HYDRODYNAMICS OVER SAND DUNES IN THE NORTHERN YUCATÁN PENINSULA COAST

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Abstract

The existence of shallow submerged dunes in the northern Yucatan coast, and its possible downdrift contribution to beach morphodynamics is not well understood. In fact, the low energy environment and the shallowness of the inner Yucatan shelf do not invite to relate these prominent and well-structured features with previous studies of coastal bedform evolution. Through field experiments, data analysis and numerical simulations, this study pretends to contribute to the understanding of the mobility of these formations. Here we present the environmental setup, a general overview of the field data, and some preliminary numerical simulation results, showing that the observed mobility of the dunes is in general terms well reproduced by the model, inviting us to pursue this effort.

Key words: shallow sand dunes, coastal morphodynamics, Yucatán continental shelf

1. Introduction

Beach erosion and beach loss in the Yucatán Coast is a major problem (Mendoza *et. al*, 2013), translated in natural habitat and property loss in numerous areas of the coast (e.g., Figure 1). Several engineering projects have been undertaken trying to solve the problem, but most of if not all of them have failed. The reasons are diverse, related in part to insufficient funds to finance appropriate large-scale engineering interventions and in part to other non-technical aspects. However, the most important reasons are related to a lack of a fully understanding of the hydrodynamic and morphodynamic processes involved in this area, including the effects of the extent of the shallow continental shelf, the existence of submerged sand dunes, as well as the influence of the existing coastal infrastructure in the regional beach equilibrium.

In particular, two aspects have not been studied closely in the northern coast of the Yucatan peninsula: on one hand, the effects on wave and current propagation to the coast, as well as on sediment transport and beach morphodynamics, of the existing shallow and wide continental shelf, with an average width of 245 km and a slope ranging from 1/1000 (Enriquez *et. al*, 2010) to 1/2000 in the first 100 km from the coastline (see Figure 2 for a general view). In fact, this extended continental shelf represents a feature that dissipates storm waves from distances far offshore of the order of tens of kilometers, which, together with a small tidal amplitude (0.10-0.80 m neap-spring amplitude), confers to the coastal zone a low energy regime in practically all circumstances. On the other hand, although some morphodynamic studies have been undertaken in the area (Cuevas-Jiménez and Euán-Ávila, 2009; Appendini *et. al*, 2012) the dynamics of existing shallow bed forms present in the inner continental have not been studied, as well as its role in the nearshore and beach morphodynamics.

Indeed, large submerged bed forms are relatively common features in the inner continental shelf around the world. They range from megaripples, to sand dunes, sandbars, sand banks and sand ridges. Their origin, persistence and dynamics are diverse, and in most cases they actively participate in the beach sand budget in different space and time scales. In particular, sand dunes can play an important role in conveying

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longshore transport in shallow shelves and non-linear shorelines, especially in low energy coasts with persistent unidirectional currents.

Recent studies have focused on the classification of these features (Dyer and Huntley, 1999), on their occurrence, formation and persistence (e.g., Trowbridge, J.H. 1995, Traykovski and Goff, 2003, Gutierrez et al., 2005), and on modeling the formation and evolution of submerged bed forms (e.g., Coco et al., 2006a and 2006b), suggesting some sort of self-organization but also a close functionality with the wave climate and its variability, water depth and sediment sorting, as well as association with longshore sediment transport (Murray and Thieler, 2004).In most cases, these studies agree in the fact that the large submerged bedforms exist in areas where the wave and/or current energy is relatively large, which is not precisely the case in the northern Yucatan coast (Enriquez et. al, 2010; Appendini et. al, 2013) due to the slope of the inner continental shelf, where even storm waves are small (Hs<1m) and currents do not exceed 0.40 m.s-1.

Furthermore, Dyer and Huntley (1999) suggest a geomorphic classification covering: (i) open shelf ridges, (ii) estuary mouth ridges or deltas and (iii) headland associated banks. In particular, the type (i) are present in mostly all sandy shallow tidal seas (as is the case in Yucatan), with currents exceeding 0.5 $m.s^{-1}$, but he reports that these formations average typically 13 km width and tens of meters in height, which again is not the case in Yucatan.

Therefore, the existence of these submerged features in a low energy and shallow coastal environment remains unexplained.

Figure 1. Example of severe beach erosion and property loss in the Northern Yucatán Coast.

Given the above, the motivation for this ongoing study is to try to identify the mechanisms responsible for the formation and evolution of the bedforms present in this low energy coast, and try to evaluate to what extend their mobility, or lack of it, is related to the beach erosion problem, which is more severe downdrift of these features. The intent is to address these aspects at two scales: first, through modeling of the hydrodynamics and sediment transport, and later by means of the analysis of high frequency measurements of currents in four locations on and around a dune field.

2. Study Site

First a description of the northern Yucatan coast is presented, followed by a description of the specific site selected.

The northern Yucatan coast is characterized by a low lying coastal area, where 57% of its length is formed by coastal lagoons with barrier islands and 43% is ocean front, and 85% of this ocean front is sandy coast (CINVESTAV, 2007). The sediment is mostly medium size sand (D_{50} ranging from 0.25 to 0.35 mm), and terrigeneous cohesive sediments are scarce, due to the absence of fluvial systems (Cuevas et. al, 2013). On the bottom floor, unconsolidated sand layer thickness is small, except in some localized areas and in particular where sand dune fields are present. As mentioned above, the wide and shallow continental shelf dissipates most of the outer-shelf wave energy in all conditions, and the currents are also mild (0.1-0.3 $m.s^{-1}$), modulated by wind and the Yucatan current (Enriquez et. al, 2010). The tide is mixed, predominantly diurnal due to an M_2 anphidromic point off the Yucatán Shelf (Salles et. al, 2012), with a range from 0.1 to 0.8 m. Longshore transport is predominantly to the West (Appendini et. al, 2012). Figure 2 (adapted from Appendini et. al, 2012), shows the potential erosive, depositional and stable sections of the northern Yucatan coast, suggesting large sections of severe erosive trends.

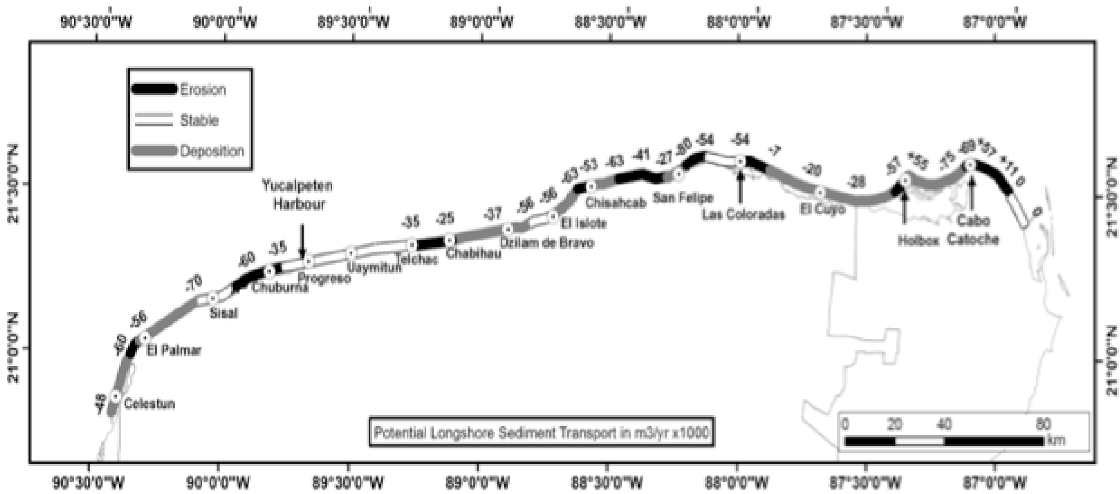

Figure 2. Potential erosive, depositional and stable sections of the northern Yucatan coast (adapted from Appendini et al., 2012).

In addition, as previously mentioned, this coast also presents several zones where dune fields can be identified, in particular in its Eastern section. It is interesting to point out that the most severe beach erosion occurs in the western portion of this coast, where no dune fields are present. This may be partly due to the accumulative effect of coastal infrastructure (groins), but also can be related to the lack of these bedforms.

Figure 3 shows four prominent locations where these submerged formations are present. In some cases they seem to exist where a curvature of the coastline is present (inset b), as if they convey a detached longshore transport. In other areas (inset d) they seem to be the mechanism for bypass across a large inlet. Insets (a) and (e) show how in some places these large features migrate and attach to the beach shoreface. The mean water depth where they are present ranges approximately from 1.5m at the southern (onshore) boundary of the fields to 4 m and up to 6 in some locations at their offshore boundary. The mean height of these bedforms range from 0.8 to 2.3 m, and the mean wavelength from 100 to 330 m (Cuevas et. al, 2013).

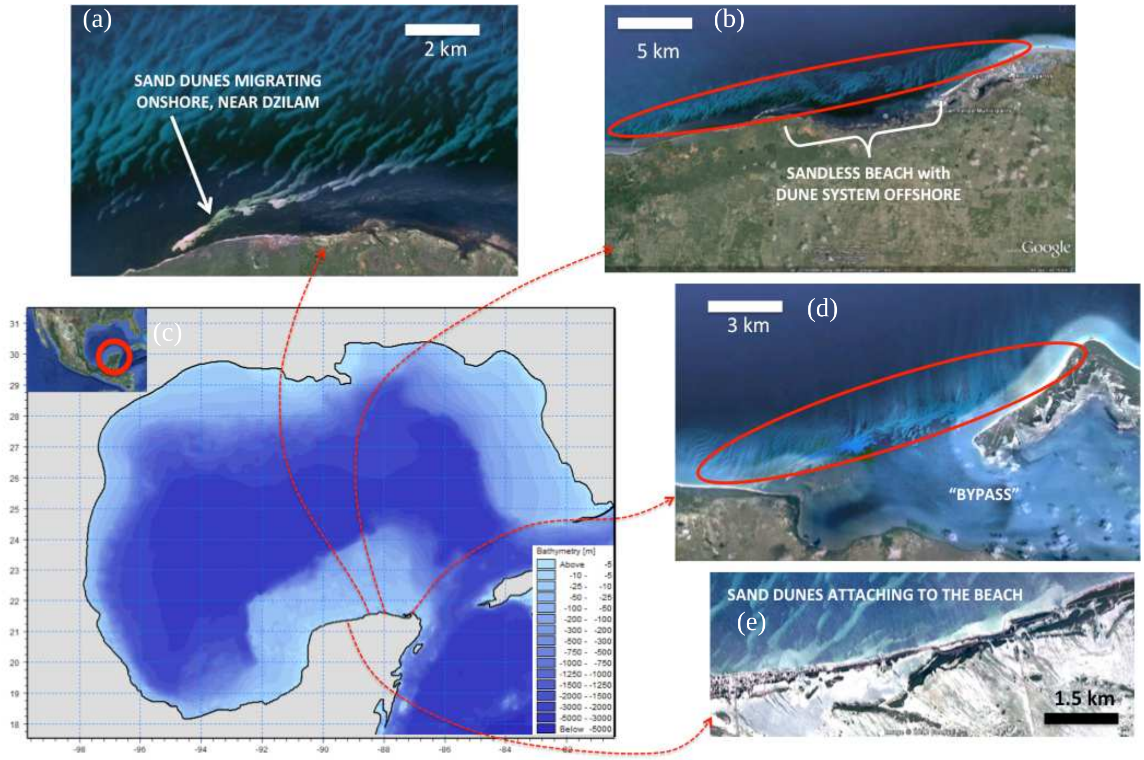

Figure 3. Map of the location and adjacent batymetry of the Yucatan península in the southern end of the Gulf of Mexico (inset c), and four examples of the most prominent areas where submerged dune fields are present.

The site selected for this study is near the town and shelter port of Dzilam de Bravo (21º23'N, 88º53'W), approximately 90 km northeast of the state capital Merida (Figure 4). According to Cuevas et. al (2013), who performed a morphological assessment with seismic data using a sub-bottom profiler along three representative profiles surveying a total of 50 dunes, this site presents 2-D and 3-D well-structured and prominent dunes with a height ranging from 0.2 to 1.7 m (μ=0.9m and σ=0.4m) and a wavelength ranging from 44 to 253 m. The mean distance between dunes was reported to range 195m to 273m. In addition, the authors report a marked asymmetry of the dune profiles, and suggest westward mobility of the dunes, in accordance with the direction of the longshore sediment transport.

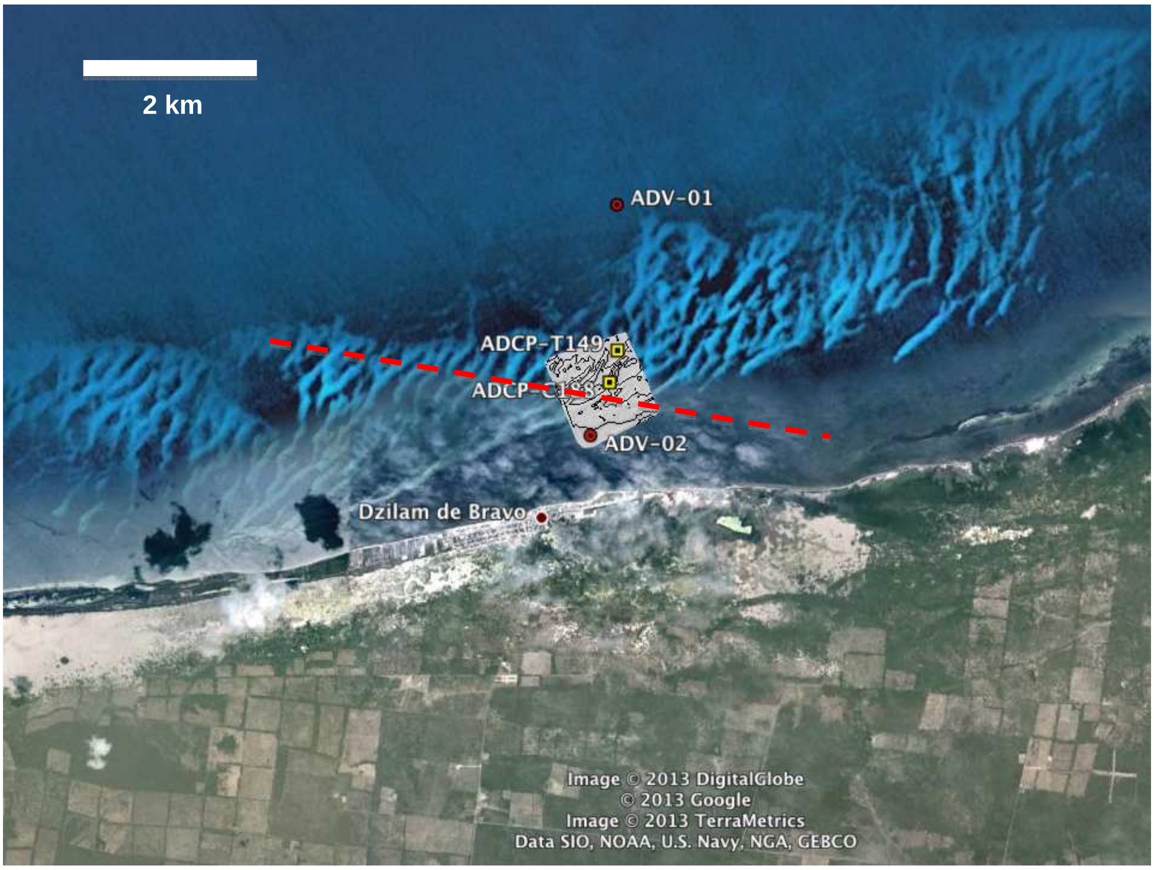

Figure 4. Study Site, near Dzilam de Bravo (21º23’N, 88º53’W). The location of the instruments is marked, together with the approximate location of one of the Cuevas et. al (2013) transects (red line). The white square corresponds to area selected for the high-resolution bathymetric surveys.

3. Field Measurements

To characterize the hydrodynamics in the site, three field campaigns were undertaken to measure waves and currents, and to perform bathymetric surveys and collect sediment samples.

The area covered by the bathymetric surveys has a surface of approximately 1 km2, and is shown as a white square in Figure 3. The first two bathymetric surveys were performed in 2012, before and after the peak of the winter cold front season (*Nortes* season, which is characterized by northerly cold front with winds roughly ranging from 8 to 20 m.s-1).

Figure 5 shows the comparison between these two surveys, and it can be seen that some mobility was detected. The comparison suggests that the mobility of the dunes, or at least their transformation (breaching, tip erosion) is not negligible, and that a new dune or shoal formed in the south of the surveyed area.

The third survey was done in early March 2013, at the same time of the current-meter survey described below, and was used to set up the models mesh.

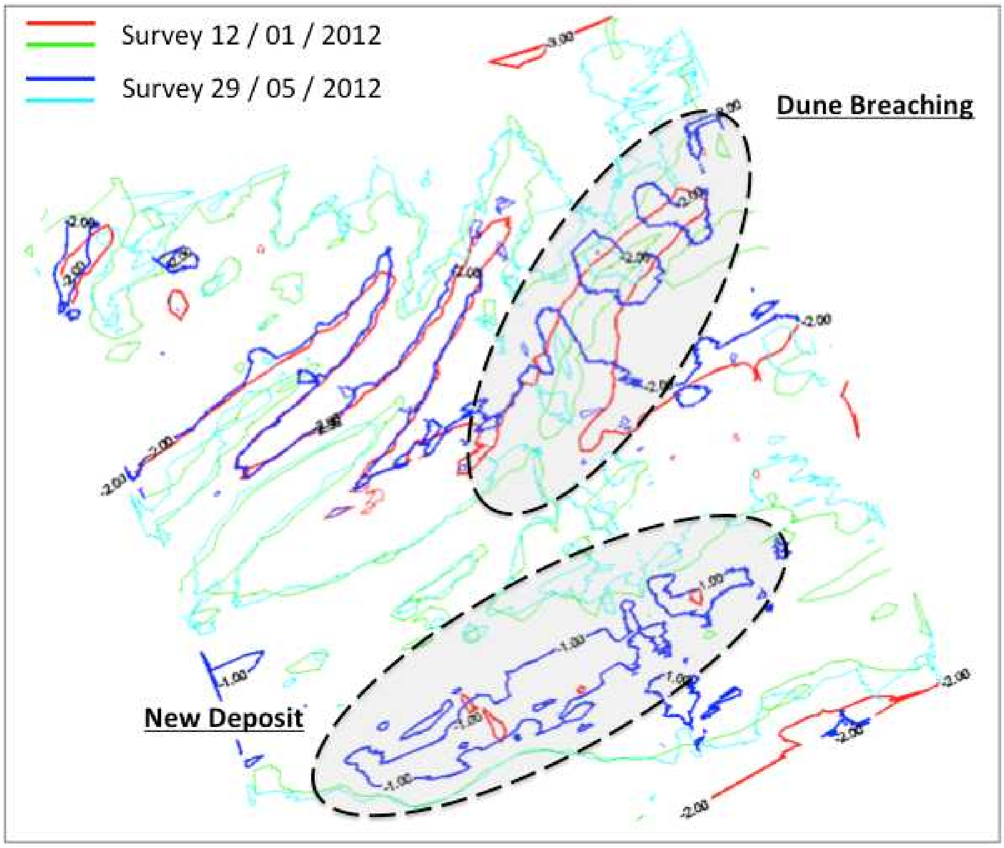

Figure 5. Bathymetry comparison from surveys before and after the peak of the winter storm season in 2012.

The waves and currents were measured with four instruments deployed from February 27th to March 5 2013, during a northerly cold front event which lasted 4 days, with winds up to 10 m.s^{-1}. Two Sontek ADV were installed offshore and onshore the dune field, measuring at 16 Hz, 20 minutes every hour. In addition, two RDI ADCPs were deployed in a dune crest and a dune trough, measuring continuously at 2 Hz. These data sets are being used for two purposes: first, to calibrate and validate numerical hydrodynamic and sediment transport models, implemented to investigate the eventual dune mobility, and second to evaluate the Reynolds stresses and the turbulent kinetic energy dissipation and production in the different areas of the dune field where the instruments were installed. In this document, only preliminary model results are presented, together with some general observations of the current, wave and wind measurements. The finer TKE variability over the different sites on and around the dune field and its eventual contribution on sediment transport gradients and dune mobility is left for further analysis.

Figure 6 shows some of the data collected with the ADV (see location in Figure 3): the surface water level (panel A), the significant wave height Hs (panel B), both from the ADV-02, current speed from both ADV (panel C), corresponding current direction (panel D), and wind vectors (panel E).

What can be drawn from this data is:

- the wave height is modulated by the surface water elevation: during high tide the waves are larger than during low tide. This is mainly due to the shallowness of the water column, and to the fact that this spot (ADV-02) is protected by the even shallower dune field. Unfortunately the ADV-01 pressure sensor failed, making difficult estimate the wave height in that spot.
- The main driving force responsible for the currents seems to be the wind. However, the current direction from both instruments is mainly West during most of the *Norte* event (from time 58.5 to time 61.0). For the offshore site the current remains that way until time 61.5 but for the onshore site the current direction becomes more erratic. After that, when the wind intensity decreases and shits direction from the West (time from 61.0 to 61.5) the current direction changes to East and remains

that way even if the wind recovers strength and blows again from the north (time 62.0 to 63.0).

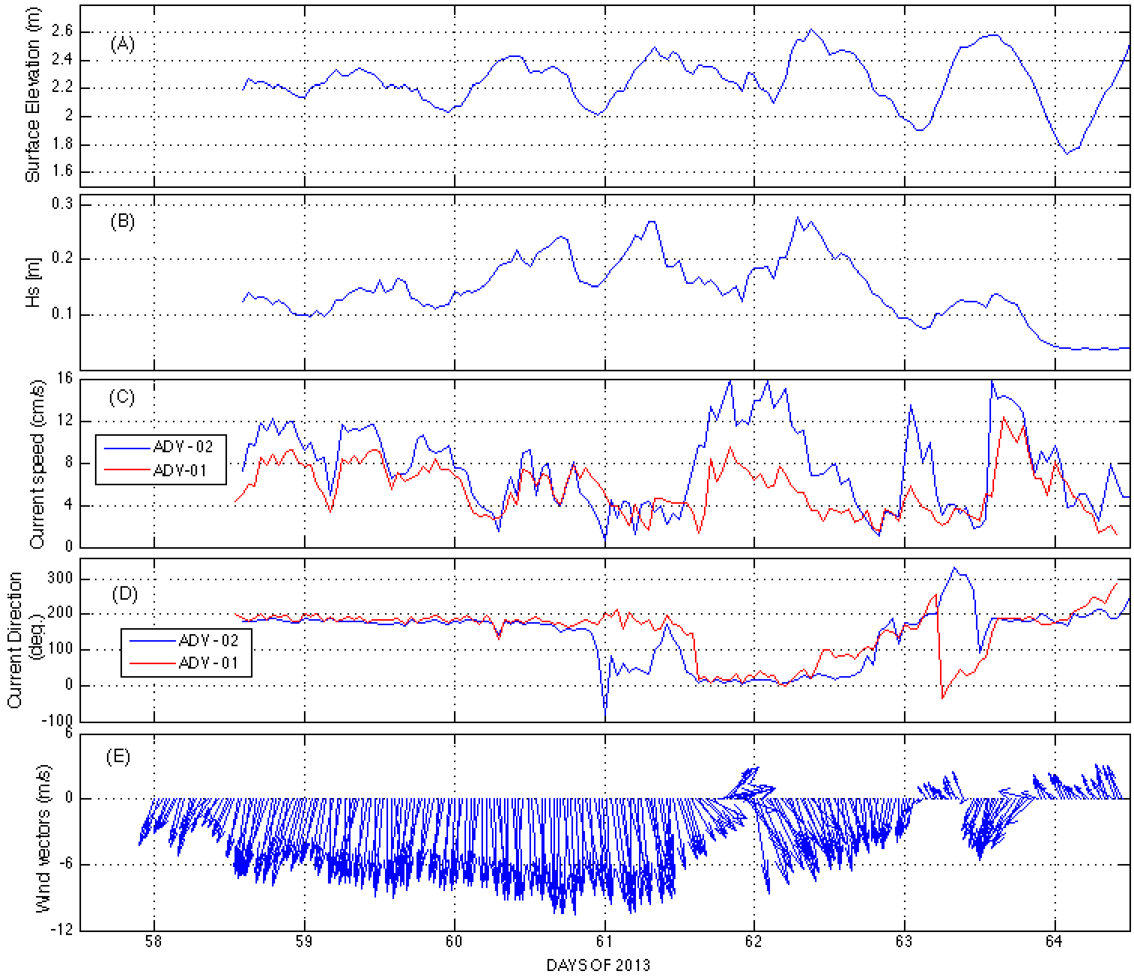

Figure 6. Wind and currents data from the ADV (offshore, ADV1, and onshore, ADV2, of the dune field): surface water level (panel A), significant wave height (panel B), both from the ADV-02, current speed from both ADV (panel C), corresponding current direction (panel D), and wind vectors (panel E).

4. Numerical Modelling

The hydrodynamics (waves and currents), sediment transport capacity and bed level changes were simulated using the MIKE21 unstructured mesh suit of models:

- Spectral wave module, SW, which simulates the growth, decay and transformation of wind-generated waves and swell in offshore and coastal areas (DHI 2009), using for these simulations a directionally decoupled parametric formulation for the spectral description, and a quasi stationary time formulation. These preliminary simulations were performed prescribing in the northern boundary a significant wave height of 2m at 10 m water depth, a peak wave period of 8s, and a mean wave direction of 45 degrees.
- Hydrodynamic module (HD), based on the numerical solution of the 2-D incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure. More details can be found in DHI (2011b). The preliminary runs used as forcing in the eastern boundary the measured surface elevation, zero flux in the northern boundary and 0m surface elevation in the western boundary.
- Sediment transport module, ST (DHI 2011) for non-cohesive sediments, which is coupled with the

SW and HD modules to recompute the waves, currents and bathymetry changes iteratively for each time step (or a number of time steps). These preliminary simulations used a sediment with a D_{50} of 0.335 mm and a porosity of 0.4.

The model was forced with the measured wind and water surface elevation. Figure 7 shows an example of the validation, and it can be seen that the model represents adequately the currents.

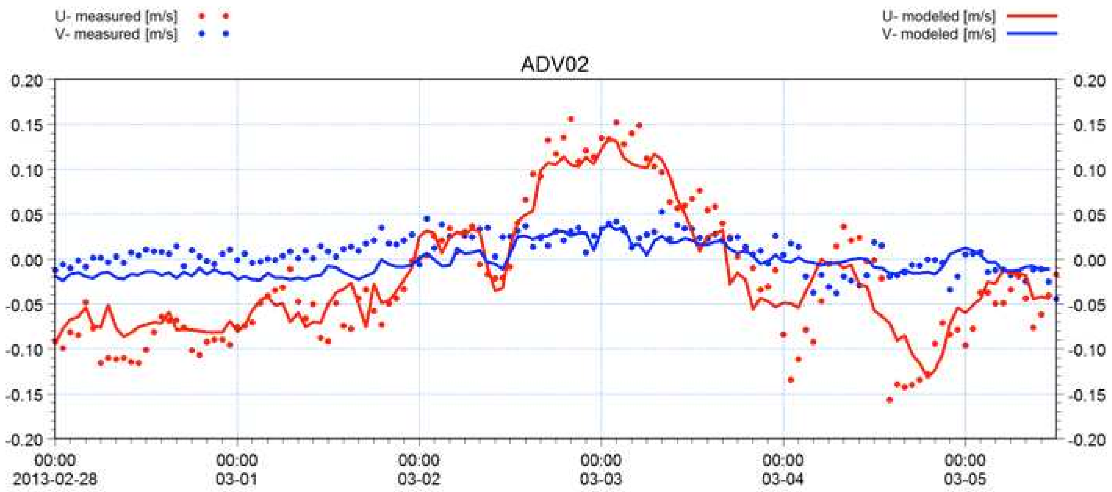

Figure 7. Model validation. Measured vs. Modeled currents in the onshore ADV location.

Figure 8 shows the bathymetry used for the simulations derived from a general bathymetric survey, complemented with the third high-resolution bathymetry surveyed in march 2013. It also shows the currents at a given time of the simulation when the wind was blowing from the north. It can be noticed that the currents follow the bathymetric contours, especially in the northern edge of the dune field. However, over the dune field and onshore from it the current direction appears to be more erratic.

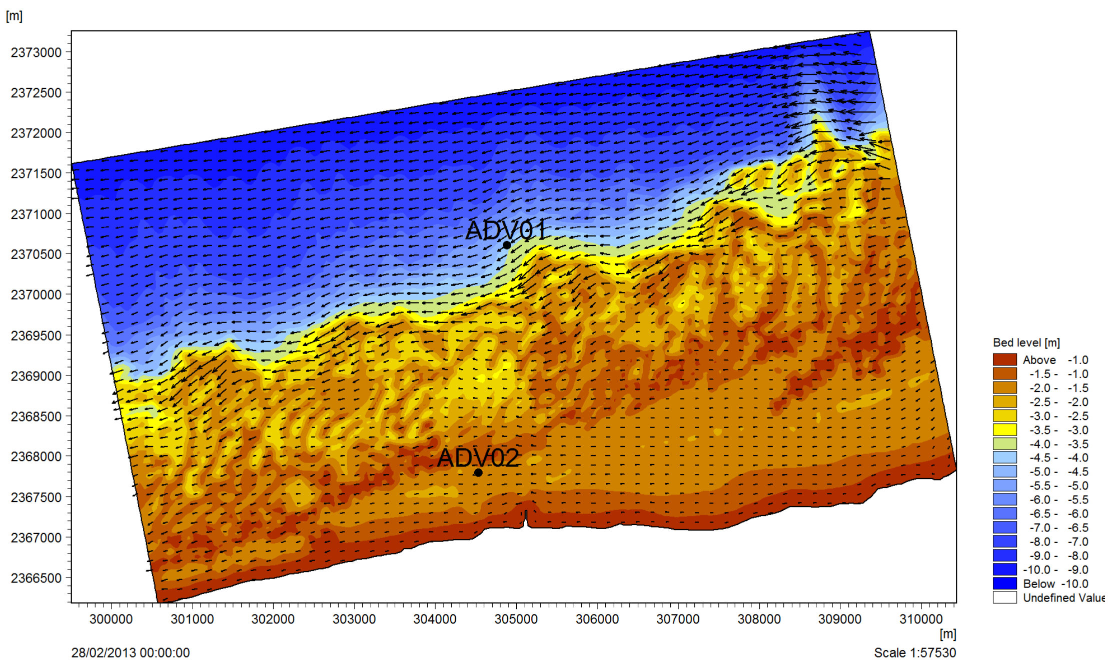

Figure 8. Initial bathymetry used to run the models.

Finally, Figure 9 shows the rate of bed level change resulting from the model runs using as forcing the measured wind, 10m depth waves and water surface elevation. The model result suggests that the mobility of the dunes is not negligible, with an erosion/deposition daily rate up to 4 cm, with mild storm conditions.

Although these model runs are preliminary, they look promising in the sense that they reproduce with at least a relative quantitative realism the mobility observed in the field.

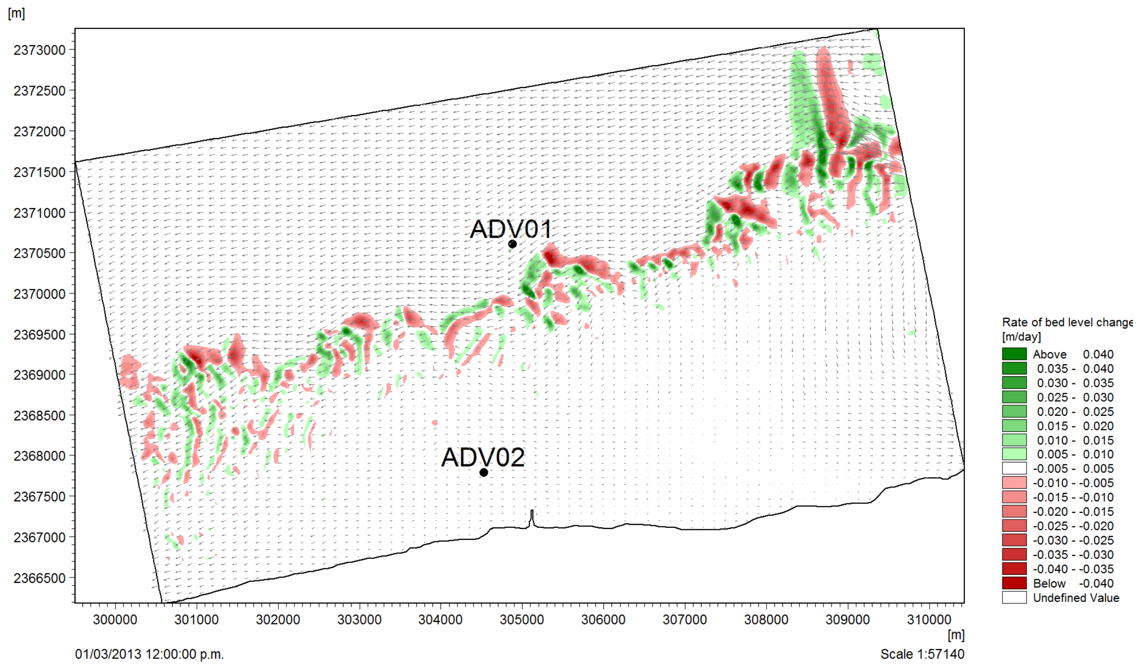

Figure 9. Simulated rate of bed level change.

5. Conclusions

The numerical simulations results seem to reproduce with some level of confidence the hydrodynamics and morphodynamics in the study area.

More extensive numerical simulations with different forcing scenarios, as well as a finer analysis of the high frequency data are needed if we pretend to authentically contribute to the understanding of the formation and evolution of these shallow but large and prominent bedforms.

6. References

Appendini, C.M., P. Salles, E.T. Mendoza, J. López y A. Torres-Freyermuth. 2012. Longshore sediment transport on the Northern coast of the Yucatan Peninsula, *Journal of Coastal Research*. 28-6: 1404-1417. ISSN: 0749-0208.

Appendini, C.M., A. Torres-Freyermuth, F. Oropeza, P. Salles, J. López y E.T. Mendoza. 2013. "Wave modeling performance in the Gulf of Mexico and Western Caribbean: Wind reanalyses assessment", *Applied Ocean Research*. 39: 20-30.

CINVESTAV, 2007. Programa de ordenamiento ecológico del territorio costero del Estado de Yucatán (POETCY), 41 pp

Cuevas E. , Liceaga-Correa M.A., Rincón-Sandoval L., Mexicano-Cíntora G., Arellano-Méndez L., Euán-Ávila J.I., Hernández-Núñez H., Mulsow S., 2013. Morphological and sedimentological assessment of submarine dune fields on the coast of Yucatan, Mexico. Ciencias Marinas, 39(1): 83-99.

Cuevas-Jiménez, A. and Euán-Ávila, J., 2009. Morphodynamics of carbonate beaches in the Yucatán Peninsula. *Ciencias Marinas*, 35: 307-320

DHI, 2009. MIKE 21. Spectral Wave Module. Scientific Documentation. DHI Water & Environment.

DHI, 2011. LITPACK, An Integrated Modelling System for Littoral Processes And Coastline Kinetics, Short

Introduction and Tutorial. Horsholm, Denmark, 64 pp.
DHI, 2011b. MIKE 21 HD FM. Hydrodynamic Module. Scientific Documentation. Hørsholm, Denmark: DHI Water & Environment.
Dyer, K. R., and D. A. Huntley (1999), The origin, classification and modelling of sand banks and ridges, Cont. Shelf Res.: 19, 1285– 1330
Enriquez, C., Mariño-Tapia, I.J. and Herrera-Silveira, J.A., 2010. Dispersion in the Yucatan coastal zone: Implications for red tide events. *Continental Shelf Research*, 30(2): 127-137
Gutierrez, B. T., G. Voulgaris, and E. R. Thieler (2005), Exploring the persistence of sorted bedforms on the inner-shelf of Wrightsville Beach, North Carolina, *Continental Shelf Research*, 25, 65– 90
Lira-Pantoja, M.A., Torres-Freyermuth, A., Appendini, C.M., Fernandez, D., Salles, P., Mendoza, E.T., Lopez, J., and Pedrozo-Acuña, A., 2012. Chronic Beach Erosion Induced by Coastal Structures in Chelem, Yucatán. *Proceedings of 33rd International Conference on Coastal Engineering*, Santander, Spain, 2012. 10 p.
Mendoza, E.T., Trejo-Rangel., M. A., Salles, P., Appendini, C.M., Lopez-Gonzalez, J. and Torres-Freyermuth, A., 2013. Storm characterization and coastal vulnerability in the Yucatan Peninsula In: Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), Proceedings 12th International Coastal Symposium (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. xxx-xxx, ISSN 0749-0208.
Murray, A. B., and E. R. Thieler (2004), A new hypothesis and exploratory model for the formation of large-scale inner-shelf sediment sorting and ''rippled scour depressions,''. *Continental Shelf Research*, 24: 295– 315.
Salles, P., Mariño-Tapia, I., Winant, C., 2012. Tidal circulation on the Yucatan shelf. *Book of abstracts of the XVII Physics of Estuaries and Coastal Seas Sympisium (PECS 2012)*, 1: 122.
Traykovski, P., Goff, J.A., 2003. Observations and modeling of large and small-scale bedforms at the Martha's Vineyard Coastal Observatory. *Proceedings of Coastal Sediments Conference*, 2003.
Trowbridge, J.H., 1995. A mechanism for the formation and maintenance of shore-oblique sand ridges on storm-dominated shelves. *Journal of Geophysical Research:* 100, 16071-16086

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