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Response of reef island shorelines to seasonal climate oscillations: South Maalhosmadulu atoll, Maldives

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[1] The Maldives experience seasonal shifts in monsoon winds from the west-northwest to northeast. The morphologic response of reef island beaches and shorelines to these predictable shifts in climate was examined on eight islands in South Maalhosmadulu Atoll based on global positioning system surveys of island shoreline planform in January and June 2002 and February 2003. Surveys show that islands exhibit large gross changes (31–120% of beach area) in shoreline position between seasons. Such changes reflect large reversals in sediment flux of $9-23 \times 10^3$ m^3 on a biannual basis driven by seasonal reversals in wind and wave conditions. Annual net change is small (2–15%), suggesting islands spatially exhibit a dynamic equilibrium. An island oscillation index (I_o) is defined that describes the spatial extent of shoreline change around islands. Island shape (ellipticity, e) is found to be positively correlated with I_o in the expression $I_o = 1.021e - 0.275$, suggesting island shape is a better indicator of the susceptibility of island shorelines to morphological change than wave energy exposure.

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1. Introduction

[2] The dynamic interaction between environmental processes and coastal morphology occurs over a range of spatial and temporal scales [*Ruggiero et al.*, 2005]. Numerous studies have examined the adjustment of shorelines to changes in incident wave and current processes caused by storms [*Russell*, 1993; *Wright et al.*, 1995; *Forbes et al.*, 2004], seasonal shifts in climate [*Aubrey*, 1979; *Nordstrom*, 1980; *Masselink and Pattiaratchi*, 2001] and longer-term changes in climate [*Komar*, 1998; *Ranasinghe et al.*, 2004; *Rooney and Fletcher*, 2005]. The majority of these studies have been undertaken on continental or large island coastlines where shorelines are compartmentalized and primarily linear in planform. These physical conditions are not met in oceanic coral reef islands. Coral reef islands are Holocene landforms composed of calcareous sand and gravel both derived and deposited on the surrounding coral reef platforms [*Stoddart and Steers*, 1977; *McLean and Stoddart*, 1978; *McLean and Hosking*, 1991]. They are typically low in elevation (<3 m above mean sea level), small in area, have a vegetated core and a narrow beach that surrounds the entire perimeter of the island. There is an abrupt break in slope that marks the transition between the mobile beach and the fixed reef flat substrate.

[3] *Gourlay* [1988] notes that the major process mechanism controlling the formation and stability of reef islands is wave action and its interaction with coral reef platforms. Waves that propagate onto reef surfaces at high tide and residual wave energy that leaks onto reef platforms following breaking at the reef edge are able to entrain reefal sediments [*Brander et al.*, 2004] which are transported to depositional nodes on reef platforms. While the filtering effect of reefs to incident wave energy is well established, *Gourlay* [1988] also argues that reef platforms act as a lens that focuses wave energy. Consequently, wave refraction around reefs and diffraction of reef top wave energy creates nodal zones favorable for deposition. These wave-reef interactions imply that (1) reef island location and shape are controlled primarily by the shape of reef platforms, (2) the stability of islands and their shorelines is dependent on reef shape, (3) changes in direction of incident wave energy are likely to shift the nodal point of deposition and promote island and shoreline change, and (4) the degree of shoreline change will vary depending on reef platform shape. These relationships have yet to be tested using empirical field observations.

[4] The potentially rapid morphological adjustment of islands and their shorelines to changes in incident processes has focused international attention on the extreme vulnerability of reef islands to longer-term adjustments in oceanic and climate boundary conditions, particularly sea level rise [*Roy and Connell*, 1991; *Leatherman*, 1997; *Kench and

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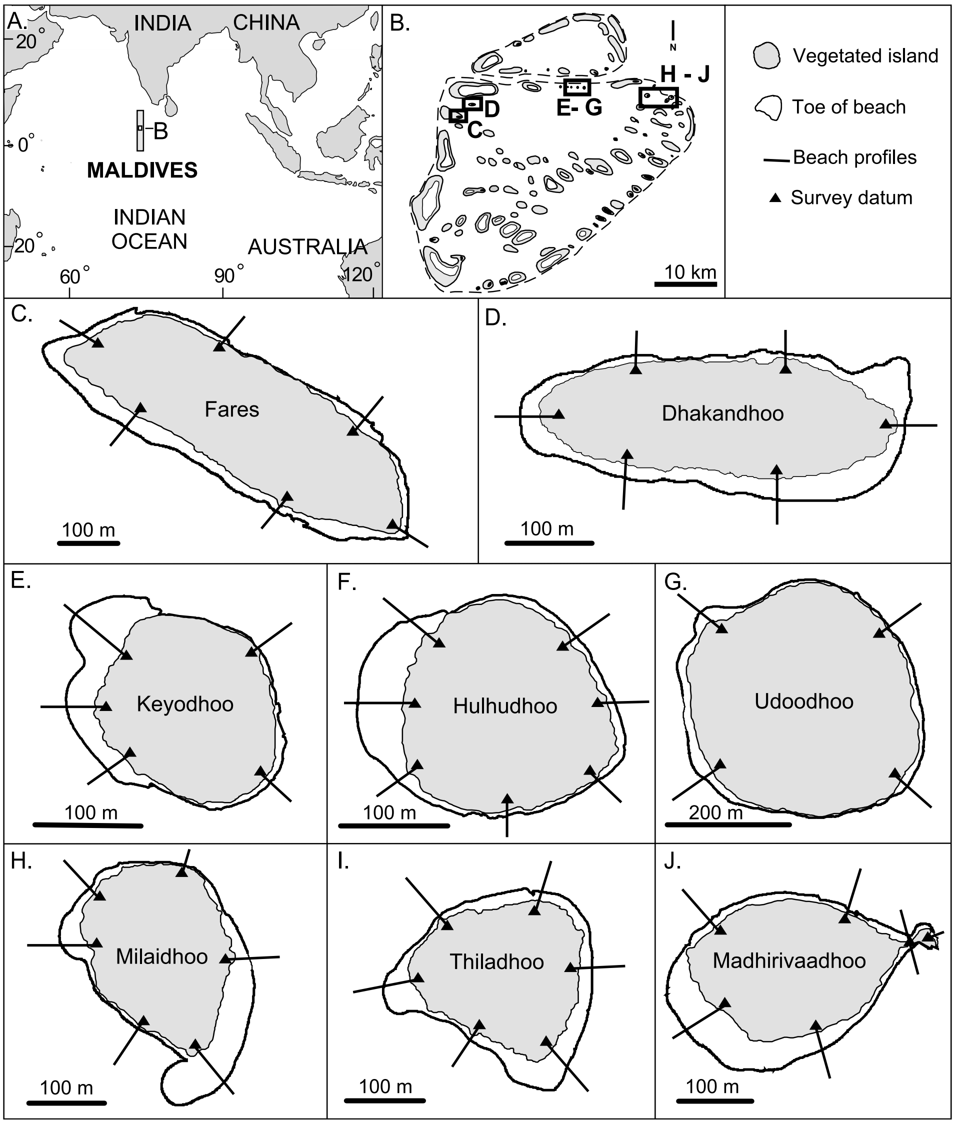

Figure 1. Location of (a) the Maldives, (b) South Maalhosmadulu atoll, and (c–j) the islands studied within the atoll. Profile lines and benchmarks are indicated by solid lines and triangles.

Cowell, 2001]. However, few studies have documented the response of reef island shorelines to short-term and seasonal changes in wind, waves and currents. Fluctuations in these island building processes over the short-term can result in significant changes in island size, shape and position on reefs [*Hopley*, 1981; *Ali*, 2000] making them inherently dynamic landforms. Given the limited land area of reef islands the magnitude and temporal scales of island change are of paramount importance to island communities.

[5] To date, studies of reef island morphological change have focused on either interannual or decadal-scale changes in island size and position on reefs [e.g., *Taylor*, 1924; *Stoddart et al.*, 1978; *Flood*, 1984; *Aston*, 1995]; or on the susceptibility of islands to change during catastrophic storms [e.g., *Stoddart*, 1963, 1971; *Maragos et al.*, 1973; *Flood and Jell*, 1977; *Bayliss-Smith*, 1988; *Harmelin-Vivien*, 1994]. *Umbgrove* [1947] and *Verstappen* [1954] were the first to develop a causal relationship between climate and reef island behavior invoking medium-term (decadal) shifts in prevailing wind direction and strength and its influence on wave energy as a control on morphological adjustment of islands in Djakarta Bay, Indonesia. *Flood* [1986] also related decadal changes in wind to progressive shifts in reef island planform in the Great Barrier Reef. In contrast, *Stoddart et al.* [1982] found that decadal change on islands within the Belize barrier reef system resulted from hurricane activity. Furthermore, existing studies of island change have focused either on islands in fringing and barrier reef settings or only on a limited number of islands. In particular, studies of atoll island change are scarce [*Kench and Harvey*, 2003].

[6] With the exception of storm events, few studies have examined the influence of short-term and predictable shifts in climate on island shoreline behavior. As noted by *Gourlay* [1988] the stability of reef islands is largely influenced by climatic variations at various scales. An improved understanding of the rate and magnitude of shoreline change in response to climate variation at all

Table 1. Summary of the Planimetric Characteristics of the Study Islands and Associated Reef Surfaces in South Maalhosmadulu Atoll, Maldives

Island	Island Area, m^2	Vegetated Area, m^2	Beach Area, m^2	Reef Area, m^2	Percent Reef Occupied by Island	Beach Area as Percent of Island Area	Island Length, m	Island Width, m	Ellipticity
Fares	125,297	101,585	23,712	3,579,945	3.5	22	691	212	0.31
Dhakandhoo	62,121	45,041	17,080	219,136	33	69	499	158	0.32
Keyodhoo	28,985	21,702	7,283	88,796	34	32	218	180	0.85
Hulhudhoo	39,236	30,579	8,657	85,512	49	35	249	209	0.84
Udoodhoo	124,340	112,957	11,383	222,275	58	13	409	403	0.98
Madhirivadhoo	57,060	40,083	16,977	170,920	34	42	339	261	0.77
Milaidhoo	51,390	36,070	15,320	350,322	14	33	341	216	0.63
Thiladhoo	46,547	33,375	13,172	217,189	22	42	281	220	0.78

timescales is vital for improved resolution of island response to global climate change and for practical management of reef islands that provide the only habitable land in atoll nations.

[7] Situated outside the storm belt, the islands of the Maldives experience predictable shifts in monsoon winds that alter reef platform and wave processes [*Kench et al.*, 2003]. Furthermore, the islands of the Maldives are situated on reef platforms of varying size and shape. Consequently, the Maldives provides a natural laboratory to evaluate the effect of changing climate and reef platform shape on island shoreline change. This study examines the shoreline response of atoll islands to seasonal climate variations using field data that encompasses a yearly monsoon cycle. The study tests the following hypotheses: (1) that predictable shifts in climate promote changes in reef island shoreline morphology and (2) that reef shape influences the magnitude of shoreline change on islands.

2. Atoll and Island Setting

[8] The Maldives is a 750 km long archipelago comprising a double chain of 22 atolls that extend from 6°57′N to 0°34′S in the central Indian Ocean (Figure 1a). The atolls are host to more than 1,200 reef islands that are middle to late Holocene in age [*Woodroffe*, 1993; *Kench et al.*, 2005]. The focus of this study is 8 uninhabited and vegetated sand cays located in South Maalhosmadulu atoll (Figure 1b), which were chosen for study as previous work on island geometry had been conducted there [*Ali*, 2000]. The atoll is approximately 40 km long and wide and unlike many Pacific atolls, has a discontinuous rim characterized by numerous deep passages which allow oceanic currents and waves to penetrate the lagoon. The lagoon contains numerous patch reefs and faros, which are patch reefs with centrally enclosed lagoons or depressions (Figure 1b). The atoll contains 53 islands found on peripheral and lagoon reefs with most islands concentrated on the east to southeastern side of the atoll (Figure 1b).

[9] Islands from the west (Fares, Dhakandhoo), center (Keyodhoo, Hulhudhoo, Udoodhoo) and northeast (Milaidhoo, Thiladhoo, Madhirivaadhoo) regions of the atoll were selected for this study (Figure 1). The location of the island groups allows for an examination of differences in shoreline response to relative exposure to incident wave energy and changes in orientation of monsoon winds across the atoll. The islands are composed of sand-size sediments deposited directly on the reef surface, ensuring that islands interact with contemporary reef platform processes. The islands are small and of comparable size (Figures 1c–1j), but occupy varying proportions of the reef platform (Table 1). Of note, islands in different locations possess similar gross shape characteristics with elongate western islands, circular central islands, and compound triangular islands in the east (Table 1 and Figures 1c–1j). Examination of aerial photographs indicates that the shape of all islands mirrors the reef platform shape with near identical ellipticity values.

[10] Surveyed cross sections across islands show a number of characteristic features of island morphology (Figure 2). All islands have high peripheral storm berms formed by overwash with maximum elevations 2.2 m above

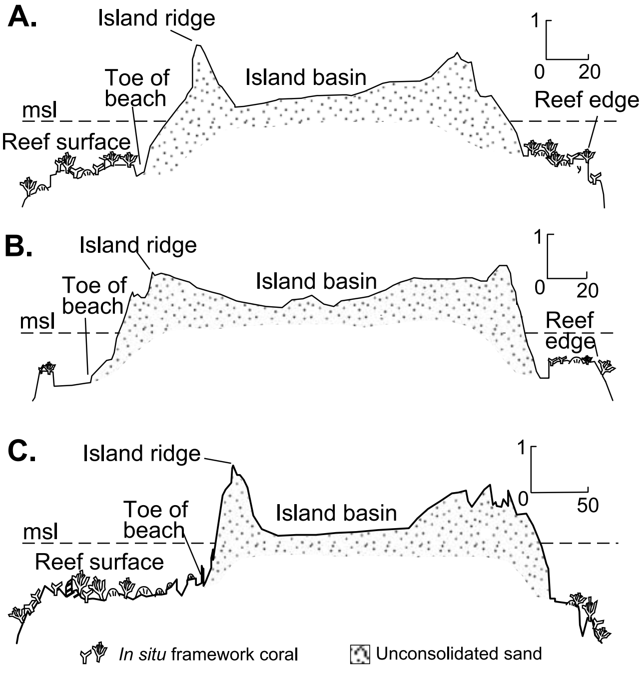

Figure 2. Example north-south cross-section profiles of study islands from each island group. (a) Dhakandhoo, (b) Hulhudhoo, and (c) Thiladhoo. Location of islands is shown in Figure 1.

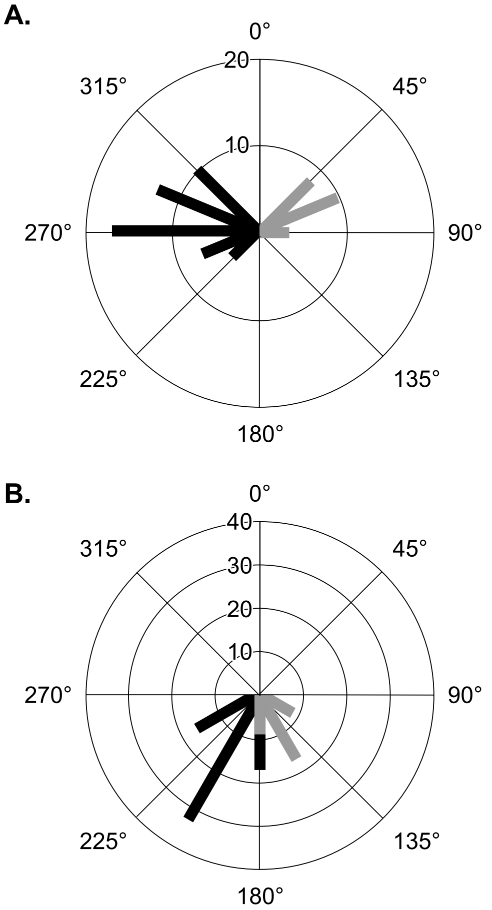

Figure 3. Wind and wave climate for the Maldives showing (a) 30-year mean percent frequency wind direction 1964–2000 for April–Novemberr (black lines) and December–March (gray lines) based on data from the Hulule climate station at Male atoll and (b) 10-year mean percent frequency swell direction for April–November (black lines) and December–March (gray lines) based on global wave climate data of *Young* [1999].

mean sea level (MSL) which enclose low central depressions (0.2–0.6 m above MSL). The contemporary beach is deposited against the vegetated island boundary and its seaward boundary is defined by a distinct break in slope associated with the transition from unconsolidated beach sediment to the fixed reef flat substrate over which the beach and shoreline can move freely. Beach width varies considerably around islands.

3. Wind and Wave Climate

[11] The climate of the Maldives can be divided into two monsoon periods marked by strong seasonal reversals in wind direction that are confined to a narrow range of wind angles. Summary wind data since 1964 (Figure 3a) indicate that the Maldives experience west to northwest winds (~225°–315°) from April to November during the *hulhangu* monsoon with a mean wind speed of 5.1 m s^{-1}. In contrast the iruvai monsoon, from December to March, is characterized by winds from the east-northeast (~45°–90°, Figure 3a) with a mean wind speed of 4.9 m s^{-1}. Wind strength is most variable during the crossover between northeast and westerly monsoons with mean wind speed falling to 3.5 m s^{-1} in March [*Department of Meteorology*, 1995]. Examination of climate records for the period of study (January 2002 to February 2003) showed that wind direction and speed values were similar to the long-term averages (Figure 3a).

[12] Information on the deepwater waves is limited, but wave climate data for the Indian Ocean region surrounding the Maldives [*Young*, 1999] indicate that the dominant swell approaches from southerly quarters (Figure 3b). On a seasonal basis, swell is from the south-southwest from April to November with a peak significant wave height (H_s) of 1.8 m in July, and from the southeast from December to March with a minimum mean H_s of 0.75 m in March (Figure 3b). Wave records obtained from wave gauges deployed on the windward reef edge of islands across the atoll during June 2002 and February 2003 indicate distinct wave energy gradients across the atoll and shifts in this gradient between monsoons (Figure 4). Overall wave energy was greatest on all islands during the westerly monsoon, in accordance with *Young* [1999], and this season possesses

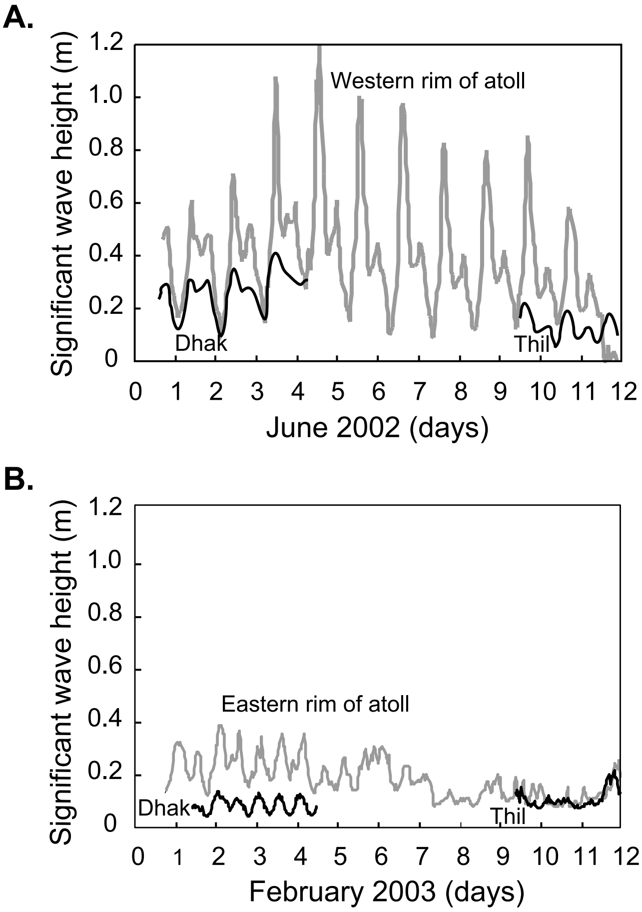

Figure 4. Across atoll (west to east) changes in significant wave height (H_s) South Maalhosmadulu atoll from (a) June 2002 and (b) February 2003. Wave records were obtained from the outer reef platform of each reef. Gray line represents wave record from windward reef platfroms in each season. Dhak, Dhakandhoo island; Thil, Thiladhoo island wave records.

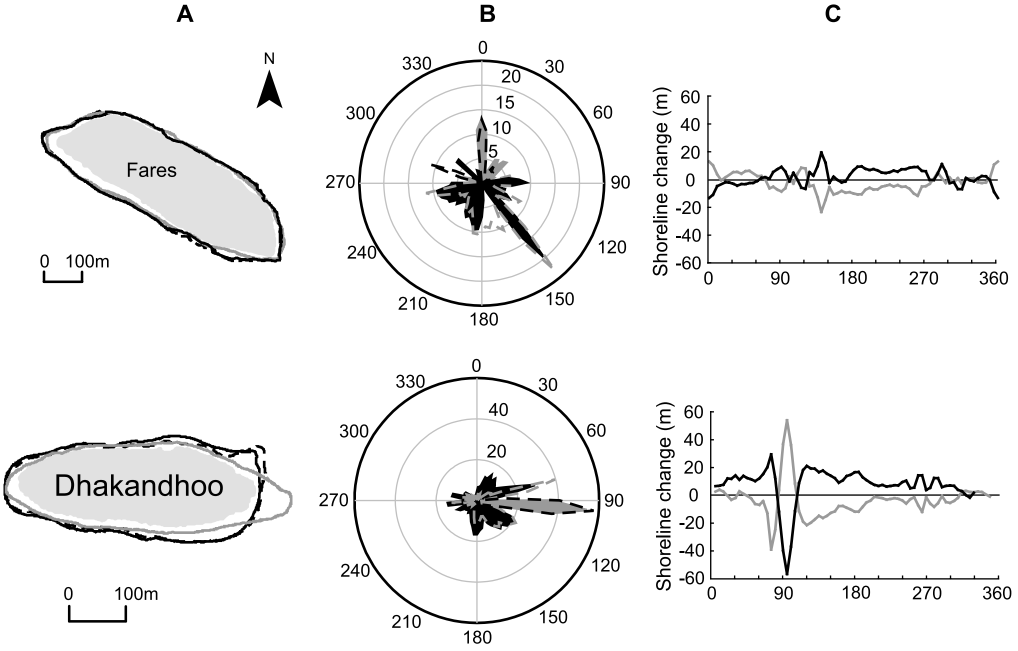

Figure 5. Shoreline change on the elongate western islands (Fares and Dhakandhoo). (a) GPS surveys of toe of beach where dashed and solid lines represent surveys in January 2002 and February 2003 and shaded line represents June 2002. (b) Polar plots of shoreline change around each island where gray shading and dashed line show deposition and erosion between January and June 2002 and black shading and dashed line reflect deposition and erosion between June 2002 and February 2003. (c) X-Y plots of shoreline change between seasons where gray line shows shoreline change between January 2002 and June 2002 and black line reflects change from June 2002 to February 2003.

the greatest reduction in wave energy across the atoll (Figure 4a). During the westerly monsoon, H_s at the windward edge of reef platforms declined by up to 0.7 m from the west (Dhakandhoo) to eastern islands (Figure 4a). A reverse gradient is apparent during the northeast iruvai monsoon with reduction in H_s by 0.27 m from east to west (Figure 4b).

4. Method

[13] Planimetric and cross-section morphological surveys of the eight islands in South Maalhosmadulu atoll were undertaken in January 2002 and repeated in June 2002 and February 2003. Data presented here focuses only on the planimetric survey data.

[14] Planimetric changes in island area, shape and position were measured using global positioning system (GPS) surveys with Trimble ProXL and Trimble Geoexplorer 3 instruments in base station and roving mode, yielding submeter accuracy in the horizontal plane. Separate radial transects of the island edge of vegetation and toe of beach were obtained by walking the instruments while logging in ‘line’ mode at a sample rate of 1 Hz. The toe of beach (ToB) is defined as the intersection of beach sediments with the reef surface and is usually characterized by a distinct break in slope (Figure 2).

[15] Each GPS survey was exported in UTM coordinates (Grid 43 North) to ArcMap. Overlaying of GPS profiles allowed planimetric differences between surveys to be determined. The Digital Shoreline Analysis System (DSAS) [*Thieler and Danforth*, 1994] was employed in ArcView to calculate rates of shoreline change from the time series of shoreline data. Using the edge of vegetation as the island baseline, planimetric shore perpendicular transects were constructed at 1 m intervals along the entire shoreline of each island. DSAS then calculated the distance from the edge of vegetation to the toe of beach for the 3 surveys. Differences between surveys were then calculated for each 1 m transect.

[16] In order to examine the spatial pattern of changes in shoreline position around the island, spokes were constructed at 1° increments radiating from the centroid of each island. Where spokes intersected a shore-normal transect, the value of shoreline change at that transect was assigned to that spoke angle. Results were then displayed as polar plots in 5° bins.

5. Results

[17] The elongate western islands exhibited greatest change at the eastern shorelines of the central axis of each island (Figure 5). Up to 25 m and 53 m of accretion were recorded between January and June 2002 at the southeast and eastern shorelines of Fares and Dhakandhoo, respectively. The west to north-northwest sectors of the islands exhibited minimal change in shoreline position. Elsewhere, shoreline change ranged from 5 to10 m (Figure 5). Of note, areas of accretion between January 2002 to June 2002 were balanced by almost equivalent amounts of erosion from June 2002 to February 2003. Of the two islands, Dhakandhoo was characterized by greater overall changes in planimetric beach area.

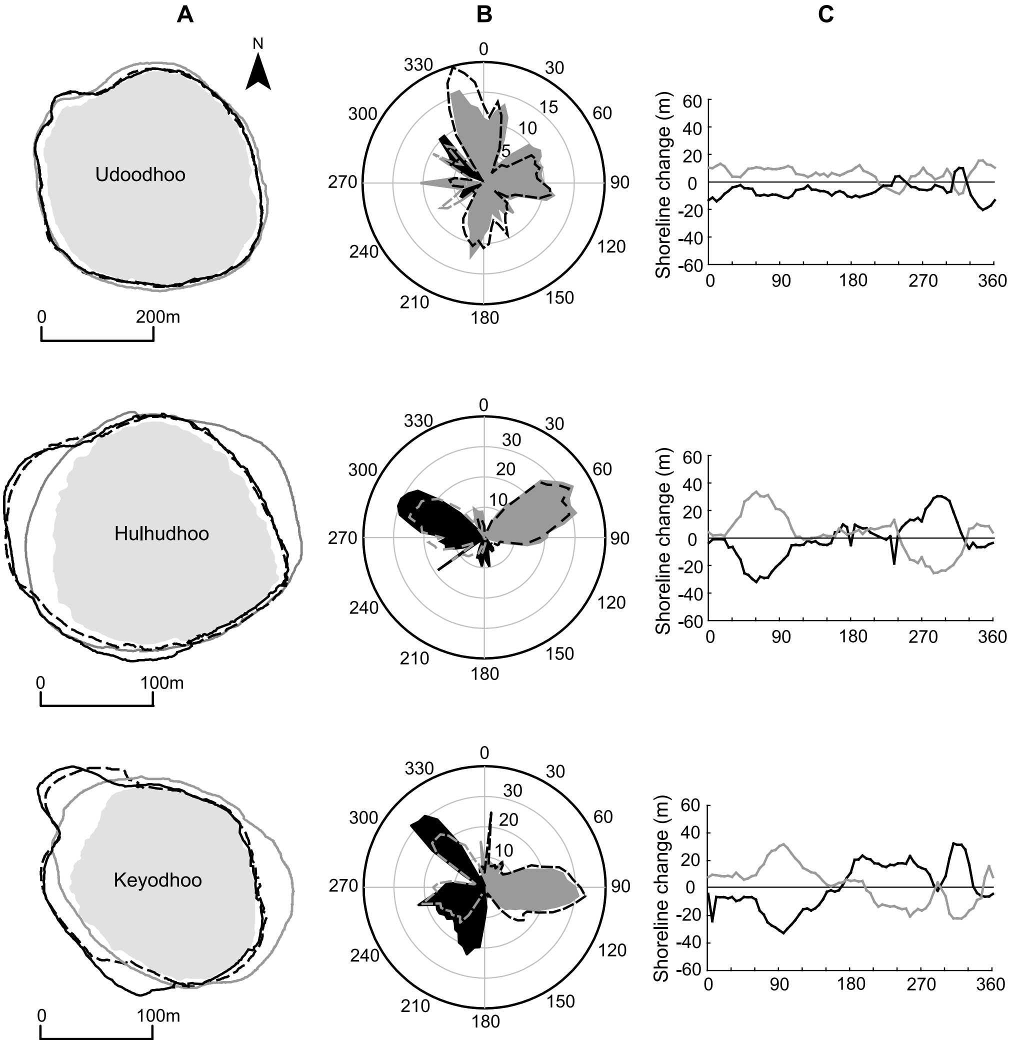

Figure 6. Shoreline change on the circular central islands (Udoodhoo, Hulhudhoo, ans Keyodhoo). (a) GPS surveys of toe of beach where black dashed and solid lines represent surveys in January 2002 and February 2003 and gray solid line represents June 2002. (b) Polar plots of shoreline change around each island where gray shading and dashed line show deposition and erosion between January and June 2002 and black shading and dashed line reflect deposition and erosion between June 2002 and February 2003. (c) X-Y plots of shoreline change between seasons where gray line shows shoreline change between January 2002 and June 2002 and black line reflects change from June 2002 to February 2003.

[18] The circular central islands are also characterized by a spatially consistent balance between accretion and erosion between surveys. However, they exhibit a greater variation in location of shoreline change around the islands (Figure 6). The magnitude of change on Udoodhoo is smallest with maximum amounts of accretion and erosion on the order of 15 and 20 m, respectively. Shoreline change is expressed along all four major compass bearings although the maximum change is observed toward the north side of the island. The western shoreline of the island (330°–220°) was characterized by accretion and erosion to June 2002 and February 2003, respectively (Figure 6).

[19] On Hulhudhoo the shoreline exhibited a marked shift in planimetric beach area from the northwest to northeast between January 2002 and June 2002 with maximum shoreline change on the order of 35 m. This pattern was almost exactly reversed between June 2002 and February 2003 (Figure 6). Shoreline change on Keyodhoo is more spatially variant with a dominant shift of beach area from the western to eastern side of the island during the period January 2002 to June 2002. This shift is also mirrored by a reversal in shoreline position by February 2003. Maximum shoreline changes are similar in magnitude (≈30 m width) to those on Hulhudhoo. The southwestern shoreline of Keyodhoo shows much greater variation than on Hulhudhoo and Udoodhoo. The northern and southern aspect of both Hulhudhoo and Keyodhoo exhibit little change in shoreline position (Figure 6).

[20] The eastern islands are more complex in shape than the other island groups and also differ in that most of the noticeable changes in shoreline position occur in the southern half of the islands. On Madhirivaadhoo, shoreline position experiences a strong seasonal oscillation almost entirely restricted to a 90° sector from WSW to SSE with

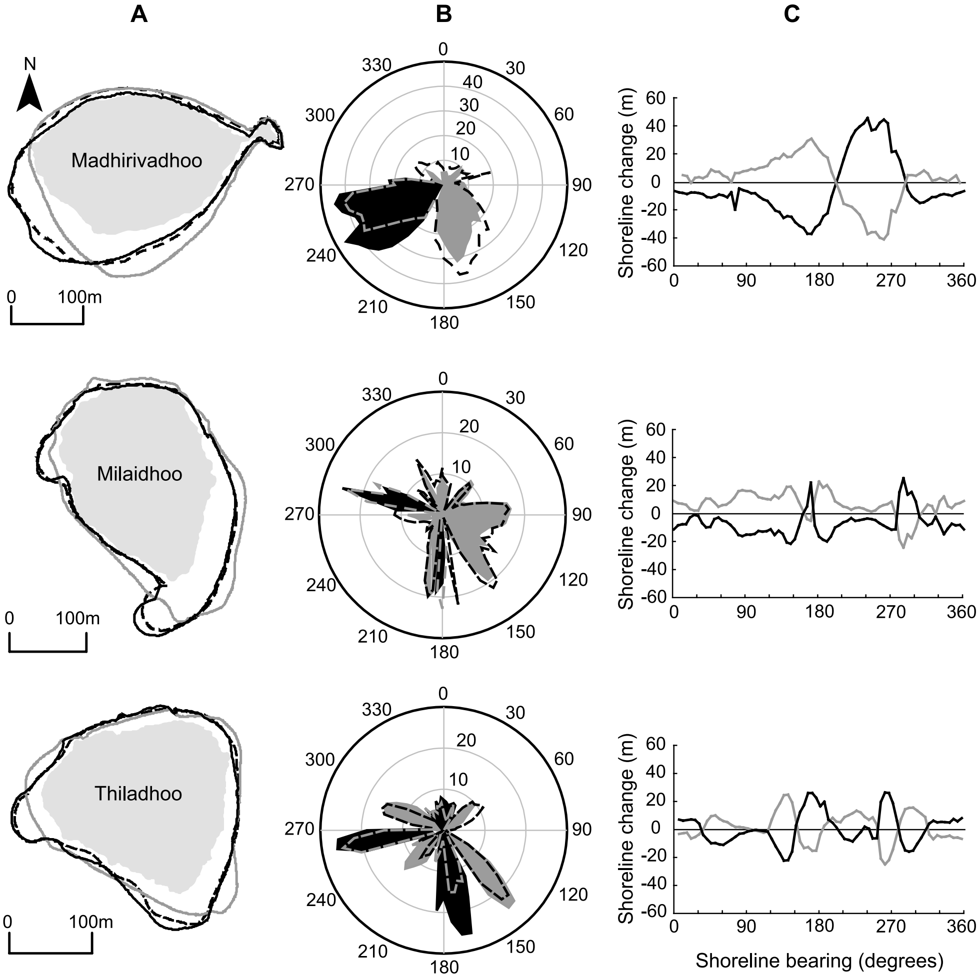

Figure 7. Shoreline change on the eastern islands (Madhirivadhoo, Milaidhoo, and Thiladhoo). (a) GPS surveys of toe of beach where black dashed and solid lines represent surveys in January 2002 and February 2003 and gray solid line represents June 2002. (b) Polar plots of shoreline change around each island where gray shading and dashed line show deposition and erosion between January and June 2002 and black shading and dashed line reflect deposition and erosion between June 2002 and February 2003. (c) X-Y plots of shoreline change between seasons where gray line shows shoreline change between January 2002 and June 2002 and black line reflects change from June 2002 to February 2003.

maximum shoreline change around 45 m width (Figure 7). On Milaidhoo, shoreline changes are smaller with a maximum of approximately ±20 m. Most change occurs on the east-southeast sector of the island being accretionary between January–June 2002 and erosional from June 2002 to February 2003. Similar sediment reversals characterize two prominent sediment lobes situated on the southern and western sides of the island (Figure 7). Thiladhoo has similar sediment lobes on the western and southeastern corners and shoreline change is concentrated in these locations reaching maxima of ±25 m. None of the eastern islands exhibit significant shoreline change along their northeastern aspects.

6. Discussion

[21] Results clearly indicate that each island undergoes substantial morphological change between monsoon seasons. Furthermore, these changes are oscillatory in nature. Indeed, comparison of shoreline positions between January 2002 and February 2003 (after one complete monsoon cycle) show they are virtually identical (Figures 5–7).

6.1. Gross Versus Net Change

[22] Table 2 summarizes gross and net changes in planform area over the yearly monsoon cycle and shows that gross fluxes are large ranging from 31 to 120% of the January 2002 beach area on Fares and Hulhudhoo, respectively. On the basis of beach auguring and the difference in elevation between the beach surface and the horizontal reef substrate that extends beneath the outer parts of the island, a conservative estimate of 1.5 m was used to define typical vertical sediment thickness across the beach profiles. Using this value, gross sediment movement is on the order of $9–23 \times 10^3$ m^3 per season, which represents very large quantities of sediment that are entrained and transported around island shorelines on a biannual basis. Moreover, this large sediment flux occurs on relatively small reef platforms.

Table 2. Summary of Changes in Island Beach Planform Area Between Surveys[a]

Island	Gross Change Jan–Jun, m^2	Net Change Jan–Jun, m^2	Gross Change Jun–Feb, m^2	Net Change Jun–Feb, m^2	Net Change Jan 2002 to Feb 2003, m^2
Fares	8 386 (35)	−4 586 (19)	7 261 (31)	3 987 (17)	−598 (2.5)
Dhakandhoo	10 692 (63)	−4 206 (25)	13 243 (76)	6 547 (38)	2 341 (14)
Keyodhoo	7 201 (99)	1 125 (15)	8 763 (120)	−359 (5)	766 (11)
Hulhudhoo	7 538 (87)	2 076 (24)	7 697 (89)	−759 (9)	1 317 (15)
Udoodhoo	8 871 (78)	7 348 (65)	8 961 (79)	−7 568 (67)	−220 (2)
Madhirivadhoo	10 783 (64)	1 164 (7)	14 587 (86)	−2 520 (15)	−1 356 (8)
Milaidhoo	8 506 (56)	3 298 (22)	9 893 (65)	−3 798 (25)	−500 (3)
Thiladhoo	6 578 (50)	943 (7)	7 253 (55)	771 (6)	1 713 (13)

[a] Values in parentheses indicate change as percentage of January 2002 beach area.

[23] While gross changes in beach area are large, the overall net change in beach area between January 2002 and February 2003 is small, varying from 2 to 15% (Table 2; $\bar{x}$ = 8.6). This variation may be attributed to the timing of the surveys relative to different stages of the monsoon. It is tempting to assume that on an annual basis, absolute net change approaches zero suggesting that a morphological dynamic equilibrium exists which is sustained by reversals in shoreline wave and current conditions created by the seasonal climate changes. However, such a perfect balance is improbable given the large gross fluxes involved, minor climatic variations between yearly monsoons, and the potential addition or removal of sediment from the island sediment reservoir, particularly with high biannual fluxes of sediment along the shoreline. Differences in beach area (presented in Figures 5–7 and Table 2) may also mask vertical adjustments in beach morphology between seasons.

6.2. Atoll-Scale Variations in Island Morphological Change

[24] As noted earlier, there is a reduction in wave energy across the atoll during each season (Figure 4). At the atoll scale it might be expected that such a decline would be associated with a cross-atoll reduction in shoreline waves and currents and hence gross movement of sediment and shoreline change. However, this is not observed in either season (Figure 8). Instead, maximum gross changes are observed in the central islands (mean gross change ΔG = 88%) followed by the eastern islands with ΔG = 57%. Of note, despite being exposed to the highest wave energy, the western islands exhibit the least amount of change (ΔG = 49%).

[25] Results also show that the mean annual net change (ΔNET) in planimetric beach area, between island groups, from January 2002 to February 2003 is almost identical (9.5, 9.3, and 8% from west to east; Table 2). This indicates that the net amount of annual morphological change on the islands is similar regardless of location within the atoll, but gross shoreline changes vary greatly between islands and must be related to other factors than simply position within the atoll. These factors are now discussed.

6.3. Island Oscillation

[26] While there is little quantitative difference in the magnitude of net annual shoreline change across the atoll, there are spatial differences in the observed pattern of island change. Islands at the atoll periphery exhibit maximum shoreline change at the lagoonward sides of islands where the impact of seasonal wave energy reversal is more pronounced. Consequently, the eastern ends of western islands are more dynamic, whereas the southern and western shorelines of eastern islands are most dynamic (Figure 5 and 7). Conversely, the oceanward margin of both groups of islands is exposed to external atoll wave energy conditions year round and the seasonal wind and wave energy reversal is therefore not as extreme and these shorelines exhibit the least amount of morphological change. In contrast, the central islands (Figure 6) undergo shoreline changes that encompass a much broader swath of the island perimeter. In particular, there appears to be significant movement of sand lobes aligned with the predominant seasonal wind directions, on the leeward sides of islands.

[27] Such observations are here quantified using a measure termed the Island Oscillation Index (I_o) that accounts for the sectors of island shoreline within which shoreline change takes place (Figure 9). In general, the entire perimeter of each island shoreline showed some degree of change. However, it is clear from Figures 5–7 that the degree of shoreline fluctuation varied spatially between islands and that some areas of the islands consistently act as sediment sources and sinks whereas others are either sediment transport pathways or experience little sediment flux.

[28] The island shoreline oscillation index is calculated by first defining the spatial boundaries that encompass $\geq$50% of the maximum shoreline change based on the seasonal areas of deposition (Figure 9). Process measurements (waves and current patterns) are then used to provide a physical basis to determine the sectors of shoreline that transfer sediments [*Kench et al.*, 2003, 2006]. Collectively this information allows boundaries to be placed around the island perimeter within which active sediment flux takes place (Figure 9). The degree of island oscillation was then determined by establishing the proportion of shoreline undergoing sediment flux and change from the entire shoreline perimeter (360°, Figure 9).

[29] For example, on Dhakandhoo (Figure 5), the planimetric zone of shoreline change, based on a maximum shoreline change of 53 m (0.5 percentile = 26.5 m), extends from 75°–100°. Significant shoreline oscillation is therefore restricted to a 25° section of the island which represents an island oscillation index (I_o) of 0.07 (i.e., 25°/360°). The implication here is that only a very small portion of the island is characterized by significant shoreline movement (erosion and deposition).

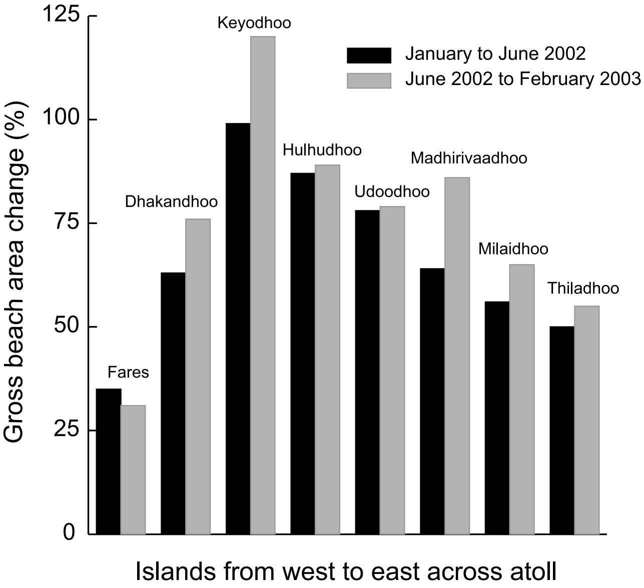

Figure 8. Gross changes in island beach area for the two monsoon periods. Percentages are based on the January 2002 beach area.

[30] On Hulhudhoo maximum shoreline change was 34 m (0.5 percentile = 17 m). Adopting the same method it is clear that major depocenters occur around nodes between 45°–105° and 250°–305°. Mean current patterns from each season summarized in Figure 9 dictate that sediment transfer must take place along the northern shoreline as current patterns prevent transport along the southern shoreline. Consequently, the extent of island perimeter that conveys and stores the major fluxes of sediment between monsoons is captured in the zone extending from 105° to 250° (totaling 215° of shoreline) which represents an I_o value of 0.60. The implication here is that a large proportion of the island shoreline is characterized by shoreline movement.

[31] Island oscillation calculations for all islands indicate that the elongate western islands, exposed to greatest incident wave energy, exhibit the lowest oscillation values ($I_o < 0.1$). The central islands exhibit the highest degree of oscillation with I_o values ranging from 0.60 (Hulhudhoo) to 0.82 (Udoodhoo) while islands on the northeastern side of the atoll have oscillation values ranging from 0.29 (Thiladhoo) to 0.38 (Madhirivaadhoo). As shown in Figure 10, a positive relationship, significant at the 95% confidence interval (R^2 = 0.80), exists between the I_o index and island ellipticity (Table 1) with I_o increasing as the islands move from elongate to circular (>0.8). This is described by the equation: $I_o = 1.021e - 0.275$ where e is island ellipticity defined by the ratio of island width: length.

6.4. Island Shape

[32] The relationship between island ellipticity and island oscillation indicates that islands with differing shapes exhibit distinct styles of shoreline behavior. Elongate islands have low I_o values (<0.1) and shoreline change is con-

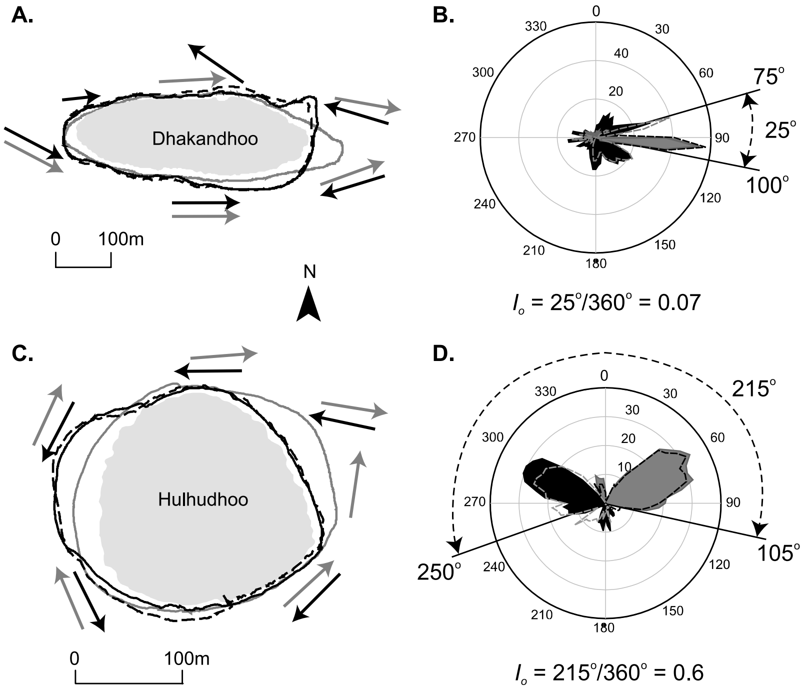

Figure 9. Representation of island oscillation index (I_o) calculations using two study islands. (a and c) Raw GPS shoreline change data. Black arrows and shorelines represent current patterns around island and the subsequent shoreline position during the northeast monsoon, whereas gray arrows and shorelines represent mean current patterns and shoreline position during the westerly monsoon. (b and d) Polar plots of island shoreline change showing boundaries in which shoreline change is greater than or equal to 50% of the maximum shoreline change. Transfer zones are inferred using current patterns shown in Figures 9a and 9c. Sectors containing shoreline change are divided by island perimeter to compute the I_o value.

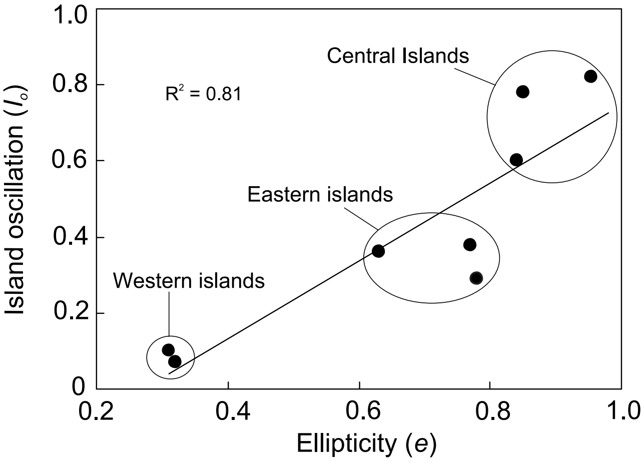

Figure 10. Relationship between island ellipticity (e) and island oscillation index (I_o) for islands of South Maalhosmadulu atoll, Maldives.

strained within a narrow band at one end of the island. Compound shaped islands have I_o values ranging from 0.2–0.4 and exhibit a dual-ended response to seasonal changes in the form of sediment oscillations around two prominent nodal positions (Figure 7). Circular islands have the highest I_o (0.60–0.82) indicating that large tracts of their shorelines are affected by the seasonally driven shifts in sediment.

[33] Furthermore, these findings suggest that island/reef shape may be a better diagnostic indicator of island morphological behavior in the short term than location within the atoll and relative exposure to energy. As identified by *Stoddart and Steers* [1977] and *Gourlay* [1988] reef islands are formed by the complex combination of wave and current processes acting over a reef platform. The key control on wave focusing on reef platforms is the configuration (shape) of the reef structure. Consequently, deposition through wave convergence often produces islands of remarkably similar shape to the reef platform. Although not shown in Figure 1, this is the case for the islands in this study with islands and reef possessing near identical ellipticity index values. Island/reef shape is the key characteristic that differentiates the island groups in this study. Consequently, differences in island shape (as reflected in the process regime in reef surfaces) must also control the susceptibility of shorelines to change. Greatest morphodynamic adjustment occurs on the circular islands (Figure 10). A possible explanation for this is that given the circular nature of both the island and reef, reef platform wave focusing patterns adjust rapidly in response to minor changes in wave approach. Spatial shifts in the shoreline depositional node are therefore more sensitive to subtle shifts in the direction of wave approach as previously noted by *Gourlay* [1988]. In contrast, on noncircular or angular reefs, wave focusing is likely to be less sensitive to directional shifts in wave energy as reef structure exerts a greater control on maintaining refraction patterns at consistent locations around the reef. Such a process can account for the dual modal oscillation on eastern islands and the constrained oscillation of shorelines on the eastern ends of western islands, both of which have lower I_o values.

[34] The suggestion that island and reef shape contribute to the observed morphologic adjustments (as they reflect a distinct process signature) is also supported by the trends shown in Figure 11. Gross change in beach area for the January 2002 to June 2002 period increases with both increasing island ellipticity (R^2 = 0.35; Figure 11a) and increasing reef area occupied by the island (R^2 = 0.58; Figure 11b). Almost identical patterns were found for the June 2002 to February 2003 period. It is interesting to note that if the primary outlier island (Keyodhoo) is removed, the regression in Figure 11b becomes significant at the 0.05 confidence level (R^2 = 0.86). In both cases there is no apparent trend whatsoever between island ellipticity, reef area occupied and the net beach area adjustment for the period January 2002 to February 2003.

6.5. Implications for Island Morphodynamics

[35] The findings of this study require a reconsideration of conventional concepts of shoreline morphodynamics as they are applied to reef islands. Our understanding of sediment transport and beach profile adjustments are traditionally based on the combination of models of littoral transport along linear shorelines and the two-dimensional

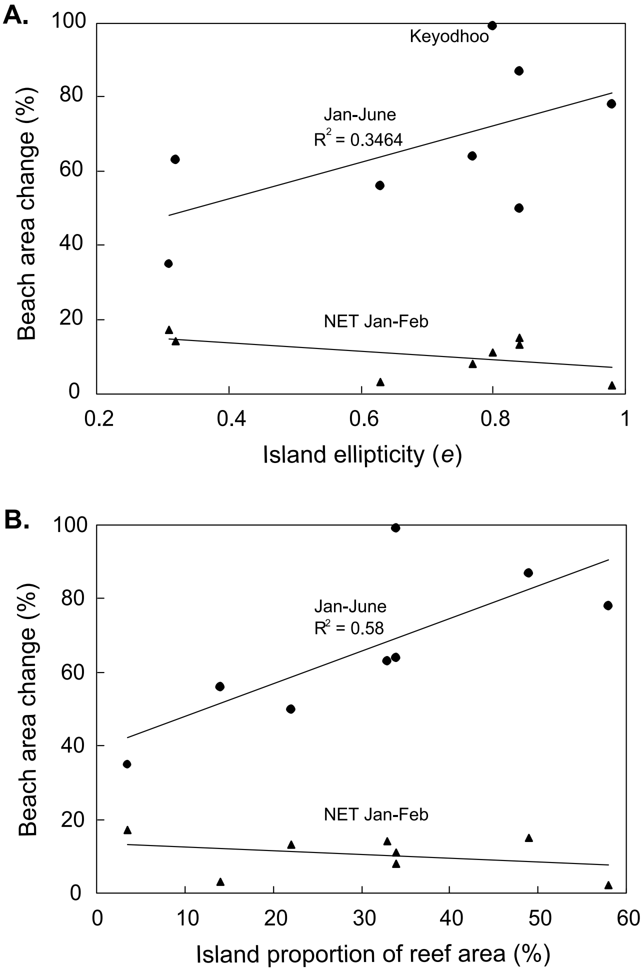

Figure 11. Relationship between (a) island ellipticity and (b) proportion of reef area occupied by island and shoreline area change for islands of South Maalhosmadulu atoll, Maldives.

cross-shore transfer of sand between the subaerial beach and the nearshore zone [e.g., *Bruun*, 1954; *Dean*, 1977; *Roelvink and Hedegaard*, 1993]. Shoreline oscillation on embayed beaches has also been attributed to beach rotation in response to medium-term fluctuations in wave climate [*Ranasinghe et al.*, 2004]. However, shoreline oscillation in the context of reef islands is unique as it is expressed as an alongshore reorganization of sediment around a continuous island perimeter where the entire 360° aspect of the island must be considered. At short timescales (hours to seasons), the amount of sediment comprising a coral cay shoreline may be considered finite [*Gourlay*,1988] and sediment can move from one side of an island to the other leaving one side bare and issues of sediment starvation must therefore be considered. The circular nature of sediment transport around reef islands also implies that island change is controlled by alongshore swash and surf zone drift processes as opposed to cross-shore sediment transport processes. Although some studies report exchanges of sediment between the reef flat and the beach [*Hopley*, 1981], the amounts, mechanics and timescales of these processes are far from fully understood.

[36] As defined by the island oscillation index (I_o), it is evident that islands of differing shape have differing segments of shoreline prone to significant sediment transfers. Such differences highlight the potential variability in sediment transport processes on islands. Islands with high I_o values are characterized by significant sediment flux along a high proportion of the shoreline. Notably on the highly oscillatory circular islands in this study, the northern shorelines exhibited little morphological change indicating that these shorelines acted as sediment transfer zones. Circular islands are therefore characterized by distinct regions of sediment deposition, erosion and transfer. In contrast, significant sediment transport on the elongate islands was almost solely confined to a narrow part of the island (Figure 5). Large sections of these island shorelines are therefore morphologically stable despite the seasonal adjustments in climate.

7. Conclusions

[37] This study reports findings from the first systematic attempt to examine the short-term morphological behavior of multiple atoll islands. Results identify significant changes in atoll island shorelines, as reflected in large reversals in sediment flux, in response to climate driven (monsoonal) changes on a seasonal basis. The monitored islands experienced extreme rates of gross shoreline change between monsoonal seasons (up to 53 m in beach width), but were characterized by minimal net shoreline change on an annual basis indicating a spatially balanced pattern of shoreline adjustment. Spatial differences in incident wave energy across the atoll were found to have little control on the relative magnitude of island shoreline change between islands. The central (protected) islands exhibited the greatest shoreline change between seasons with change on the higher-energy and exposed peripheral islands occurring primarily on their lagoonward shorelines.

[38] A new parameter termed the island oscillation index (I_o) allows for quantification of the degree of shoreline change on islands in response to shifts in wind and wave processes on reefs. Results indicate the degree of shoreline change varies according to island and reef shape. Circular islands exhibited the greatest degree of shoreline oscillation with shoreline change on elongate islands constrained within a narrow zone. High I_o values on circular islands also suggest these islands are more susceptible to shoreline change in response to subtle alterations in the wind and wave climate (as also discussed by *Cowell and Kench* [2001]) whereas low I_o values suggest a lower susceptibility for shoreline change. Consequently, the island oscillation index has potential for assessing the morphological stability of islands to climate change.

[39] The observed differences in island shoreline behavior and the identification of spatial variability of sediment transport patterns both within and between islands provides an initial morphodynamic framework for the appropriate management and planning of island shorelines. Unlike the uninhabited islands documented in this study, approximately 200 islands in the Maldives are populated and many examples exist where traditional shoreline engineering structures have been implemented without consideration of the natural seasonal reversals of sediment transport and shoreline position, with often disastrous results [*Kench et al.*, 2003].

[40] It is clear that island shoreline management strategies should be cognizant of the dominance of alongshore sediment transport processes around reef islands and should be aware of the location and extent of the sediment oscillation around islands of different shape and the timescale of change.

[41] Ongoing monitoring of islands in South Maalhosmadulu will provide insights into how the short-term changes observed in this study are manifest in medium- to long-term island change. Such studies should be extended to a wider range of reef islands with contrasting morphology, oceanic and climate setting in order to improve our overall understanding of short-term morphodynamic island behavior and further refine the island oscillation index.

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