Maldives Field Survey after the December 2004 Indian Ocean Tsunami

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The tsunami of 26 December 2004 severely affected the Maldives at a distance of 2,500 km from the epicenter of the magnitude 9.0 earthquake. The Maldives provide an opportunity to assess the impact of a tsunami on coral atolls. Two international tsunami survey teams (ITSTs) surveyed a total of 13 heavily damaged islands. The islands were visited by seaplane on 14–15 and 18–19 January 2005. We recorded tsunami heights of up to 4 m on Vilufushi on the basis of the location of debris in trees and watermarks on buildings. Each watermark was localized by means of a global positioning system (GPS) and was photographed. Numerous eyewitness interviews were recorded on video. The significantly lower tsunami impact on the Maldives as compared with Sri Lanka is largely due to the topography and bathymetry of the atoll chain. [DOI: 10.1193/1.2201973]

INTRODUCTION

On Sunday 26 December 2004 at 00:58:53 UTC, a great earthquake with a moment magnitude of 9.0—or possibly greater (Stein and Okal 2005)—occurred on the Indo-Australian Southeast Asian plate boundary, off the shore of northern Sumatra, Indonesia. Large tsunamis were generated and severely damaged coastal communities in countries across the Indian Ocean, including Indonesia, Thailand, Sri Lanka, India, the Maldives, and Somalia (Synolakis et al. 2005). The tsunami death toll is currently estimated at 300,000—exact numbers are likely never to be determined, given that detailed pre-tsunami population censuses were not available in several affected regions, and human remains were occasionally buried in mass graves without identification. Beyond the loss of human lives, the tsunami also destroyed livelihoods, traumatized whole populations, and severely damaged habitats. In the near field of the epicenter, Sumatra was hardest hit by the tsunami (Borrero 2005). In the far field, the tsunami severely affected Sri Lanka across the Bay of Bengal at a distance of 1,600 km from the epicenter (Liu et al. 2005). In East Africa, the tsunami impact focused on Somalia some 5,000 km to the west of the earthquake epicenter (Fritz and Borrero 2006, this issue).

The tsunami severely affected the Maldives at a distance of 2,500 km from the epi-

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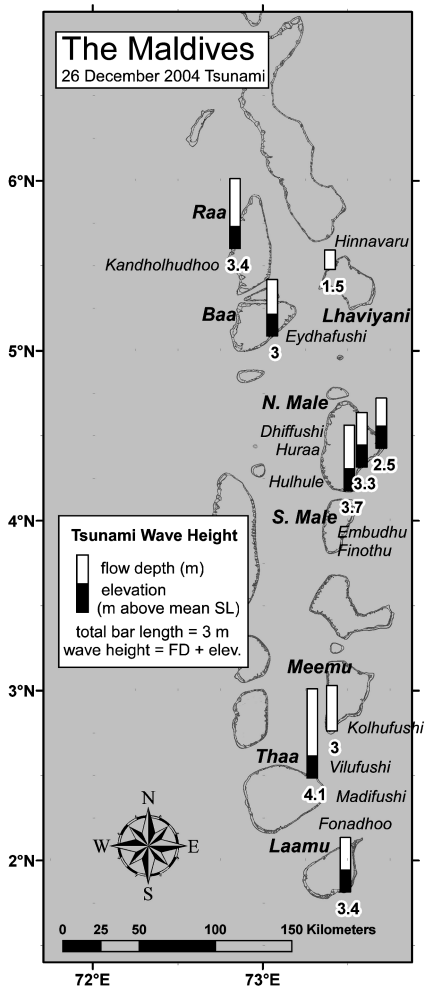

Figure 1. Locations of the Maldives islands surveyed and the maximum tsunami flow depths observed.

center, or at the halfway point between Sumatra and Somalia along the westward path of the tsunami. The country stretches 823 km north to south and 130 km east to west (Figure 1). The numerous coral reef islands, 1,190 in total, form an archipelago of 26 natural atolls. Open seas or deep channels with a depth of more than 200 m separate the atolls. The largest atoll, Huvadhoo, is 65 km wide and 82 km long, while Thoddoo, the smallest, is about 1.8 km in diameter. Depths within the atoll lagoons usually vary from 30 to 50 m, but in some places, such as Huvadhoo, depths may reach up to 90 m. Over 99% of the Maldives' area is ocean. Only 0.331% of its 13,423 km^2 area is land, corresponding to 298 km^2. Out of the incredibly large number of islands, only 200 islands are inhabited. The total population of the Maldives in 2004 was 270,101. At first sight, the

archipelago—with elevations of less than 2 m above sea level—appears extremely vulnerable. Reports indicate more than 82 people confirmed dead, with an additional 26 missing and presumed dead, and over 12,000 people homeless.

Roughly 90% of the casualties were reported on 4 atolls (Meemu, Dhaalu, Thaa, and Meemu) in the southern part of the Maldives. Some 4,000 houses were damaged. In the tourism sector—which is the country's largest source of foreign income—out of the 87 resorts, 19 were severely damaged and had to be closed down, while 14 others suffered major partial damage. Agricultural crops were swept away, and most parts of the agricultural land were covered with a thin layer of salty carbonate mud (which is centimeters thick), leaving the land unusable.

POST-TSUNAMI FIELD SURVEY

A tsunami survey plan was initiated within a week of the earthquake; the authors formed part of the international tsunami survey teams (ITSTs) on the south coast of Sri Lanka (Liu et al. 2005). Two separate survey teams were dispatched from Sri Lanka to the Maldives on 13 and 16 January 2005. Both survey teams were supported by the local disaster management center and various local researchers. On 14–15 January, the third author surveyed a total of 7 islands on 3 different atolls: Dhiffushi, Huraa, Hulhule and Malé (North Malé Atoll), Embudhu Finothu (South Malé Atoll), and Gan and Fonadhoo (Laamu Atoll). On 18–19 January, the first two authors surveyed a total of 6 heavily damaged islands on 5 different atolls: Vilufushi and Madifushi (Thaa Atoll), Kolhufushi (Meemu Atoll), Kandholhudhoo (Raa Atoll), Eydhafushi (Baa Atoll), and Hinnavaru (Lhaviyani Atoll). The islands were visited by seaplane and speedboats. The locations of the islands within the chain of atolls are shown in Figure 1.

The goals of the ITST were to document inundation, which is the horizontal extent of water penetration; to document runup, which is the maximum vertical elevation above mean sea level at tsunami arrival of the land flooded; and to collect information on the human impact of the tsunami. A variety of standard tsunami field survey techniques (e.g., Synolakis and Okal 2005) were used. However, these had to be adapted to the special topography of the Maldives. Most islands were completely flooded by the tsunami, due to their low-lying land. Therefore, neither inundation lines nor classic runup were observed. The team measured local flow depths (i.e., the water level above terrain) on the basis of the location of debris in trees and watermarks on buildings. The maximum tsunami flow depth was determined in relation to the sea level at the tsunami impact. Each watermark was located by means of a global positioning system (GPS) and was photographed. Numerous eyewitness interviews were recorded on video to estimate the number of waves, their height and period, and the tsunami arrival time. The acquired data set is shown in Table 1. The team surveyed a total of 78 locations, some with multiple data points. Maximum tsunami heights are typically on the order of 1–4 m. Thus, the absolute values are roughly half of those reported in Somalia at twice the distance from the epicenter along the same ray path of the tsunami (Fritz and Borrero 2006, this issue). However, in Somalia, mostly runup was measured on relatively steep beaches, in sharp contrast to the flat Maldives, which were overwashed by the tsunami.

Table 1. Data set surveyed in the Maldives by the two ITST teams in January 2005

No.	Island	Atoll	Latitude (°N)	Longitude (°E)	Vertical survey asl (m)		Dist. from shore (m)	Date and time surveyed		Watermark
					Terr. elev.	Flow depth +terr. elev.		Day & month	(UTC)	
1	Vilufushi	Thaa	2.50356	73.30856	1.02	2.11	135	18 Jan.	06:08	Inside house
2	Vilufushi	Thaa	2.50330	73.30868	1.02	3.29	139	18 Jan.	06:09	Debris in tree
3	Vilufushi	Thaa	2.50333	73.30892	1.02	2.36	111	18 Jan.	06:14	Outside house
4a	Vilufushi	Thaa	2.50322	73.30929	1.02	2.77	74	18 Jan.	06:18	Seaweed outside
4b	Vilufushi	Thaa	2.50322	73.30929	1.02	2.35	74	18 Jan.	06:18	Inside house
5	Vilufushi	Thaa	2.50315	73.30956	1.02	3.71	45	18 Jan.	06:22	Seaweed on tree
6	Vilufushi	Thaa	2.50317	73.30952	1.02	3.07	49	18 Jan.	06:23	Seaweed on tree
7	Vilufushi	Thaa	2.50329	73.30969	1.02	3.70	28	18 Jan.	06:26	Fishing net on tree
8	Vilufushi	Thaa	2.50316	73.30986	1.02	3.75	11	18 Jan.	06:28	Seaweed on pole
9	Vilufushi	Thaa	2.50317	73.30986	1.02	3.57	10	18 Jan.	06:28	Seaweed on pole
10	Vilufushi	Thaa	2.50364	73.30961	1.02	3.43	14	18 Jan.	06:36	Seaweed on tree
11	Vilufushi	Thaa	2.50375	73.30960	1.02	4.07	8	18 Jan.	06:38	Debris in tree
12	Vilufushi	Thaa	2.50399	73.30940	1.02	3.74	13	18 Jan.	06:41	Seaweed on tree
13	Vilufushi	Thaa	2.50444	73.30935	1.02	3.67	4	18 Jan.	06:48	Seaweed on tree
14	Vilufushi	Thaa	2.50617	73.30790	1.02	3.27	21	18 Jan.	06:57	Debris in tree
15	Vilufushi	Thaa	2.50546	73.30759	1.02	2.14	72	18 Jan.	07:07	Inside house
16	Vilufushi	Thaa	2.50556	73.30728	1.02	3.03	102	18 Jan.	07:07	Stairway
17	Vilufushi	Thaa	2.50423	73.30899	1.02	2.66	39	18 Jan.	07:16	Outside house
18	Vilufushi	Thaa	2.50194	73.31004	1.02	3.44	5	18 Jan.	07:22	Debris on column
19	Vilufushi	Thaa	2.50247	73.30857	1.02	3.59	163	18 Jan.	08:25	Person on roof
19	Madifushi	Thaa	2.35708	73.35457	1.34	2.10	140	18 Jan.	09:28	Inside house
20	Madifushi	Thaa	2.35750	73.35568	1.34	2.35	40	18 Jan.	09:40	Debris in tree
21	Madifushi	Thaa	2.35777	73.35563	1.34	2.76	56	18 Jan.	09:46	Inside house
22	Madifushi	Thaa	2.35802	73.35587	1.34	2.13	48	18 Jan.	10:04	On pole
23	Madifushi	Thaa	2.35632	73.35522	1.34	3.21	37	18 Jan.	10:23	Inside house

Table 1. (cont.)

No.	Island	Atoll	Latitude (°N)	Longitude (°E)	Vertical survey asl (m)		Dist. from shore (m)	Date and time surveyed		Watermark
					Terr. elev.	Flow depth +terr. elev.		Day & month	(UTC)	
24	Madifushi	Thaa	2.35555	73.35497	1.34	2.85	42	18 Jan.	10:28	Inside house
25	Madifushi	Thaa	2.35608	73.35490	1.40	2.56	82	18 Jan.	10:38	Outside house
26	Kolhufushi	Meemu	2.77183	73.42510	0.93	2.76	23	18 Jan.	12:27	Debris in tree
27	Kolhufushi	Meemu	2.77225	73.42503	0.93	2.90	30	18 Jan.	12:33	Damaged tree
28	Kolhufushi	Meemu	2.77297	73.42533	0.93	2.83	30	18 Jan.	12:39	Debris in tree
29	Kolhufushi	Meemu	2.77343	73.42473	0.86	2.91	129	18 Jan.	12:47	Debris in palm tree
30	Kolhufushi	Meemu	2.77385	73.42442	0.86	2.87	192	18 Jan.	12:49	Inside house
31	Kolhufushi	Meemu	2.77402	73.42363	0.93	2.23	290	18 Jan.	12:54	Outside house
32	Kandholhudhoo	Raa	5.62015	72.85435	1.18	2.87	147	19 Jan.	06:03	Outside house
33	Kandholhudhoo	Raa	5.61995	72.85457	1.18	3.02	138	19 Jan.	06:06	Outside house
34	Kandholhudhoo	Raa	5.61997	72.85465	1.18	2.95	125	19 Jan.	06:10	Inside house
35	Kandholhudhoo	Raa	5.61850	72.85565	1.18	2.21	68	19 Jan.	06:20	Outside house
36a	Kandholhudhoo	Raa	5.61832	72.85583	1.18	3.39	54	19 Jan.	06:33	Outside house
36b	Kandholhudhoo	Raa	5.61832	72.85583	1.18	3.10	54	19 Jan.	06:33	Outside house
37	Kandholhudhoo	Raa	5.61822	72.85568	1.18	2.72	71	19 Jan.	06:36	Outside house
38	Kandholhudhoo	Raa	5.61803	72.85578	1.18	3.13	61	19 Jan.	06:38	Outside house
39	Kandholhudhoo	Raa	5.61775	72.85580	1.18	2.42	64	19 Jan.	06:41	Inside house
40a	Kandholhudhoo	Raa	5.61768	72.85587	1.18	2.66	60	19 Jan.	06:43	Outside house
40b	Kandholhudhoo	Raa	5.61768	72.85587	1.18	2.74	60	19 Jan.	06:43	Outside house
41	Kandholhudhoo	Raa	5.61765	72.85588	1.18	2.82	57	19 Jan.	06:44	Telephone booth
42	Kandholhudhoo	Raa	5.61757	72.85590	1.18	3.05	59	19 Jan.	06:45	Outside house
43	Kandholhudhoo	Raa	5.61753	72.85620	1.18	3.10	28	19 Jan.	06:47	Outside house
44	Kandholhudhoo	Raa	5.61762	72.85630	1.18	3.10	15	19 Jan.	06:48	Outside house
45	Kandholhudhoo	Raa	5.61858	72.85493	1.80	2.30	143	19 Jan.	07:14	Outside house

Table 1. (cont.)

No.	Island	Atoll	Latitude (°N)	Longitude (°E)	Vertical survey asl (m)		Dist. from shore (m)	Date and time surveyed		Watermark
					Terr. elev.	Flow depth +terr. elev.		Day & month	(UTC)	
46	Eydhafushi	Baa	5.10142	73.07308	1.44	3.04	64	19 Jan.	08:43	Outside house
47	Eydhafushi	Baa	5.10145	73.07278	1.44	2.11	171	19 Jan.	08:46	Outside house
48	Eydhafushi	Baa	5.10177	73.07245	1.44	2.00	178	19 Jan.	08:50	Outside house
49	Eydhafushi	Baa	5.10248	73.07215	1.44	2.00	229	19 Jan.	08:54	Outside house
50	Eydhafushi	Baa	5.10265	73.07197	1.44	1.95	192	19 Jan.	08:55	Outside house
51	Eydhafushi	Baa	5.10302	73.07147	1.44	1.61	175	19 Jan.	08:57	Outside house
52	Hinnavaru	Lhaviyani	5.49463	73.41283	0.77	1.13	206	19 Jan.	10:44	Outside house
53	Hinnavaru	Lhaviyani	5.49460	73.41245	0.70	1.30	248	19 Jan.	10:47	Outside house
54	Hinnavaru	Lhaviyani	5.49373	73.41225	0.60	1.15	263	19 Jan.	10:53	Outside house
55	Hinnavaru	Lhaviyani	5.49297	73.41190	0.70	1.30	309	19 Jan.	10:59	Outside house
56	Hinnavaru	Lhaviyani	5.49288	73.41188	0.55	1.49	311	19 Jan.	11:01	Outside house
57	Hinnavaru	Lhaviyani	5.49272	73.41178	0.55	1.26	322	19 Jan.	11:05	Outside house
58	Hinnavaru	Lhaviyani	5.49218	73.41317	0.55	0.98	174	19 Jan.	11:08	Outside house
59a	Hinnavaru	Lhaviyani	5.49195	73.41360	0.55	1.24	128	19 Jan.	11:10	Outside house
59b	Hinnavaru	Lhaviyani	5.49195	73.41360	0.60	1.04	128	19 Jan.	11:10	Outside house
60	Hulhule	N. Malé	4.19453	73.52565	0.97	1.22	104	14 Jan.	04:30	On wall
61	Malé	N. Malé	4.17208	73.50235	0.95	1.15	82	14 Jan.	06:15	On wall
62	Malé	N. Malé	4.16942	73.50581	0.00	1.45	28	14 Jan.	06:15	Damaged wall
63	Malé	N. Malé	4.16970	73.51338	1.15	2.05	20	14 Jan.	06:15	Damaged fence
64	Malé	N. Malé	4.17372	73.51788	1.65	1.15	54	14 Jan.	06:15	Wall overtopping
65	Malé	N. Malé	4.17866	73.51416	0.85	1.25	15	14 Jan.	06:15	On wall
66	Malé	N. Malé	4.18020	73.50963	1.05	1.35	0	14 Jan.	06:15	Seawall damaged
67	Embudhu Finothu	S. Malé	4.18010	73.52455	0.33	2.33	0	14 Jan.	09:12	On dock
68	Embudhu Finothu	S. Malé	4.18010	73.52455	0.33	1.83	0	14 Jan.	09:12	In bungalow

Table 1. (cont.)

No.	Island	Atoll	Latitude (°N)	Longitude (°E)	Vertical survey asl (m)		Dist. from shore (m)	Date and time surveyed		Watermark
					Terr. elev.	Flow depth +terr. elev.		Day & month	(UTC)	
69	Embudhu Finothu	S. Malé	4.18010	73.52455	1.23	2.93	0	14 Jan.	09:12	In bungalow
70	Fonadhoo	Laamu	1.83240	73.50333	1.62	3.12	130	14 Jan.	17:15	Inside house
71	Fonadhoo	Laamu	1.82420	73.49506	1.02	1.52	158	14 Jan.	17:15	Outside house
72	Fonadhoo	Laamu	1.82463	73.49520	1.13	2.13	115	14 Jan.	18:15	Outside walls
73	Fonadhoo	Laamu	1.93235	73.60000	1.88	3.28	0	14 Jan.	18:15	Road flooding
74	Fonadhoo	Laamu	1.92293	73.54980	1.57	2.87	179	15 Jan.	02:50	On wall
75	Dhiffushi	N. Malé	4.44435	73.71480	1.20	2.20	80	15 Jan	08:20	On wall
76	Dhiffushi	N. Malé	4.44392	73.71365	1.00	2.30	13	15 Jan	08:20	On window
77	Huraa	N. Malé	4.33356	73.60093	1.54	2.34	200	15 Jan	09:45	Debris in mangroves
78	Huraa	N. Malé	4.24918	73.53676	1.84	3.34	0	15 Jan	09:45	On wall

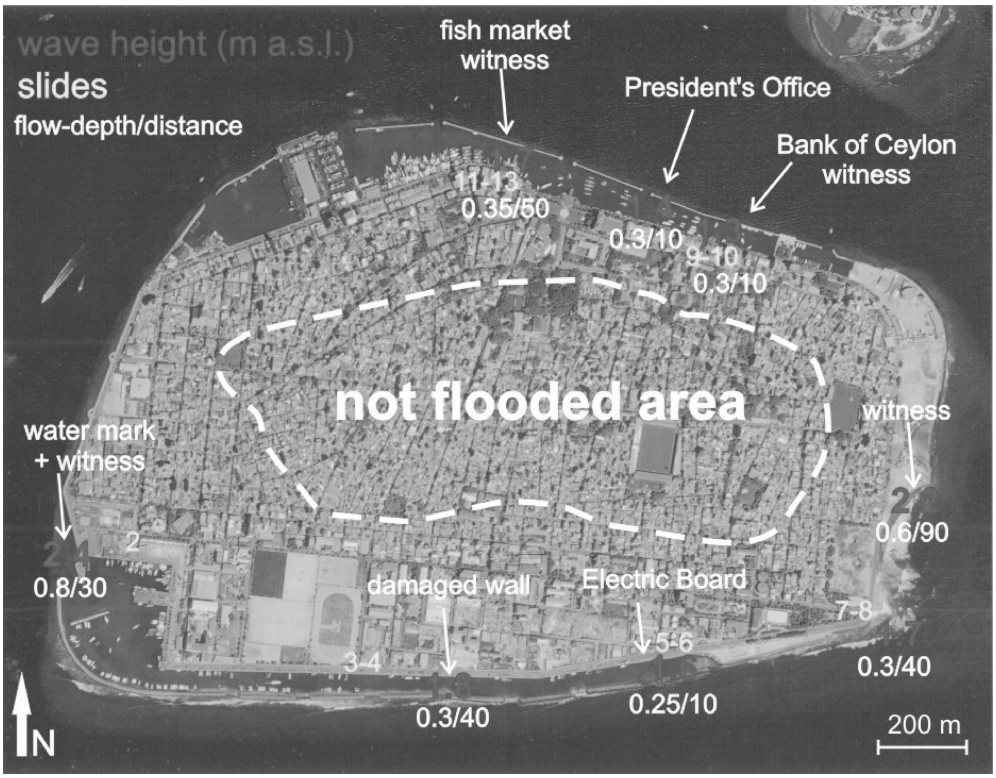

Figure 2. Flow depths at several locations around Malé. The interior of the island (inside the dashed line) was not flooded during the tsunami.

FIELD OBSERVATIONS

MALÉ (NORTH MALÉ ATOLL)

The capital of the Maldives, Malé, was one of the few islands in the country that was not completely overwashed by the tsunami (Figure 2). Consistent with other reports, the first of three waves arrived as a positive wave at about 9:15 A.M. local time. Witnesses describe a gradual rise in the ocean level from all directions. The island has been markedly reclaimed with detached concrete seawalls and tetrapods placed on the outer reef. The north side of the island was damaged less than the south. This could be due in part to protection afforded by the runway at the Malé International Airport on Hulhule Island west of Malé, which was overwashed by the tsunami. Most of the visible damage on Malé consisted of seawalls and roads that were undermined by the advancing or retreating waves. Buildings suffered surprisingly little obvious structural damage. In several places, we witnessed watermarks on plate glass windows that were not broken, suggesting a slow and gradual wave rather than a rapid and turbid wave, as seen in the other affected areas.

DHIFFUSHI (NORTH MALÉ ATOLL)

There was very little visible structural damage on Dhiffushi Island. Multiple eyewitnesses reported three waves—the third was larger than the first two, and it came from the west (the lagoon side). Watermarks in windows at three different levels confirm the observations of the separate waves. Flow depths averaged about 1 m for all three waves.

EMBUDHU FINOTHU (SOUTH MALÉ ATOLL)

The resort island of Embudhu Finothu was completely overwashed by the tsunami. We measured a maximum wave height of 2.9 m inside a bungalow on the east side of the narrow island (less than 100 m wide). According to eyewitnesses, the first wave rapidly overwashed the island at an elevation of about 2 m above the ground, then receded to the east with the wave's trough, exposing the seafloor toward the outer reef for several hundred meters. A second wave came from a northerly direction about 10 minutes after the first had receded. The sea had returned to its normal state after about half an hour. Damage to structures was limited to vertical offsets (such as buckled floors, and bungalows that floated off their foundations) rather than lateral displacements resulting from being pushed by the wave.

VILUFUSHI ISLAND (THAA ATOLL)

The Thaa Atoll is 200 km south of the capital Malé. The British Admiralty conducted the most comprehensive bathymetric survey of the islands. An extract of the digital nautical charts is shown in Figure 3. The atoll is of roughly circular shape, with an average diameter of 45 km. The deepest point inside the atoll, with a depth of 88 m, is in the center. Thaa Atoll is separated from its northern neighbors Dhaalu and Meemu by channels roughly 17 and 28 km wide whose depth is about 500 m. The 30-km-wide channel separating Thaa from Laamu is 1,800 m deep. The total population on the atoll was 8,513 in 2004. The tsunami killed 19 people on the atoll and damaged 563 buildings. The team surveyed the two hardest-hit islands, Vilufushi and Madifushi.

The island of Vilufushi (Figure 4a) is on the northeast corner of the Thaa Atoll facing Kolhufushi on the Meemu Atoll across the narrowest part of the channel between Thaa and Meemu. Vilufushi is barely 1 km long and up to 300 m wide. The island is bounded on the east by a coral reef roughly 1 km offshore. The land is flat, with an elevation of 1 m. Vilufushi is one of the largest communities on the Thaa Atoll, with a population of 1,886. Unfortunately, Vilufushi was the hardest-hit individual island in the Maldives. As of this writing, the death toll remains at 18. In addition to the human loss, 192 houses were damaged. Characteristic houses are properly designed and built out of coral stones or concrete stones, sometimes with steel reinforced concrete columns (Figure 4b). This is in sharp contrast to the wooden huts found along Sri Lanka's coasts (Liu et al. 2005).

Vilufushi was completely overwashed by the tsunami. Abundant watermarks were found on the outside and inside of remaining houses as well as in the form of seaweed, clothing, and fishing nets on trees and concrete columns. Examples of tsunami flow depth measurements are shown in Figure 5.

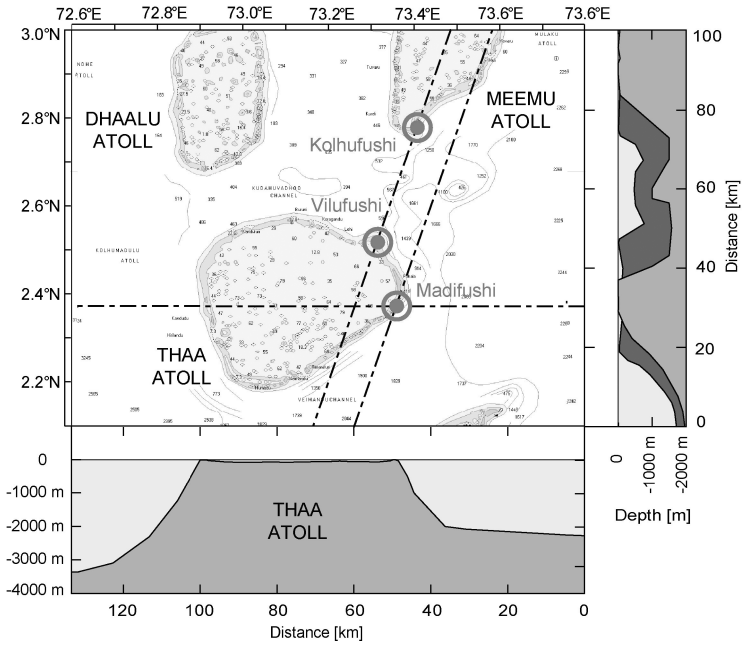

Figure 3. Thaa and Meemu atolls, with surveyed islands on a digital nautical chart modified for use with GPS (after updated British Admiralty maps and selected bathymetric profiles).

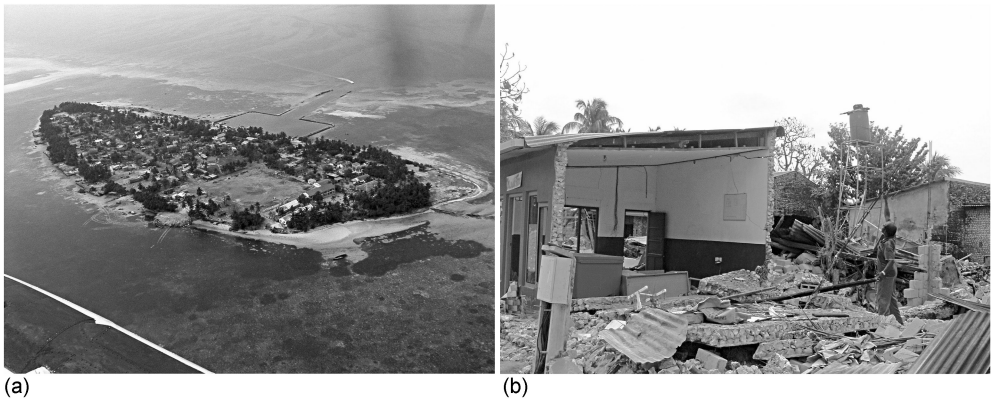

Figure 4. Vilufushi Island (Thaa Atoll): (a) southwest view with the harbor toward the inner portion of the atoll, as seen during the landing approach from a seaplane; (b) classic blowout failure of a coral stone wall.

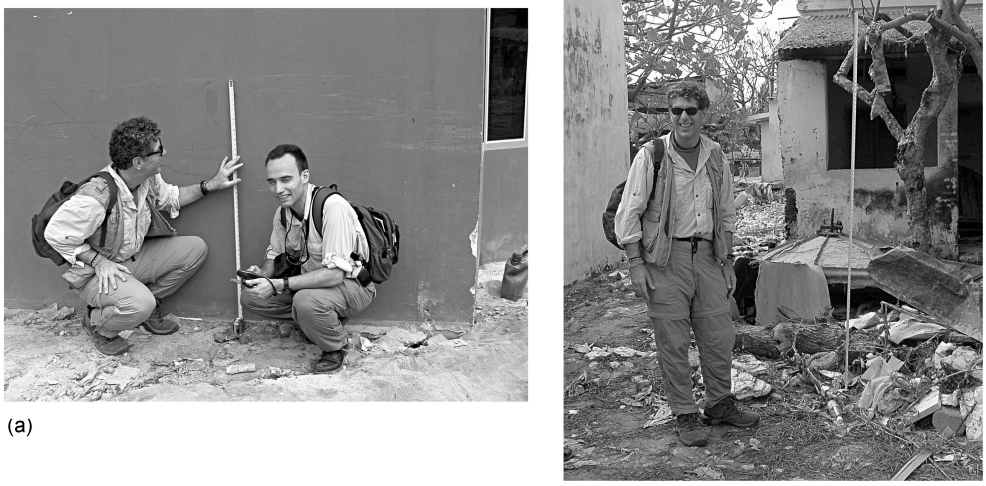

Figure 5. Flow depth measurements on Vilufushi: (a) a watermark on an outside wall; (b) seaweed on a tree.

The highest flow depth of just over 3 m was measured on Vilufushi, which corresponds to a maximum tsunami height of over 4 m in relation to the mean sea level at the time of the tsunami attack. A summary of all the measured flow depth points on Vilufushi is shown in Figure 6.

Several eyewitnesses were interviewed and recorded on video. Most inhabitants survived by fleeing in fishing boats toward the inner portion of the atoll, while others climbed to the roofs of their houses and held on. The accounts generally mentioned one to four waves, with a leading elevation in most cases. Some accounts mentioned an initial depression. The tide gauge records shown in Figure 7 all indicate an initial rise. The first wave arrived at about 9:15–9:30 A.M. local time, depending upon the location within the island chain, as indicated by the tide gauges shown in Figure 7. On the east coast of Vilufushi, we recovered a broken clock, which stopped at 9:26 A.M. local time (which equals UTC+5 hours). This is in agreement with the tide gauge records. Given the epicentral distances of about 2,600 km and taking into account the variable depth of the Indian Ocean basin, travel times are expected to be 3.25–3.5 hrs (Titov et al. 2005). With a seismic origin of 00:58:53 UTC, this predicts first arrivals at about 9:15–9:30 local time, matching the initial rises on the tide gauge recordings as well as eyewitness accounts.

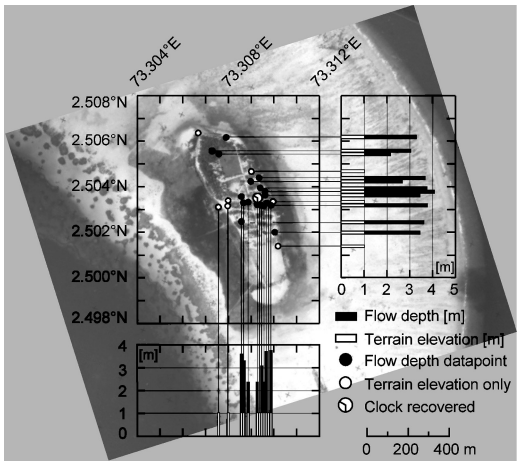

Figure 6. Measured tsunami flow depths and surveyed locations at Vilufushi, on a pre-tsunami satellite image provided by the Maldives Disaster Management Center.

KOLHUFUSHI ISLAND (MEEMU ATOLL)

The island of Kolhufushi is on the Meemu Atoll some 30 km northeast of Vilufushi across a channel 500 m deep. The islands along the deep ocean channel separating the Thaa Atoll from the Meemu Atoll accounted for half the victims in the Maldives. The total population on Meemu was 4,845 in 2004. Reportedly, there were 34 tsunami victims on the atoll—16 on Kolhufushi alone—and tsunami damage to 346 buildings. The team surveyed the hard-hit Kolhufushi Island on the southwestern tip of the atoll. Kolhufushi was completely overwashed by the tsunami. A summary of all the measured flow depth points is shown in Figure 8.

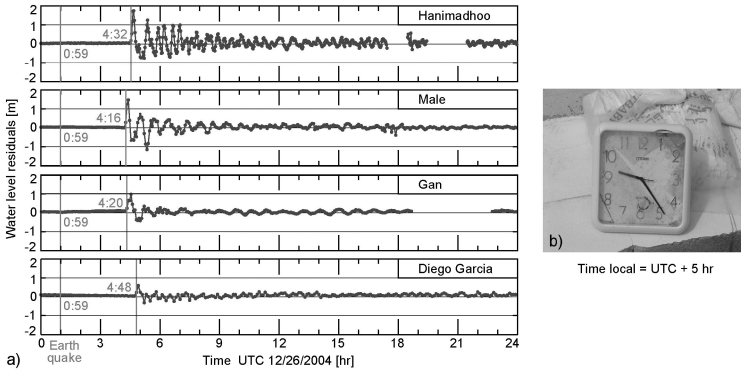

Figure 7. Tsunami arrival time: (a) analysis of tide gauge residuals; (b) broken clock recovered on Vilufushi Island.

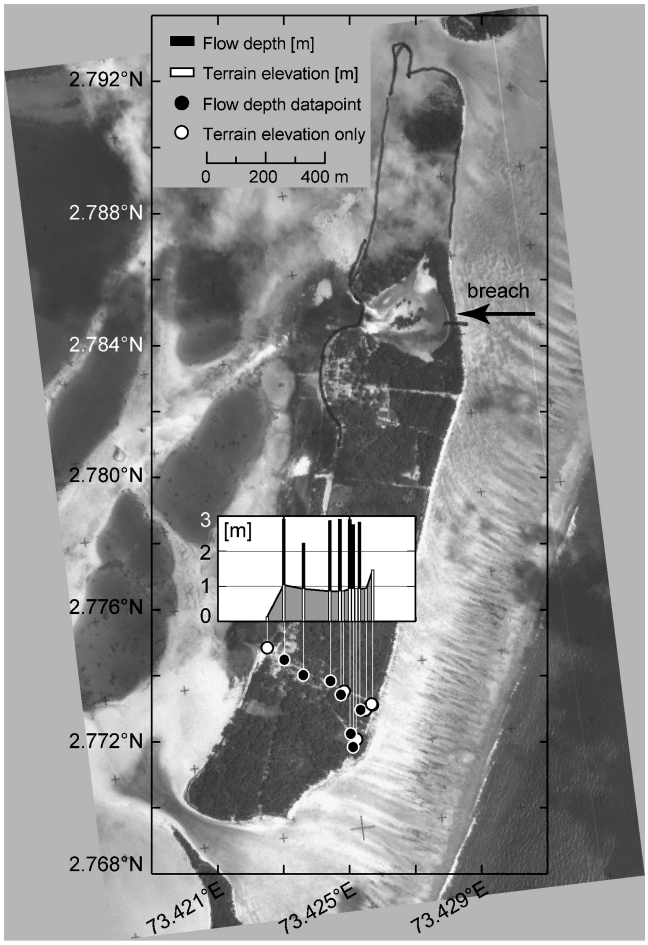

Figure 8. Kolhufushi Island (Meemu Atoll): measured tsunami flow depths and surveyed locations. The sand spit connecting the northern end of the island is not breached in this pre-tsunami satellite image provided by the Maldives Disaster Management Center.

Kolhufushi is roughly 2.5 km long and 400 m wide. The transect recorded across the island indicates an even flow depth of 2 m above terrain across the entire island. The pre-tsunami satellite image shows a lagoon cutting into the island, separating the northern third from the rest of the island. The two segments were connected by a narrow sand spit covered with vegetation along the eastern shoreline of the island. The sand spit had lost its vegetation and was partially breached prior to the tsunami. However, the final breaching was induced by the overflow of the tsunami. The resulting cut separating the two island parts is shown in Figure 9, as seen from a seaplane in its final landing approach.

Figure 9. Westward view of the Kolhufushi lagoon and the sand spit, which was breached by the tsunami.

FONADHOO AND GAN (LAAMU ATOLL)

The southernmost atoll we visited was the Laamu Atoll, more than 250 km south of Malé, where 4 people died in the village of Fonadhoo. The tsunami height here was 3.3 m above sea level, as measured by a water line in a house. Despite thick stands of vegetation, the island was completely overwashed. The only structural damage we saw consisted of walls that had been knocked down in the first houses that were within 20 m of the ocean. Further north at Gan, the wave overwashed the island with a flow depth of 50 cm (~2 m above sea level); however, structural damage was minimal. Glass windows facing the flow direction remained intact, recording the wave height with preserved mud lines. Damaged vegetation shows that the wave direction came from ENE (060). Curiously, multiple eyewitnesses reported changes in water wells up to one hour before the first waves hit, and another witness recalled the garbage dump (a depression in the ground about 2 m deep) filling up with water minutes before the first noticeable wave came onshore.

KANDHOLHUDHOO ISLAND (RAA ATOLL)

The Raa Atoll is 180 km north-northwest of Malé. The atoll is of elongated shape, spanning some 60 km north to south and 30 km across. The Raa Atoll is separated from its southern neighbor Baa only by a channel that is 3 km wide and 200 m deep. The total population on the atoll was 15,331 in 2004. Reportedly, the tsunami was responsible for 3 fatalities on the atoll and damaged 854 buildings. The team surveyed the hard-hit Kandholhudhoo Island (Figure 10a) on the west side of the atoll—one of the few locations with an available amateur video recording showing the tsunami arrival. The island of Kandholhudhoo is on the west side of the Raa Atoll. The bathymetry inside the atoll is very shallow, with less than a 10-m depth between Kandholhudhoo Is-

(a) (b)

Figure 10. Kandholhudhoo Island (Raa Atoll): (a) eastward view of the island from the air; (b) collapsed seawall with exposed armor on the northwest side of the island.

land and the center of the atoll protecting the island toward the east. Kandholhudhoo is barely 500 m long and 250 m wide. Part of the island was reclaimed from the sea by the construction of an encircling seawall within the last five years, which partially collapsed due to tsunami-induced erosion (Figure 10b). The land is flat, with an average elevation of 1.2 m in relation to the sea level at the time the tsunami arrived.

Kandholhudhoo is one of the largest communities on the Raa Atoll, with a population of 3,664. The island is 70 km west of Malé. Fortunately, the people of Kandholhudhoo were warned by a phone call from Malé of the approaching tsunami 15 minutes prior to its arrival. The death toll was limited to 3 victims, while 520 buildings were damaged. The damage on the west side surpassed the destruction on the east side of the island. The west side is on the outer rim of the atoll, whereas the east side, although oriented toward the tsunami ray path, faces the shallow inner lagoon of the atoll. Nevertheless, Kandholhudhoo was completely flooded by the tsunami. A summary of all the measured flow depth points is shown in Figure 11.

On the east side of Kandholhudhoo Island, an amateur cameraman—alerted by the phone call warning from Malé—recorded the arrival of the tsunami. Figure 12 shows a view looking east toward the center of the atoll. The amateur video shows the initial rise of the tsunami flooding the streets, similar to a rapid rise of the tides beyond normal high tide. An extracted video image during the flooding is shown in Figure 12a. At a later stage, the white wall disappeared completely underwater. The survey team revisited the exact location on 19 January 2005 and documented watermarks, a partially collapsed white wall, and massive scouring along the road corner (Figure 12b).

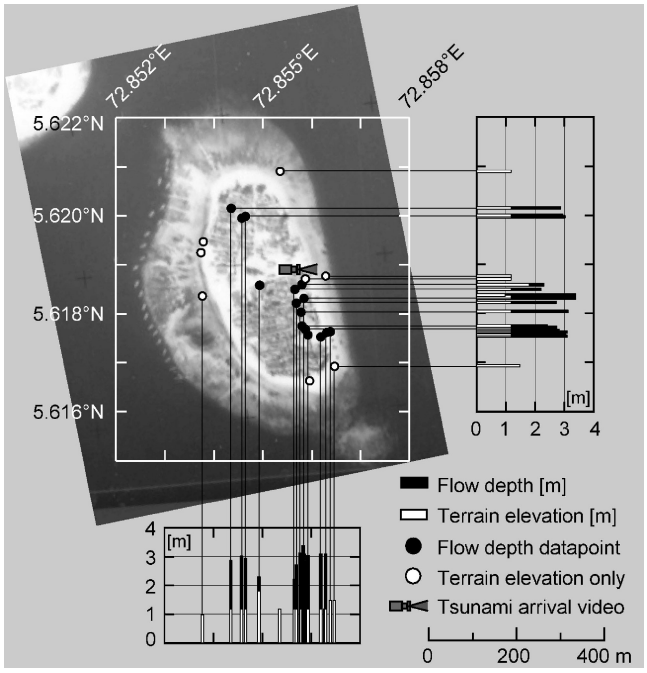

Figure 11. Measured tsunami flow depths and surveyed locations at Kandholhudhoo, on a pre-tsunami satellite image provided by the Maldives Disaster Management Center.

(a) (b)

Figure 12. Amateur video at Kandholhudhoo: (a) during flooding by the tsunami; (b) the same location in the aftermath, with partial wall collapse and massive scouring.

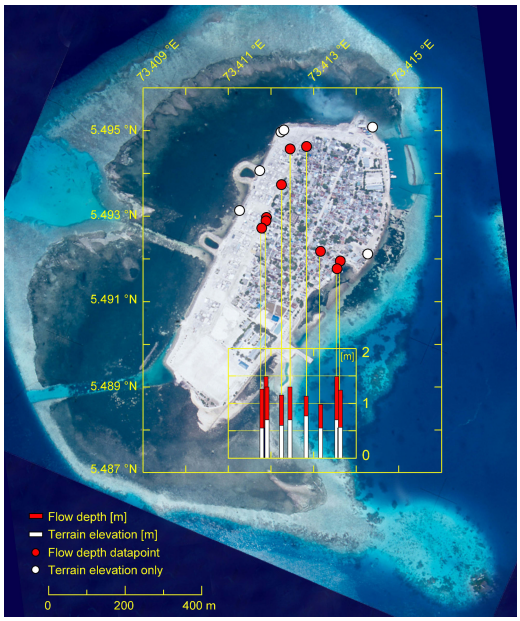

Figure 13. Hinnavaru Island (Lhaviyani): measured tsunami flow depths and surveyed locations on a pre-tsunami satellite image provided by the Maldives Disaster Management Center.

HINNAVARU ISLAND (LHAVIYANI ATOLL)

The island of Hinnavaru is on the Lhaviyani Atoll some 150 km north of Malé. The total population on Lhaviyani was 8,158 in 2004. The tsunami caused no fatalities on the atoll, and only 25 buildings were damaged. The team surveyed the minimally affected Hinnavaru Island on the northwestern rim of the atoll. Hinnavaru was completely overwashed by the tsunami. A summary of all the measured flow depth points is shown in Figure 13. The highest point on Hinnavaru was elevated less than 1 m above mean sea level at the time of the tsunami arrival. Most remarkably, the flow depth did not exceed 1 m above terrain. Hinnavaru fared remarkably well during this devastating tsunami and perfectly represents the majority of the islands in the Maldives.

CONCLUSIONS

The rapid ITST response in visiting the Maldives after the 26 December 2004 event led to the recovery of important data on the characteristics of the tsunami effects and inundation on coral atolls, which are astonishingly different from the effects along the coastlines of major land masses. Furthermore, the complete submergence of the settlements during the main tsunami waves resulted in important documentation of structural behavior upon tsunami impact. In the Maldives, the maximum tsunami heights reached up to only 4 m above sea level on Vilufushi Island. The unique topography and bathymetry, with offshore coral reefs and deep channels separating individual atolls, signifi-

cantly reduced the impact of the tsunami, as compared with Sri Lanka or even Somalia—which was twice the distance from the epicenter along the main westward tsunami trajectory. The human loss was orders of magnitude smaller than in Sri Lanka, and a third of the death toll that was reported in Somalia along the same ray path but on steep shores (Fritz and Borrero 2006, this issue). Most remarkably, the victims and the bulk of the destruction were concentrated on a dozen islands on four atolls in the southern part of the Maldives, while the majority of the islands reported no victims and only minimal damage. Although the terrain elevations of the entire island chain are lower than 2 m, the 26 December tsunami had limited impact on the Maldives, because of the characteristic bathymetry with deep ocean channels separating the individual atolls.

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