoll, September 2009. White section is recently killed coralline algae.

Crustose coralline algae (Rhodohyta, Corallinales) are plants that deposit calcite, a particularly hard and environmentally resistant form of calcium carbonate. These marine plants bind surficial carbonate materials, debris, and other calcareous organisms to create stable substrata. Tropical reefs in high energy environment depend on calcareous coralline algae for the maintenance of wave resistant intertidal ridges (Littler and Littler, 1997). Many crustose corallines have a prostrate type growth form and are conspicuous as maroon, red, pink and purpose pavement covering large areas, whereas other forms develop vertically branching heads much like some corals.

Functionally, crustose coralline algae, particularly *Porolithon*, are the principal binding agents that generate the structural integrity and shock resistance of the reef rim in high energy systems. Coralline algae are important for the absorption of massive wave energy that would otherwise erode shoreward land masses and for the facilitation of the development of many other sheltered shallow reef communities. All coralline algae proved fatally susceptible to the bacterial pathogen, CLOD (Littler and Littler, 1997). The bacterial disease should be included in future monitoring efforts.

Sponge Abundance and Distribution

Overall non boring sponges represent <1% of the total cover in the 17 sites in the NCRMS. Overall the cover was: 3 m - 0.7% cover, 10 m - 0.7%. Non boring sponges were so uncommon that they were not present in transect line at Hirimaradhoo, Fesdhoo, Velidhoo, Kandholhudho, Udhafushi, Maniyafushi, Gan, Vilingili and Hithadhoo (Figure 42). The greatest cover of sponges occurred at Anbaraa (6.3%) and En'boodhoofinolhu (5.6%).

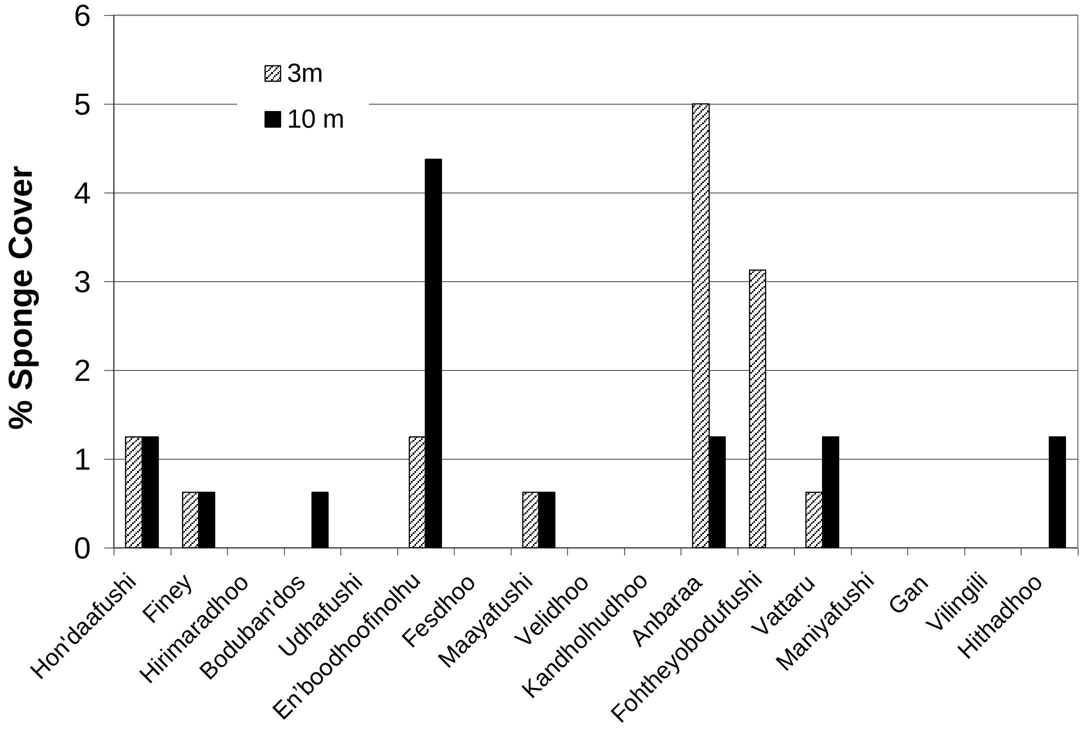

Figure 42. Geographic and depth variation of % sponge cover in NCRMS sites in 2009.

Terpios sp. (Demospongia, Order Hadtomrida) is an encrusting sponge which kills corals (Placer-Rosario, 1987) by getting nutrients from coral tissue. It is only about 1 mm thick but in the Maldives it has been observed by the roving diver surveys to cover many species of coral as well as competing for space with corals. The occurrence of *Terpios* sp. in the Maldives has not been previously reported in the literature. Although not specifically recorded in the sampling protocol, the sponge was seen overgrowing corals at Kandholhudhoo (Figure 43), one of the most luxuriant shallow water reefs surveyed. Kandholhudhoo is a picnic island used by resort guests. Kikinger (pers. comm.) reported the occurrence of *Terpios* in Ari atoll in 2005. However, in 2009, the occurrence of *Terpios* was rare at NCRMS, but future monitoring efforts need to identify it and minimally record its presence.

Figure 43. *Terpios* sp. overgrowing *Acropora* coral, Kandholhudhoo, Ari atoll, 10 m, April 2009.

Echinoderms

Crown of Thorns starfish - *Acanthaster planci*

The Crown of Thorns (CoT), *Acanthaster planci*, and *Culcita schmidelina* starfish feed on live coral. In the late 1960s to the 1990s large swarms of CoT were observed feeding on the Great Barrier Reef and other Pacific reefs. Large areas of live coral on the GBR were killed and the CoT was seen as a major threat to the GBR's sustainability.

No CoT were observed at any of the 17 survey sites or during about 30 hours of roving diver surveys in the NCRMS in 2009. The only CoT observed was a juvenile CoT collected at Bodumohoraa Island, Vaavu atoll in 2008 (Figure 44).

Figure 44. Dead juvenile Crown-of-Thorns starfish, *Acanthaster planci,* from Bodumohora reef, Vaavu Atoll, October 2008.

The presence of *C. schmidelina* was not part of the survey protocol and was not specifically recorded in the transects. However, typically at least one individual starfish was observed at each site. The occurrence of the starfish should be included in the protocol for future surveys.

The Maldives Protected Area System Project observed two adult COT at Addu atoll during their resource evaluation in 2003 (Ministry of Environment, Energy and Water, 2006). The report concluded at that time, the standing stock of COT in Addu atoll was no threat to the reefs.

A team lead by A. A. Hakeem collected both CoT and *Culcita schmideliana* several times a month from Vabbinfaru (4^o 18' 35" N., 73^o 25' 26"E.) and Ihuru (4^o 18' 24" N., 73^o 24' 58"E.) reefs in 2006 and 2007. In two years, a total of 84 CoT and 104 *C. schmideliana* were collected at Vabbinfara ranging from 7 to 14 starfish per month (Figure 45). At Ihuru reef, a total of 66 COT and 84 *C. schmideliana* were collected ranging from 3 to 11 starfish per month (Figure 46). About 20% more starfish were collected at Vabbinfaru than at Ihuru reef in that period. In 2006, the team collected 44 CoT and 61 *C. schmideliana* from Vabbinfaru reef. The number collected in 2007 was 40 CoT and 43 *C. schmideliana*. At Ihuru reef in 2006, 37 CoT were collected and 47 *C. schmidelina* were collected. In 2007, 29 CoT and 40 *C. schmidelina* were collected.

Vabbinfaru reef is bigger than Ihuru reef. If each collection was from the entire reef one would expect more starfish to be collected at Vabbinfaru than at Ihuru reef. Also, since, there is insufficient information to standardize for collecting effort per month, we can only make the generalized observation that there appears to be a low level, persistent population of *A. planci* and *C. schmideliana* on Vabbinfaru and Ihuru reefs. It is also likely that the vigilant collection activities have helped to keep the population is check, although feeding scars are commonly seen on the reef.

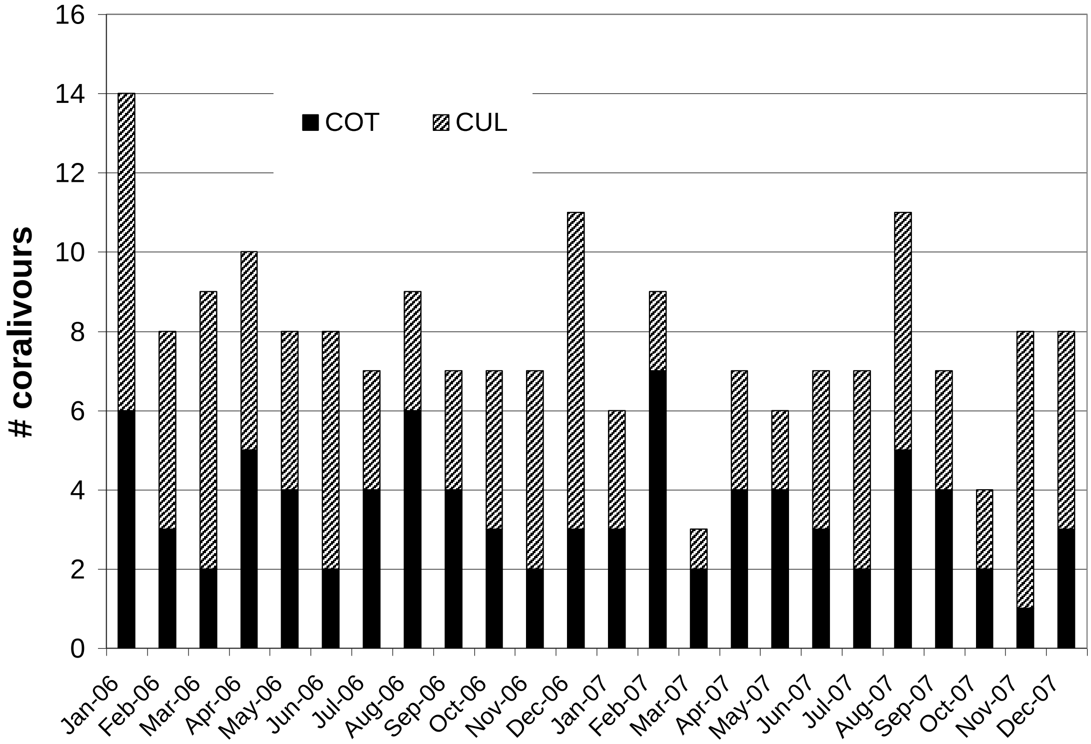

Figure 45. Monthly records of *Acanthaster planci* and *Culcita schmideliana* collected from Vabbinfaru reef in 2006 and 2007 (Azeez, pers. comm.).

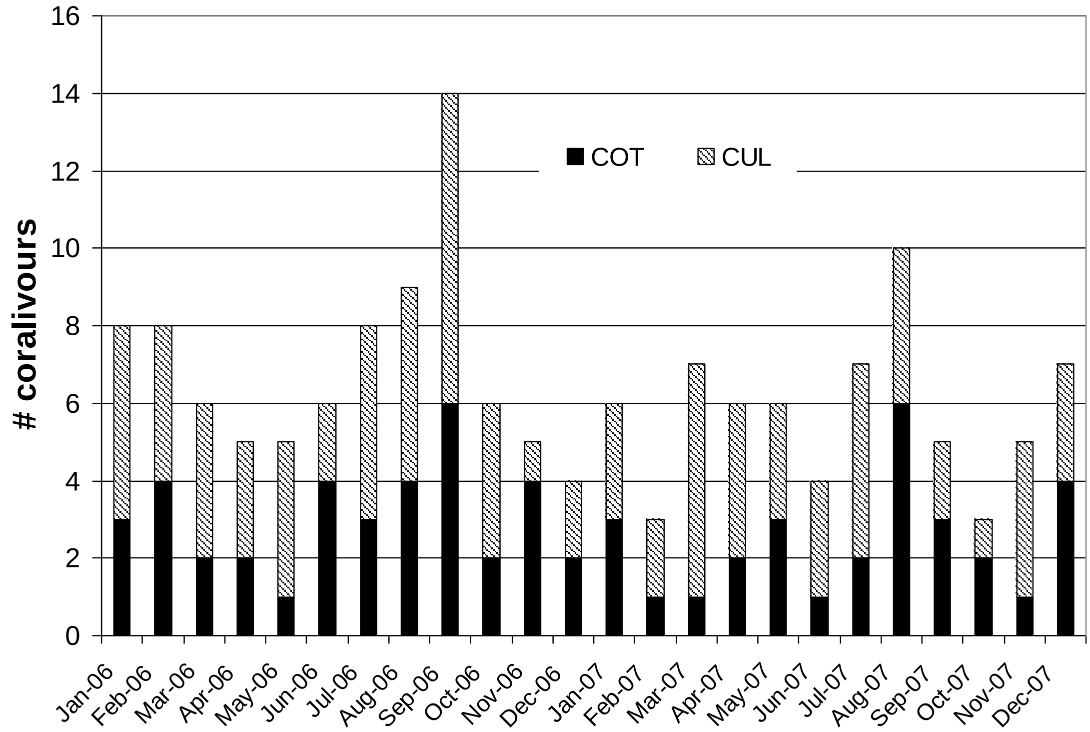

Figure 46. Monthly records of *Acanthaster planci* and *Culcita schmideliana* collected from Ihuru reef, North Male' atoll in 2006 and 2007 (Azeez, pers. comm.).

Echinoids

A total of 35 individuals of *Diadema antillarum*, 45 pencil urchins (*Heterocentrotus mammillatus*) and no collector urchins (*Tripneustes gratilla*) were observed from 17 sites and 13,600 m^2 of reef. The number does not increase when roving diver observations are considered as 98% of the urchins were observed in the shallow transect. *H. mammillatus* urchins were only recorded at the sites in Haa Dhaalu (Figure 47). *D. antillarum* was most abundant at Udhafushi. It was not observed in 12 sites, included all sites in Ari atoll (Figure 47).

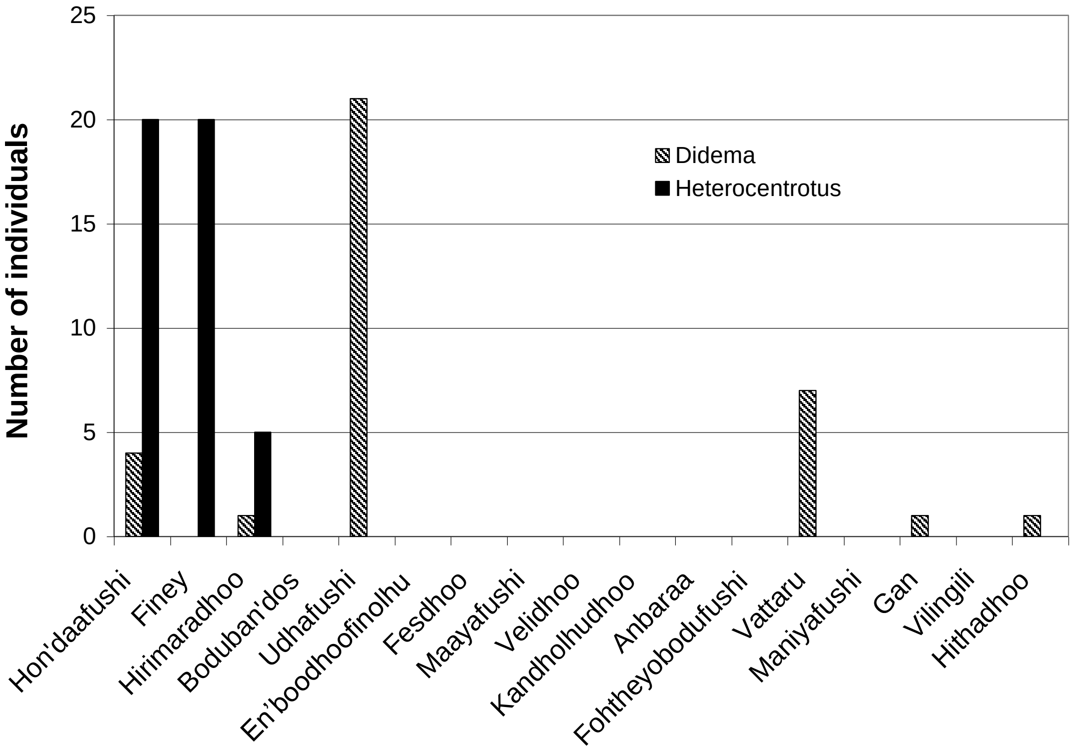

Figure 47. Abundance and distribution of two urchin species in the NCRMS sites in 2009.

The Indian Ocean is not the Caribbean Sea and urchins play a different role in the reef community. Urchins in the Caribbean are important to clear space for coral settlement in a sea with only sparse herbivore fish populations. The absence of many urchins in the Indian Ocean does not correlate with the condition of the reef. Herbivores fish are not a target species and their large population function to keep fleshy algal levels low and space available for coral settlement.

Holothurians

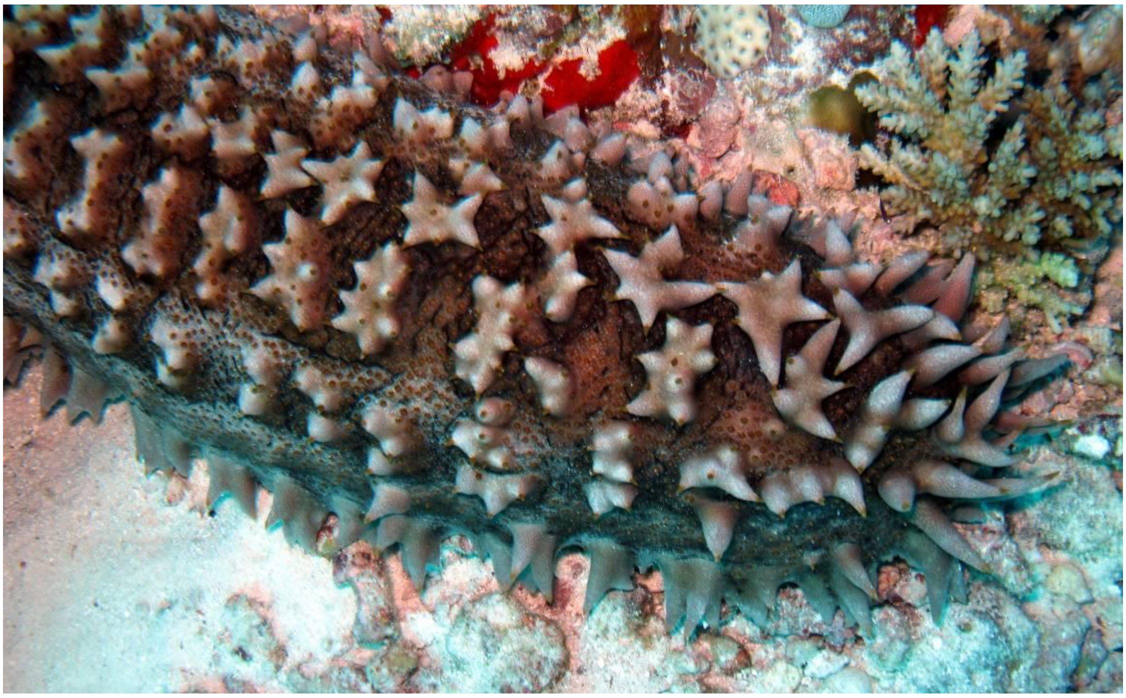

Figure 48. *Thelenota ananas* at 20 m at Coral Gardens, North Male' atoll, October 2009.

Crustacean Abundance and Distribution

Lobsters

The following four species of spiny lobster have been reported in the Maldives: *Panulirus penicillatus* (the doubled spine lobster), *P. longipes fermoristriga* (the long legged spiny lobster), *P. versicolor* (the painted lobster) and *P. ornatus* (ornate lobster) (Ahmed, *et al*., 1997). The lobsters occupy a wide range of habitats, however each species responds differently to habitat gradients, such as depth, turbidity, coral cover, wave action and feeding preferences (Wright, 1992).

P. versicolor is the most common lobster within lagoons and is found underneath table corals and in crevices. While it can be found in exposed reef slopes it is rarely found deeper than 6 m (Ahmed, *et al*., 1997). The species is also nocturnal and shelters in crevices during the day and forages at night. The species can be seen during the day as they are known to aggregate together with their long white antennae protruding from the crevice. Lobsters were first recorded in the NCRMS protocol in 2009. The previous field survey was Jonklass (1961).

In a total of 17 NCRMS sites covering five different atolls and a total area of 13,600 m^2 only four adult and one post puerulus lobsters were recorded. The number only slightly increases by eight lobsters when about 30 hours of roving diver observations are included. The low lobster population may be a consequence of few refuges associated with relatively low habitat relief and intense fishing pressure to supply resorts.

At Gan, Addu atoll, a post puerulus lobster (C.L. ~ 1 cm) was observed at 5 m among the rubble / coralline algae (Figure 49). No information is available about spawning seasons in the Maldives. This would be an excellent future research project done in collaboration with fishermen and resorts.

Lobsters are mainly caught by hand while free diving. Lobsters are not prized as a food for the local citizens. However, there is a constant demand by tourist resorts for fresh lobsters, so fishing pressure is high. The catch is either sold to local resorts or sent to Male' for resale. The catch statistics from MoFAMR for the period 1988 to 2005 ranged from 20,000 lobsters in 2005 to almost 70,000 lobsters in 2002 (Anderson, 2006). The resorts could assist in coral reef monitoring by recording and reporting number, weight and value of lobsters purchased. However, this would presumably only provide an estimate for adult male lobster abundance and distribution. The capture of female lobsters and those less then 25 cm in total length have been banned since 1993 (No: FA-A1/29/93/14 (15-05-1993)). Several resorts have strict policies about only purchasing legal catches.

Banded coral shrimp

The banded coral shrimp (*Stenopus hispidus)* was only present in 6% of the sites – on the single site adjacent to the harbour at the Bandos Island Resort and Spa. While the shrimps are collected for the aquarium trade (Saleem, 2009) it is not considered a good indicator of human exploitation because of its scarcity, even on remote reefs.

Figure 49. Post puerulis lobster on Gan reef, 5 m, May 2009. Carapace length estimated at 1 cm.

Mollusc - Abundance and Distribution

Giant Clams – *Tridacna* spp.

Within the Indian Ocean there are eight species of giant clams, two of which are present in the Maldives, *Tridacna maxima* and *T. squamosa* (Figures 50, 51). Collectively they are locally called "*gaahaka*" and were the basis of a commercial export clam fishery (Ahmed, *et al*., 1997) before it was banned in 1993 (Notice No: FA-A1/29/93/14 (15-05-1993)). In October 2009, *Tridacna* valves (55 cm TL) were for sale in souvenir shops in Male' for Rf12000 (US$ = 12.75).

Figure 50. Giant clam, *Tridacna squamosa*, about 35 cm long at Vattaru, Vaavu atoll, 10 m, March 2009.

The clams host a symbiotic dinoflagellate, *Symbiodinium microadriaticum*, which live freely inside the clam's blood passages. The dinoflagellates' products of photosynthesis assist in meeting the nutritional needs of the clams. Consequently, abundant sunlight is important for the health and rapid growth of the clam.

This is the first time *Tridacna* clams were included in the survey protocol. Consequently, there is no historical record to compare the abundance and distribution with. The survey protocol pools both species into a single taxonomic unit – clams. A total of 391 clams were recorded in 17 surveys. *Tridacna* spp. clams were found in 100% of the surveys at 3 m and 93% of the surveys at 10 m. The densities varied between atolls. The greatest numbers were observed (pooled 3 m and 10 m depth surveys representing 800 m^2) at Vilingili (68 clams) Addu atoll, Hon'daafushi (43 clams) Haa Dhaalu atoll, Hithadhoo (32 clams) in Addu atoll and at Anbaraa, Vaavu atoll (33 clams) (Figure 52). The fewest clams were observed at En'boodhoofinolhu (5 clams) and Fohtheyobodufushi (6 clams), Vaavu atoll. Seventy-six percent of the clams occurred along the shallow transect (3 - 5 m) with the remaining 24% present at the deeper (10 m) transect.

Future studies should separate the species as they are different sizes at first egg release. *Tridacna maxima* first develops eggs at 8 cm TL and *T. squamosa* develops eggs at 15 cm in the Pacific Ocean (Munroe, 1993) and are probably at least five years old. Initial maturity in *Tridacna* species is known to vary with geographic location in the Pacific Ocean (SPC, 2005). Initially the clams are males and then become hermaphroditic. Very old clams are generally all are functionally female.

Setting a minimum size that corresponds to the size at which 50% of the population reaching sexual maturity is a frequently used measure that allows at least half of the giant clams to reproduce at least once before they are harvested. No data for size at initial reproduction and maximum growth length in the Indian Ocean was found. Research on the reproductive biology of *Tridacna* clams is needed to assist in the management of their stocks.

The majority (57%) of the clams were initial recruits (<10 cm T.L.) (Figure 53). Eleven percent of the juveniles occurred at Hon'daafushi. Less then 1% of the clams were >40 cm TL and are estimated to be at least 20 years old. Single individuals of this size class were only observed at Hon'daafushi, Udahafushi and Vilingili. In the Pacific Ocean, *Tridacna squamosa* and *T. maxima* are reported to grow to 40 cm and 30.5 cm total length (TL) respectively (Munro, 1993). The remainder of the clams was ranged between 10 - 40 cm TL. If we assume that 50% of the clams in the 10 – 20 cm size class > 15 cm TL are reproductive, then at least 25% of the clams surveyed were likely to be females capable of releasing eggs.

Figure 51. H. Zahir, photographing a large *Tridacna squamosa* (TL 45 cm) at Hithadhoo reef, 10 m, Addu atoll, May 2009.

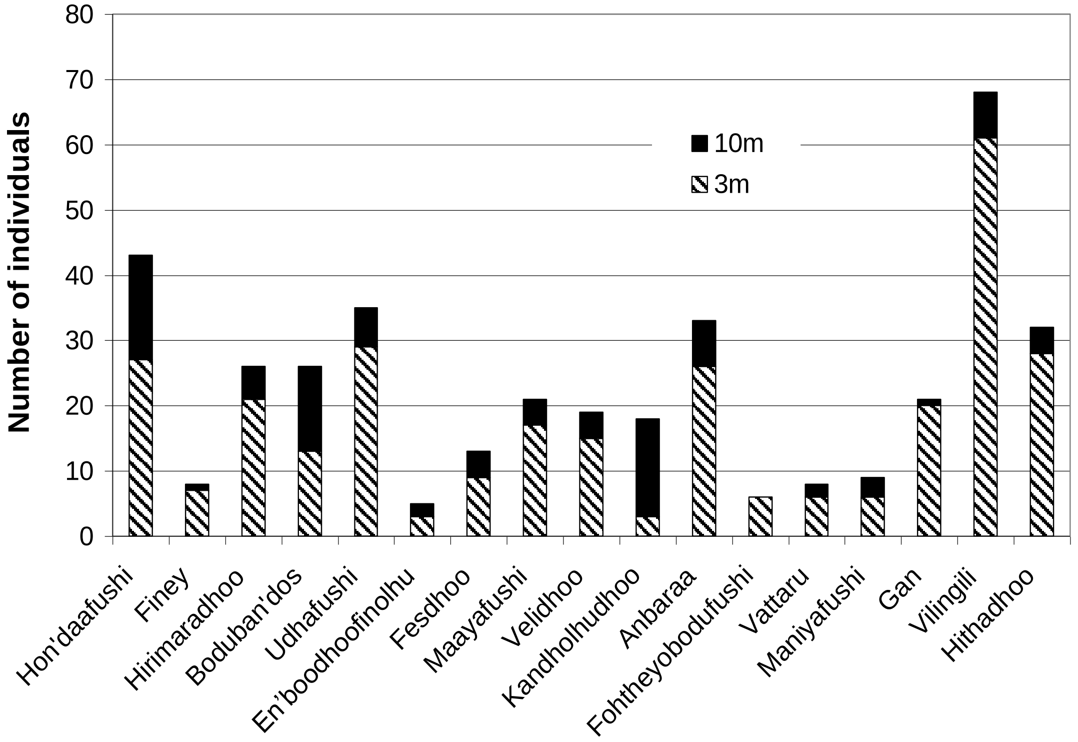

Figure 52. Abundance distribution of giant clams, *Tridacna* spp., in NCRMS sites at shallow and deep transects in 2009.

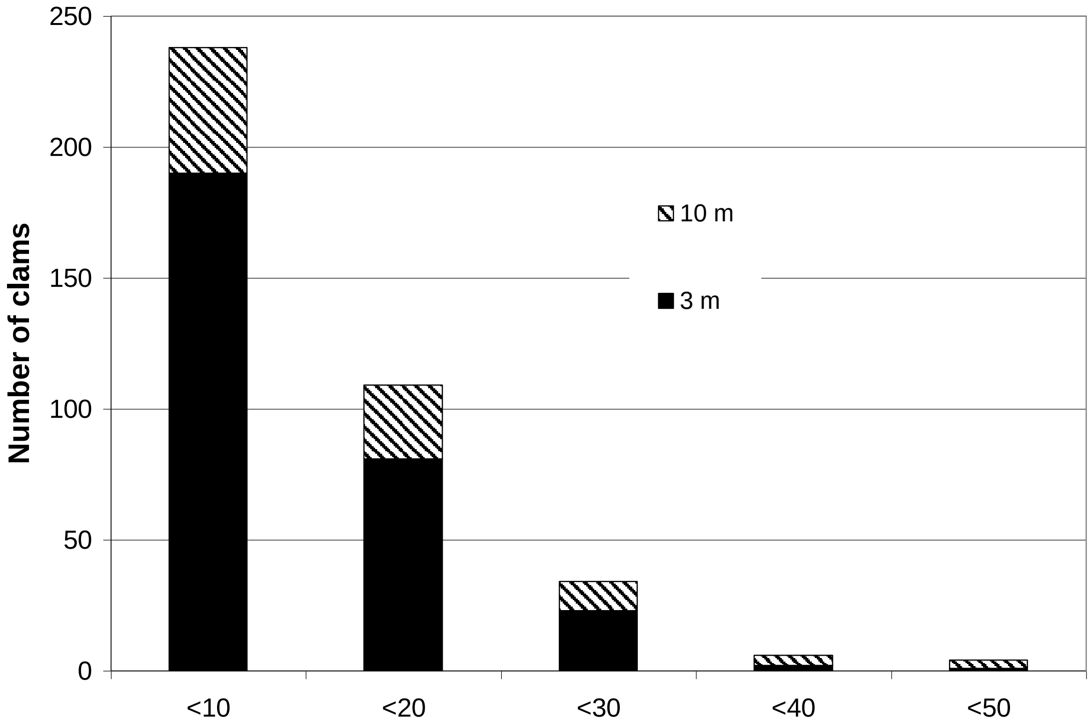

Figure 53. Size frequency distribution of giant clams, *Tridanca* spp., from the 2009 NCRMS.

Triton Shells

Triton is the common name given to a number of very large sea snails, predatory marine gastropods in the genus *Charonia*. Adult tritons are active predators and feed on other mollusks and starfish including adult Crown of Thorns starfish and *Culcita schmideliana*.

Many people find triton shells attractive as a design object, and so they are collected and sold as part of the international shell trade. The souvenir shops, Kaashi Boat and Gloria Maris, in Male' sell *Charonia tritonis* (TL 25cm) for Rf1300. In recent years this has doubtlessly contributed to the animals' scarcity. Traditionally Maldivians have removed the tip of the shell, or drilled a hole in the tip, and then used the shell as a trumpet.

Although the shell was included in the survey protocol, no shells were observed on the transects or in the roving dives.

Anthropogenic Disturbances

Over all the direct physical effects by humans on the reefs surveyed appeared to be negligible. Sand bags on the reef at En'boodhoofinolhu were quite obvious. Fishing lines were present at many sites. On occasion there appeared to be anchor damage. There were also coral observed that were damaged for no apparent reason. There was no evidence of sewage, poison fishing, blast fishing, aquarium fish collection, or invertebrate collection for the curio trade. Aquarium fish trade is an important business in the Maldives and has recently been reviewed by Saleem (2009). Only En'boodhoofinolhu has evidence of industrial activity with the increased siltation and discarded sand bags. Sand mining of the lagoon has been done manually for many decades.

Other anthropogenic disturbances such as non point source pollution are likely to affect the reefs in subtle ways. One example is the practice of fumigation on islands. This introduces toxic chemicals into the marine system without any knowledge of it effects on coral reefs, insect, bird and bat populations (Figure 54) and needs further research into the accumulation of the toxins on an island ecosystem.

Figure 54. Worker fumigating on island resort, North Male' atoll, September 2009.

Sea Water Temperature Variation

Edwards, *et al*. (2001) used the Global sea-ice and SST data set version 2.3b (GISST2.3b) for 1° latitude x longitude areas for January 1950 to May 2000 to examine the 1998 warming anomaly in the central Maldives (1 ± 5° N., 72° ± 74° E.) without any *in situ* "ground truthing". The 1950 - 99 monthly SST data for the eight 1° grid squares covering the central atolls were used to calculate long-term monthly means (`normals') and standard deviations against which anomalies could be assessed. The satellite data inferred that monthly mean SST was 1.2 ± 4.0 S.D. above average during the warmest months (March – June 1998) with the greatest anomaly in May of 2.1°C (Edwards, *et al*., 2001). This May anomaly was 1.1°C above the highest mean monthly SST (30.3°C) expected in any 20 yr period.

Advanced Very High Resolution Radiometer **(**AVHRR**)** data has a 4.4 km spatial resolution and a seven day temporal resolution. Satellite derived SST observations only measure the temperature of a few millimeters of the ocean surface from which scientists infer temperatures tens of meters below the surface, where the reef community is (Quinn and Kojis, 1994). While this technique is effective for observing broad brush, large scale events it has limitations for observing localized changes, accurately assessing the temperature at which bleaching occurs, and for detecting upwellings (Quinn and Johnson, 1996; Sheppard, 2009).

NOAA satellite data is good as an early warning system to predict the general area where bleaching may occur (Liu, *et al*., 2005), but it is not perfect for predicting bleaching (McClanahan, *et al*., 2007). Monitoring programs need accurate, precise *in situ* underwater temperature loggers to monitor specific habitats in order to increase the resolution to better understand thermal variation. Identifying corals from similar habitats tolerate to higher temperature may help provide a population of coral that can be used for coral restoration.

In August / September / October 2009, a Reef Net Sensu Ultra underwater temperature recorder was attached to a diver. The recorder was programmed to record depth and water temperatures every 10 seconds. The data was downloaded and the mean subsurface sea water temperature (S3T) was calculated based on temperatures recorded between a depth of 10 – 30 m. On 28 August 2009, the mean S3T at Akiri Channel (4^o 38' 54" N., 73^o 24' 40" E.) was 28.62 ^oC, well within Edward's, *et al*. (2001) temperature range (Figure 55). Two weeks later at the nearby site (Barakuda Point – 4^o37' 49" N., 73^o23' 37" E.) the mean temperature was 28.50^{o}C. However, the same week inside the atoll at Ihuru mean S3T was 28.89^o C, 0.4^{o}C warmer than channel water at Barakuda Point. Likewise, at En'boodhoofinolhu, in inner atoll site at South Male' atoll the mean S3T was 28.49^{o}C. In late September 2009, at Han'dahaa, Gaafu Alifu atoll (0^o 30'19" N., 73^o 27' 14" E.) the mean S3T at the same depth range was 29.55^{o}C, over a 1^{o}C warmer than Barakuda Point 4^o latitude north. In early October at Udhafushi, North Male' atoll, the temperature was 29.04^{o}C. About 0.25^{o}C above Edwards, *et al*. (2001) $\underline{+}$ 4 S.D. temperature range.

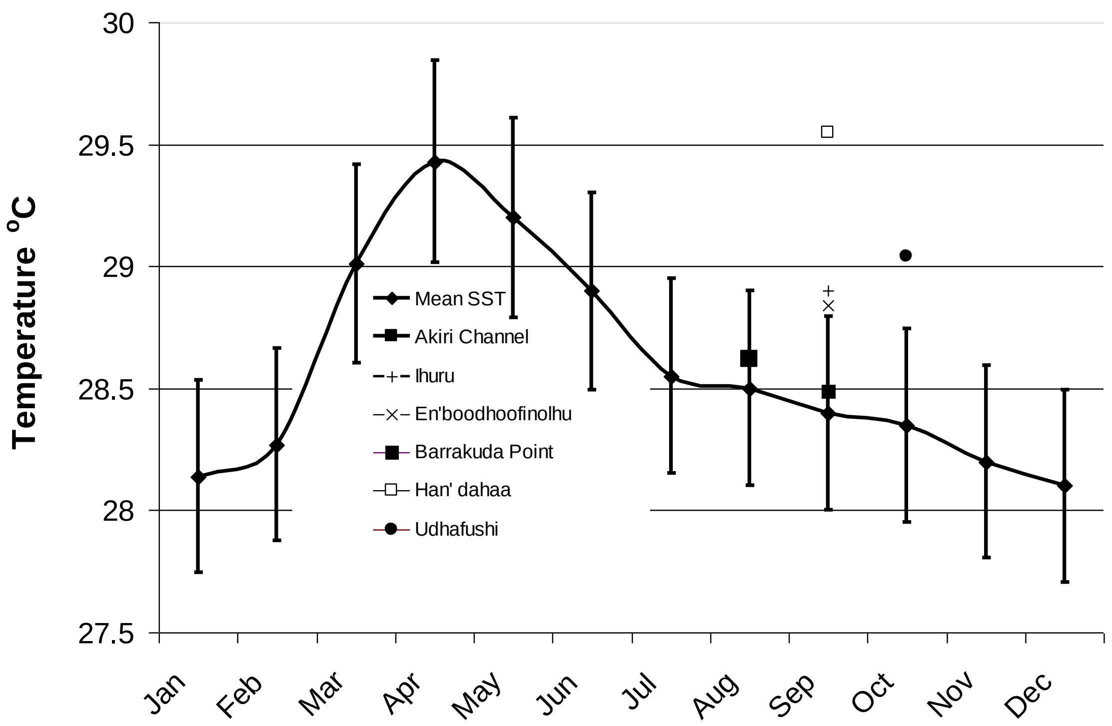

Figure 55. Mean satellite derived surface sea water temperature for the central atolls from 1950 – 1999 ± 4 S.D. (after Edwards, 2001). 2009 data recorded between 10 - 25 m in 2009.

The mean monthly S3T (MMS3T) (n = 8698) at 3 m at Huvafenfushi island (4^{o} 22' 10.40" N., 73^{o} 22' 19.81" E.) from August 2007 – February 2008 was 0.28^{o}C to 1.0^{o}C warmer than the mean monthly SST calculated from the GISST2.3b data set (Figure 56). While bleaching might be expected based on the satellite MMSST, none occurred. Corals in different habitats develop thermal tolerances allowing them to survive.

Below the surface the water is generally well mixed, probably due to a good current flow. At Rasdhoo the maximum variation in MMS3T at 8 m and 16 m is only 0.13^{o}C, with an annual mean difference of 0.03 ^{o}C (Figure 57). At these depths the MMS3T was about 0.2^{o}C warmer than 4 S.D. above Edwards, *et al*., (2001) MMSST. At Barakuda Point, North Male' atoll, the temperature ranged from 29.7 ^{o}C at 10 m to 29.3 ^{o}C at 32 m (Figure 58) during a 43 minute period in the morning in September 2009. There is only about a 0.5^{o}C temperature variation associated with depth even at the atoll outer reef.

The temperature logger at Rashdoo recorded several spikes in temperature in December 2008 and January 2009. The largest occurred on 11 January 2009 when the temperature dropped >3^{o}C for a period less than eight hours (Kikinger, pers. comm.). It is uncertain what caused these upwellings and how common they are throughout the archipelago. This phenomenon needs further study with a series of underwater temperature loggers deployed throughout the country.

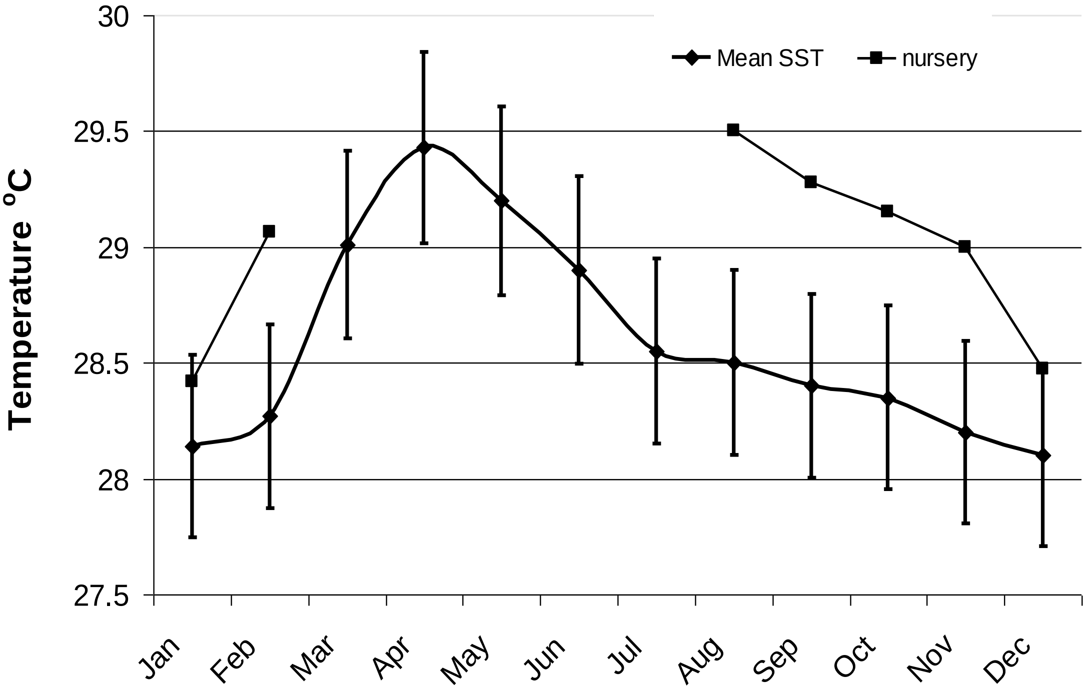

Figure 56. Mean S3T at coral nursery (3 m) at Huvafenfushi, North Male' atoll, from August 2007 to February 2008.

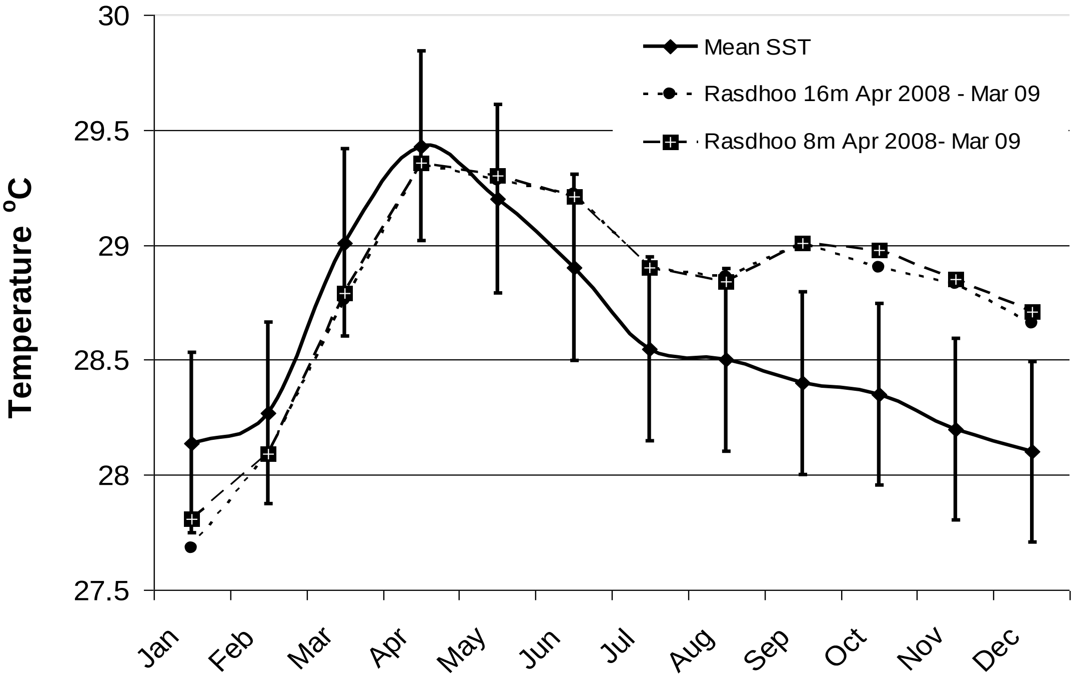

Figure 57. Mean monthly sea water temperatures at 8 m and 16 m from Rasdhoo, Ari atoll, April 2008 – March 2009 compared with Edwards, *et al*. (2001) SST.

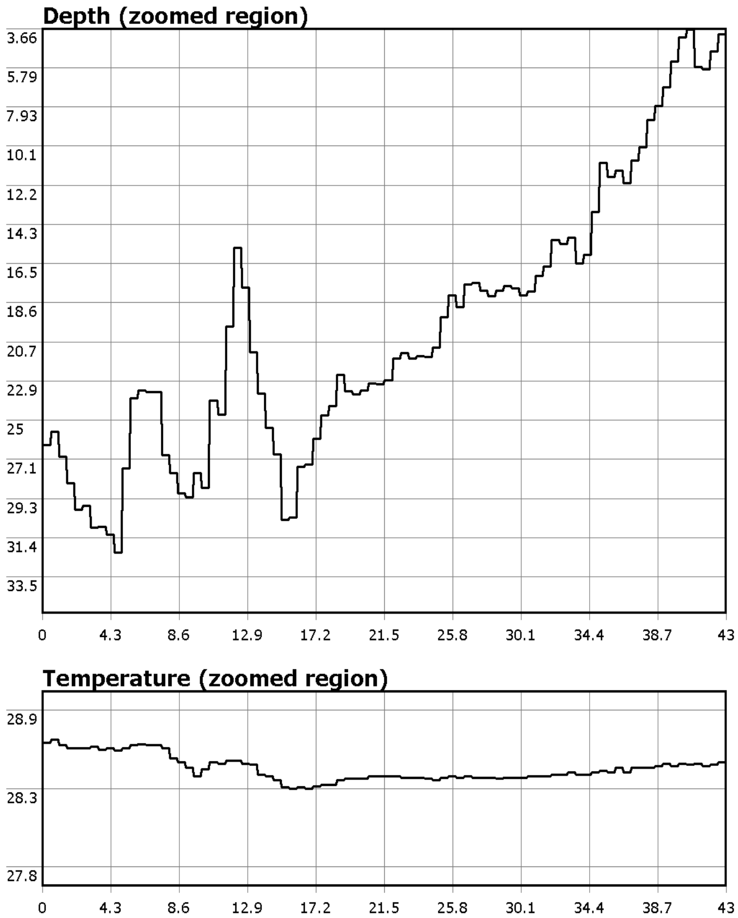

Figure 58. Temperature by depth profile at Barakuda Point, September 2009. Y axis on the top figure is depth in meters and the ^{o}C in the bottom figure. The x axis represents dive time in minutes 10 minutes from the start of dive at 9:40am.

Based on historical satellite imagery Edwards, *et al*. (2001) suggested that sea water temperature in the Maldives could rise of 0.16°C per decade. They suggested that if this trend continues, by 2030 mean April SST in the central atolls will exceed, in most years, the anomaly level at which corals there are susceptible to mass bleaching. Recurrences of mass coral mortality has been predicted for several coral reef sites in the Indian Ocean including the Maldives (Sheppard, 2003).

Adaption to Sea Water Temperature Variation

Global warming may not mean death for all the coral communities around the world. Studies are showing that coral may be able to adapt to higher temperatures by forming new symbiotic associations with heat tolerant algae. In 1998, large areas of reefs were devastated throughout the world. Reefs surviving in Kenya, Panama and the Arabian Gulf provided clues that some zooxanthellae were heat tolerant. Field studies showed that coral in these areas contained more D-type algae than non heat tolerant C-type algae (Baker, *et al*., 2004). This was also demonstrated by experimental studies in Panama, Guam and Great Barrier Reef. The researchers showed that the common Indo-Pacific coral *Acropora millepora* was able to increase it upper thermal limit by 1 ^{o}C - 1.5^{o}C when it changed from C-type to D-type algae.

The genus *Symbiodinium* is diverse, and many corals are relatively flexible in the type(s) of algal symbiont they contain, although one type is usually dominant in any given species and environment. The conditions needed for a coral to change its algal symbionts are unknown. Baker *et al*. (2004) considered that the symbiont changes are a common feature of severe bleaching and mortality events, and predicted that these adaptive shifts will increase the resistance of these recovering reefs to future bleaching. The implications are that if this mechanism of acclimatization is as widespread as it appears, coral reefs may have significantly more flexibility to respond to climate change than previously thought. However, it is not known whether symbiont change alone is sufficient for coral reefs to adapt to current climate warming predictions of 1-3^{o}C. Even if this acclimatization mechanism can match global warming, the structure of the world's coral reefs may change dramatically with fewer species and probably lower coral cover (Berkelmans and Oliver, 1999).

Future Coral Reef Monitoring Efforts and Awareness Development

Assessing the recovery of the reefs in the Maldives is like the story of three blind men each describing an elephant by touching the trunk, leg or tail. There is considerable variation among reefs and among habitats within reefs. This variation is a function of the wide latitudinal range of the atolls, the structure of the atolls, and chance. These factors create considerable variation in the abiotic factors that influence reef development and, therefore, considerable variation among reefs.

While this survey has expanded the depth at which reef transect data was collected (10 m), future surveys should include sites at depths of 15 – 20 m and include the outer atoll reef crest and slope habitats (Figure 59). Expansion of sampling sites to deeper depths and more exposed sites would require an experienced dive team with advanced diver qualifications.

Figure 59. South Male' atoll, outer reef, 15 m, August 2009. Future surveys need to include coral communities on the outer reef slope of the atolls. Lateral visibility estimated at over 35 m.

The recovery of most of the reefs surveyed by MRC during the past decade is remarkable and suggests the question of where were the new recruits coming from. Zahir (2006) observed that recruitment was not a limiting factor for reef recovery. The currents in the Maldives are very unpredictable. On each dive a dive master enters the water to assess the direction and strength of the current which seems to move independently of tidal phase and wind direction. A detailed study of currents around the

Maldives would help to determine the larval dispersal for both invertebrate and reef fish stocks. This information is necessary to better understand and manage these larval source communities.

One needs to be careful in extrapolating predictions to a larger scale based on specific observations to a single reef. Schuhmacher, *et al*. (2006) observed an "… ongoing deterioration of the reef or at least a prolonged time for recovery…" for the Komandoo reef flat based on seven years of study. Even the results of a spatially diverse data set based on a 150 m sample of a reef can be misleading. For example, Zahir (2006) reported a change in percent coral cover in the 16 NCRMS sites from -65% to 5916%. Because of the very low level of coral cover small changes in the presence of coral result in large percent changes. The coefficient of variation was greater than 70% for 12 of the 15 sites in 1999 and 9 of 15 sites in 2005. Ten of the 15 sites had <9% coral cover and only one site (Fesdhoo) had moderate coral cover (>30%). Coral cover in the early years of the NCRMS was sparse and variable both within a reef at a given depth and throughout the country. Consequently, small changes in cover could result in misleading inferences if extrapolated to larger dimensions.

For centuries the coral reefs have adapted to changes in sea levels associated with climate change. Kench, *et al*. (2009b) has demonstrated by drilling through several reefs in South Maalhosmadulu atoll that healthy coral reefs produced sufficient skeletal material to allow reef islands to accommodate rising sea levels on the order that is projected for the next century. The question today is: Are the reefs sufficiently healthy to continue to keep up with sea level rise and maintain the islands or are global and local stresses to the reefs so intense as to diminish the growth and reproduction of the corals resulting in submergence of all or some of the islands of the Maldives?

Uninhabited or lightly inhabited islands may survive. Sand can accumulate and raise the height of the islands. Beach rock can form and storms can carry coral rocks about sea level. They can't do it on the heavily inhabited, manufactured islands without destroying the infrastructure. Male' will need to be manually protected even if reefs keep up as the sand produced will just be washed into the lagoon. As sea level raises the freshwater lens in Male' will become increasingly saline. Roof top water catchments for storage in underground cisterns may be a partial solution. Other islands that have already physically destroyed parts of their reef and are creating an environment that is probably slowing coral growth, reproduction, and recruitment are also in need of survival strategies.

Future monitoring efforts should focus on providing a scientific framework for the management and justification of Marine Protected Areas (MPAs). Marine Protected Areas in the Maldives lack the necessary elements for effective management (Mohamed, 2007). She considered these MPAs to be only "paper parks" in that they are protected through legislation with no real funding for outreach and education and enforcement to protect them. She also suggested that the main reason for this the lack of enforcement was little awareness and understanding of the true value of reef resources.

The only NCRMS site within a MPA was Hithadhoo, Addu atoll. Hithadhoo reef had been included in a resource assessment for the establishment of the Maldives Protected Area System (Ministry of Environment, Energy and Water, 2006), prior to its recent inclusion in the NCRMS. The Vattaru site was within a kilometer of the Vattaru MPA. Future coral reef monitoring efforts should include MPAs in order to assess their effectiveness. Without proper monitoring it is difficult to assess the effectiveness of these MPAs in protecting the reefs. The NCRMS could support the MPA concept by providing information within an MPA and at a suitable control site.

Socio economic studies should also be undertaken to assess the usage of the parks by water sports organizations and the effectiveness of the parks in enhancing nearby fish stocks. Coral reef monitoring efforts need to be linked with the education curriculum and with social organizations in each atoll to foster greater adult understanding of science based management principals. More effort could be made to develop swimming, diving and snorkeling skills in Maldivian youth on all islands. The many Maldivians that NJQ has shared dives with are among the most passionate conservationists he has met.

The threat of increasing atmospheric CO_3 on coral reef calcification poses a chronic and increasing threat to coral reefs. However, it is also a creeping and nearly invisible stress that receives much less attention than the more visible and acute coral reef problems like bleaching and diseases. Long term time series data for abiotic parameters need to be included in a NCRMS program. Data loggers for subsurface seawater temperature are inexpensive and reliable and should be deployed at all survey sites. Other recorders for salinity, pH, dissolved oxygen, wave height and nutrient levels require more maintenance and could be deployed during surveys and at an easily accessible site near Male' where they can be frequently monitored and maintained.

Incident waves and their interaction with coral reef platforms are considered the main mechanism controlling the formation and stability of low lying coral reef islands. Large differences in incident wave energy between the SW and NE monsoons can affect the pattern of beach erosion on islands (Kench, *et al*., 2009a). Wind driven incident waves are both refracted and diffracted around the reef platform creating currents which result in nodal location for sediment deposition (Kench, *et al*., 2009a). The seasonal occurrence of various intensities and the direction of wind results in movement of islands. While scientists monitor changes in island configuration, few place the movement within a meteorological or diffraction/ refraction context. Consequently, when beaches erode on inhabited islands, climate change is considered the cause, rather than considering natural variations in wind intensity and direction or man-made changes in current patterns and wave action caused by the placement of breakwaters and structures or dredging of the lagoon. The placement of automated meteorological stations on several islands within an atoll would help provide better data for understanding localized climatic conditions which influence incident waves and the resultant island movement.

It is hypothesized that the Maldives is a CO_2 sink and could actually sell carbon credits on the international market. This of course requires a detailed scientific survey. The implementation of a series of underwater fluorometers would begin to measure the photosynthesis of corals, algae, plankton and sea grasses. Photosynthesis is a process that converts carbon dioxide into organic compounds, especially sugars, using the energy from sunlight (Figure 60. Photosynthesis is vital for life on Earth. As well as maintaining the normal level of oxygen in the atmosphere, nearly all life either depends on it directly as a source of energy, or indirectly as the ultimate source of the energy in their food.

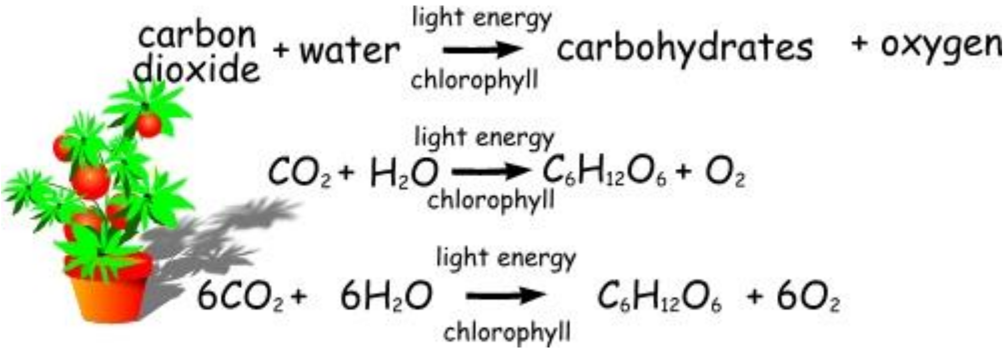

Figure 60. Photosynthesis is a process that converts carbon dioxide into organic compounds, especially sugars, using the energy from sunlight. In the sea, instead of a tomato plant, photosynthesis is done by plankton, coral, algae and sea grass.

The Government of the Republic of Maldives has applied for financing from the International Development Association (IDA) to cover the cost of the Maldives Environmental Management Project. The project seeks to: (i) strengthen Maldives' existing national coral reef monitoring program by the inclusion of additional monitoring stations and parameters such as water quality and proxies for reef health, (ii) support the development of a community-based coral reef monitoring and community awareness program aimed at improving the understanding about the importance of coral reef systems to the integrity of the island and atoll ecosystem. A report is currently under review and the acceptance of the final report will determine the scope of future coral reef monitoring activities in the Maldives.

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