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Hurricane-induced shoreline change and post-storm recovery: northeastern Yucatan Peninsula, Mexico

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ABSTRACT

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Storms are major drivers of shoreline change on barrier beach systems. In tropical environments many such systems are fronted by coral reefs; however, little is known about how these reefal structures influence beach response during hurricanes. This study provides a detailed assessment of the impacts of Hurricane Wilma on the coral-fringed barrier beaches of the northeastern Yucatan Peninsula, Mexico. Hurricane Wilma made landfall in late October 2005 as a Category 4 storm, bringing sustained wind speeds of 67 ms^{-1}, and storm waves with significant wave heights (H_s) ≈ 13 m. To determine the impact of Hurricane Wilma, satellite imagery was used in conjunction with beach profile data to quantify immediate storm impacts and subsequent shoreline recovery. The beaches responded to storm waves in two broadly different ways. Reef-protected beaches accreted by between 2.1 and 24.6 m, while unprotected beaches underwent erosion of over 10 m. In the years following Hurricane Wilma, reef-protected beaches transgressed landwards as they readjusted to their pre-storm equilibrium shoreline position. Exposed beaches responded much more rapidly, with the majority of shoreline adjustment occurring within eight months of the storm; however, the responses were found to be highly variable alongshore. The results indicate that, under contemporary climatic conditions, hurricanes are key drivers of barrier beach evolution over the short to medium terms, but are not so influential over longer time scales.

ADDITIONAL INDEX WORDS: *Shoreline change, barrier beaches, hurricanes.*

INTRODUCTION

Barrier beaches are dynamic landforms, sensitive to changes in sediment supply, wind and wave conditions, sea level, and tectonics (Hesp and Short, 1999). Storms have historically been seen as important drivers of barrier beach evolution; however, the response of barrier beaches to storms can be highly variable, with geomorphic changes influenced by site-specific factors (Sallenger, 2000; Morton, 2002; Wang *et al*., 2006). Research to date has largely focused on the immediate impacts of storms, often neglecting short and medium-term post-storm responses. Additionally, research into the response of barrier beaches on coral-fringed coastlines is scarce, with most studies focused on the quartz-dominated barrier islands of the Gulf and East Coasts of the United States (Morton, 2002; Morton and Sallenger, 2003).

The northeastern Yucatan Peninsula, Mexico, provides an ideal location to study the significance of hurricanes to barrier beach evolution on coral-fringed coastlines. With the passage of Hurricane Wilma, 15-25 October 2005, the immediate geomorphic response of barrier beaches to a major hurricane could be assessed. The lack of geomorphically significant tropical storms or hurricanes since Hurricane Wilma also enabled the post-storm response to be evaluated.

This study aims to quantify the significance of tropical storms and hurricanes on the short to medium-term shoreline evolution of shore-attached barrier beaches on coral-fringed coastlines.

Background

The northeastern Yucatan Peninsula is characterised by shore-attached calcium carbonate barrier beaches, which are separated from a late Pleistocene dune-ridge system (Marine Isotope Stage (MIS) 5e) by mangrove wetlands; together they form a coastal plain of Holocene age (Szabo *et al*., 1978). The barrier beach is fronted by the Mesoamerican Reef Tract, which runs from the Yucatan Channel in the north to Honduras in the south (Coronado *et al*., 2007). The section of reef relevant to this study is characterised by discontinuous fringing reefs and shallow backreef lagoons; as such, both reef-protected and unprotected barrier beaches are present along this coastline (Ward, 1985; Coronado *et al*., 2007).

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The northeastern Yucatan Peninsula is periodically exposed to tropical storms and hurricanes (Landsea, 1993). In the five years prior to Hurricane Wilma, six storm events, ranging from tropical depressions to category 4 hurricanes, tracked within 130 km of the study site.

Hurricane Wilma made landfall in late October 2005 as a Category 4 hurricane, bringing sustained wind speeds of 67 ms^{-1}, and storm waves with significant wave heights (H_s) ≈ 13 m; this is the most intense storm recorded to date in the Atlantic Basin (Pasch, 2006). The storm persisted for over 20 hours, while storm waves inundated the low lying barrier beaches and rainfall flooded inland wetlands and lagoons.

This study examines the immediate and post-storm shoreline response of shore-attached barrier beaches on predominately natural sections of the northeastern Yucatan Peninsula to Hurricane Wilma. The beaches studied are situated between Punta Nizuc in the north and Playa del Secreto in the south, an expanse of approximately 35 km (Figure 1). The study area has been broken into six zones based on the exposure to waves, barrier beach morphology (barrier beach width and foredune height), and the extent of coastal infrastructure development.

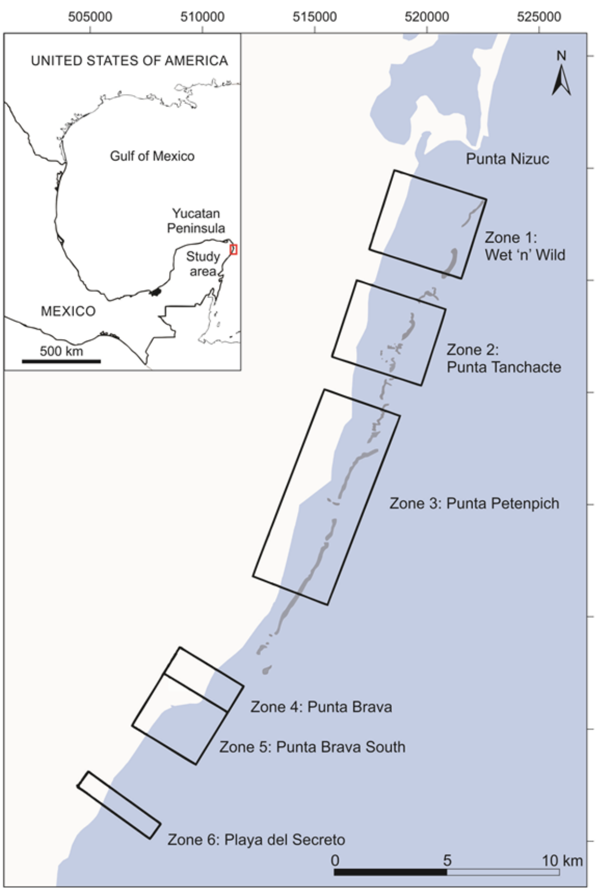

Figure 1. Location of the study area on the northeastern Yucatan Peninsula, Mexico. The six zones investigated in this study are outlined.

METHODS

Imagery from Digital Globe's Quickbird Two Satellite was used to map shoreline change resulting from Hurricane Wilma. The imagery was also used in conjunction with beach profile data to measure post-storm readjustment. The images analysed were taken prior to Hurricane Wilma, immediately following the passage of the storm, and a number of times following the event (2006 and 2010). The images were georeferenced and georectified, and ground truthed during on-site assessment in April 2010.

Dune crest data, captured using a GPS during ground truthing, was used as the baseline position from which all satellite imagery measurements of beach width were taken. The measurements were taken across-shore to mean high water (MHW), marked by the line of seagrass debris during calm periods and the wetted line following Hurricane Wilma. MHW is often used as a shoreline indicator when measuring shoreline change, and provides an accurate point of comparison under normal conditions (Moore, 2000; Boak and Turner, 2005). However, under storm conditions there is greater error (Boak and Turner, 2005).

RESULTS

Hurricane Wilma had a dramatic impact on the low-lying barrier beaches of northeastern Yucatan Peninsula. Results from two contrasting sites, Punta Tanchacte, a reef-protected barrier beach, and Punta Brava, an exposed section of coastline, are presented here in detail.

Punta Tanchacte is situated behind a fringing reef which encloses a lagoon 1.35 - 1.80 km wide and 3 - 4 m deep (Figure 2). It is characterised by the highest foredunes in the study area, which range from 3.0 - 6.5 m above MHW.

Figure 2. Punta Tanchacte, showing the location of the transects measured in this study.

Storm waves from Hurricane Wilma reworked the beach and part of the foredune at Punta Tanchacte. Lower sections of foredune were overtopped, and the beach widened to 78.2 ± 8.6 m. This represented an average increase of 16.3 ± 3.9 m, but varied from 24.6 m at the southern end to 7.7 m in the north.

By June 2006, eight months after Hurricane Wilma, the beach had narrowed to 74.7 ± 8.3 m. However, this was highly variable, with the greatest erosion experienced at the southern end (9.7 m), no change in the centre of the zone, and shoreline accretion further north (2.7 m). By April 2010, a further 48 months later, the beach had undergone continued erosion at all sites, with an average reduction of 11.8 ± 5.7 m since June 2006, amounting to 15.5 ± 4.9 m since Hurricane Wilma (Figure 3).

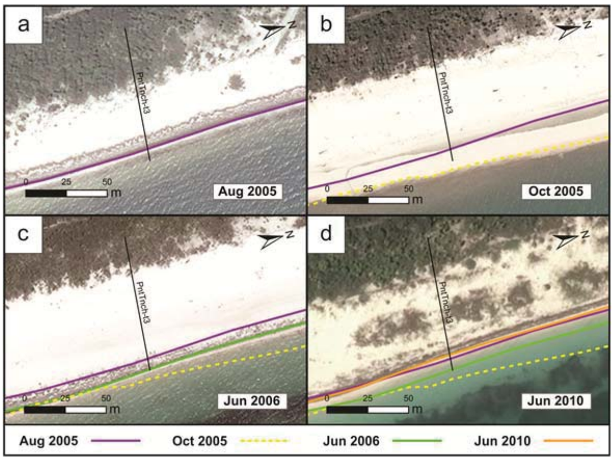

Figure 3. Shoreline change at Punta Tanchacte showing (a) pre-storm, (b) immediately post-storm, (c) and (d) following Hurricane Wilma.

In contrast, Punta Brava, situated in the south of the study area, is directly exposed to waves from the Caribbean Sea due to its location within a gap in the Mesoamerican Reef Tract (Figure 4). The site has a relatively steep shoreface, and the dunes reach up to 3.0 m above MHW.

Storm waves inundated the site during Hurricane Wilma, reworking and overwashing the beach and foredune. Considerable volumes of sediment, including large coral boulders, were transferred into the backdune and mangrove wetlands. As a result, the barrier beach eroded by an average of 5.3 ± 4.8 m, with the greatest erosion at the southernmost site.

By June 2006, the barrier beach had undergone some shoreline recovery. The response was, however, highly variable, with on average 6.3 ± 6.7 m of accretion. The barrier beach was therefore 1.1 ± 2.0 m wider than the pre-storm beach width, indicating the shoreline had largely recovered. By June 2010, the shoreline had shifted once again, with shoreline transgression of up to 4.4 m at the northern and southern ends of the site, contrasting beach accretion of 2.8 m in the centre (Figure 5). This indicates that the prevailing energy regime, and other site-specific factors, contribute to regular shoreline movement at Punta Brava.

Figure 4. Punta Brava (top box), showing the location of the transects measured in this study.

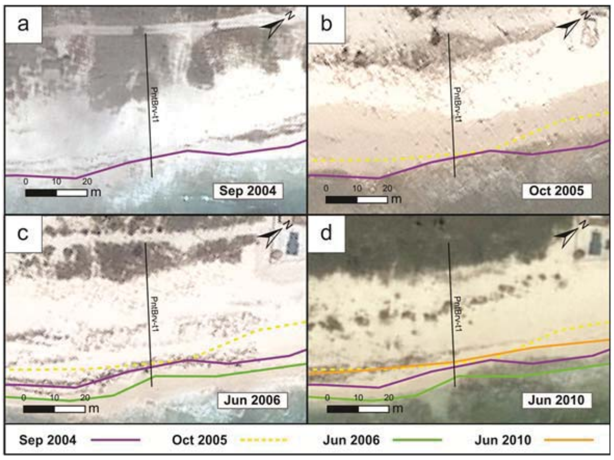

Figure 5. Shoreline change at Punta Brava showing (a) pre-storm, (b) immediately post-storm, (c) and (d) following Hurricane Wilma.

Shoreline response to Hurricane Wilma and post-storm recovery varied considerably across the other areas investigated (Table 1). Similar to Punta Tanchacte, Wet 'n' Wild and Punta Petenpich experienced storm-driven shoreline accretion, followed by post-storm shoreline erosion. However, shoreline response was highly variable, and was also influenced by coastal development at Punta Petenpich. Similar to Punta Brava, Punta Brava South and Playa del Secreto experienced storm-driven erosion, followed by regular post-storm shoreline fluctuations.

Table 1. *Variation in beach width (m) across the study area from 2004/05 to June 2010.*

Site	Pre-storm 2004/05	Immediate post-storm Oct 2005	Post-storm Jun 2006	Post-storm Jun 2010	Δ 2004/05 - Jun 2010
Wet 'n' Wild	34.5 ± 5.1	49.5 ± 5.2	45.3 ± 4.9	35.9 ± 5.7	+ 1.4
Punta Tanchacte	61.9 ± 9.0	78.2 ± 8.6	74.6 ± 8.3	62.9 ± 9.0	+ 1.0
Punta Petenpich	-	-	45.0 ± 16.4	37.5 ± 17.3	-
Punta Brava	29.3 ± 1.4	24.0 ± 5.2	30.3 ± 2.7	29.2 ± 1.6	- 0.1
Punta Brava South	26.1 ± 3.6	21.6 ± 1.4	22.8 ± 8.8	17.1 ± 6.9	- 9.0
Playa del Secreto	36.1	27.6	35.2	29.0	- 7.1

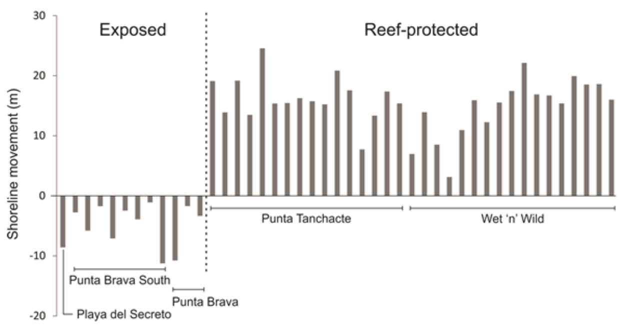

Figure 6. Immediate shoreline response driven by Hurricane Wilma.

DISCUSSION

Tropical storms can drive considerable geomorphic changes on barrier beaches in a short period of time. Storm surge, combined with large storm-generated waves, can remove large quantities of sediment from the beach and dune system and transport it offshore, alongshore, or, if the inundation is great enough, wash sediment inland (Morton and Sallenger, 2003).

Local environmental factors and conditions influence the distribution of wave energy at the shoreline, and therefore determine the way sediment is redistributed across the system. The presence of dissipative structures (such as coral reefs), pre-storm beach morphology, and storm duration and intensity can all influence storm-driven shoreline response (Sallenger, 2000; Morton, 2002).

Wave heights recorded during Hurricane Wilma showed that there was a significant difference between waves in the backreef lagoon and in areas exposed to the Caribbean Sea. Coral reefs were found to dissipate wave energy by over 80%; as such, reef-protected beaches were inundated by storm waves of up to only $H_s \approx 2.4$ m, while exposed sections of coastline were subject to waves of up to $H_s \approx 13$ m (Blanchon *et al*., 2010).

Based on the considerable difference in wave energy reaching reef-protected and unprotected beaches, it would be expected that different patterns of storm-driven sediment redistribution would result from Hurricane Wilma. As outlined earlier, a clear distinction was observed between the storm-driven response of reef-protected and unprotected barrier beaches in this study; the former accreted by up to 24.6 m, while the latter eroded by up to 11.3 m. While the magnitude of erosion and accretion varied alongshore, all sites followed this distinct pattern (Figure 6). The presence or absence of coral reefs evidently is the primary determining factor driving immediate shoreline response on these barrier beach systems.

In the months and years following tropical storms and hurricanes, barrier beaches tend to recover towards their pre-storm conditions (Morton *et al*., 1994). Following Hurricane Wilma, the wave energy regime of northeastern Yucatan Peninsula was characterised by relatively low energy conditions. Reef-protected and exposed barrier beaches again showed different responses.

Despite the low-energy conditions following Hurricane Wilma, approximately a quarter (24%) of the accreted shoreline on reef-protected barrier beaches eroded within eight months. This is likely due to the most easily reworked beach features, such as the beachface and sand bars, being realigned with wave swash under the prevailing conditions. This trend continued over the following years, with many of the beaches returning to their pre-storm shoreline position within 54 months. This likely represents the equilibrium shoreline position of these barrier beaches under current climatic conditions. However, the post-storm recovery was found to be more variable than the initial storm-driven response.

Exposed barrier beaches, in contrast, tended to return to their pre-storm shoreline position relatively quickly (within eight months of the storm), then fluctuated about this position. This indicates that the impact of tropical storms and hurricanes on exposed barrier beaches is only clearly evident in the short term, after which the prevailing conditions are the major control on shoreline position.

On the northeastern Yucatan Peninsula, the return period of storms similar to Hurricane Wilma where $H_s > 12$ m has been calculated by Silva-Casarín *et al*. (2009) to be 100 years; storms producing waves of $H_s \approx 8$-10 m have a calculated return period of 5-10 years. These lengthy return periods indicate that the barrier beaches of northeastern Yucatan Peninsula likely have sufficient time to readjust post-storm to their equilibrium shoreline position, prior to the landfall of another storm on a similar scale. Therefore, under current climatic conditions, tropical storms and hurricanes strongly influence barrier beach evolution over the short (0-8 months) to medium terms (8-54 months) on the northeastern Yucatan Peninsula; however, they may be less influential over the longer term. The varying responses of reef-protected and exposed barrier beaches to tropical storms and hurricanes, as they relate to storm intensity and return period, are conceptualised in Figure 7.

However, future climatic change is predicted to result in increased intensity of major tropical storms and hurricanes, and subsequently an increase in the scale of their geomorphic impacts. As a result, the barrier beaches of northeastern Yucatan Peninsula may be more frequently inundated by waves greater than 8 m or even 12 m, with the return period of the most intense storms likely to reduce. If this occurs, the difference between the beach recovery time and the storm recurrence interval would become shorter. Over time, these high energy events may start to have greater influence on the longer-term evolution of barrier beaches, with successive catastrophic storms potentially making landfall prior to full beach recovery. This could result in a landward shift of the long-term equilibrium shoreline position.

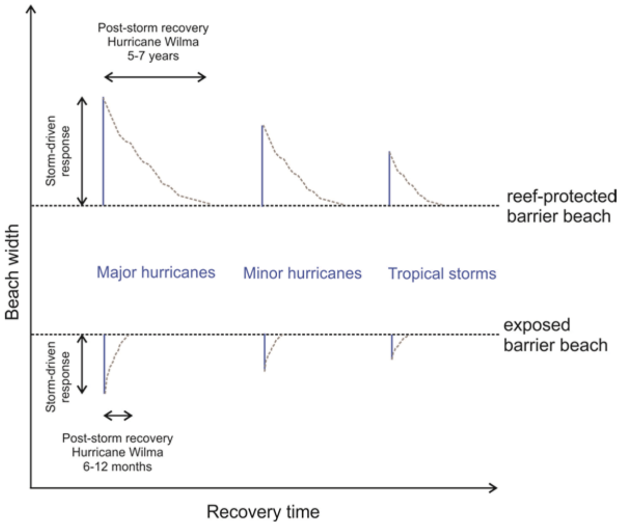

Figure 7. Conceptual model of barrier beach width change and post-storm recovery time, with respect to storm intensity.

CONCLUSIONS

This study found that the barrier beaches of the northeastern Yucatan Peninsula responded to Hurricane Wilma in two broadly different ways. Reef-protected beaches underwent rapid accretion during the passage of the storm, followed by gradual erosion over subsequent years. In contrast, exposed barrier beaches were eroded during the storm and then rapidly accreted back to their pre-storm shoreline position.

Under contemporary climatic conditions, tropical storms and hurricanes were found to be key drivers of barrier beach evolution over the short to medium terms. These events are considered less influential over longer time scales due to current storm recurrence intervals generally exceeding barrier beach recovery times. An expected increase in the intensity of major storms in the future may increase the significance of hurricanes to longer-term barrier evolution; storm impacts are likely to be greater and storm recurrence intervals may be shorter than the time required for recovery.

However, of potentially greater immediate impact to the study area, development on the Yucatan Peninsula is progressively extending along this coastline. The construction of seawalls and other structures will restrict shoreline movement and across-shore sediment exchange, inhibiting the natural dynamics of barrier beaches, and reducing their resilience to future storm events.

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