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Island morphology, reef resources, and development paths in the Maldives

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Abstract
Maldivian paths for economic development have historically been constrained by the morphology of atoll islands and the availability of material resources. These constraints are most evident when examining the development of Male', the Maldives' capital and most populous island. Before the 1970s, Male' was a rather typical atoll island, consisting of accumulated rubble and sand with an underlying lagoonal reef (faro) structure. Rising population and standard-of-living expectations in Male' led to accelerated coral mining of Male's reefs in the 1970s and 80s for both landfill and construction material, extending the island's land surface across Male's lagoon and reef flats, close to the edge of its underlying faro. This combination of mining and fill degraded the island's natural defenses against wave events, resulting in disastrous floods in April 1987 and the fortification of the coastline with seawalls shortly thereafter. The degree of degradation to natural defenses and amount of investment in urban building stock have jointly locked Male' into a "hard path" for coastal resilience engineering, and both the damage patterns and response to the 2004 Indian Ocean tsunami demonstrate that the Male' model of development and degradation has spread to smaller Maldivian islands. While hard measures have proven successful in preventing further damage, their expense has led to greater interest in "soft path," ecosystem-based resilience measures. The degree of local ecosystem damage, combined with high vulnerability to climate change and Male's continued growth, means that such measures can only be seen as supplements to heavier fortification in the future, including raised (Th. Vilufushi) or artificial islands (Hulhumale'). The intersecting role hydrological stress on Maldivian groundwater has played in Male's development path is also discussed.

Keywords
Maldives, coastal vulnerability, small island states, adaptation paths

I. Introduction

The past decade has brought an increased awareness of the Maldives's precarious environmental situation. Low elevations leave the Maldives' population – 300,000 people spread across nearly 200 islands – highly vulnerable to both long-term changes such as sea level rise and short-duration disasters such as wave events. The most recent such disaster was the 2004 Indian Ocean tsunami, which left 108 presumed dead, 12,000 homeless, caused millions of property damage and even forced the

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relocation of R. Kandholhudhoo's population off their island (Section V.3). Yet there was comparatively little damage to the Maldives' capital island of Male'. Male' had already endured a wave event in the April of 1987 and fortified its coastline shortly thereafter (Section V.1). The difference in damage the more provincial Maldivian islands and Male' illustrates how resilience to disaster in small island states is not merely a consequence of the islands' morphology but also one of choices in approaches to development and coastal protection.

Events like the 2004 tsunami or 1987 long period swells are naturally occurring, short-duration phenomena, and atoll islands in the Maldives have exhibited morphological resilience up to such storms and tsunami since their formation in the mid-Holocene (Kench et al., 2006). The Maldivian civilization's current vulnerabilities are consequences of the intensity and distribution of settlement, particularly modifications to coastlines and land cover that intend to accommodate more people at a higher standard of living; such modifications are common to atoll settlements across the Indian and Pacific Oceans (the latter of which also face typhoons). Furthermore, given the consequences of climate change – increased sea level, added degradation of ecological systems, salination of freshwater and increased frequency and power of storms of storms (and consequently wave events) – vulnerabilities exposed in short-term disasters can presage problems that will worsen over the medium-to-long term (Nurse et al., 2014).

Although there are important geomorphological differences between the Maldives and other atoll nations in the Pacific (Sections II and V.4), Male' and the Maldives offer an excellent case study for how economic growth, coastal protection, and local geomorphology are interlinked on atoll islands. Not only is Male' one of the most developed atoll islands and the Maldives one of the most developed atoll countries (Male' is totally urbanized and the Maldives was promoted out of the UN's list of less developed states in 2011; Sobir et al., 2014), historic approaches to vulnerability have been well-documented and have deep roots in Maldivian history: the earliest detailed European description of Male', made François Pyrard de Laval (ca. 1578–ca. 1623), includes a detailed description of harbor maintenance after a storm and seawall construction. Twentieth-century alterations to the shoreline and reef flats have been extensively recorded in reports made by domestic and international development agencies and similar grey literature. This paper contextualizes this data into a fuller portrait of how development and protection in Male' is constrained by the islands' physical geography, using insights from literature both pertaining to Male' and the more urbanized Pacific atoll islands (particularly Majuro, islands in Tarawa, and Funafuti), field observations and remote observations of Maldivian infrastructure and island morphology.

II. Overview of Maldivian physical geography

The Maldives is a chain of 19 atolls (from the Dhivehi *atolhun*), large annular reefs containing a central lagoon (some of which have been filled; such atolls are sometimes termed platform reefs), stretching 750 km north-south in the central Indian Ocean. Water depths in the atolls are typically between 25 and 50 m, deepest in the center and rising towards the rim, where most reef growth occurs, before a steep drop-off to the surrounding ocean floor (Betzler et al., 2013; Droxler, 1992). While the contemporary atolls are themselves built on 3000 m tall platforms of karstified Tertiary reefs formed as former islands of the Laccadives-Chagos ridge subsided, likely following the model outlined by Darwin in *The Structure & Distribution of Coral Reefs* (1889), they only represent latest growth phase in a cycle of response to rises and

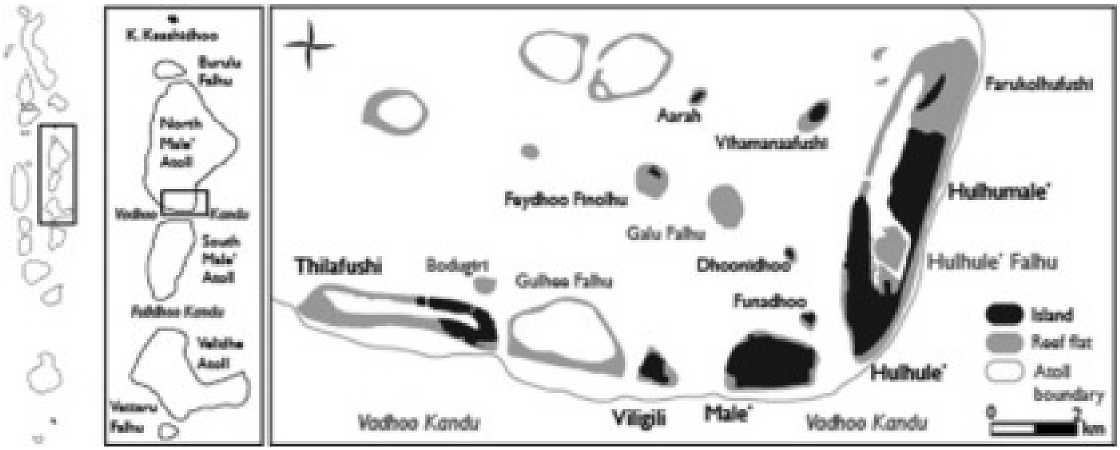

Figure 1. Map of Male' and its environs along the southern rim of North Male' Atoll (after Amooo and Jameel, 2008; Google Earth, 2014c; Fujima et al., 2005). Male', Hulhule', Hulhumale', Viligili, Gulhee Falhu, and Thilafushi are all part of Male's administrative area. As of writing, Gulhee Falhu is being filled to provide for more recreation space.

falls in sea level since the Pliocene (Kench, 2011; Woodroffe, 2008).

Atoll formation must be distinguished from island formation. Most of the islands of the Maldives are not relatively continuous along the rims of atolls, as is the case for Pacific atolls such as Majuro, Tarawa or Funafuti. With the exception of the southernmost atolls, Maldivian atoll rims are discontinuous with discrete faro reefs (from the Dhivehi *faru* or *falhu*) and islands (Kench, 2011), whose annular shapes exhibit a degree of self-similarity with the larger Maldivian atolls. Reef islands typically formed via the accumulation of reef rubble in the lagoon, with additional sediments being added to this core by wave action to form an island. The current islands began forming around 5500 BP, before the Indian Ocean sea level highstand at roughly 4000–2000 BP (Kench, 2011; Kench et al., 2009; Preu and Engelbrecht, 1991).

Male' is a typical example of such an island, or at least was in pre-modern times. Sized at an unremarkable 105 ha, Male' was a southwest-sloping sandy island sitting on the northern portion of a shallow bowl-shaped faro. Immediately south of Male's landmass was the Dhekunu Falhu, Male's lagoon, which rose to a brim at its southern edge and hosted a living barrier reef (see Figure 2). The southern rim of Dhekunu Falhu was Male's only natural protection, the island likely saw little modification after formation: although seasonal monsoon currents shifted sands around the perimeter of Male' and other atoll islands, morphologically they were quite stable over long time scales. This is consistent with what we would expect from an atoll subject only to weak and infrequent storm surges, a consequence of the Maldives' location in the doldrums. Male' lacks the reef ridges, rubble ramparts or boulder conglomerates seen on the stormward sides of islands in the Lakshadweep, under the influence of cyclones north of the Maldives, or in Pacific atoll islands subject to typhoons (Woodroffe, 1992, 2008).

While still relatively vulnerable – Male' sits on the southeastern edge of North Male' Atoll[2] facing the Vaadhoo Kandu, the channel separating North from South Male' Atolls (Figure 1) and the Indian Ocean, with a sheer 2000 m drop off to the latter (Fujima et al.,

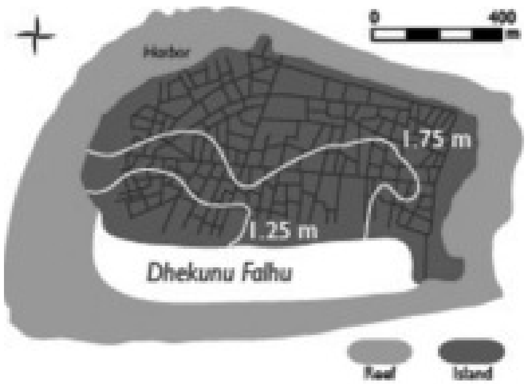

Figure 2. Before land reclamation began in the 1970s, Male' was a generally southwest-sloping sandy island sitting on a shallow bowl-shaped faro, deepest in the Dhekunu Falhu, Male's lagoon, extended reef flats, finally riding to a higher barrier reef brim at the edge (the definition of the Dhekunu Falhu should be taken as approximate; Amooo and Jameel, 2008; Bell, 1928; Edwards, 1989). Palace grounds, older coral stone mosques, and markets were found on the larger northern blocks.

2005) – Male' has likely endured many tsunami and other wave events without much morphological change (Kench et al., 2006). The main risks to island inhabitants come from damage incurred during the wash-over, not the destruction of islands themselves, as indicated by accounts of major disasters in 1812 (which forced the abandonment of twelve islands), 1896–98 (which temporarily submerged approximately half of B. Thulhaadhoo), 1987, and 2004 (Section V; Cazes-Duvat, 2005). The washed-over Maldivian cemeteries described by Indian Navy Lieutenant Prentice in *The Structure & Distribution of Coral Reefs* were likely the result of a similar wash-over event, not local subsidence as Darwin hypothesized. Maldivians also reported to Prentice that islets were being eroded away by changes in currents in the same area (Darwin, 1889). Even slight changes can cause shifts favoring coastal erosion or deposition, altering shorelines of whole islands (Kench et al., 2003; Zammath Khaleel and Ali Shareef, 2010, personal communication). Increased coastal engineering since the 1970s has resulted in more dramatic shoreline changes, especially on Male': landfill has since left the old faro morphology completely obscured (see Figure 4, Section IV.2).

There is almost no surface water in the Maldives (only Fuvahmulah, whose lagoon was blocked off from the ocean water, has a noteworthy surface resources) and most usable freshwater in the Maldives is groundwater. Derived from infiltrated rainwater, this groundwater exists as a narrow freshwater lens floating on infiltrated seawater (Edwards, 1989). The long-term stability of freshwater supplies depends on the balance between surface area available for capturing rainwater, saltwater intrusion and recharge,[3] defined as total precipitation minus total evaporation (Bailey et al., 2014). Surface evaporation, interception, and transpiration all exert significant pressure on total recharge in the Maldives. Interception and transpiration losses are especially high thanks to the prevalence of coconuts both in natural vegetation and in agriculture: to interception rates in regions with coconut trees average 15% and the trees transpire 70–130 L of water per day, comparable to the average daily water consumption of a Maldivian citizen (Woodroffe, 1989).

III. Pre-twentieth century responses to coastal vulnerability in Male'

Unlike in the Pacific island nations, where populations were spread across long, relatively semi-continuous stretches of island and urbanization only began with the arrival of European traders and colonists (Cocklin and Keen, 2000), Maldivian settlement patterns have long taken village or urban forms, a consequence of the Maldivian atolls' more discrete island morphology. These settlements typically grew

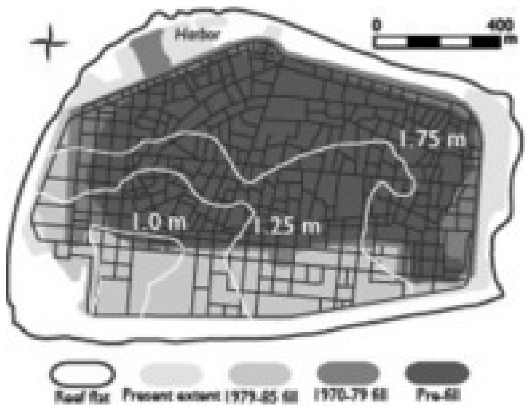

Figure 3. Dates of fill projects on Male' (after Amooo and Jameel, 2008; Bell, 1928; Edwards, 1989; Google Earth, 2014c; Fujima et al., 2005).

around religious (first Buddhist, then Islamic starting in the twelfth century) and administrative centers, the most prominent and enduring of which has been Male'. Detailed accounts of pre-modern Male', made by François Pyrard de Laval (ca. 1578–ca. 1623) and H.C.P. Bell (1851–1937), describe how the pre-modern Maldivians took advantage of Male's geography to protect important buildings and commercial infrastructure. Royal, religious, and market activities were concentrated on the northern, more elevated side of the island, facing the calmer lagoon of North Male' Atoll (Figure 2) and protected from waves by Male's bulk and the Dhekunu Falhu; despite lower densities and different island morphology, Pacific cultures shared this lagoonward preference (Duvat et al., 2013, Spennemann, 1996). The southern flats and Dhekunu Falhu were rendered unnavigable by rubble tossed into it by waves and storms from the Vaadhoo Kandu and the Indian Ocean. Untouched, Dhekunu Falhu continued to serve as a natural breakwater and Bell recounts it being a defense against flooding when monsoonal storms rolled through (Section V.1; Bell, 1928).

The Maldivians established their primary harbor on the northeastern reef flats. The steep drop-off beyond the flats (Section II) gave boats and ships a clean approach to Male' while the continuous clearing of rubble from the northern flats allowed for safe navigation within the harbor. Cleared coral also gave Male' a source of masonry. According to Pyrard, coral mining and clearance was a routine activity, "done nearly every day," and even claimed that after a storm "the harbour of Malé [sic], which was formerly so full of big rocks [coralline rubble or perhaps coral heads] that ships could not sail nor anchor there in safety, to be improved and navigable, with a good anchorage in less than fifteen days" (Gray, 1890).

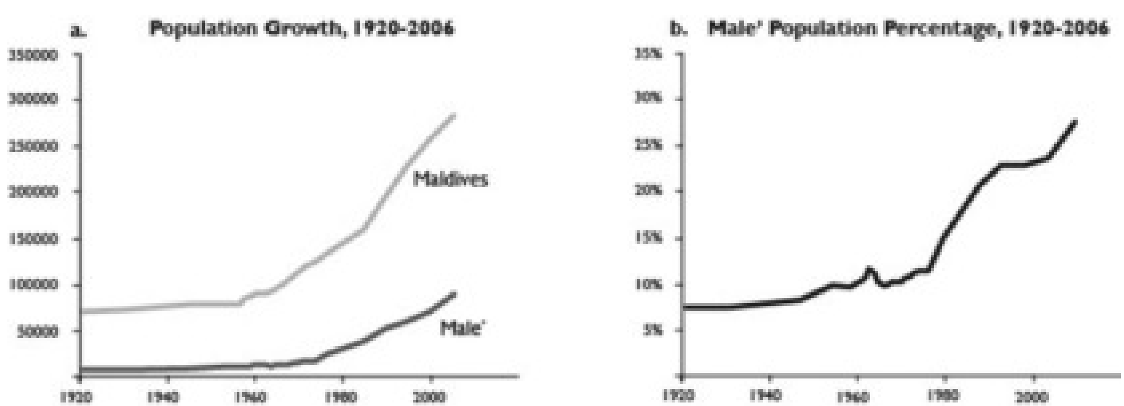

Figure 4. Population trends in Male' (administrative area) and the Maldives (Maldives Ministry of Planning and National Development, 2005; Maldives Ministry of Planning and National Development, 2007).

Such storms and accompanying swells were recognized as the main threat to civilization on Male'. Bell recounts the early-twentieth century seawall protecting Male's harbor was largely constructed of coral harvested from it. Important structures like the royal palace and mosques were also constructed of hard coral masonry, though here it was polished into smooth blocks with ornamental carvings. Coral clearance and construction allowed pre-modern Maldivians to pursue a "hard" path towards coastal resilience, modifying the environment (clearing the north reef flat) and building rigid structures to fortify commercial, religious, and governmental structures from disaster. By Pyrard's time the Maldives had a long-standing and sophisticated tradition of coral rock masonry: even in pre-Islamic times large Buddhist structures (stupas and monastic structures) were made from rubble and polished coral heads (typically of *Porites lutea*; Forbes, 1987; Woodroffe, 1992). While coral is found as a building material in the Pacific island nations, it is only found in limited applications as part of the foundations or support for mostly wooden or thatched structures and never extended to coastal protection (Saini and Moore, 2007), which was mostly achieved by settling on the lagoonward shores of the longer Pacific atoll rim islands (cf. the example of Majuro in Spennemann, 1996).

Coral remained too expensive for most Maldivian structures and coconut was the dominant residential building material until the mid-twentieth century. Coconut wood formed a Maldivian house's skeleton, which was thatched *cadjans*, mats of woven coconut leaves, and sometimes boarded with coconut planks. While described as "ill-built and dark" by the Indian Navy Lieutenant Wilmott Christopher in the early 1800s, the shady interiors and air gaps in thatching kept Maldivian houses cool in the equatorial heat (Gray, 1890). Furthermore, the flimsiness was itself something of an adaptation to local conditions: a very gracile house structure causes minimum damage when blown over and is easy to rebuild or replace. Indeed, the traditional Maldivian house resembled the traditional Maldivian boat, the *dhoni*. Constructed of planks of coconut wood sewed together coconut fiber (coir) rope and fitted with *cadjan* sails, the Dhivehi term for shipbuilding directly translates into "ship tying" (*dhoni banun*). Such a boat would not break apart if thrashed against a reef in a storm – though it would certainly be damaged, the *dhoni* could be quickly tied back together and limp to the nearest port (Mohamed, 2005).

After an extreme disaster, Maldivian populations would resort to resettlement from damaged to less-damaged, undeveloped islands, as happened to twelve islands following floods in 1819 (Cazes-Duvat, 2005). Island populations would also uproot themselves for economic reasons, such as in search for better fishing grounds: the inhabitants of R. Dhuvaafaru in eastern Northern Maalhosmadulu (Raa) Atoll are thought to have abandoned their island in the early second century in pursuit of better fishing grounds in the west (Bluepeace Maldives, 2009; for more on R. Dhuvaafaru, see Section V.3 and Figure 9). The flexible design of non-ceremonial or governmental structures supported a society that accepted the need to shift with landscape and resources.

Such a flexible lifestyle suited the extremely diffuse Maldivian population: at most 65,000 people were spread across the nearly 200 inhabited islands (Ghina, 2003). Low population densities allowed for a resource economy that, with the exception of Male', did not push the carrying capacity of islands and reefs. Even in the late 1970s the World Bank would conclude that "low money incomes . . . are not an accurate indicator of the standard of living in the atolls" due to the richness of locally-harvested resources and domestic fruit cultivation, and even on Male' domestic mango cultivation continued through the 1980s (Edwards, 1989; Sarwar Lateef et al., 1980). The main environmental limiting factor on growth was availability of clean freshwater: porous soil and poor elevations meant that human wastes contaminated freshwater lenses, spreading dysentery. Male' historically had the worst freshwater quality, due to its higher population density of both people and graves on the island. By the seventeenth century Male's groundwater was not considered potable, and the Maldivian sultan would only drink water imported from other, less populated islands (Asian Development Bank (ADB), 1999; Bell, 1928; Gray, 1890). The combination of dysentery and malaria kept the Maldives' population capped at 70,000 people and Male's around 5000 (Ghina, 2003).

IV. Growing Male': population, economy, and land area

1. Demographic and economic drivers

Public health improvements in the twentieth century – most importantly the eradication of malaria and the expansion of basic health services to the entire country in 1965—reduced death rates (life expectancy went from 50 in 1983 to 73 in 2002) allowed Maldivian population growth to accelerate beyond replacement levels. By 2000 there were more than three hundred thousand people living in the Maldives (Figure 3(a), Ghina, 2003; Global Urban Observatory (GUO), 1999).

The Maldives' economy only took its modern contours in the early 1970s's with the rise of tourism and the motorization of the *dhoni*, which revolutionized fishing, inter-island travel, and coral mining (see Section V.1). Male's earlier strength as a population and trade center allowed it to capture much of the new economic and population growth. Additionally, a high level of public investment in the capital (Section IV.2) further increased the opportunity gap between Male' and the atolls, incentivizing migration to the capital and stimulating yet more projects to accommodate this growth. This is typical urban agglomeration, made more intense by a policy bias towards the capital and Male's insular nature (Sarwar Lateef et al., 1980). The most populated Pacific archipelagos, such Majuro and Tarawa, form continuous sequences of islands connected by filled causeways, allowing for population to grow in low-density, peri-urban centers while remaining relatively easy reach of major urban and service centers (Cocklin and Keen, 2000; Duvat et al., 2013; Spennemann, 1996). The wide and deep spacing between islands in North Male' Atoll makes such sprawling growth patterns and causeway fill impossible: one either settles in urbanized Male' (or Viligili or Hulhumale', see Section V.2) or not.

Despite a temporary slowdown in growth in Male' and period of catch-up in the atolls, by the 2000s Male's growth accelerated again, a trend which continues today (Figure 3(b); Edwards, 1989; Maldives Ministry of Planning and National Development, 2005). When the Maldives' total population passed 300,000 in July 2006, the percentage in Male' (now including some neighboring islands, Figure 1 and Section IV.3) was at its largest point in history, with almost 25% of the nation's population living on the island proper and one-third in its administrative area (Figure 3, GUO 1999; Maldives Ministry of Environment, Energy and Water, 2007; Maldives Ministry of Planning and National Development, 2007). Much of this growth is driven by migration – in 2000 44% of Male's population was born in the atolls, contributing to stagnant-to-dropping populations there (Shaig, 2006). Though most jobs attracting migrants to Male' are low-income, they nonetheless pay better than equivalent jobs in the outlying atolls (Shaig, 2006; Shaljan, 2004).

Primary sector jobs harvesting the Maldives' diffusely spread natural resources are now less attractive avenues for employment. The recent uptick in Male's growth has been driven by tertiary sector, which benefits from the person-to-person contact facilitated by dense urban settings: today approximately as many people are employed in community, social and personal services as in tourism and fishing combined. Among governmental services the drive towards centralization is probably strongest labor-intensive sectors such as health care and education. Since the 2011–12 Maldivian political crisis, health care in the atolls has deteriorated to such a degree that even minor ailments needed to be treated at Male' hospital, meaning transportation (and accommodation in Male') eats into the health budget (Sobir et al., 2014). It was not until the 2000s that secondary education was significantly expanded beyond Male' and Addu, but the better quality and availability of education in Male' means educational opportunity is still a major driver of relocation (Azza, 2008; Sobir et al., 2014). This disparity in education only exacerbates the divide in employment between the Male' and the outer atolls: in 2010 unemployment in Male' stood at 17%, compared to 34% in the atolls (Sobir et al., 2014).

2. Landfill, new construction, and pressure on natural resources

Population growth, economic expansion, and government enlargement in the 1960s and 70s threatened to overrun the Male's small area. In the early 1970s 15 ha were added to the northwestern face of the island (Figure 3). Though this landfill successfully modernized the island's port infrastructure, the amount of new land proved insufficient as people continued to press into Male' (Edwards, 1989). Additionally, with Male' was taking a central role as the country's center for service provision, administrative, educational and hospital facilities were becoming crowded: institutional overcrowding was as much a driver for landfill as population growth.

The fill itself was locally sourced coralline rubble and sand, the same stuff as a typical Maldivian island, though the rubble was made by quarrying and blasting local reefs. Coral mining accelerated with the start of the Male' Land Reclamation Project in 1979, adding another sixty acres to the island's area by filling in the Dhekunu Falhu and extending the island towards the edge of its underlying faro (see Section I). By the end of the 1980s, 906,240 m^3 of coral had been quarried away for fill, and any reef that was not covered by new land was left significantly degraded (Edwards, 1989).

Through the 1970s and 80s new construction swept across both the old and filled parts of Male'. The wood-framed house with *cadjan* walls had mostly fallen out of use by this point. By 1935, T.W. Hockly only saw palm wood-and-*cadjan* houses in Male's poorer quarters, sometimes with corrugated iron panels sheltering topping an otherwise traditional structure (Hockly, 1935). While they impeded airflow and conducted more heat into homes, corrugated iron roofs require less maintenance than thatched coconut roofs and shielded the sides of houses – still typically covered by *cadjans* – further reducing maintenance demands and extending the lifetimes of building elements. Beyond shifting preferences in building materials, by the 1960s and 70s Maldivian coconut wood resources were becoming increasing strained. Almost all coconut agriculture was done on densely packed plantations both to maximize trees per acre and to stress the trees for curved wood that, while useful for *dhoni* manufacture, was generally unsuited for residential construction (Sarwar Lateef et al., 1980). In the atolls wood remains the major fuel source (ADB, 1999; Ghina, 2003), but in areas with coconut plantations often weeds are used as well, reducing the incentive to weed plantations and adding another competitor for scarce groundwater and nutrients (Sarwar Lateef et al., 1980). Though population and living standards grew at a slower rate than in Male', competition between increased water consumption and coconuts in the atolls (see Section I) nonetheless depleted freshwater sources, allowing more salt to intrude on groundwater lenses. Motorized *dhonis* also increased the mobility of pests, particularly *Rattus rattus* (Edwards, 1989).

The main environmental effect of motorized *dhonis* was to make larger-scale coral mining economically feasible (ADB, 1999), and for the first time coral became attractive for ordinary residential construction. Coral construction allowed for better fire resistance, thicker walls and multi-story buildings, key advantages in the increasingly-dense island settlements, especially Male'. When residential coral construction started to expand in the early 1970s it became a sign of conspicuous consumption, with the historic use of coral in palace and mosque construction imparting coral with strong cultural connotations of stability. During the Male' Land Reclamation Project the annual amount of coral mined near Male' for construction purposes quadrupled from 1000 to 4000 m^3 between 1981 and 1985; by 1992 this had increased to over 11,000 m^3, indicating that coral had become the dominant construction material on the island (ADB, 1999; Khaleel and Saeed, 1997; Naseer, 1997).

Large, mature coral heads, especially *Porites lutea*, were favored for new construction, as had been the case since the Buddhist period (Forbes, 1987; Naseer, 1997). Used either as building blocks themselves or broken into brick-sized pieces (Figure 5), coral was cemented together with mortar made from coconut sap, lime, and sand. Beams for multiple stories would be either of timber or sometimes steel (Edwards 1989). Underneath the roof – typically of imported corrugated steel or asbestos cement – would be an edifice of mostly or completely local manufacture. Thus even though the Male' Land Reclamation Project finished in 1985, boats regularly came in bringing fresh coral heads from nearby reefs well into the nineties.

Figure 5. Detail of a typical rough coral wall, likely dating from the late 1980s. Here coral heads were broken into brick-like blocks rather than being used whole (*Porites lutea* on the right and likely *Platygyra sinesis* on the left). This wall rims the municipal dump on Male', in southern landfill created by the Male' Land Reclamation project. In many cases such walls are covered by stucco.

V. Vulnerabilities and adaptations

1. Disaster and response on Male' and Hulhule'

Between April 4 and 7, 1987, a massive storm occurred in southern Indian Ocean. Long period swells traveled a great circle route 4500 km across the Indian Ocean to the central Maldives. Upon reaching Male' on April 10, the swells' maximum height was 5 m above sea level, easily flowing over the new, low-lying land of the Male' Land Reclamation Project and inundating much of Male' for two days (Figure 6). Sixty hectares of landfill, corresponding almost exactly to the Male' Land Reclamation Project, were inundated by the swells, and approximately 300,000 m^3 of fill was washed away completely (Cazes-Duvat, 2005; Edwards, 1989). The severity of the disaster was largely the result of the Reclamation Project. The filled area sloped from 1.0 m near the original coastline of Male' to

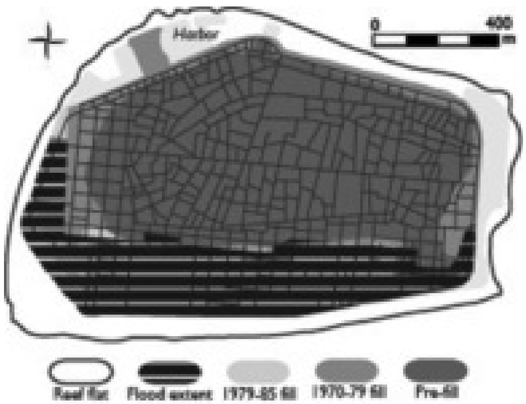

Figure 6. Extent of the floods in April 1987 – note that they are essentially contiguous with the 1979–87 Male' Land Reclamation project, which filled the lagoon. Flood extent over the island is rectilinear because flooding was recorded per city block (after Amooo and Jameel, 2008; Bell, 1928; Edwards, 1989; Google Earth, 2014c).

0.7 m at its southern edge, exposing more, lower land to wave damage. Before the Male' Land Reclamation Project, Male's barrier reef robbed waves of energy, and the Dhekunu Falhu provided a basin for any additional overflow. The mining activities off of Male' reduced the height of the remaining reef by a half-meter, and the extension of land closer to the edge of Male' meant the new land was also closer to deeper water (Edwards, 1989).[4]

While the total cost of the Male' Land Reclamation project was US $94 million (2014), the cost repairing the damage and protecting against further inundation was US $96 million (2014) – a distant storm had effectively reversed nearly a decade's worth of work (Ghina, 2003). The damaged area was refilled in the aftermath of the disaster, and the entire island was encircled by tetrapod barriers (Figure 7), donated by the Japanese government at a cost of US $23 million (2014), giving an approximate estimate for the monetary value of the old healthy reef's breakwater functions, though falling short ecologically and aesthetically (Cazes-Duvat, 2005; Edwards, 1989). Those sea walls proved their worth during the 2004 Indian Ocean Tsunami, helping to prevent a repeat of 1987. Wave heights never reached above 0.8 m and the minor levels of damage to buildings, roads and the southern seawall indicated a relatively gentle flow pattern (Fritz et al., 2006). Since they enclose the entire island of Male' the seawalls also shut down the natural flow of sediments around the island (Ali Rilwan and Saffah Faroog, 2010, personal communication). The shutdown in sediment flow also means that Male' is not as plagued by the unpredictable disruptions to natural erosion and deposition/siltation patterns emerging from *partial* coastal protection measures, a problem common elsewhere in the

Figure 7. Tetrapod barrier along Male's western coast, bordering land created during the Male' Land Reclamation Project. The tetrapod barriers interlock, and are anchored in coral rubble (blackened by sun exposure and algae) and are backed up by a concrete barrier wall (photo by the author, April 2010).

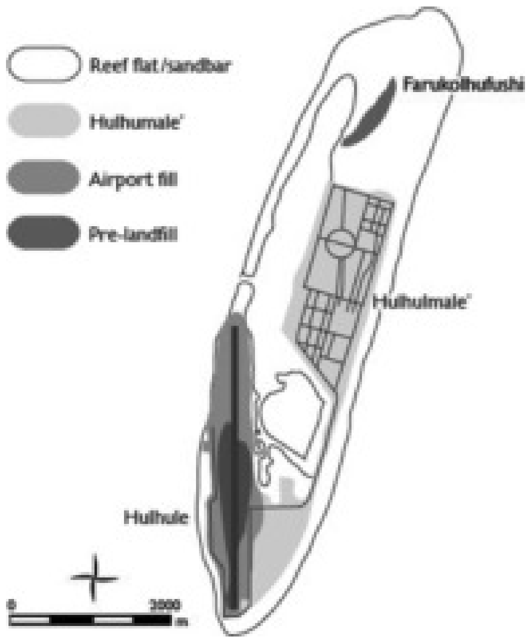

Figure 8. Hulhule Falhu, consisting of Hulhule' (expanded to accommodate Male' International Airport), Hulhumale' (constructed by filling in reef flat), and the resort island of Farukolhufushi (after Amooo and Jameel, 2008; Edwards, 1989; Google Earth, 2014c; Fujima et al., 2005).

Maldives and on Pacific atoll islands in South Tarawa (Duvat et al., 2013; Kench et al., 2003; Zammath Khaleel and Ali Shareef, 2010, personal communication). Male' is more secure from coastal change, though at the expense of its natural dynamics.

The nearby island of Hulhule' (Figure 8), home of Male' International Airport, was also damaged. Like Male', Hulhule' is a lenticular island, but it with narrower, more oblong geometry with a long eastern bank faces the Indian Ocean. Hulhule's fill, which allowed the airport to accommodate larger planes, only lengthened the oceanward side of the island, making it even more expensive to protect, and even after its post-1987 repairs waves regularly lapped onto the runway (Edwards, 1989; Ministry of Housing, Transport & Environment and the United Nations Economic Program (UNEP), 2009). However, the fact that the 2004 tsunami waves first passed over Hulhule' also helped rob them of their destructive power, protecting Male' and Viligili (Fritz et al. 2006).

The 1987 swells also exposed weaknesses in Male's water and sewerage infrastructure: a major waste disposal compound was damaged, finally jolting Male' into installing a proper sewerage system, though the flow of sewerage around the island, where it promotes algal growth and inhibits the recovery of hard corals, remains an issue (Ghina, 2003). Aggravating contamination problems was the continuing shortage of groundwater, despite the incorporation of dedicated soakways into road surfaces to aid recharge. Domestic fruit (particularly mango) cultivation declined as groundwater degraded in the eighties and is impossible to practice today (Edwards, 1989; interview with Ali Rilwan and Saffah Faroog, 25 April 2010). While Maldivian governments have promoted rainwater harvesting since 1904, it only became widespread for home use after several major cholera and shigellosis outbreaks in the late 1970s (Edwards, 1989). Today graywater recycling is mandated for all toilets and desalinated tap water now supplements rainwater, providing water for import to other islands with degraded water supplies in a reversal from the premodern norm (see Section V.3, ADB, 1999).

In the wake of 1987 wave event coral mining was outlawed, but for much of the nineties this had no significant effect. Mining was easy (one could simply fill a *dhoni* with coral), the Maldives lacked the manpower to enforce a ban, and local builders still preferred coral blocks to concrete blocks, despite the ability of standardized concrete blocks to support more sophisticated construction techniques and taller buildings (see Section IV.3, ADB, 1999). The decision was made to subsidize concrete block manufacture, manufactured by the public sector at low prices and high volumes, in order to disrupt the market for coral heads; coupled with demand for taller concrete buildings and bettering enforcement this has helped reduce the demand for mined coral (Naseer, 1997). Continued economic growth through the nineties allowed for the importation of more building materials. Although concrete with locally sourced sand had been used in limited applications in the past (particularly in the construction of a former British military base in Addu), the concrete industry in Male' imports aggregate. In addition to being salt-free, unlike local sands, importing aggregate allows for increased concrete output while restricting sand mining, which like coral mining can increase coastal vulnerability (Shaig, 2006; UNEP, 2009).

2. Expansion onto nearby islands

Despite the higher densities enabled by concrete construction, Male' still needed room to expand. Construction became more difficult in Male' as land prices increased and the amount of developable land decreased: while the number of households increased by 19% in the 1990s, the rate of construction slowed (UNEP, 2009). Male's status as capital leads to competition between government (primarily administrative) and private (primarily residential) land use, with the former having an upper hand due to the nominal rents charged to government bodies, promoting increased institutional land use at the expense of residential construction. As a consequence, though Male's citizens are comparatively wealthy, with median yearly incomes of *Rf*120,000, about US $10,000 (2014), their median space consumption is low, at only 3.7 m per person (Bertaud, 2002; Sobir et al., 2014).

In the late 1980s, Male' City annexed Viligili,[5] a small island just west of Male' that was developed as a tourist site in the 1970s (Figure 1; Edwards, 1989). It serves mainly as a bedroom community, with almost the entire population commuting by ferry to Male' every day for work and school, though Viligili also houses educational and medical facilities (Edwards, 1989, Ghina, 2003). With a population of approximately 7000, Viligili is too small to significantly relieve Male's population pressure, though this also has allowed Viligili to preserve its freshwater lens and beach space (Maldives Ministry of Planning and National Development. 2007).

Rising standards of living in the 1990s led to greater garbage production. The average Male' citizen produced almost 2.5 kg of garbage per day in 2003, as compared to 0.66 per person per day in the atolls. The Male's dump proved insufficient, and garbage began to gather in informal piles around the city (ADB, 1999; Ghina, 2003). The permeability of Male's sediments and the reef platform below meant that dumping offshore was not an option, and Maldivian law bans the dumping of municipal wastes in the ocean. Instead garbage was used as fill in Thila Falhu, a faro approximately five kilometers west of Male', to make the new island of Thilafushi (Figure 1), which continues to grow at roughly one square meter per day (Omidi, 2009). While this has led to significant local environmental degradation, local currents have prevented toxins from leeching beyond the immediate vicinity of the island (adb, 1999). Thilafushi is not suitable for permanent inhabitation, though, or even most industrial uses, meaning that it is only a solution to Male's waste problem.

Though the sharp drop-offs beyond their reef flats (Figure 1, Section II) preclude further landfill on Male' (or expanding Viligili), the large reef flats of Hulhule' offered a large, nearby opportunity for more fill. Beginning in 2003, Hulhule' Falhu was partially filled with sand dredged from the nearby seafloor, creating Hulhumale'. Hulhumale' is the Maldives's single largest landfill project: the entire 182 ha island is artificial, and there are plans for further expansion. As with the Male' Land Reclamation Project, the landfill that makes up Hulhumale' extends almost to the edge of the reef flat, but the island has been built as a

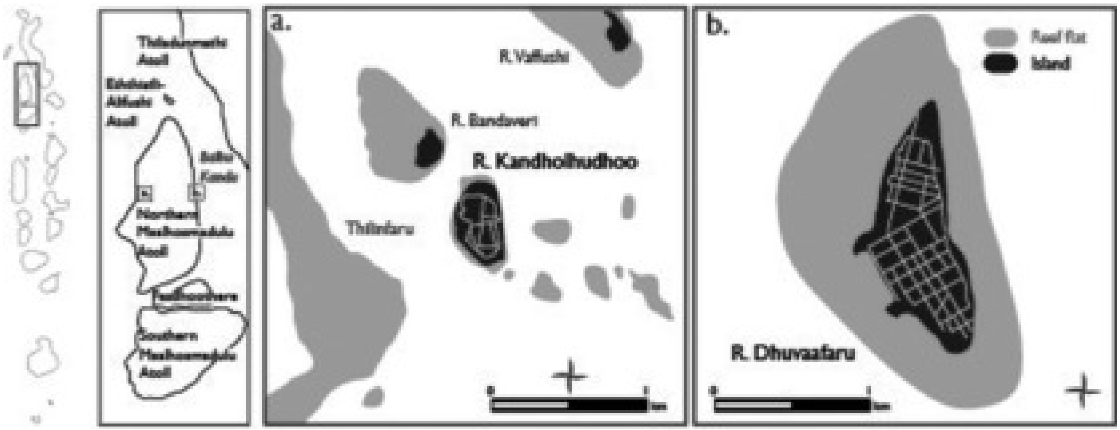

Figure 9. Comparison of R. Kandholhudhoo (a) and R. Dhuvaafaru (b) in Northern Maalhosmadulu (Raa) Atoll (Amooo and Jameel, 2008; Google Earth, 2014a, 2014b; Kan et al., 2007). R. Kandholhudhoo only had a handful of roads, with most houses being crowded together with thin pedestrian passageways between them, so the perimeter line represents the limit of developed land. Though the larger island of R. Dhuvaafaru houses R. Kandholhudhoo's former population, even more land is covered by development and coastal exposure is greater.

two-meter high platform, edged with a sandy beach tumbling from the high fill to sea level. While this elevation corresponded with centennial sea level rise estimates at the time of Hulhumale's construction, the height was chosen based wave events like April 1987's, not long-term sea level forecasts (Hamilton, 2008). In 2004, Hulhumale' was opened to settlement and by 2010 the Hulhumale' Housing Development Corporation (HDC) claimed a population of 12,000 (HDC, 2011). By 2020 the entire project is expected to house 150,000 inhabitants, with space provision for utilities, commercial and industrial space (Barta, 2008; Bertaud, 2002; Hamilton, 2008; Luxner, 2009). Despite Hulhumale's advantages in space and land value, it is still distant enough from Male' to be at a disadvantage for many tenants and developers. When the Holiday Inn chose a cramped Male' site over Hulhumale' in 2008 it was reported as a sign the island was failing (Barta, 2008). While this judgment was premature, it underscores the strength of Male' as an urban center and the difficulty of disrupting existing patterns of urban agglomeration.

Despite Hulhumale's obvious artificiality (it is the Maldives' only rectangular island), there have been attempts to develop the sort of natural amenities than have been left out of Male. Greenery (albeit non-native) is has been planted everywhere. Hulhumale's soil has similar infiltration characteristics to other atoll islands, which combined with the island's large surface area has endowed Hulhumale' with a sizable freshwater lens. The sandy beach that has accumulated on the island's eastern face is largely of natural origin, coral has also begun to recolonize the remaining edges of reef flats, and the beach of Hulhumale' is full of fauna. As Ali Rilwan told me, "Hulhumale's more natural than Male', even though it's artificial" (2010, personal communication).

3. Following Male's lead: responses on small atoll islands to the 2004 Indian Ocean Tsunami

Atoll islands have not seen the level of investment in coastal protection as Male', though there have been plans to address this. Even

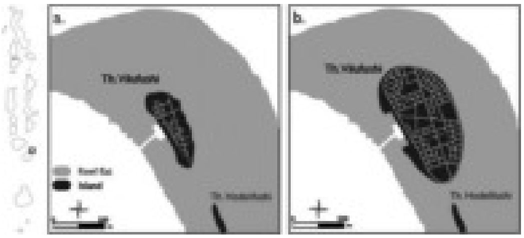

Figure 10. Comparison of (a) Th. Vilufushi before the 2004 Indian Ocean Tsunami and (b) after the Safer Island-type improvements (Bosschieter, 2007; Google Earth, 2014d; Kan et al., 2007).

before the 2004 Indian Ocean Tsunami the Maldives was studying a Safer Islands Strategy (SIS, also referred to as the Safer Islands Development Program, SIDP, or Safer Islands Program, SIP). The SIS would have been coupled with a population consolidation program, relocating much of the population to 10–14 designated islands throughout the archipelago where lessons from Male' and Hulhumale' (seawalls, elevated landfill, etc.) would be applied. These fortified bases were envisioned as regional centers from development, fostering local agglomeration of population and economic activity and providing an outlet for development away from Male' (Ministry of Environment, Energy and Water, 2007; Sovacool, 2011). As a short-term solution after the tsunami five "host islands" (not necessarily covered by the Safer Island Strategy) made in direct response to damage from the tsunami (UNEP, 2009): R. Dhuvaafaru (Figure 9), M. Muli, L. Gan, L. Funadhoo, and Th. Vilufushi (Figure 10).

The most dramatic shift was the relocation of the population of R. Kandholhudhoo, rendered uninhabitable by the tsunami, to R. Dhuvaafaru. Despite having a population of only 3664 (three of whom died in the tsunami) Kandholhudhoo's recent history parallels Male's: one of the largest settlements in Northern Maalhosmadulu (Raa) Atoll, it had a density of 9330 people per square kilometer, and its freshwater lens was completely degraded. Like Male', R. Kandholhudhoo's reef was mined and was expanded onto its former lagoon, using both fill and dykes (Figure 9(a); Bluepeace Maldives, 2009; Fritz et al., 2006; *Haveeru Daily*, 2004; Kan et al., 2007). Before the tsunami R. Kandholhudhoo was recognized as a particularly vulnerable island – in June 2004 the *Haveeru Daily* reported that coastal fortifications were weak and monsoon rains and waves were already causing coastal and property damage. This also indicates that surfaces on Kandholhudhoo were impermeable compared to those on Male', which prevented recharge of the overdrawn freshwater lens. The island's population started to form a consensus towards resettlement to R. Dhuvaafaru.[6]

R. Dhuvaafaru has the advantage of being the second-largest uninhabited island in Northern Maalhosmadulu Atoll (Figure 9(b)), but otherwise it has no protection advantages. Indeed, in the process of grading the island for inhabitation approximately a third of a meter of soil was removed (Bluepeace Maldives, 2009). Rather than concentrating homes in the center or lagoonward side of the island, the decision has been made to develop the entire island to the edge with lower densities and larger houses. While there is "high ground" on R. Dhuvaafaru, it is in the form of architecture, not landscape: the local community center, designed to double as a shelter in the event of a disaster, is on concrete stilts (Vince, 2009).

Th. Vilufushi, a lenticular island on the northeastern rim of Kolhumadulu (Thaa Atoll), was the hardest-hit island in the Indian Ocean Tsunami, with 18 causalities (out of a population of 1886). Despite protection from a (living) barrier reef a kilometer offshore (Figure 10), the tsunami still inundated the island (indeed, the reef also reflected waves, causing inundations from the north and west too), with the highest flow depths reaching as high as 2.6 m (Kan et al., 2007; Fritz et al. (2006) reported a maximum flow depth of 3 m, but this was based on an assumption that Th. Vilufushi was uniformly 1 m in height). Rather than moving the population, Th. Vilufushi was rebuilt in accordance with the Safer Island Strategy. Like the relocation from R. Kandholhudhoo to R. Dhuvaafaru, this was in planning stages even before the tsunami – the devastation gave the project urgency and an inflow of aid made it possible on a short timescale (Saleem and Sattar, 2009). By 2009, Th. Vilufushi had tripled in land area and its mean elevation was raised from 1 to 1.4 m above sea level (and a new maximum elevation at 2.4 m), with care taken to ensure that dredging for fill did not disturb living reef (Figure 10(b); Bosschieter, 2007). Recent satellite imagery of Th. Vilufushi seems to indicate that population is mostly concentrated towards the harbor and high ground (surviving trees clearly indicate the island's original perimeter), though current land use plans envision development spreading to the shoreline (Isles, 2014).

Despite the apparent success of Th. Vilufushi, since 2010 the SIS (under all its names) has been quietly abandoned in favor of the Integrating Climate Change Risks into Resilient Island Planning (ICCR) program. Though the benefit–cost ratio for Th. Vilufushi was favorable (reported at 1.95 in Shreve and Kelman, 2014), capital for heavy investments in the Maldives typically only comes in the form of aid *after* a disaster and funding for island raising and comprehensive coastal protection was lacking in normal circumstances (the proactive planning of Hulhumale' as a taller island being a notable exception). The population consolidation envisioned by the SIS was also quietly abandoned. Lower initial costs and the potential for greater local involvement have driven interest in "softer" engineering strategies (the terms "soft" and "hard path," originally used by Lovins (1976) in reference to energy, have since expanded across engineering and policy disciplines, cf. Sovacool, 2011). Rather than molding the environment with hard-engineering strategies like seawalls or raised fill, the aim of soft engineering to take advantage of and plan around diffuse ecosystem services (Sovacool, 2011).

4. Emerging climate risks

Wave events such as the 1987 swells or 2004 tsunami have occurred periodically since the Maldives' formation – what made 1987 and 2004 different was the degree of development on the islands. The fortification around Male' reflects the increased importance of the island as an population, economic and political center relative to smaller, less fortified islands. Yet the Maldives – and all other small island states – do face a new threat from anthropogenic climate change, and the response to floods and wave events can help reveal vulnerabilities in geomorphological and biological systems, both stemming from natural limitations and human modification.

In contrast to the Pacific Islands, the Maldives are not expected to see any notable uptick in storm or wave intensity, with the Indian Ocean becoming calmer as the Pacific gets more typhonic. Sea-level rise is the most obvious threat to low-lying islands, with the Indian Ocean likely seeing a rise of 0.4–0.5 m over the course of the century compared with 0.5–0.6 m in the Pacific (Nurse et al., 2014). Kench et al. (2009) argued that this does not necessary spell disaster for the current Maldivian islands: they were formed *before* the Indian Ocean reached its Holocene highstand (Section II), which was comparable with the IPCC's estimated 2081–2100 rise estimates, demonstrating that islands and reefs are able to respond and withstand even to relatively swift changes in sea level and that there are potential equilibria between island sedimentation and sea level (Webb and Kench, 2010; Woodroffe, 1989). However, in 4000–2000 BP there was both much less alteration to the islands themselves (no fill or grading) and to the living reefs. Despite Webb and Kench (2010) being bullish on the chances for island accretion to continue in the Pacific, Duvat et al. (2013) noted that closer examination of inhabited islands in South Tarawa revealed that while human shoreline modification can play a role in short-term accretion and preservation of shorelines, new land is often not resilient and accompanied by accelerating erosion in other parts of affected islands. Furthermore, while the all-around protection on islands such as Male' and Hulhumale' prevents such uneven patterns of erosion and deposition (Section V.2), they also interfere with potential equilibrium responses between sedimentation and sea level rise, assuming the rate of sea level rise over the twenty-first century does not overpower any such potential response (Woodroffe, 1989). The kind and quality of human interventions in shorelines and coastal processes are likely to be the determining factor in the survival of inhabited islands over this century.

While Maldivian reefs have historically been capable of catch-up growth in response to sea level changes, they have been weakened by both local factors as coral mining as well as increasing sea surface temperatures (SST) and ocean acidification, phenomena that spell disaster for the reefs worldwide. Increasing SST increases coral mortality: Maldivian reefs still have not made much recovery from the 1998 ENSO-influenced bleaching event, which reduced average live coral cover from 45 to 5% (Jaleel, 2013). Acidification inhibits the calcification of coral skeletons, sending reefs systems in the Maldives and worldwide towards a primarily erosive regime (Hoegh-Goldberg et al., 2007; McClanahan et al. 2014).

Beyond disrupting natural responses to sea level change, increasing stress on reef ecosystems poses problems for shore-based Maldivian civilization. This is increasing the depth and decreasing the roughness of seafloors, making reefs less effective as coastal defenses. In the Seychelles reef damage since the mid-1990s, largely the result of the 1998 ENSO and increased sea surface temperature, has already resulted in greater wave power reaching the shore (Sheppard et al., 2005). Stress on reefs also makes it more difficult to encourage reef growth as "soft," ecosystem-based protection measures, which are often listed as a favorable alternative to large-scale hard coastal protection. Living reefs *are* attractive alternatives to hard protection: on a case-by-case basis reef preservation typically entails lower capital costs than building new protections and reefs have ecological, aesthetic, and economic (tourism and fisheries) benefits that cannot be reproduced with artificial barriers (Jaleel, 2013). Yet the amount of damage and degradation already seen in reefs across the Maldives means that the technical challenge of reef repair on a scale wide enough to restore lost protection benefits may be insurmountable (Vince, 2009), a problem comparable to the challenge of expanding hard protections across the populated islands.

Sea level rise also threatens land-based ecosystems. It would both force the freshwater lens upward and increase salt intrusion levels. Increased intrusion after the 2004 tsunami hurt both the growth of crops and other trees, and increased, consistent intrusion would be a threat to coastal vegetation, which can play a role in stabilizing coastlines (United Nations Development Program (UNDP) and The Global Environment Facility (GEF), 2007; UNEP, 2009; Woodroffe, 2008). Increasing water tables would force freshwater lenses closer to the surface, damaging structures' foundations: buildings in Male' are already limited to approximately ten to twelve stories by groundwater and soil stability (UNDP and GEF, 2007; Woodroffe, 1989). Additionally, the higher SSTs in the Indian Ocean are likely to be accompanied by a drying climate (Nurse et al., 2014), intensifying evaporative losses and reducing recharge rates.

VI. Conclusion: implications of path-dependence and morphology for coastal protection in the Maldives and elsewhere

The Maldives share the same core vulnerabilities of the Pacific atoll nations: periodic wave-borne disaster, risk of total inundation with sea level rise, reliance on rainfed freshwater lenses, and recent histories of rapid urban development coupled with extensive coastal modification and environmental degradation. Yet the Maldives stand distinct from the Pacific atolls, both in terms of its geomorphology and built morphology, the latter often being a consequence of the former. The smaller, disconnected islands of the Maldives have led to major differences in urban development patterns. Major urbanized Pacific atolls like Majuro and South Tarawa consist of long islands connected by causeways, allowing for low-density, peri-urban growth on more peripheral islands in between larger population centers. In the Maldives one is either in an urbanized island or one is not, and even remote, "rural" islands (such as R. Kandholhudhoo) are often settled at high densities. The preexisting economic and governmental importance of Male', a centrally located but otherwise unremarkable island, made it a center of agglomeration, forcing very high population densities (that have been artificially increased by inefficient land-use practices). On all the major inhabited atoll islands, as populations increased they expanded into less-protected regions. The Tarawan island of Eita-Bangantebure and the Tuvaluan island of Funafuti, in particular, exhibit similar progressions to flood-vulnerable fill, though in this case it was a swampy lagoonal enclosures rather open-water lagoons like Dhivehi Falhu, and almost all urbanized atoll islands are typified by development intensifying directly along the coastline. The relatively small size and economic importance of Male', though, has also allowed the entire island to be fortified, preventing the uneven accumulation/erosion effects that come with fortifying limited stretches of coast, common to both Pacific and smaller Maldivian islands (Duvat et al., 2003; Kench et al., 2003; Spennemann, 1996; Yamano et al., 2007). Furthermore, the presence of numerous faros and large amount of available fill makes either new island construction (Hulhumale') or island raising (Th. Vilufushi) easier than in Pacific atolls, though still expensive.

The other main distinction between the Maldives and other atoll nations is the long-standing use of local coral rock masonry, first for religious and administrative buildings, then for coastal structures, and finally in the twentieth century residential structures and fill. While the advancement from locally-gathered coral blocks to large-scale coral quarrying was enabled by modern technology and fueled by increasing standards of living, it was an intensification of traditional practices, not something new. Prior to the twentieth century the main conservation technique in the Maldives was simply treading lightly, having a widely spread culture with low material requirements and the flexibility to move when necessary. Environmental engineering on denser Male', though, has long tended towards "harder" solutions: masonry for coastal defense to tetrapods, imported water to desalinated water. This history makes it difficult to dislodge a hard engineering mindset from Maldivian engineering culture, even on smaller islands—Male's lead was largely followed by R. Kandholhudhoo, for instance. Furthermore, the aforementioned availability of local building resources and widespread knowledge of masonry techniques contradicts the distinction made by Sovacool (2011) between "complex, capital-intensive" hard engineering and "simple and modular" soft engineering: hard construction as practiced in the Maldives *is* relatively simple and modular. In contrast, the complexity of offshore sediment dynamics, the need to avoid siltation on nearby reefs, and the difficulty of encouraging new reef growth and conservation in the midst of increasing development on nearby islands makes it a much more human capital-intensive project. Accordingly much current work on soft, ecosystem-based coastal engineering techniques has focused less on specific solutions and more on building the capacity to create potential solutions (Ali Rilwan and Saffah Faroog, 2010, personal communication; Sovacool, 2011). Additionally, natural coastal protections are also under threat from global stressors, making soft solutions even more difficult. Even with a robust soft infrastructure program hard protections are still likely to be necessary.

This remains an expensive path to take – the dispersion of the Maldivian population across a number of small (and often oblong) islands, makes coastal protection particularly expensive, leading to one of the highest coastal protection cost-to-GDP ratios of any nation (Nurse et al., 2014). In the Maldives coastal protection measures tend to advance most quickly in the immediate aftermath of disasters, fueled by aid money. In addition to only being reactive to disaster, the need for quick responses to disaster can lead to compromised solutions, as with R. Dhuvaafaru and other new "host islands" the main new protection was just a protected safe house (UNEP, 2009). Despite policymakers' enthusiasm disaster resilience and climate adaptation *strategies*, in practice Maldivian investments in coastal protection are done in a more *tactical* manner. More consistency in financing (and aiding) of coastal protection measures would likely allow for more comprehensive and anticipatory plan making. Additionally, such disasters also result in a spike of interest after disasters like the 1987 waves or 2004 tsunami (or similar flood events elsewhere, such as Funafuti) – the uneven monitoring of small island nations can make it difficult to assess causes of shoreline change and the effects of interventions (Duvat et al., 2013; Yamano et al., 2007). More sustained observations of small island states is necessary to better understand their geomorphological and socio-economic vulnerabilities – while disasters help demonstrate weaknesses, they can only provide partial windows on coastline processes or coastal protection decision-making.

Nor can we divorce climate and coastal vulnerability from broader socio-economic and political concerns – though I was not able to perform any formal survey during my time on Male', Viligili, and Hulhumale', even during the more environmentally-focused Nasheed presidency the lingering effects related to global economic downturn of 2008 were foremost on people's minds, as were issues of inequality and quality-of-life. Most of the alterations to Male's environment were responses to increasing populations with increasing expectations of standards of living, and the unipolar pull of Male' has exacerbated inequality across the islands (Section IV.1). The problem was first identified in the late seventies by Sarwar Lateef et al. (1980), who suggested the development of alternative growth centers throughout the atolls to channel growth away from Male'. More recently the Maldivian environmentalist group Bluepeace has suggested constructing three meter-high islands throughout the atolls to both provide alternate urban centers for development and to allow for settlements more resilient to sea level rise. While this represents a hard path solution similar to Hulhumale', Bluepeace also suggests supplementing them with soft path measures coastal forest, development restrictions close to the island's edge (unlike on Hulhumale' or Th. Vilufushi), natural rainwater collection and freshwater lens maintenance. Should the Maldives continue to be inhabited through the twenty-first century – Bluepeace Maldives' proposals (2008a) are explicitly framed as alternatives to a planned relocation of the Maldivian population as sea levels rise (Ali Rilwan and Saffah Faroog, 2010, personal communication) – it will be because of synergies between, ecosystem service protection, carefully-designed hard fortification techniques, and archipelago-wide economic development.

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Notes

1 Male' is considered a contraction of "mahal," so it is properly spelled with an apostrophe at the end, not an acute accent.

2 The Republic of Maldives also uses "atoll" as a political subdivision—in physical geographic terms, Male' is part of North Male' Atoll, while in administrative terms North and South Male' Atolls, Gaafaru Atoll and Kaashidhoo are all part of Kaafu Atoll. Due to the number of islands with common names, islands other than Male' and Addu City (which have the political status as independent cities) have the initial of their political atoll placed in front of their proper name, so the Kaashidhoo discussed here is K. Kaashidhoo, not G. Kaashidhoo, an atoll island in Southern Huvadhu (administrative atoll Gaafu Dhaalu) Atoll. "The atolls" is typically used to contrast the rest of the country with Male'.

3 Water depth of a freshwater lens can be simply put as $Z_{MAX} = Z_{Lim}(1 - e^{-bR})S$, where Z_{MAX} is freshwater lens depth, Z_{Lim} and b describe island size, R is recharge, and S hydraulic conductivity to saltwater (Bailey et al., 2014).

4 Wave energy dissipation across a reef front is described by $\partial(Ec_g)/\partial x = -(\epsilon_f + \epsilon_b)$, where E is wave energy (proportional to the square of wave height), c_g is wave group velocity, ϵ_f wave bottom friction, and ϵ_b wave breaking. The removal of half a meter of coral significantly reduced the bottom friction ϵ_f and had some effect on wave height, though most of the reduction occurs when a wave encounters a carbonate platform.

5 Also called Villingilli or Vilimale'.

6 The flooding on R. Kandholhudhoo was likely the result of the large number of hard surfaces on the nearly-totally-urbanized island. Although on Male' soakways allow for quicker infiltration than natural atoll soil, it is unlikely that this amount of care was taken in the design of R. Kandholhudhoo's infrastructure.

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