1 Introduction

Since the 1960s, scientists around the world have been warning about possible climate changes and their potential effect on the planet. The recent increase in the number and magnitude of hurricanes has been related to global warming [1–3]. Consequently, ecosystems and coastal zones around hurricane trajectories are seen to be more vulnerable. When hurricane Wilma crossed the Yucatan peninsula close to the Cancun beach system, in 2005, approximately seven million cubic meters of sand were removed from the shoreline. This caused an approximate loss of one billion USD in tourist revenue, prompting the Mexican Federal Government to invest more than 50 million USD in a beach nourishment program. On the other hand, the damage caused to the sand barrier also initiated an exceptional natural cleaning process in the Cancun lagoon system (Nichupte–Bojorquez, see Fig. 1, especially at the northern end where over-wash was widespread.

The resort of Cancun offers the tourist long beaches of medium-fine white sand, and the clear, turquoise sea is a perfect place for bathing. Indeed, Cancun is one of the most important tourist resorts in Mexico, with an incomparable infrastructure (148 hotels of 4 and 5 stars, 27,000 hotel rooms) and enviable tourist expenditure (around 2–3 billion USD per year, http://sedetur.qroo.gob.mx/estadisticas/estadisticas.php).

Any extraordinary storm unquestionably modifies the natural state of any beach, but where there have been badly planned, man-made alterations on the coastline which cause erosion under normal conditions, a hurricane will considerably accelerate this process. The present article describes the morphodynamics of the littoral and lagoon systems of Cancun. The wave climate in the region and the characteristics and effects of hurricane Wilma are also presented, and evidence is given of some changes to the littoral and lagoon systems, caused by the hurricane, and which cannot be re-established naturally.

Wilma was a record breaking hurricane in many ways, e.g.: (i) The hurricane occurred in 2005, the warmest year on record and unprecedented in the Atlantic in terms of tropical cyclone activity [4]; (ii) During the strengthening episode the eye of the hurricane contracted to a diameter of 2 n mi, reportedly the smallest eye known to the National Hurricane Center [5]; (iii) The barometric pressure registered by the hurricane was 882 mbar, the lowest recorded for a storm in the Atlantic basin [6]; (iv) Wilma was the fastest growing tropical cyclone, intensifying its wind fields from 60 to 150 kt within just 24 h, an unprecedented event for an Atlantic tropical cyclone (www.ncdc.noaa.gov/special-reports/wilma.html#overview); (v) The hurricane moved very slowly across the Mexican Caribbean, staying over 48 h in the region. Some of the consequences of her passage are still being felt in the region, 6 years on; (vi) For Mexico, Wilma was the most powerful meteorological extreme event, producing a rainfall of 1637 mm in 24 h. It also registered the most intense wind...
for any hurricane observed in Mexico, with a maximum speed of 201.1 km/h on October 21, 2005 at 7 pm [7]; (vii) Finally, the economic losses resulting from the passage of the hurricane were estimated at US$1–3 billion, the highest cost related to any hurricane in Mexico [8].

2 Materials and methods

2.1 Geophysical information of the Cancun beach and lagoon systems

The configuration of the lagoon system results from a series of beach ridges accreted along the mainland coast during the last Pleistocene high stand in sea level. The sea level later fell several meters, during the early stages of the last glacial period, and these carbonate dune ridges were left exposed. Carbonate mud deposits were laid during the Holocene [9]. The lagoon system contains seven water bodies: Bojorquez Lagoon, Nichupte Lagoon (which is formed by North, South and Central basins, San Buenaventura is part of the North Basin), Ingles Lagoon, Caleta Lagoon, and Ciega Lagoon.

Using coastal geo-morphological terminology, the area known as Cancun is classified as a barrier island with a headland beach system. It is in the north east of the Yucatan peninsula, in the state of Quintana Roo, (lat. 21.15° N, lon. 86.79° W to lat. 21.02° N, lon. 86.77° W) on the Mexican Caribbean Sea. The island is around 17 km long and <700 m wide (Fig. 1).

The Yucatan Peninsula is part of a large limestone shelf, of approximately 350 000 km², on top of which lie carbonate rocks and sediments. The Cancun beach system was formed by an accumulation of carbonate grainstone which built a strand plain along the Yucatan coast during the late Pleistocene high stand of sea level (125 000 years ago). The carbonate and oolitic grainstone was mainly deposited by waves and by longshore currents along the prograding mainland shoreline. Punta Cancun and Punta Nizuc are remnants of a Pleistocene eolian ridge, from which tombolos, composed of bioclastic-oolitic sands, extend toward the mainland, intermittently broken by channels linking the lagoon system to the open sea. The Caribbean shore, or barrier island, is composed of fine to medium grained oolitic sands blown into dunes, as high as 17 m. Lithification of the dunes produced a ridge of Holocene limestone. Large breaking waves and strong currents have produced a gentle and often rhythmic configuration on the foreshore of the beach, behind which remnants of hurricane-produced escarpments are preserved at the juncture of the beach with the eolian dunes.

2.2 Morphodynamics of the Cancun beach system

All coastal landforms tend to oscillate around a particular equilibrium. The Cancun beach system is classified as one of dynamic metastable equilibrium [10]; the forms and processes of the beach over time are stable. When an extreme event changes the processes and characteristics of the beach, the equilibrium is modified and Nature tries to recover the conditions and patterns present before the storm. However, if the beach is unable to restore the last equilibrium, the beach will develop a new stage of equilibrium which will be different after another storm or hurricane. In this article, several extreme meteorological events are discussed, being defined as a storm event with offshore significant wave heights $H_s$ $>$4 m; three times the annual average significant wave height.

Fundamental to understanding the morphodynamic behavior of the Cancun littoral system is the wave climate. A hybrid wave model was used to build a wave climate database and shows that over 60 years (1948–2007), under normal conditions, 68% of the time, the waves arrived from the East and the East South East. Wave directions did not change significantly during the year, with the exception of summer, when some waves arrived from the East-Northeast. The range of modeled significant wave heights was 0.5–3 m and that of wave periods was 4–10 s, which exceeds the 1-m threshold for 3066 h/year (35% of the time). Using this framework of wave climate, it is easy to infer that alongshore currents will carry most sediment toward the north. However, there is little evidence of significant sand accumulation at the northern end of the system (Punta Cancun). On the contrary, sand loss is predominant here. This implies that the sand transported toward the north escapes from this littoral cell, offshore, and to the north, driven by the prevailing background shelf currents. Recent analysis of morphological data and the results of propagation models [11] clearly show that refraction and diffraction processes generate a divergence of sediment transport at the far end of Cancun, near Punta Nizuc, generating a divergence of long shore transport and predominant transport to the south. Occasionally, under intense storm events further north, produced by the passage of cold fronts, sediment transport can switch directions and transport southward predominates.
Before the tourist resort was developed, the geomorphology of the area allowed an active exchange of water between the sea and the lagoon and therefore renewal of the lagoon water was possible from time to time. This was especially true under extreme meteorological conditions, when the sea level rose and the storm surge filled the estuarine system and breaching of the barrier island could occur. These temporal channels could drain the excess water, thus cleaning the lagoon, as will be shown later with the numerical modeling results. Another important effect of the infrastructure built on the dunes along the barrier island is that the cross-shore sediment transport induced by wind is now restricted and conditions for the natural regeneration of the dunes no longer exist.

### 2.3 Wave data records

In August 2005, a 1-MHz acoustic Doppler current meter (AWAC) was installed 2 km off Cancun, outside the fringing reef lagoon, at a depth of 20 m. The instrument was set up to measure 1 min velocity averages every 600 s, in 22 cells of 1 m thickness. Sea surface elevations and water temperatures were measured at the same frequency. Wave data was recorded at 2-h intervals, taking 2048 samples at 2 Hz. The instrument manual reports accuracies of 0.25% for the pressure sensor, 1% of measured value for velocity, and 0.01 °C for temperature. These values are small in comparison with the extreme conditions generated by hurricane Wilma in October; the instrument was successfully, and surprisingly, recovered in November. Figure 2 shows the wave height and wind rose diagrams with the data recorded from October 19th to 25th of 2005. The direction of the colored blocks corresponds to that from which the waves and wind were coming.

### 2.4 Wave climate atlas

Reanalysis of data from 1948 to 2007 of wave and wind modeling has been undertaken [12] based on the hybrid wave model WAM-HURAC. This tool has two modules or two sub-models; a parametric model HURAC [13], and a third generation wave model WAM [14], combining the best features of each.

Using the WAM-HURAC model it was possible to: (i) obtain the continuous wave hindcast (WAM), (ii) identify the hurricane and storm dates, (iii) get the storm hindcast (HURAC), and (iv) replace the extreme events data in the normal sea states. The results were validated and tested, using the records of seven buoys which are located in the Gulf of Mexico and Caribbean Sea. In this case, the hurricane Wilma data which these buoys measured were compared with the computed data, producing an average correlation parameter for the seven buoys of 0.89. For more details of the description of the hybrid model and the validation, see [15].

### 2.5 Numerical models

Two different numerical models have been applied in order to reproduce the main storm surge and wave field behavior associated with the passage of hurricane Wilma over the Cancun area: The WAPO and MATO models that have been successfully used in previous studies [16, 17]. In the next paragraphs, a synthesis of the general characteristics is explained.

**WAPO model**: Using a second-order approximation of the modified version of the mild-slope [18], a numerical wave propagation model (WAPO) capable of representing open, partially reflected and fully transmitting conditions for both incoming and outgoing waves was developed. This linear WAPO can solve implicitly refraction, reflection, and diffraction. The model is robust and can be used in complex geometries and has fewer restrictions associated with wave obliqueness at boundaries than traditional models based on the mild-slope equation.

**MATO model**: The numerical model MATO, developed by [19], solves the nonlinear depth-averaged shallow waters equations with a finite volume scheme in two dimensions, and this is based on a Gudonov scheme, using a hierarchical mesh. To resolve inviscid flows, the model employs a Riemann solver to calculate the approximation proposed by Roe.

Time-integration is carried out with a first-order Adams-Bashforth scheme. A 2D hydrodynamic model has the capability to simulate the floods, originated by storm surges, using a module which permits the numeric cells to change from wet to dry.

### 2.6 Photographic sources

Over the years the Coastal Engineering Group of the UNAM has acquired a wide range of aerial, satellite, and video images of...
Cancun. These images have been used to compare the changes in and around the barrier island over the last four decades.

3 Results

3.1 Extreme meteorological events and their effects: Hurricane Wilma

Atlantic hurricanes form around the equator and propagate west, often entering the warm waters of the Caribbean Sea and traveling toward the Gulf of Mexico. The Yucatan peninsula is located between the Gulf of Mexico and the Caribbean Sea and is consequently vulnerable to many hurricanes. Of the extreme meteorological events registered from 1948 to 2007, 47 hurricanes had significant wave heights of >4 m. Of these, 11 events had significant wave heights of >8 m. In these 60 years, Cancun has seen seven hurricanes with significant wave heights of >10 m and four have exceeded a significant wave height of 12 m. The period in which most hurricanes hit Cancun is from July to October, with September being the month in which most hurricanes occur. According to the Wave Climate Atlas for the Mexican Atlantic [12], the average storm duration for significant wave heights of 10–11 m is 11.57 h, whereas for heights of 12–13 m, the average duration is 7 h. Over the period 1948–2007, the Cancun shoreline was affected by $H_s > 12$ m for a total of 22 h well above average. Extreme analysis of wave climate gives the mean return period for storms with significant wave heights of 8–10 m as 5–10 years, while the mean return period of hurricanes which generate significant wave heights of 12–13 m is a 100 years.

The incident directions of the hurricanes show that all events with significant wave heights of over 10 m arrived from the East. In order to characterize the individual hurricanes, the energy generated by each was obtained using the database of the hybrid wave model. To make an energetic comparison between the different hurricanes, a non-dimensional energy parameter was computed. This ratio relates the storm energy of a hurricane with the energy of a standard storm; the energy of this event being equivalent to a storm of 24 h, with the wave energy obtained as a function of the root-mean-square significant wave height of 2 m. This means of standardizing wave energy could be interpreted as a quantification of how many “standard storms” a given region has experienced. It is evident from Fig. 3 that the NE tip of the Yucatan peninsula, where Cancun is located, is the most energetic area in all the Gulf of Mexico and Caribbean Sea, with an equivalent of 100 standard storms being experienced from 1948 to 2007. As previously mentioned, 47 hurricanes have been registered at Cancun, of those, the seven which caused most damage were: Allen (1980), Gilbert (1988), Roxanne (1995), Isidore (2002), Ivan (2004), Emily (2005), and Wilma (2005). Reviewing the maximum significant wave heights (average height of the one-third highest waves) of the hurricanes, it is clear why these seven events are considered the most important: Ivan and Allen developed significant wave heights of 7.6 and 8.6 m, respectively; hurricanes Roxanne and Isidore registered significant wave heights of around 10.5 m, while Emily, Gilbert, and Wilma had heights of 12.3, 12.7, and 12.9 m, respectively. From the data collected, the energy parameters of the hurricanes were calculated. The normalized energy was estimated as the total specific energy of each event divided by the energy equivalent of a storm with significant wave height of 2 m and duration of 24 h. Hurricane Allen exhibited the lowest standard storm energy parameter of the seven hurricanes, Ivan and Roxanne showed energy parameters of 20. Hurricane Gilbert with an energy parameter of 32 had greater significant wave heights, but its energy ratio was less than that of hurricane Isidore which recorded 41. Wilma had the highest energy parameters, with 91 [8]. Examination of the main characteristics of the most important hurricanes which hit Cancun shows that hurricane Wilma was the most powerful extreme meteorological event to have been recorded in the region in the period from 1948 to 2007.

In 2005, hurricane Wilma formed over the north western Caribbean Sea and rapidly became an extremely intense event. This hurricane, with the lowest central pressure recorded for an Atlantic basin hurricane since records began, devastated the North East of the Yucatan Peninsula. Wilma arose from an unusually large, monsoon-like, lower-tropospheric circulation, developing a broad area of disturbed weather over most of the Caribbean Sea. On October 22, Wilma moved from the warm waters of the Caribbean Sea onto the Yucatan mainland between Cancun and Puerto Morelos. As a consequence the mid-tropospheric high pressure area to the north of Wilma dissipated and the hurricane moved slowly northward, crossing and severely battering the area around Cancun to emerge, 24 h later, in the south of the Gulf of Mexico.

In many scientific, engineering, and oceanographic reports, hurricane Gilbert (1988) is considered to be the hurricane which most affected Cancun. However, the erosion generated by Wilma (2005) was unprecedented. In order to explain the extreme morphological behavior, the HURAC model was used to compare the pressure, wind, and wave fields generated by hurricanes Gilbert and Wilma. From the numerical results it was concluded that Gilbert has been the most intense hurricane to affect Cancun, in terms of the surface pressures, wind speeds, and significant wave heights in the period from 1948 to 2007. However, the terrible damage caused by Wilma was due to the duration of the hurricane, as persistent extreme waves and winds raged over the area for an unusually long period [20].

In order to understand the effects of Wilma, a 2D numerical model was implemented [19] for the Cancun region, to study the effect of winds associated with a Category 4 hurricane on the hydrodynamics in the lagoon system, including the effects of storm surge.
Comparing the medium sea level with the storm surge (with sustained winds of 200 km/h from East-West direction) a difference of 4.5 m was recorded (Fig. 4a–e). On the barrier island of Cancun the maximum water level calculated with respect to the terrain level was between 0.4 and 0.6 m. The numerical simulation also demonstrated that a Category 4 hurricane causes the seven water bodies of the lagoon to merge into one large system, allowing active water circulation between them and hence cleaning the lagoons. In addition,
the model predicted that multiple breaching occurs along the barrier island in accordance with photographic evidence from 1970 (Fig. 4f), confirming the strong relationship which exists between the littoral and lagoon systems.

In Fig. 5, the left panel shows the temporal evolution of the storm surge for four points located in Laguna de Buenaventura (Fig. 5a), Laguna de Nichupte (Fig. 5b), Bojorquez Lagoon (Fig. 5c), and in the beach area (Fig. 5d). The right panel of the same figure pinpoints these locations. It can be seen that for the first 15 h of modeling; cell (Fig. 5a) was always in a flooding condition, during the first 6 h cell (Fig. 5b) decreased its level which then increased for the following 9 h, for the first 4.5 h cell (Fig. 5c) decreased its level, then remained dry for 4.5 h, and from the ninth hour began a process of flooding, and, cell (Fig. 5d) decreased its level to become dry in the fourth hour then, after 10 h began flooding. It is worth noting that the level of the dune between cells (Fig. 5c) and (Fig. 5d) is \(< 2 \text{ m}\), so it is clear that communication between the sea and the lagoon of Bojorquez was reached after 14.5 h of modeling.

Numerical experiments suggest that the breaching process could also have a profound effect on the storm surge and therefore on erosion on the frontal beach of the barrier island. The rise in sea level caused by an extreme meteorological event could easily produce over-washing on the undeveloped barrier island, alleviating the storm surge on the remaining coastline and producing milder erosion effects on the sub-aerial beach. But a rigid coastline fixed with manmade structures would restrict the advance of the sea inland, and would produce larger storm surges with increased erosion as the offshore transport process in the stormy surf zones could reach higher up the beach (see Fig. 4).

In order to evaluate the possible wave effects on the coast and taking into account the wave conditions induced by hurricane Wilma, Fig. 2, we applied the WAPO model for the wave dominant condition. Figure 6 shows, from left to right, the instantaneous free-water surface patterns and maximum wave height maps. The wave period \(T = 12 \text{ s}\) and incident wave height \(H = 2 \text{ m}\) with incidence coming from the West-Southwest. The computational domain has a grid size \(\Delta = 12.5 \text{ m}\) and 981 by 361 cells, the cell size was chosen with the same criteria as that suggested by [21], \(\Delta > 12 \text{ cells per wavelength in deep water. These results also show the maximum wave concentrations in the same zones where the maximum storm surges were evaluated (see Fig. 4).}

The increased vulnerability to hurricane damage on the littoral and lagoon systems of Cancun due to sea level rise is undeniable, but it is also necessary to consider the role that anthropogenic changes have had on these systems. The risk and vulnerability parameters in the Cancun systems are increased by intrinsic changes caused by human action; these changes are abrupt erosional adjustments that come about as result of accumulated change without specific external stimuli [22]. Coastal erosion processes have always been present in the Cancun area, but the equilibrium of the systems was previously maintained naturally. Hurricanes are agents which accelerate erosion processes but because the systems have been substantially changed, they are now unable to regain their equilibrium.

4 Discussion

Analysis of satellite images and aerial photographs, points to a direct relationship between the degradation of the littoral environment and the development of the tourist resort. The hurricanes which have hit the shoreline since the 1960s have further deteriorated and made still more vulnerable the beaches of Cancun. From the beginnings of the development (1970–1983), the eroded area on the barrier island was around 60% with respect to the initial beach characteristics. In this time, the eroded surface was approximately 303 000 m². From 1983 to 1990, the eroded area was 218 000 m². During the
1990s, the level of erosion was lower, 19,600 m², though the instability of the system continued. As a consequence of this gradual loss of sand and the lack of natural sand sources, the beach was not able to retain the remaining sand. The eroded surface from April to October 2005, during which time Hurricane Emily struck, was 265,000 m² [23]. Then came hurricane Wilma and in some sections of the barrier island the sand was removed completely, leaving the underlying bedrock exposed (Figs. 7 and 8).

Figure 8 shows that by December 2, 2005: 6 weeks after the hurricane, the southern region of Cancun beach had started a sluggish natural recovery, gaining a thin (∼10 cm thick) sand layer. GPS surveys show that in this same region there had been a sand layer of 1.5 m. Unfortunately, there was an urgent need to artificially recover the beach for economic reasons, therefore a substantial beach nourishment project was started in January 2006 making it impossible to monitor the natural recovery rate of the beach. On the other hand, it is well known that after hurricane Gilbert (1988), Cancun beach was unstable for almost a decade.

Over recent years important ecological changes in the lagoon system have been noted as well as aesthetic changes to its waters. These changes are due to more intensive use of the lagoons and the continuing, permanent modifications of the natural boundaries of the lagoons. The lagoons present different levels of eutrophication, an increase in harmful species (plant and animal) as well as an unpleasant smell noticeable around the lagoons. The eutrophication is considered to be a consequence of excessive tourist development in the form of the construction of hotels, roads, and golf courses on the barrier island, blocking ephemeral and permanent channels. The new rigidity of the system has drastically changed water circulation patterns. Natural breaching, before the tourist resort was developed, allowed the renewal of the lagoon water through the mitigation of the storm surge over the beach, a mechanism which brought equilibrium between the sea levels inside and outside the lagoon, and reduced the erosion potential in the beach system. The recent modifications to the bar restrict both the free flow of water into the lagoon system through ephemeral inlets as well as between the individual water bodies that make up the system. Water in the lagoons is now renewed only partially and is therefore prone to stagnate. Meanwhile on the ocean side of the lagoon there is a greater erosion potential and more storm surge damage due to the increased flows and elevations on the more rigid barrier system, unmitigated by natural breaches or channels (Fig. 9).
During the erosion process at Cancun sand is moved by waves and littoral currents and deposited on the long shore bar and trough. From here sand is then transported offshore from where, due to bathymetric conditions, it cannot return to the long shore bar and the beach. Prior to development the sand lost from the beach used to be recovered from the dunes, but nowadays this natural process cannot occur as tourism infrastructure has been built on top of the dunes. As a result of human activities, the sand from the backshore is deposited on the foreshore and the erosion continues.

Unfortunately, when the tourist resort was developed, only economic profit and social benefits to the area were considered; no adequate coastal management procedures were examined and an understanding of the natural processes affected by human actions was not taken into account.

5 Conclusions

The present contribution analyses the effects of human interventions, made without environmental considerations, at Cancun, Mexico, using a 2D hydrodynamic numerical model MATO which includes the effects of storm surge. The model was run with hurricane winds (sustained 200 km/h) and morphological data gathered from recent bathymetric and topographic surveys but ignoring the presence of manmade structures. The results of the model show that the greatest effects of storm surge occur inside the lagoon. After 7 h of sustained winds the seven water bodies of the lagoon system merge, storm surge reaches 3.4 m and, more importantly, several inlets develop between the ocean and the lagoon. This would have a very important effect on water quality, as water in the lagoon could be renewed. It is also hypothesized that the breaching inlets could alleviate storm surge on the beach front, thereby avoiding extreme erosion and loss of sand to the sea. The numerical results obtained with the WAPO model show that the waves contribute to the breaching process in the same areas.

To understand the behavior of coastal systems the dynamics of all natural agents and processes must be taken into account, as well as the modifications imposed by man; actions which alter the natural balance of the system. In order to understand the changes in natural mechanics and patterns when an extreme meteorological event hits the coast, it is necessary to carry out studies that focus not only on the short term but also include analysis of how the system will respond to any alteration of its elements in the middle and long term. The present problems at Cancun are the result of the way the behavior of the beach was considered independently from the lagoon. This perspective consequently excluded other parts of the littoral system and produced the irreversible alterations that are seen today. Hurricanes are not responsible for permanent damage to Cancun beach; they have only speeded up processes which anthropogenic changes caused.

It is also worth remarking that while hurricanes increase the risk and vulnerability of natural coastal systems and are seen as negative events, for the repercussions they have in society (mainly related to the economy and the loss of human life), they also produce some beneficial effects that can be seen as responsible for re-establishing new phases of stability.

The analysis of the behavior of coastal systems for different time-spans and the study of the interrelationships between all the natural agents and processes have significance in the prevention of undesirable consequences for people and ecosystems under hurricane conditions. For the case of Cancun and probably many other places, in the short term, human modifications to the coast have induced more risk than the climate changes.

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