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Tsunami Survey Expedition: Preliminary Investigation of Maldivian Coral Reefs Two Weeks After the Event

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Abstract On December 26th 2004, a earthquake west of Sumatra generated a devastating tsunami. Hundreds of thousands of people fell victim. Economic losses were greatest in those countries dependant on tourism. The impact in the Maldives on persons and things was modest. Immediately following the event and notwithstanding the lack of scientific data, the mass media gave catastrophic reports on the state of coral reefs in the area. This paper reports on the first survey on coral reefs in the Maldives after the Tsunami. Ocean walls, passes, inner reefs, and shoals in the North and South Malé atolls, were surveyed two weeks after the event. Significant damage was recorded in the passes in the South Malé atoll. Our observations showed that the damage was more or less extensive depending on latitude and topography. Sri Lanka may have broken the wave's rush, reducing the extent of the impact on northern atolls. The water's acceleration inside the passes was so intense as to cause reef collapses. The observed damage represents a minimum fraction of the entire coral reef system. Tourist perception of the area seems unchanged. These data may be used to disseminate correct information about the state of Maldives coral reefs, which would be useful in relaunching local economy.

Keywords Tsunami · Maldives · Maldivian Coral Reefs · Tsunami impact · Mass media behaviour · Tourism industry · Local economy · Coral reefs survey

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1 Introduction

On 26 December 2004, a earthquake in the Indian Ocean, with its epicenter to the west of the northernmost tip of the island of Sumatra, generated the most human devastating tsunami ever reported in the history of mankind (Pearce & Holmes, 2005). More than 300,000 victims were reported either dead or missing in Indonesia (253,958), Sri Lanka (40,220), India (16,393) and Thailand (8,514) (Stone, 2005). The scope of the disaster in human terms is so great that there are no words to express it.

According to specialists from Morgan Stanley (http://www.morganstanley.com), the economic damages caused by the disaster are not substantially significant in areas in which the economy is based on manufactured goods. The most devastated areas are, in fact, rural and poor areas while the larger industrial centers were only partially affected. This means that the estimated rate of increase of Indonesia's GNP for the year 2005 remains unchanged (+4.5%), while countries where tourism makes up the better part of the economy were greatly affected due to the total or partial destruction of tourism infrastructure and the decision of tourists to choose alternative destinations. Although the estimated loss to Thailand's GNP was minor, ranging from +6.00% to +5.7%, other countries in Southeast Asia will probably be hit much harder economically.

The Maldive Islands archipelago lies in the center of the Indian Ocean (Figure 1). It is 864 km in length and 130 km wide and is made up of 1,190 coral islands that, when grouped together, cover an area of 300 km^2. The population of the archipelago numbers 270,000 inhabitants and the economy is largely based on tourism. Tourism to this area, largely associated and/or linked to its coral reefs, has greatly increased over the past 30 years (Rajasuriya, Venkataraman, Muley, Zahir, & Cattermoul, 2002). According to data published by the Maldivian Government (http://www.maldivestourism.gov.mv), 'coral tourism' to the area currently contributes ~30% to the country's GNP. Italian tourism, for example, with between 130,000 and 140,000 people yearly, accounts for 21.2% of tourist flow to the area.

The impact of the Tsunami on persons and things in the Maldives was less extensive when compared to other areas, such as the western coast of Indonesia where waves reached heights of 34 m and totally destroyed coastal infrastructure and tree vegetation (Y. Nishimura, University of Hokkaido, unpublished data). The Maldivian Government reported 82 deaths (79 of these people lived in the Maldives and three were tourists) and 26 people missing (all Maldivians); 3,997 homes were destroyed and 12,478 peoples were evacuated. According to government data, the tourist hosting capacity was not greatly affected: 63 tourist islands out of 87 (72.4%) have remained fully functional; of the 24 remaining islands, four were being built-up in preparation for hosting tourists and 20 have suffered damage. Of these 20, six have suffered serious damage and it will take more than six months before they may be opened to tourism; the remaining 14 were only slightly damaged. After the Tsunami, the number of tourists present in the Maldives went from 17,000 on the 26th of December 2004 to 4,708 on January 7th 2005, a reduction of 72.3%.

Although the extent of information reporting the impact of the Tsunami on human life and on the economy is substantial, we still know very little about its impact on ecosystems (Pennisi, 2005). Notwithstanding the lack of information regarding scientific

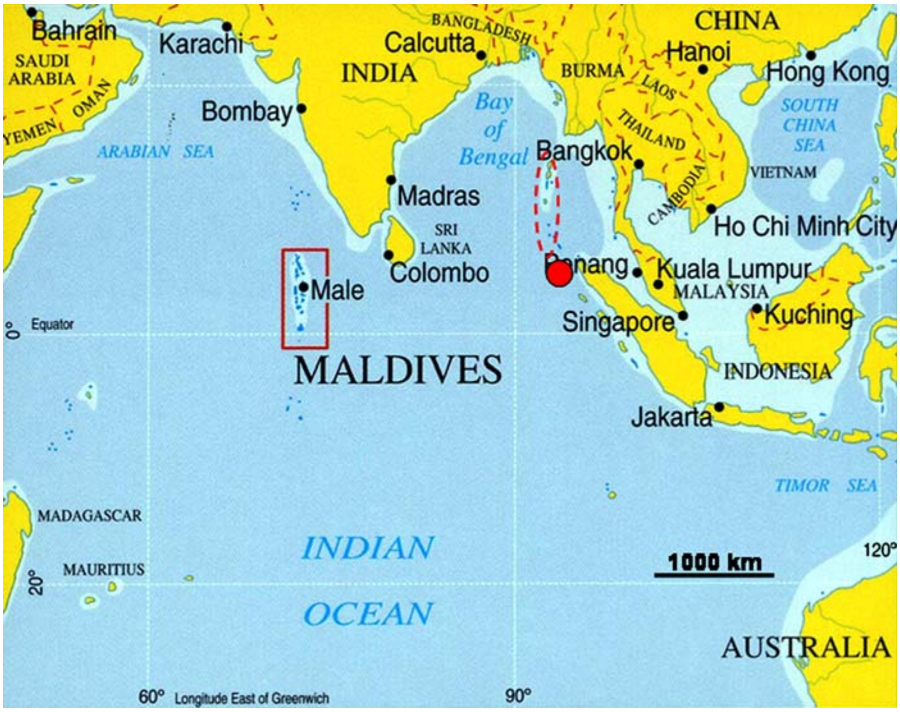


Figure 1 The Maldivian archipelago. The *dot* shows the earthquake's epicenter that generated the Tsunami on December 26th 2004; the *ellipse* indicates the area from which the wave spread (data from the NOAA, National Oceanic and Atmospheric Administration, USA computerized models).

inquiries and investigations, information spread by the mass media in the days following the event was at times characterized by catastrophic alarmist comments with no scientific basis: according to some media news, coral reefs would have had to disappear entirely in some areas. If we are to make scientific hypotheses about the conditions of coral reefs after the event, beyond bearing in mind that the organisms that built these reefs are ‘rather resilient’ having been on the planet for million of years (extant species have dominated modern reefs for the past half-million years, and reefs have shown remarkable persistence in their community structure in spite of global environmental change and disturbance; Hughes et al., 2003; Nyström, Folke, & Moberg, 2000; Pandolfi, 1999; Rosen, 1984), we must at least consider the topographic location of these coral structures. Simplifying classification as much as possible by dividing the reefs into only two major categories, oceanic and continental, may aid in the process of predicting incidence of damage to the reefs concerned. It is possible that there may be significant differences between these two categories, as a result of the quantity and type of the material dragged into the sea by the ebbing wave and we can therefore assume that the impact on oceanic atoll coral structures was not very high. The degree of human presence (urban centres, industries etc.), forestation, and quality of the terrigenous sediments, may lead to a greater negative impact on continental reefs.

The intent of this investigation was to collect early data on the conditions of the Maldives coral reef system after the Tsunami. The information collected can serve as a starting point from which to design future investigations and restoration interventions. The present investigation can also contribute to the dissemination of correct information on the state of the Maldivian reefs, which might be helpful in relaunching the local economy.

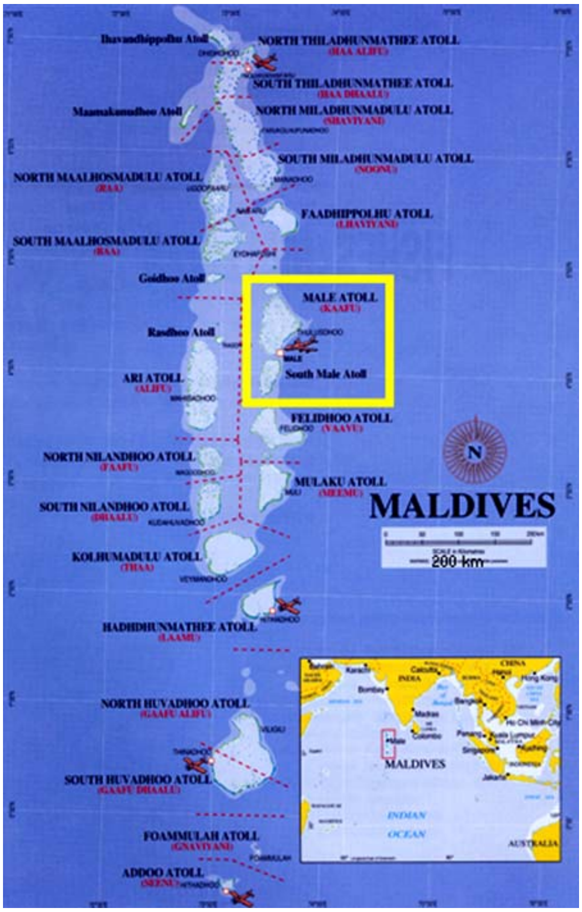


Figure 2 The Maldivian archipelago. The *boxed off area* at the center highlights North Malé and South Malé atolls, the areas investigated.

2 Materials and Methods

2.1 Collected data

This survey took place between the 8th and 17th of January 2005, by invitation of the authorities of the Government of the Republic of the Maldives. Logistics coordinators for the study were ASTOI (Association of Italian Tour Operators), MATI (Maldives Association of Tourism Industry) and MTPB (Maldives Tourism Promotion Board). The underwater surveys were performed in collaboration with the diving centers Ocean-Pro Dive Team (Meerufenfushi, North Malé Atoll) and Ocean Venture Diving (Fihalhohi, South Malé Atoll). Logistics were coordinated in situ by Crown Company PVT. LTD.

In order to assess the general topographic characteristics before diving to collect data, for each station surveyed, we held interviews with local professional instructors and/or took preliminary SCUBA and snorkeling dives. We used the following survey method:

(a) videotransects: five depths per station were investigated: 30, 20, 13, 7, and 1.5 m. At each diving depth, we used a metric measuring tape to delineate a rectangular area of 37.5 m^2 (1.5 m×25 m) for a

Figure 3 The *dots* indicate the survey stations. The *numerical codes* are the same as those used in Table I.

total of 187.5 m^2 per station. A professional video cameraman generated footage of the area concerned using a Sony PD 170 P digital camera. Photographic sequences from the digital videos were then examined in our imaging analysis labs in the Department of Evolutionary and Experimental Biology at the University of Bologna in order to obtain quantitative data on the composition of the biodiversity in the surveyed areas. Video transects were deployed only in those stations that were safe for diving. In stations with strong currents or those that involved decompression diving, video transects were replaced by a less demanding method of investigation (b).

(b) free videos: we filmed at least 42 min of reef between depths of 0 to 30 m for each station. The area surveyed was comparable to the average area explored in the course of average recreational dives (10,000 m^2). The videos taken this way allowed us to assess general conditions of the reef.

(c) snorkeling: observations were made using snorkeling gear for each station in order to assess the area's topography, reef status, and safety conditions (current strength and configuration) for underwater investigations. For some stations, several observations were made along the reef before deciding the exact point at which underwater investigations using SCUBA would be performed.

2.2 Data analysis

Projections: it was assumed that the condition found at each station was representative of the condition of the entire portion of homogeneous reef in which the station was located.

2.3 Topographical definitions

Ocean wall	fore-reef slope exposed towards the outer part of the atoll that is hit head-on by oceanic waves, i.e., frontal exposure to impact.
Inner reef	a reef situated in the sea that lies within the atoll and therefore not normally exposed to direct impact from oceanic waves.
Pass	a channel that connects the outer ocean with the inner sea of the atoll.
Shoal	submerged reef.

3 Results

The North and South Malé (Kaafu) atolls are located in the central part of the Maldivian archipelago (Figure 2). Eighteen survey stations were established (Figure 3): 10 in the North Malé Atoll and eight in the South Malé Atoll. The stations were classified according to topographical features as follows (Table I, Figures 3, 4):

– North Malé: five ocean wall stations (stations 1, 3, 5, 6, 7), two stations in passes (stations 9, 10), three stations in inner reefs (stations 2, 4, 8);
– South Malé: three ocean wall stations (stations 11, 13, 16), three stations in passes (stations 12, 14, 17), one station in an inner reef (station 18), one station in a shoal (station 15).

We found no damage in any of the ocean wall stations (stations 1, 3, 5, 6, 7, 11, 13, 16; Figures 3, 4) nor in those located in reefs inside the atolls (stations 2, 4, 8, 18; Figures 3, 4). We also found conditions to be normal in the only station located in the shoal (station 15; Figure 4). Of the five stations located in passes (stations 9, 10, 12, 14, 17), the two in the North Malé atoll showed no signs of damage that could be ascribed to recent events, but did show a chronic deterioration apparently caused by anthropogenic stress (stations 9, 10 near the capital of Malé City; Figure 3). The three located in the South Malé atoll suffered significant damage caused by recent traumatic events (stations 12, 14, 17; Figure 4). In Station 12, we found many branching corals, most of which were of the genus *Tubastrea*, (midnight corals), that were partially broken or completely torn off. At Station 14 we found broken or torn off branched corals (again mainly of the genus *Tubastrea*) and damage to massive corals (*Porites*, Faviidae). Parts of the reef had also collapsed at this station. Station 17, the one with the most damage, showed entire blocks of reef, up to 1–2 m^3 in size, uprooted from the walls and scattered on the seabed. In addition to the taxa mentioned above, we also found shattered corals belonging to other taxa. The depth of this pass was diminished by 2 to 3 m after the Tsunami because of the debris that had accumulated (Frederic Boch, personal communication).

Our observations indicate that most of the damage occurred in the passes (67.7% of the damage based on a projection of 6.8 km; in ocean walls 0% of the damage based on a projection of 30.4 km; in inner reefs 0% based on a projection of 5.2 km; in the shoals 0% based on a projection of 1.1 km).

4 Discussion

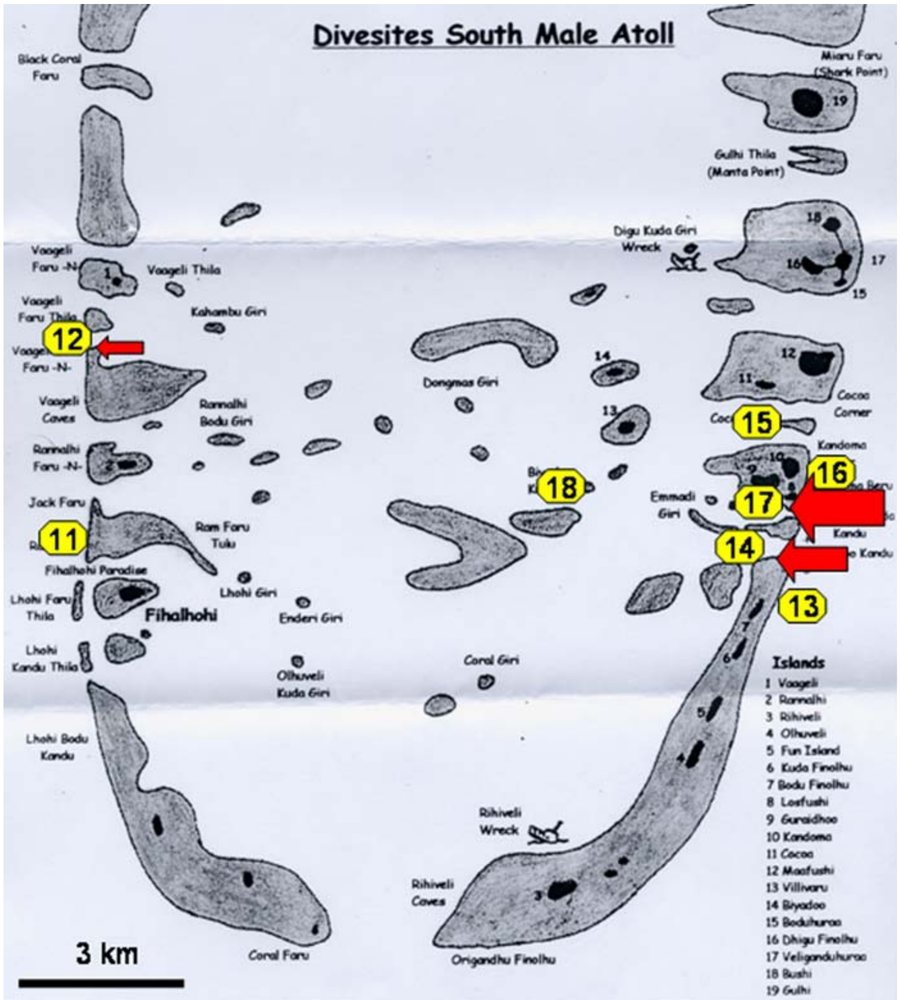
This is a preliminary investigation on the state of coral reefs in a limited section of the Maldive archipelago following the Tsunami, covering stations located in the North and South Malé atolls in the Maldives' central zone (i.e., two atolls out of 23, i.e., 8.7%). From the data collected, we found that the extent of the damage was related to the latitude and topography of the area. The North Malé atoll was less affected than the atoll located more to the south. We did not find significant damage in all 10 stations surveyed in the north atoll. We interviewed professional divers of the Ocean-Pro Dive Team Diving Center on the island of Meerufenfushi and they did not mention having found damaged sites. Considering the area from which the tsunami wave spread according to data from the NOAA, National Oceanic and Atmospheric Administration, USA computerized models (http://www.noaanews.noaa.gov/stories2004/s2357.htm), it follows that the island of Sri Lanka probably broke the wave's momentum thereby reducing the strength of impact on the northern atoll. The South Malé atoll, being more exposed, was more severely hit. In fact, both from our own observations and based on interviews with diving instructors and underwater guides of the Ocean Venture Diving center (Fihalhohi), we surmise that the greatest

Table I Geographic, topographic, and environmental characteristics of survey stations; methodology of investigation and condition detected

Station code	Date	Time (0–24)	Atoll	Point	Geographic coordinates	Topographic characteristics	Reef length (km)	Air temp °C	Water temp °C	Survey method	Conditions
1	January 11, 2005	15:44	Malé (Kaafu) North: east coast	Palm Reef (Thulusdhoo Beru)	N 04° 22.070′, E 073° 39.107′	Ocean wall	1.3	30	29	Video transects	No significant damage caused by recent traumatic events
2	January 11, 2005	20:00	Malé (Kaafu) North: east coast	West Rock	N 04° 27.478′, E 073° 40.806′	Inner reef	0.6	30	29	Free videos	No significant damage caused by recent traumatic events
3	January 12, 2005	9:15	Malé (Kaafu) North: east coast	Guruwa Faru	N 04° 33.460′, E 073° 37.178′	Ocean wall	4.1	30	28	Video transects	No significant damage caused by recent traumatic events
4	January 12, 2005	11:30	Malé (Kaafu) North: east coast	Trixie's Caves	N 04° 34.600′, E 073° 35.418′	Inner reef	2.9	30	28	Free videos	No significant damage caused by recent traumatic events
5	January 12, 2005	14:00	Malé (Kaafu) North: west coast	Olahali	N 04° 41.387′, E 073° 26.479′	Ocean wall	1.2	30	28	Video transects	No significant damage caused by recent traumatic events
6	January 12, 2005	15:30	Malé (Kaafu) North: west coast	Rasfari	N 04° 26.145′, E 073° 21.493′	Ocean wall	3.1	28	28	Video transects	No significant damage caused by recent traumatic events
7	January 12, 2005	16:30	Malé (Kaafu) North: west coast	Rasfari-Manta Point	N 04° 26.145′, E 073° 21.493′	Ocean wall	3.1	28	28	Free videos	No significant damage caused by recent traumatic events
8	January 13, 2005	11:00	Malé (Kaafu) North: south sector	Banana Reef (Gaathu Giri)	N 04° 15.000′, E 073° 32.000′	Inner reef	0.6	31	29	Free videos	No significant damage caused by recent traumatic events
9	January 13, 2005	13:00	Malé (Kaafu) North: south coast	City of Malé: west coast	N 04° 10.496′, E 073° 30.063′	Pass	1.3	31	29	Video transects	No significant damage caused by recent traumatic events; chronic deterioration apparently caused by anthropogenic stress
10	January 13, 2005	15:00	Malé (Kaafu) North: south coast	City of Malé: east coast	N 04° 10.733′, E 073° 31.095′	Pass	0.9	30	29	Video transects	No significant damage caused by recent traumatic events; chronic deterioration apparently caused by anthropogenic stress

11	January 14, 2005	9:30	Malé (Kaafu) South: west coast	Ram Faru	N 03° 53.223′, E 073° 21.274′	Ocean wall	1.9	29	28	Video transects	No significant damage caused by recent traumatic events
12	January 14, 2005	12:15	Malé (Kaafu) South: west coast	Vaageli Bodu Faru North	N 03° 56.426′, E 073° 21.066′	pass	1.4	29	28	free videos	Significant damage: many branching corals, most of which were of the genus *Tubastrea*, (midnight corals), were partially broken or completely torn off
13	January 14, 2005	15:00	Malé (Kaafu) South: east coast	Guraidhoo Kandu south-oceanic wall	N 03° 53.260′, E 073° 28.156′	Ocean wall	14.1	30	28	Video transects	No significant damage caused by recent traumatic events
14	January 14, 2005	16:15	Malé (Kaafu) South: east coast	Guraidhoo Kandu south-pass	N 03° 53.260′, E 073°28.156′	Pass	0.8	30	28	Free videos	Significant damage: broken or torn off branched corals (mainly of the genus *Tubastrea*) and massive corals also (*Porites*, Faviidae). Parts of the reef collapsed.
15	January 14, 2005	17:15	Malé (Kaafu) South: east coast	Cocoa Thila	N 03° 53.633′, E 073° 28.612′	Shoal (15 m depth)	1.1	30	28	Free videos	No Significant damage caused by recent traumatic events
16	January 15, 2005	9:30	Malé (Kaafu) South: east coast	Kandoma Beru	N 03° 53.882′, E 073° 28.392′	Ocean wall	1.6	28	28	Video transects	No Significant damage caused by recent traumatic events
17	January 15, 2005	11:00	Malé (Kaafu) South: east coast	Guraidhoo Kuda Kandu (=South Kandoma Korner)	N 03° 53.633′, E 073° 28.241′	Pass	2.4	28	28	Free videos	Reef collapsed. Entire blocks of reef, up to 1–2 m^3 in size, uprooted from the walls and fallen to the floor. Shattered corals belonging to many taxa. Depth of the pass diminished by 2 to 3 m after the Tsunami because of the accumulated debris
18	January 15, 2005	12:30	Malé (Kaafu) South: central-south sector	Biyadoo Kuda Giri	N 03° 54.211′, E 073° 26.646′	Inner reef	1.1	28	28	Free videos	No significant damage caused by recent traumatic events

Figure 4 South Malé Atoll. The *dots* show the survey stations. The *numerical codes* are the same as those used in Table I. The *arrows* indicate that stations where damage was found. The larger the arrow, the greater the damage.



damage occurred in the southern atoll and was concentrated in the passes. The water from the Tsunami picked up so much speed within the channels that connect the outer ocean with the sea inside the atoll that the added force caused the reef ruptures and collapses we observed. If we assume that the entire length of the South Malé atoll passes, 35.6 km, suffered significant damage and relate the extent of the damage to the total size of the atoll's coral reef system (627.7 km, including ocean reefs – 202.9 km – and inner reefs – 424.8 km), we obtain a potential damage incidence of about 5.7%. We can hypothesize that this relatively low extent of damage may be recovered within less than 10 years, as predicted for coral reefs impacted by the Tsunami in other areas of the Indian Ocean (Pennisi, 2005). The larvae from the reproductively active areas would recolonize the damaged spaces restoring biodiversity to its state before the Tsunami hit. In some areas the recovery process may be hampered by the light coating of sand noted in some sites, which may interfere with settlement. A recruitment assessment in the damaged areas should be designed.

Other large-scale impacts can dramatically damage local economies, and coral reef systems. Reaching wind speed of more than 250 km/h, storm surge of more than 6 m in coastal regions, and flash flooding due to excessive precipitation, tropical cyclones can have catastrophic consequences, with thousands of fatalities, and serious economic damage with dozens of billions of costs (Bengtsson, 2001). In the Caribbean for example, Hurricanes Hattie in October 1961, Camille in August 1969, David and Frederic in August 1979, Allen in July 1980, Gilbert in September 1988, Joan in October 1988, Hugo in September 1989, Andrew in August 1992, Mitch in October 1998, Lenny in November 1999, and Ivan in September 2004 have been among the more destructive and played a significant role in ecological perturbation of coral reef communities during the past 45 years. Their impact has resulted in reports of massive disturbance to large areas of coral reefs, adjacent seagrass beds, and coastal mangrove habitats (J. C. Bythell, M. Bythell, & Gladfelter, 1993; Bythell, Hillis-Starr, & Rogers, 2000; Lirman & Fong, 1997; Mumby, 1999; Rodriguez, Webb, & Bush, 1994; Rogers, McLain, & Tobias, 1991; Steneck & Walton Smith, 1993; Stoddart, 1974, 1985; Tilmant et al., 1994; Woodley, 1992; Wulff, 1995). Hurricane Allen for example, a category 5 hurricane with winds of 285 km/h and waves over 12 m, inflicted extensive damage on Jamaican coral reefs, even to a depth of 50 m (Woodley et al., 1981). Shallow-water branching species, most notably the elkhorn and staghorn corals, were smashed and leveled, and both architectural complexity of reefs and the abundance of living corals were reduced (Kjerfve, Magill, Porter, & Woodley, 1986; Knowlton, Lang, & Keller, 1990; Porter et al., 1981; Woodley et al.1981). The hurricane also increased the relative importance of coral predators (feeding by the snail *Coralliophila sp.* and the polychaete *Hermodice carunculata*, and 'gardening' behavior of the damselfish *Stegastes planifrons*) causing coral populations to continue to decline rather than return to their previous high densities (Knowlton et al., 1990; Knowlton, Lang, Rooney, & Clifford, 1981). More over, two-to-four years after the hurricane, a mass mortality from a species-specific pathogen struck the herbivorous echinoid species *Diadema antillarum,* throughout its entire geographic range (Bak, Carpay, & De Ruyter Van Steveninck, 1984; Carpenter, 1990; Lessios, Robertson, & Cubit, 1984). Without *D. antillarum*, and with the overfishing-induced decline in megaherbivorous fishes (Koslow, Hanley, & Wicklund, 1988; Munro, 1983; Russ, 1991; Steneck & Walton Smith, 1993), the entire reef system of Jamaica has undergone a spectacular and protracted benthic algal bloom ever measured in the tropics, up to 40 m or deeper, with coral abundance declining to zero in some sites (Hughes, 1994; Hughes, Reed, & Boyle, 1987; Steneck & Walton Smith, 1993). As a result of this preemption of space, coral larval recruitment has failed, and most adult colonies that survived Hurricane Allen have been killed by algal overgrowth (Hughes, 1989; Liddell & Ohlhorst, 1986). Bleaching events in subsequent years produced additional mortality (Gates, 1990; Hughes, 1994). In 1988, eight years after Hurricane Allen, another hurricane, Gilbert, struck Jamaica with the effect of zeroing any recovery processes, and returning the reefs to their immediate post-Allen severe devastated condition (UNEP, 1989). In Jamaican reefs, a striking phase shift has occurred from a coral-dominated to an algal-dominated system (Hughes, 1994; Nyström et al., 2000). This sequence of events in Jamaican coral reefs highlights how quickly a healthy coral reef can be severely damaged on a spatial scale of hundreds of kilometers, if natural and anthropogenic stresses combine (Hughes & Connel, 1999; Paine, Tegner, & Johnson, 1998). The implementation on a global scale of scientifically based management of disturbance (Turner, Baker, Peterson, & Peet, 1998) and warning system procedures (Stone & Kerr, 2005) is urgently needed to avoid further catastrophic damage, especially in light of the recent increases in hurricane activity (Goldenberg, Christopher, Mestas-Nuñes, & Gray, 2001). In particular, the last Atlantic hurricane season (year 2005) was the most active in recorded history. The impact of the season was widespread and ruinous with at least 2,280 deaths and recorded damages for over $100 billion USD: of the storms that made landfall, the hurricanes Dennis, Emily, Katrina, Rita, and Wilma were responsible for most of the destruction (NOAA, National Hurricane Center: http://www.nhc.noaa.gov). The most catastrophic effects of the season were felt on the United States' Gulf Coast, were a 10-m storm surge from Hurricane Katrina caused devastating flooding that inundated New Orleans, Louisiana and destroyed most structures on the Mississippi coastline (Day, 2005; Kintisch, 2005; Travis, 2005).

In conclusion, the data collected during our Maldivian coral reefs survey suggest that the impact of the Tsunami on the coral reef ecosystem followed a North–South gradient. This hypothesis found support in the extent of the damage caused by the Tsunami to persons and things in the southernmost atolls where the greatest devastation was recorded as well as the greatest number of deaths (for example in the island of Vilifushi in the Kolhumadulu Atoll-Thaa, 148 km to the south of the southernmost areas we surveyed;

information from governmental sources). The sections of the coral reefs located in the passes were the most affected; these areas, representing only a minor fraction of the entire coral reef ecosystem, will in all likelihood recover in a few years time. From the standpoint of how tourists perceive the situation, it would seem that the marine environment of the Maldives is still considered as attractive as it was before the earthquake. In any case, it is important to note that the impact on tourism perceptions is not limited to Tsunami related impacts. Appeal of Maldivian reefs has been significantly affected by the consequences of the bleaching events of the late 90s, causing the lack of color of many reefs. During the 1998 bleaching event, Maldivian coral reefs were heavily degraded, with approximately 90% loss of live coral cover on the reef tops (Rajasuriya et al., 2002) Encouragingly, a generalized slight recovery is recorded (personal observations; Rajasuriya et al. 2002), and it should continue if there are no further major high temperature events. The negative consequences of bleaching on dive tourists' perceptions are well known by diving guides and instructors.

The results of this first survey on Maldivian coral reefs after the Tsunami are in agreement with the findings of the subsequent Australian Government mission, started on 23 January 2005 (http://www.ausaid.gov.au/publications/). The team of this wider mission was formed by 11 Australian scientist, joined with 11 local scientist, and included expertise in coral and coral reef fish ecology, reef health assessment, reef management, reef island geomorphology and baitfish assessment. During the 17-day Australian mission, 124 reef sites were surveyed in seven atolls, with additional information from 65 tourism dive sites. Also the results of the Australian mission generally indicated that direct damage to Maldivian reefs from the Tsunami was minor.

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