COMPARATIVE MORPHODYNAMICS BETWEEN EXPOSED AND REEF PROTECTED BEACHES UNDER HURRICANE CONDITIONS

I. Mariño-Tapia [1], C. Enriquez [2], R. Silva-Casarín[3], E. Mendoza-Baldwin[3], E. Escalante Mancera[4], F. Ruiz-Rentaría[4]

It has been widely documented that coral reefs play a very important role in the dissipation of wave energy. Observations of beach morphology, made before and after a major hurricane that hit SE Mexico in October 2005 (Wilma), show widespread erosion at an exposed beach (Cancun), but unexpected beach accretion 25 km south at a beach fronted by a fringing reef (Puerto Morelos). The DELFT 3D morphodynamic model is used at a regional scale to explain the divergent morphological behavior of both beaches and explore the processes involved at both sites. A combination of offshore transport at the exposed beach, large scale southward sediment transport and onshore transport along the reef protected beaches seems to be the main explanation for the observed morphological behavior. Dune erosion and beach face sand relocation are also partially responsible for the beach progradation at the reef protected site.

Keywords: coral reefs; hurricanes; sediment transport

INTRODUCTION

Beaches fronted by fringing reefs have efficient means of natural protection, and are generally more stable and less prone to erosion than exposed beaches The reason is twofold, on one hand the reef structure causes waves to shoal and break, reducing wave energy by an average of 97% (Ferrario, et al. 2014); on the other hand the high roughness elements (coral reef colonies) also dissipate a considerable amount of wave energy. Recent modeling studies have also shown that reefs with diminished roughness can have ~ 30% larger significant wave heights inside reef lagoons than a reef with high roughness values (Franklin, et al. 2013). This problem is particularly important since there is a clear trend of decreasing reef roughness that has been reported for the Caribbean over the last 40 years (Alvarez-Filip et al., 2009). This can have serious implications for ecosystem functioning and coastal protection, since an extreme loss of roughness could also alter the cross reef bathymetric shape. It is likely that the beach retreat observed in some Caribbean sites is linked to coral degradation and the associated increase in wave energy at the coast (Ruiz de Alegria, et al. 2013, Odériz, et al., 2014). The reasons for the loss of structural complexity are varied. On one hand we have the effects of ecological phase shifts, where reefs change from coral to algae-dominated environments (Done, 1992). This process is mainly linked to inappropriate environmental management, such as overfishing of herbivores and excess nutrient and pollutant input from coastal developments. On the other hand we have the effects of climate change, such as temperature increase, linked to coral bleaching, and the effects of ocean acidification (Pandolfi et al., 2011). Changes in atmospheric CO_2 concentration can alter the aragonite saturation state (ASS) of the ocean. As ASS levels drop, the ability of species such as corals and shelled invertebrates to create calcium carbonate structures diminishes (De'ath et al. 2009; Silva et al., 2014). It has been argued that governments and businesses are increasingly interested in identifying where nature based solutions could be a cost effective coastal defense strategy (Ferrario, et al. 2014). In the case of coral reefs, this could encourage investments to enhance reef resilience and reverse the collapsing tendency that reef ecosystems are currently experiencing.

One of the most obvious ways of assessing the role of coral reefs on beach morphodynamics, is to perform a comparative study of two sites subjected to very similar offshore wave conditions but with a different morphological setting (i.e. reef vs no reef). In this study, these conditions are met; therefore, the morphological response and sediment transport processes under hurricane conditions can be assessed at an exposed beach (Cancun) and at a beach protected by a reef (Puerto Morelos). It is very well known that under energetic wave conditions, beach circulation is dominated by undertow currents (Longuet-Higgins, 1983; Thornton, et al. 1996), which drive sediments offshore and generate beach and dune erosion. This process is expected to dominate at the exposed beach, but could also be acting on reef fronted beaches if the distance between the reef crest and the beach is long enough, and if

[1] CINVESTAV-Mérida, Antigua carretera a Progreso km 6, Merida, Yucatan, 97310, Mexico
[2]Faculty of Science, UNAM, Puerto de Abrigo, S/N, Sisal, Hunucma, Yucatán, 97356, México
[3] Instituto de Ingeniería, UNAM, Ciudad Universitaria, Coyoacan, D.F, 04510, México
[4] Instituto de Ciencias del Mar y Limnologia, UNAM, Prol. Av. Niños Héroes s/n, Puerto Morelos, Q. Roo, 77580 Mexico,

waves are not too attenuated by the reef crest. On the other hand, circulation in fringing reef systems is also dominated by wave breaking processes, but in this case waves break on the seaward reef slope generating strong onshore cross-reef flows towards the reef lagoon (Hearn, 1999; Gourlay and Colleter, 2005; Coronado, et al. 2007) which can potentially drive sediment onshore over the reef crest, towards the beach and lagoon. This process could be especially important during energetic hurricane conditions. The present contribution will examine the sediment transport processes that occur under hurricane conditions at a regional scale (O[10km]) including nearshore wave-driven processes, and shelf scale dynamics using a 3D numerical model.

THE STUDY SITE

The site of study is located along the NE corner of the Yucatan peninsula, in the state of Quintana Roo, Mexico, from Cancun beach to Puerto Morelos (PM)|. Figure 1 shows the bathymetry of the area which has a general shelf slope of 1:100, is fairly uniform across the entire region, with important differences in the nearshore. The beaches of Cancun and Puerto Morelos are composed of medium carbonate sand of biogenic origin, and the mean sediment sizes are ~0.4 and ~0.2 mm, respectively. The beach of Puerto Morelos is fronted by a fairly uniform fringing reef which extends 4 km alongshore and creates a ~2 km wide shallow reef lagoon of 3 to 4 m depth. The beach is more dissipative and linear. To the north of Puerto Morelos the reef becomes more fragmented and the reef lagoon is larger (~ 4 km wide). Cancun (~25 km north of PM) is a steep beach with no fronting reef and therefore has a very active morphology that often presents clear signs of rhythmicity and nearshore sandbar dynamics.

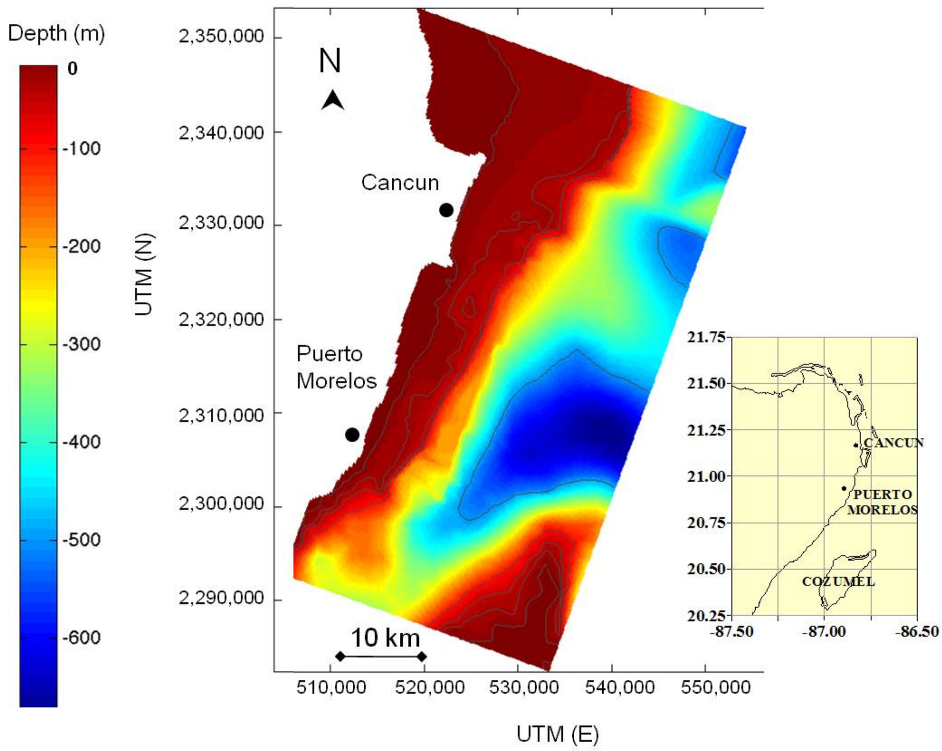

Figure 1. Bathymetry of the study site. The region also comprises the numerical model domain.

The astronomic sea level variations in the region are small with a mean tidal range of ~0.17 m and semi-diurnal dominance. Low frequency sea level variability also occurs due to geostrophic balance of the Yucatan current, generating a decrease in surface elevation at the coast when the current intensifies. The amplitude of such oscillations could be in the order of 0.3 m (Coronado, et al., 2007).

The dominant waves approach the region from east/southeast, are of low energy (Hs ~ 0.5–1.5 m) and short period (Tp = 4 – 6 s). From May to October the incidence of hurricanes is common, and these can generate very large wave heights of longer periods (Hs = 6–15 m; Tp = 8–12) (e.g. Silva et al., 2009, Escalante, et al., 2009 and Silva et al., 2012). Northerly energetic waves (Hs = 2–3 m) of longer period (Tm = 6–8 s) occur frequently from November to April due to the transit of cold fronts (Ruiz de Alegria-Arzaburu et al., 2013 and Gonzalez-Leija et al., 2013).

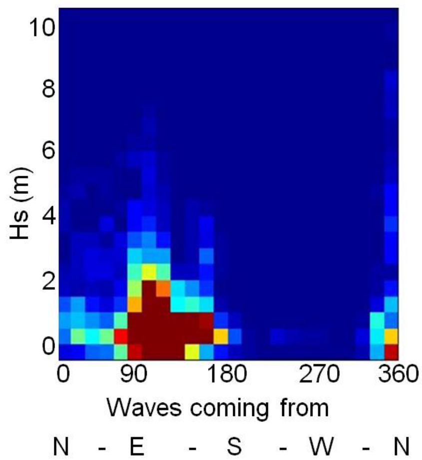

Figure 2. Wave statistics from NOAA buoy 42056, located at 4684 m depth, 120 nautical miles ESE of Cozumel Island. The Figure shows one year of data (2010).

NUMERICAL MODEL SET UP AND DATA SOURCES

The numerical model used to investigate the hydrodynamics and sediment transport processes at shelf scale is the DELFT 3D numerical model, with a domain that encompasses an area of approximately 50 x 30 km, as presented in Figure 1. The mesh has 152 x 249 points with a minimum grid resolution of 125 m, and 10 vertical levels with sigma coordinates. The time step was set to 0.2 min to achieve stability. Waves measured at 20 m depth with an acoustic Doppler profiler (Nortek-AWAC) in front of Puerto Morelos were propagated with the SWAN model. More details on the Doppler profiler measurements are given by Silva et al. (2006), Mariño-Tapia et al. (2008), and Silva et al. (2009). The wave and hydrodynamic models were two-way coupled, where the wave model would provide the radiation stress tensor to the flow model to calculate wave driven currents, and the hydrodynamic model updates water levels and accounts for refraction by currents, which change wave propagation. Sediment transport is calculated using the Van Rijn method and is also coupled with the wave and hydrodynamic models so that the bathymetric changes affect both the currents and the waves.

Two scenarios were modeled; the first scenario was forced with the measured surface elevation and wave-driven dynamics (Hs, Tp, θ, directional spread, and JONSWAP spectra with $\gamma = 5$). The second scenario also included wind effects. The wind intensity and direction were obtained from the high resolution wind products of NOAA (Hurricane Research Division) for hurricane Wilma, in the closest grid point to Puerto Morelos. The spatial behavior of the wind within the model domain was uniform enough, hence a time varying but spatially constant wind stress was used to force the surface boundary. to define a unique wind direction for the entire domain.

The data that quantifies the amount of morphological change experienced by Cancun beach as a consequence of the passage of hurricane Wilma was acquired during two field campaigns where beach profiles were measured every 150 m with a differential GPS (Ashtec ProMark 2) along the 12 km beach fronting the Caribbean Sea. The campaigns were carried out in August 2005, after the passage of hurricane Emily, and on October 25, three days after the passage of hurricane Wilma (Silva et al. 2006). Beach profiles were not measured at Puerto Morelos, therefore, morphological change was qualitatively assessed with in situ photography and satellite images (Quickbird) from before (April 2005) and after (October 2005) the hurricane.

RESULTS

Figure 3 shows the data measured by the acoustic profiler (AWAC) at 20 m depth, and the vertical lines indicate the moments where numerical results will be shown (Figures 4 to 6), namely at the start of the storm (October 20 00:00), at the peak of the significant wave height (October 2118:00), and at minimum set down, once the hurricane made landfall (October 2312:00). This figure shows the measured significant wave height (a), peak spectral period (b), mean wave direction (c), sea level (d), velocity magnitude (e) velocity direction (f), and atmospheric pressure as an indication of the hurricane proximity (g).

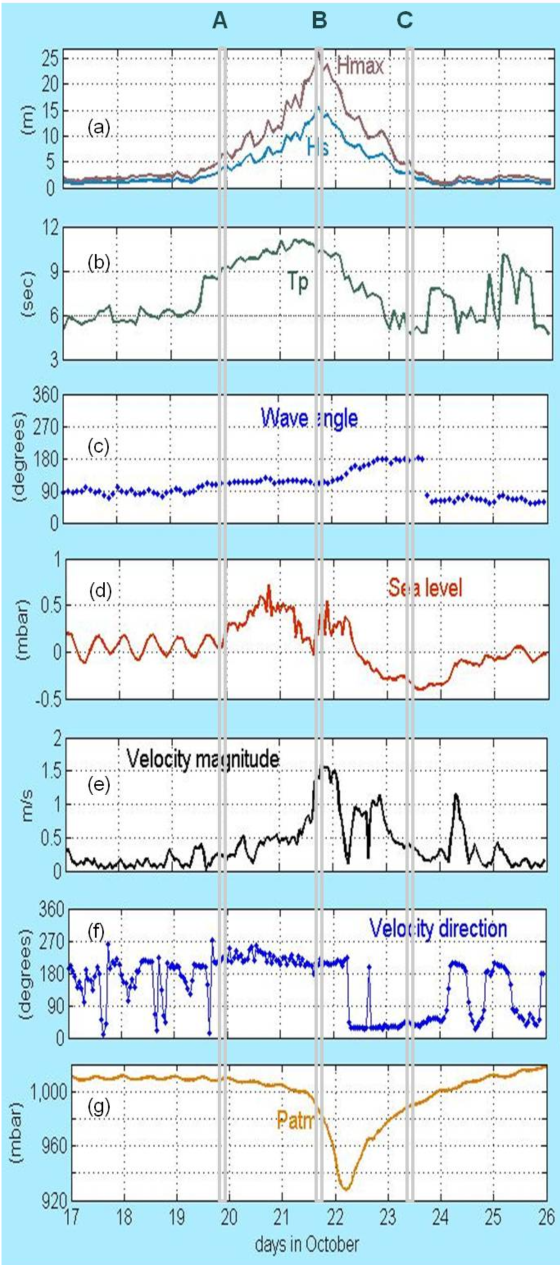

Figure 3. Hydrodynamic conditions imposed by hurricane Wilma, as measured by an AWAC (Nortek) installed at 20 m depth offshore of the reef crest at Puerto Morelos. The figure also shows atmospheric pressure measured at a local meteorological station.

The effects of Hurricane Wilma on the local dynamics were evident on October 20, when wave heights started to build up, wave periods started to increase, and tidal variability vanished to be replaced by storm surges. By October 21, 42 hours later, wave heights reached their maximum, with values of Hs

~15 m, maximum southward currents of 1.5 m/s, and a secondary storm surge of 0.5 m. From this moment onwards the storm started to wane. The eye of the storm passed over the instrument early on October 22 prior to making landfall, drastically altering wind direction with consequent changes in current and sea level patterns. During October 23 at 12:00 a minimum set down, northward currents, and diminishing waves were recorded 27 hours after the hurricane made landfall.

Figures 4, 5 and 6 show the detailed dynamics generated at the three moments indicated in Figure 3 with vertical lines. The panel on the left shows the bottom circulation generated by waves only (a), the middle panel is also the circulation at the bottom but including waves and winds (b), and the right panel shows the sediment transport patterns at the bottom for the scenario corresponding to waves and winds.

On October 20 at 00:00 hrs, when the storm started (Figure 4), wave driven currents on the exposed beach had a clear offshore trend, whilst inside the reef lagoons (cells close to coast) currents were random with no clear patterns. When winds are included in the simulation (Figure 4b), the trend of offshore transport along the exposed beach and southward movement offshore becomes quite clear. For this scenario, currents are small inside the reef lagoons, and near bottom sediment transport is clearly directed onshore along most reef lagoons to the south of Cancun (Figure 4c).

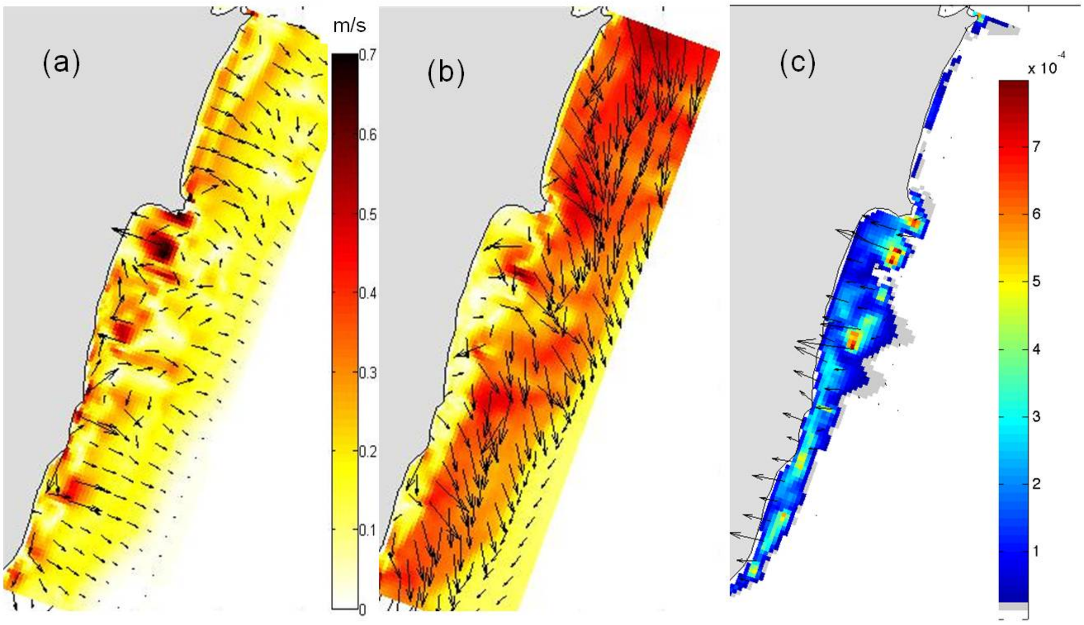

Figure 4. Near-bottom modeled currents for October 20 2005 00:00. (a) Wave and surface elevation forcing, (b) wave, winds and surface elevation, (c) near-bottom sediment transport for the wave + wind scenario (m^3/s/m).

After 42 hours, during the peak of the storm (maximum Hs and currents), wave driven currents are still offshore along the exposed beach but also along the reef lagoons (Figure 5a). Inclusion of the wind-driven dynamics shows that the main tendency is southward, everywhere, with an important onshore component along the reef lagoons (Figure 5b). Sediment transport is very active in the offshore side of the reef, but less so inside the reef lagoons, and with an onshore tendency when present. From this moment onwards the storm starts to wane but the sediment transport processes remain the same, up to the point when the hurricane makes landfall in the early hours of October 22. When this occurs, the wind pattern radically changes and winds blow towards the NE, seawards. This situation in turn, drastically changes the circulation pattern (see Figure 3e and f) and develops a very prominent set down (Figure 3g).

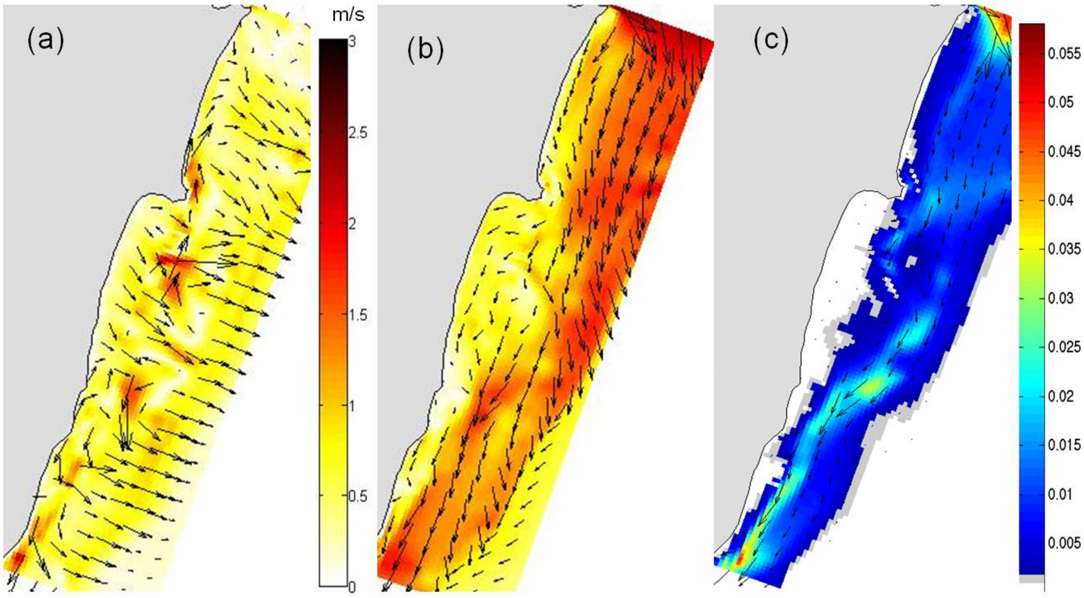

Figure 5. Near-bottom modeled currents for October 21 2005 18:00. (a) wave and surface elevation forcing, (b)wave, winds and surface elevation, (c) near-bottom sediment transport for the wave + wind scenario (m^3/s/m).

On October 23 12:00, set down levels are at their minimum, but waves and currents have diminished considerably. Wave driven flows are strongly onshore along both reef lagoons, and circulation is predominantly northward. Sediment transport values are in general very small.

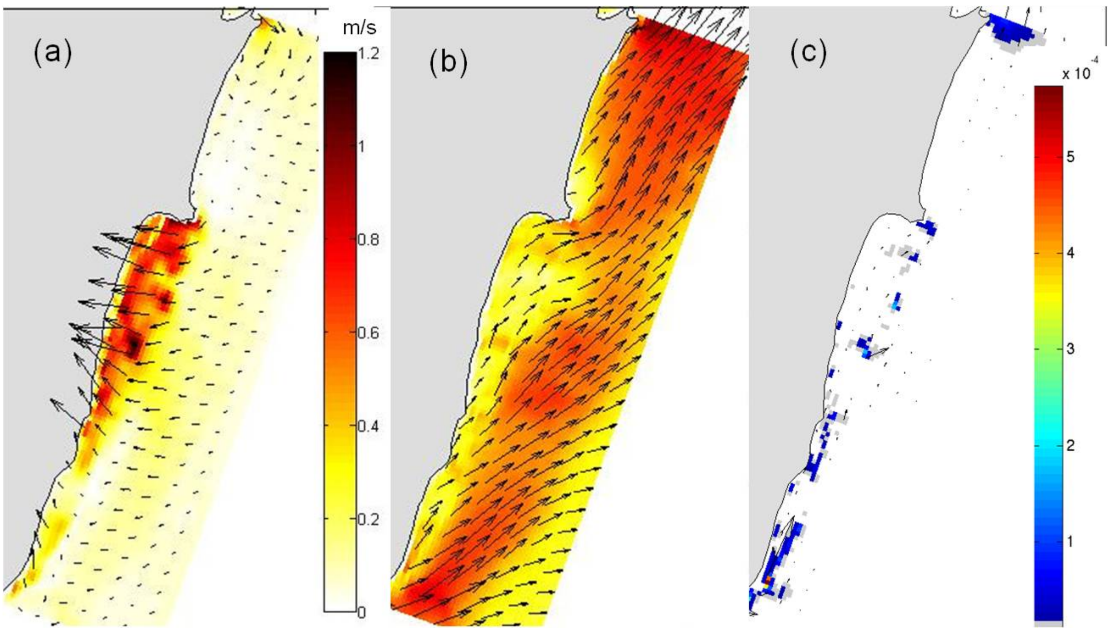

Figure 6. Near-bottom modeled currents for October 23 2005 12:00. (a) wave and surface elevation forcing, (b)wave, winds and surface elevation, (c) near-bottom sediment transport for the wave + wind scenario (m^3/s/m).

DISCUSSION

Circulation and sediment transport patterns presented in Figures 4 to 6 are able to explain the overwhelming erosion observed at Cancun (Silva, et al. 2006). Modeling results suggest that wave-driven offshore currents dominate along the exposed beach from the start of the storm until when it leaves the peninsula. This is approximately 3.5 days of continuous offshore sediment transport. Similarly, wind-driven shelf currents act southwards persistently and with a very high intensity of 1.5 – 2.5 m/s. This current transports the sediment that is exported from Cancun beach to the south, until the moment Wilma makes landfall (October 22, 3:00), when the current is forced northwards by the wind. Inside the reef lagoons, the model suggests that sediment transport is very clearly driven onshore at the beginning of the event, and to the south from the peak of the storm onwards. One important characteristic of the reef lagoons is the diminished currents and waves compared to the circulation offshore of the reef. This would enhance sediment deposition and beach growth. Figure 7 shows photographs of before and after the hurricane's impact at Cancun and Puerto Morelos.

Figure 7. Photographic sequence of the beach at Cancun (above) and Puerto Morelos (below) before and after the hurricane.

The rather dramatic erosion experienced by sections of Cancun beach is what would, somehow be expected from a major hurricane. This was thoroughly documented by Silva et al. (2006). However, the observations of beach accretion along large portions of the beach at Puerto Morelos are rather unexpected. It is well known that coral reefs are capable of protecting the coasts from erosion by the attenuation of wave energy (Ruiz de Alegría, et al. 2013; Ferrario, et al. 2014), but beach progradation (~ 30 m) under very large hurricane conditions (Hs_{max} ~ 15 m), is to the authors best knowledge unprecedented. Unfortunately, no beach profiles are available for Puerto Morelos following the hurricane, nevertheless Quickbird satellite images exist. A preliminary analysis of such images confirms the considerable beach growth shown by the in situ photographic evidence (e.g. Figure 7). Additionally, the Quickbird images clearly show that along many sections of the beach the vegetated dune was also eroded, which very likely contributed to beach accretion. Nevertheless, the accretion was very uniform along the PM coast, and not only located where a healthy dune existed. There was beach accretion even at sites where the dune was already occupied by buildings (Silva et al. 2014).

CONCLUSIONS

A 3D morphodynamic numerical model was set up to study the sediment transport processes driven by hurricane conditions (waves, currents, water levels and wind) at a regional scale that includes a beach exposed directly to wave energy (Cancun) and a beach protected by a fringing coral reef (Puerto Morelos). Widespread erosion was observed at Cancun and substantial (30 m) beach accretion was observed at Puerto Morelos.

Although dune erosion at the protected site could account for part of the sand gained on the beach, satellite images and the results from the numerical model strongly suggest an important contribution of sand from northern beaches. Three main processes are proposed to contribute to this:

- At the exposed beach offshore sediment transport dominated throughout the event, as would be expected for storms at beaches. The lack of a dune buffer at the site, due to the presence of buildings, aggravated the observed beach erosion.
- Shelf currents, dominated by the effect of hurricane winds, drove circulation southwards for approximately 50 hrs during the most energetic part of the event. This carried large amounts of sediment to the south. When the hurricane made landfall, currents reversed (northward) but sediment transport was considerably diminished as the storm was waning.
- Sediment transport patterns as the storm was growing, strongly suggest that onshore sand transport dominated at the reef lagoons. At the peak of the storm, circulation was more dominated by wind, driving sand southwards, but as soon as the hurricane made landfall and sea level decreased, wave dissipation over the reef must have increased. A calmer lagoon would promote sand deposition and beach growth.

The behavior of the beach during this event is a strong reminder of the importance of coral reefs for the protection of the coast. In this case and due to the particular conditions of hurricane Wilma, the presence of the reef not only protected the beach but induced its growth.

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