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# The Impact of an Extreme Storm Event on the Barrier Beach of the Lefkada Lagoon, NE Ionian Sea (Greece)

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## Abstract

The present investigation examines the characteristics of a high energy storm event, that took place on November 9-11, 2007 in the NE Ionian Sea (eastern Mediterranean), and its impact upon the barrier beach that separates the Lefkada lagoon from the open Ionian Sea. The storm event was caused by NW winds with speeds exceeding 20 m/s (40 knots), which have an annual frequency of occurrence less than 0.015%. This high energy event produced waves with >5 m significant offshore height and 9.5 s period; these waves developed on 10$^{th}$ November during the rapid rise of barometric pressure (~1.4 hPa/hr), which followed the barometric pressure drop from 1020.5 hPa at 06:00 (UTC) of 9$^{th}$ November to 1001.7 hPa at 06:00 h (UTC) of 10$^{th}$ November. Secondary breaking at the shoreline produced wave heights >1.5 m, associated with a surge of >0.4 m and a run-up capability of >2.4 m. The waves managed to overtop the barrier beach (elevations ~2.5 m), lowering the seaward side of the barrier beach by 10-30 cm and causing a coastline retreat of 0.9 to 2.2 m; these morphological changes correspond volumetrically to a sediment loss of approximately 8 m$^3$/m of coastline length from the sub-aerial part of the beach. During the last three decades a significant change in the frequency of occurrence and direction (from S-SW-W to N-NW-NE) of severe storms with wind speeds exceeding 40 knots has been recorded, affecting the sediment transport pattern and contributing to the erosion of the north beaches of Lefkada.

**Keywords**: Atmospheric forcing, storm surge, erosion, Eastern Mediterranean, climate change.

## Introduction

Among the large number of processes affecting coastal morphology, extreme storm events have been recognised as one of the major factors responsible for coastal morphological changes such as rapid shoreline retreat and coastal floods that are often responsible for damages and/or destruction of property and infrastructure (Ferreira *et al*., 2006; Paskoff & Kelletat, 1991; Pirazzoli & Tomasin, 2002; Ullmann *et al.,* 2007). In the case of low to moderate wave energy shores, storms have been shown to play the dominant role in beach zone morphodynamics and their overall evolution (*e.g.,* Elliot *et al*., 2006; Seymour *et al*., 2005). Temporary coastal inundation is usually associated with extreme sea levels induced by storms, while coastal erosion is due to the removal of large volumes of beach zone sediment by the interacting nearshore waves and currents, often enhanced by a storm surge. Such coastal processes are expected to become more intense in the future due to the climate change that is expressed either by a faster sea level rise (>3 mm/a for the current century) or by the increased frequency and intensity of sea storms and associated surges (Bindoff *et al*., 2007; Pfeffer *et al*., 2008; Rahmstorf, 2007). Recent investigations on the effects of sea storms on the microtidal western Mediterranean coasts have been conducted for the cases of the north Italian Adriatic coast and the Catalan and French coasts of the NW Mediterranean (Costas *et al*., 2005; Jiménez *et al*., 2009; Mendoza & Jiménez, 2008; Mosso *et al*., 2011; Pirazzoli & Tomasin, 2002 ).

The present work describes the dynamics of a rare storm event that took place on November 9-12, 2007 in the NE Ionian Sea (eastern Mediterranean) and its morphological consequences upon the barrier beach that separates the Lefkada lagoon from the micro-tidal open Ionian Sea. It also investigates the frequency of occurrence of such storms, the frequent repetition of which may have a catastrophic impact on the NE coastal zone of the Lefkada Island, as it can lead to destabilization and breaching of the barrier beach system, threatening the existence of the lagoon and the low-lying outskirts of the town of Lefkada.

## Study Area

The Lefkada lagoon is located on the N coast of the homonymous island and is separated from the NE Ionian Sea by a barrier beach (Fig. 1), which does not exceed 3 m in height and has a mean width of approximately 100 m. The barrier beach consists of sandy material

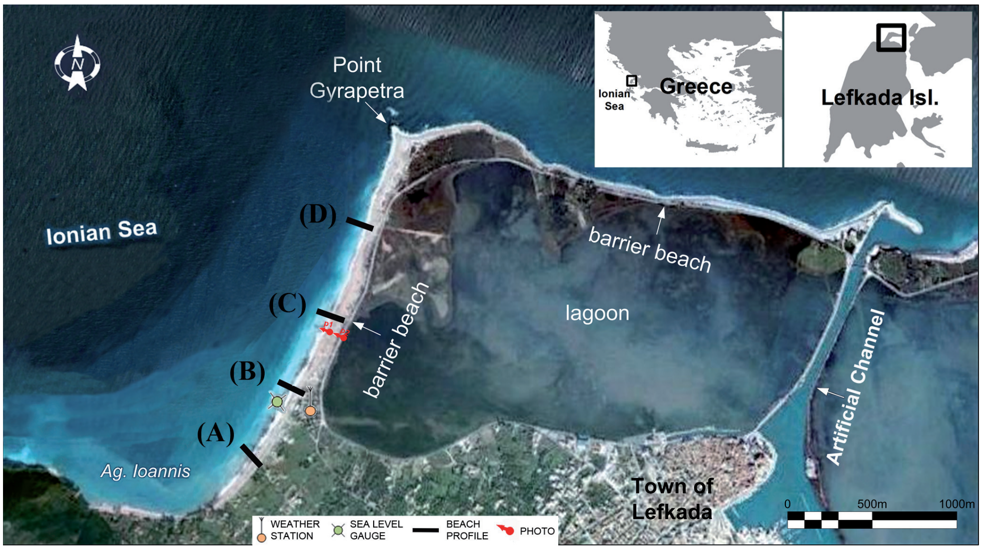



***Fig. 1:*** Location map showing the four profiles (A, B, C and D), the weather station, the sea-level/wave gauge and the position and look direction of the photographs (p1, p2) taken during the November 2007 storm event and the wave overtopping of the barrier beach. The Lefkada lagoon and barrier beach system and their location relative to the Lefkada Island and the Ionian Sea are shown in the insert map (Imagery source: Google Earth).

(mostly coarse sand) with small percentages (<10%) of pebbles and granules, while extensive beachrock formations, extending from the shoreface to water depths >5 m, are present along most of its coastline. This surficial appearance of beachrock on the beach face and the nearshore bottom is evidence that the locally observed shoreline retreat of several metres during the last few decades (Verykiou *et al*., 2008a) is part of a generalised trend along the northern coastline of Lefkada. The hydrodynamic, neotectonic and climatic controls of the evolution of the Gyra barrier beach are discussed in detail in Poulos *et al.* (2015).

The barrier beach protecting the Lefkada lagoon is exposed to wind-generated waves approaching from W, NW and, secondarily, from N directions. Statistical analysis of the wind records of the nearby Hellenic Meteorological Office weather stations at Preveza and Aktion showed that the offshore wind conditions are characterised by the dominance of W winds in terms of both annual frequency (19%) and maximum speed (10 Beaufort/48-55 knots). The most frequent wind speed, of all directions, is 3 Beaufort (7-10 knots) with an annual frequency of 23.1%. Wind speeds are less than 6 Beaufort (≤27 knots) for 99.2% of the time, while only 0.14% exceed 8 Beaufort (>40 knots). The maximum recorded speed for N and NW winds is 9 Beaufort (48-55 knots) with an annual frequency of only 0.011%.

The associated wind-generated offshore (Ionian Sea) waves have maximum significant heights and corresponding periods that do not exceed 6 m/12 s for SW (Cavaleri *et al*., 1991), S and W waves and 6.4 m/9.3 s for NW waves (Ghionis, 2001). Statistical analysis of the wave height observations in the North Ionian Sea for a period of 40 years, presented by Athanassoulis & Skarsoulis (1992), showed that the annually averaged offshore significant wave height is 0.79 m.

The north coast of Lefkada is microtidal with astronomical tides not exceeding 10 cm (Tsimplis, 1994), while higher sea level fluctuations recorded at the gauge station of Lefkada (HNHS, 2005) are attributed to meteorological forcing and coastal morphology.

## Materials and Methods

Most of the data used in this paper to describe the characteristics and the impact of the extreme NW storm event that was recorded in November 2007 were collected during the environmental monitoring program (from March 2007 to June 2008) for the assessment of the stability and the erosion rates of the north beaches of Lefkada Island and for the investigation of possible protection measures (Verykiou *et al*., 2008b).

The meteorological conditions in the coastal zone of North Lefkada were recorded with a Davis Vantage Pro2 weather station installed on the backshore at a height of 6.5 m above sea level (for location see Figure 1). Changes in the wind regime of the broader region of the NE Ionian Sea were investigated using the wind records (1961-2010) of the Hellenic Meteorological Service coastal weather stations at Aktion (15 km to the NE) and Andravida (115 km to the SSE).

Hydrodynamic measurements were made with the use of a Hobo U20-001-01-Ti self-recording water level gauge, installed 0.4 m above the seabed at a water depth of 2.9 m and a Druck PDCR 1830 water level sensor installed at a water depth of 0.5 m close to the shoreline and connected to a shore-based data acquisition system. The sea water temperature in the nearshore zone was also measured by the water level gauge, at a water depth of 2.9 m.

The offshore wave conditions during the study period were obtained from the operational wave forecasting model of the Atmospheric Modelling & Weather Forecasting Group (AM & WFG) of the University of Athens (http://forecast.uoa.gr/wamindx.php). The wave forecast is based on the ECMWF version of the WAM (Cycle 4) model (Komen *et al*., 1994; WAMDI Group, 1988).

Following the approach adopted by Jiménez *et al*. (1999), all waves with heights exceeding 1.6 m (twice the annually averaged offshore significant wave height) are considered as storm waves in the present study.

The topographic measurements of four beach profiles (A, B, C and D; for locations see Figure 1) along the WNW-facing part of the barrier beach, which received the full impact of the November 2007 storm, were used to document the impact of the storm on the barrier beach. These profiles were surveyed seasonally (between April 2007 and June 2008), with the use of a NIKON A20 total station, to monitor the topographic changes of the barrier beach (for details see Poulos *et al*., 2015). The northern part of the barrier beach and the Ag. Ioannis beach were not affected significantly by the NW storm of November 2007 (because of their orientation), so the corresponding profiles are not included in this analysis. Additional morphological and elevation data were obtained from topographic maps (scale 1:5000) of the Hellenic Army Geographical Service.

Surficial sediment samples were collected from the shoreface at each profile and were analysed granulometrically by dry sieving, according to the procedure described by Folk (1974), in order to reveal changes in sediment texture.

Maximum elevations of the wave run-up *(R)* with respect to the mean sea level were calculated with the use of Komar's (1998) equation:

$$R = 0.36 \cdot g^{0.5} \cdot S \cdot H_{so}^{0.5} \cdot T \qquad (1)$$

where S is the tangential beach slope, T is the wave period and $H_{so}$ the maximum significant offshore wave height during the storm.

## Results

The meteorological conditions that prevailed in the nearshore zone of Lefkada during the 3-day period of the highly energetic event of November 2007 are presented in Fig. 2a. A low pressure system developed in the area of Lefkada, starting with a barometric pressure drop from 1021.5 hPa at 06:00 h (UTC) of 9th November to 1001.7 hPa at 06:00 h of 10th November (Fig. 2b), followed by a rapid increase from 1003.5 hPa at 11:30 h to 1015.9 hPa at 21:00 h of 10th November and a further increase to 1019.1 hPa at 10:00 h of 11th November.

On the basis of the wind characteristics, the storm event at the north coast of Lefkada started at about 02:00 h (UTC) of 10th November (Fig. 2a), just before the completion of the barometric pressure drop phase, with wind speeds of 7.6 $m \cdot s^{-1}$ from the W, which increased quickly to 15.8 $m \cdot s^{-1}$ from WNW at 03:00 h and remained at 15-16 $m \cdot s^{-1}$ from WNW until 11:00 h. During the period of rapid barometric pressure rise that followed, the wind speed increased rapidly to 21.0 $m \cdot s^{-1}$ from NW and remained around 20 $m \cdot s^{-1}$ from the same direction until 15:30 h. Subsequently the wind speed started to decrease, falling to 9.8 $m \cdot s^{-1}$ from NNW to N directions at 18:00 h, 4.9 $m \cdot s^{-1}$ from N at 19:30 h and remaining between 3.0 and 5.0 $m \cdot s^{-1}$ from N until the completion of the phase of rapid barometric pressure rise at 21:00 h of 10th November. As the barometric pressure continued to rise at a lower rate until 10:00 h of 11th November, the winds became variable from easterly directions with speeds less than 2 $m \cdot s^{-1}$ and remained so until the decay of the storm waves and the end of the storm event at 12:00 h of 11th November.

In terms of sea state, the aforementioned strong NW winds blowing over the North Ionian and Adriatic Seas produced extreme storm waves with heights exceeding 6 m in the open Ionian Sea, offshore from Lefkada Island. These offshore storm waves started arriving at the coastal zone of North Lefkada at 01:00 h of 10th November, as swell waves approaching from NW. The nearshore storm wave heights and the resulting storm surge increased as the wind speed increased (Fig. 2b) and continued to increase until 16:00 h of 10th November, when wind speeds started to drop. The peak of the rough sea conditions appeared towards the end of the rapid barometric pressure increase phase, coinciding with the peak speeds of the onshore winds and the high water level of the semi-diurnal tidal cycle (Fig. 2b). The rough sea conditions persisted until 09:00 h of 11th November, approximately 17 hours after the decay of the onshore winds, mainly due to the incoming swell waves that were generated in the open Ionian Sea. Thus, the high sea levels observed between 02:00 h of 10th November and 09:00 h of 11th November were due to the combined effects of incoming waves (wave set-up), storm surge and astronomical tides. According to the AM & WFG operational wave forecasting model (http://forecast.uoa.gr/LINKS/WAM/adriatic/sheight/), the storm waves approached from the NW with maximum offshore wave heights of 6-7 m and significant offshore wave heights of 5-6 m (Fig. 3). These wave heights are 6.3 to 8.9 times larger than the annually averaged offshore significant wave height (0.79 m). The total duration of the storm conditions (wave heights >1.6 m) in the coastal zone of North Lefkada was 22 hours, while the total duration of the storm event (including the building-up and decay phases, when wave heights were <1.6 m) was 39 hours.

The average sea surface elevation (SSE), at the commencement of the storm event, was 4 cm above mean sea level (MSL), when during the peak of the storm the aver-

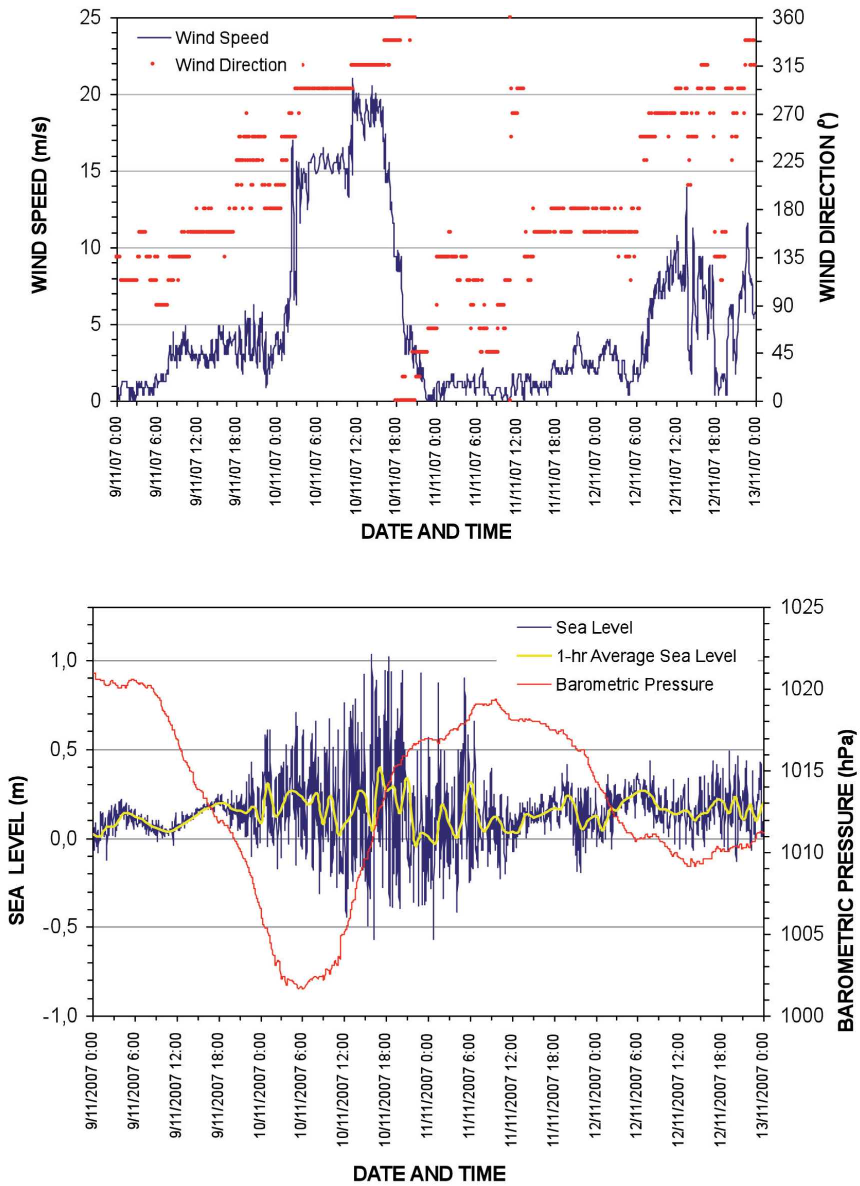



***Fig. 2:*** Records of meteorological and oceanographic parameters during the extreme storm event of November 2007: (A) wind speed and wind direction; and (B) sea level and barometric pressure.

age sea surface elevation rise was 16 cm, according to the water level recorder that was installed at a water depth of 2.9 m. The maximum and minimum recorded sea surface elevations, with respect to MSL, during the storm were +1.0 m and -0.6 m, respectively (Fig. 2b).

The recorded sea level rise during the peak of the storm in combination with the computed wave run-up potential (R=2.42 m) of the incoming storm waves ($H_{so}$=5.5 m, T=9.5 s, S=0.096), produce run-up elevations that exceed the average elevation of the barrier beach crest (2.5 m) and can lead to significant overtopping of the barrier beach. Indeed, such overtopping has occurred during the peak of the storm on 10$^{th}$ November, as shown in photographs taken from the top of the barrier beach (for exact locations see Fig. 1); the first photograph (Fig. 4a) depicts successive breaking waves surging up the beach face and reaching the vegetation line at the upper part of the backshore zone, while the second photograph (Fig. 4b) shows waves overtopping the crest (2.3 m elevation) and flowing down the landward side of the barrier beach. The washover flow on the landward side of the barrier beach was decelerated through percolation and by the existing vegetation and no significant sediment transport and morphological changes were observed on the back-beach area. Storm waves and overtopping of this magnitude had not been observed along the barrier beach of North Lefkada for at least 50 years, according to local witnesses (including scientific personnel of the Town of Lefkada) and the archives of the local newspapers.

This extreme storm event resulted in major morphological changes of the sub-aerial part of the beach zone, which were documented by pre- and post-storm topographic measurements (Fig. 5). In addition, the overall erosional trend of the studied coastal zone is shown by

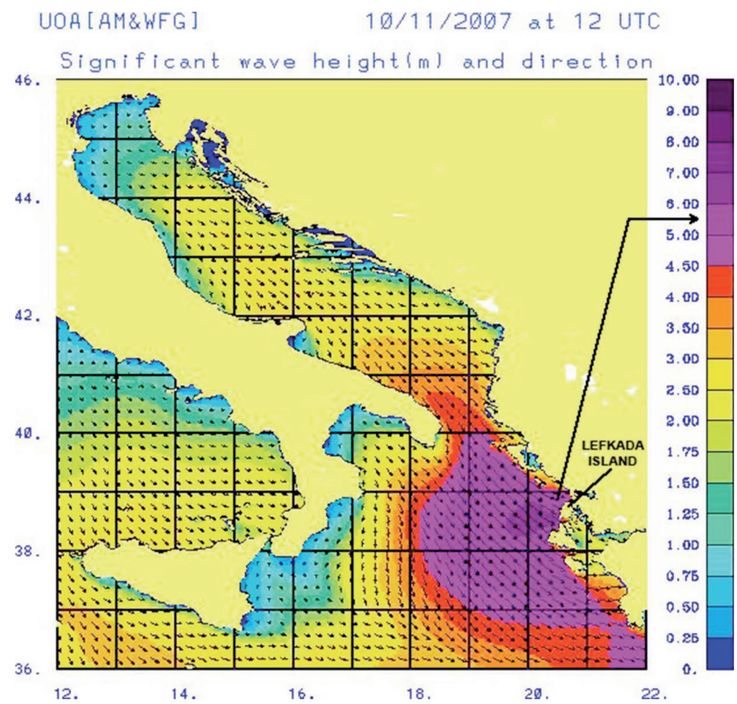
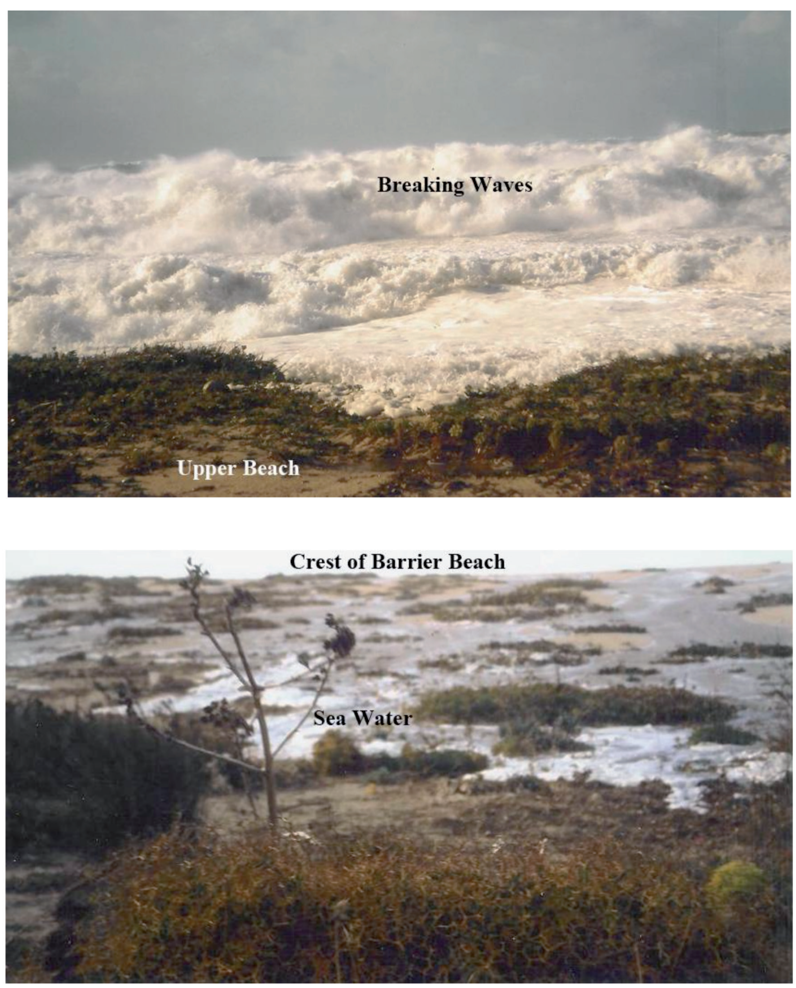



***Fig. 3:*** Significant offshore wave height and direction at 12:00 h (UTC) of 10th November 2007, during the peak of the storm. (Source: http://forecast.uoa.gr/LINKS/WAM/adriatic/ sheight/).




(A)

(B)

***Fig. 4:*** Photographs taken during the storm showing: (A) waves surging up the beach face and reaching the vegetation line and (B) waves overtopping the crest and flowing down the landward side of the barrier beach.

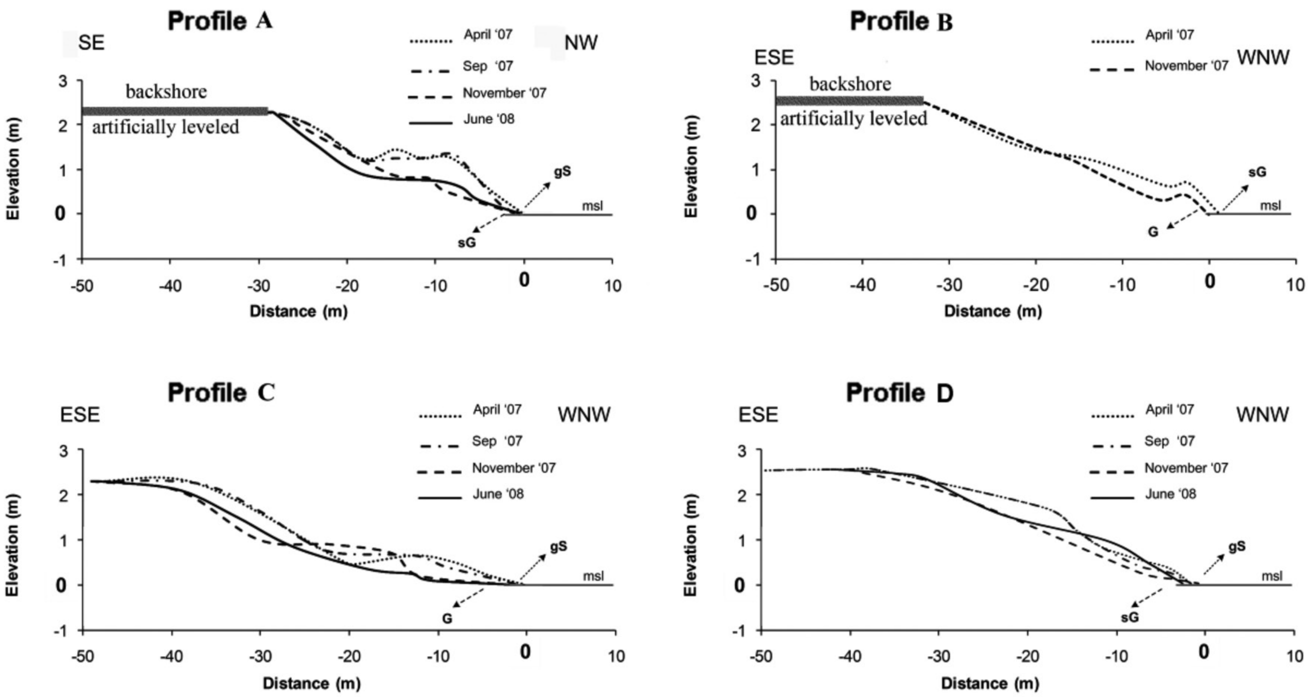



***Fig. 5:*** Morphological changes of the sub-aerial part of the beach zone along the profiles A, B, C and D from April 2007 to June 2008 (profiles based on topographic data from Poulos *et al.* (2015); for profile locations see Fig. 1).


(A)

(B)

***Fig. 6:*** Photographs of the beach zone 3 days after the storm event of 9-11/11/2007, showing: (A) lowering of the beach face by 25 cm; (B) planation of the beach face and homogenization of its textural characteristics.

the morphological changes revealed from the comparison of the four profiles that were measured repetitively from April 2007 to June 2008. After the storm, the owners of local recreational facilities in the area of Profile B intervened repeatedly with the evolution of the beach profile in an effort to reverse the adverse effects of the storm. Therefore, only the measurements of April 2007 and November 2007 are presented in Figure 5b and used in the analysis.

The comparison of the pre- and post-storm profiles (A, B, C and D) of the WNW-facing part of the barrier beach (Fig. 5), shows that the average post-storm profile of the beach is much 'smoother', with an overall lowering and flattening of the sub-aerial beach surface. As shown in the photograph of Figure 6a and the profiles of Figure 5, a layer of surficial sediments, approximately 25 cm thick, has been eroded from the beach face during the storm. The overall flattening of the beach is evident in the photograph of Figure 6b.

Furthermore, the impact of the storm event on the sub-aerial beach zone includes a shoreline retreat of 0.9-2.2 m, associated with berm erosion, lowering of the beach profile and reduction of the average slope of the beach face from 7.6° (S=0.133) before the storm to 4.6° (S=0.080) after the storm (Table 1). The smaller reduction of the average slope of the active lower part of the beach profile, from 3.9° (S=0.068) to 3.5° (S=0.061), was due to the removal of sediment from the upper part of the beach and its partial deposition on the lower part of the beach, contributing to the formation of a lower berm. Over the whole width of the sub-aerial beach (from the unchanged stable top of the profile to the shoreline) a slight increase of the average beach slope, from 3.8° (S=0.066) to 4.0° (S=0.070), was observed after the storm, as a result of the shoreline retreat. In addition, the beach face sediment has become coarser (Fig. 5; Table 1) due to the removal of the finer sandy material towards deeper waters of the nearshore zone.

On the basis of the morphometric changes of the pre- and post-storm (15th November 2007) beach profiles (Fig. 5) it is estimated that approximately 8 $m^3$ of beach sediments have been removed per meter of shoreline length during the storm (Table 1), resulting in approximately 15,000 $m^3$ of sediment loss from the sub-aerial beach zone. This volume represents approximately 88% (on average) of the sediment loss from March 2007 to November 2007, revealing the important role of extreme storm events in the evolution (in this case erosion) of this particular beach zone. The remaining 12% of the sediment loss during this period is the result of the generalized erosional trend, which became evident since the mid-1980s and has been attributed mainly to the reduction of the volume of sediment supplied by the longshore transport from the west coast of Lefkada Island (Verykiou *et al.*, 2008b).

## Discussion

According to the five-class storm classification scheme proposed by Dolan & Davis (1992) for the NE ocean storms attacking the USA Atlantic coast, the Lefkada (NE Ionian Sea) storm with maximum significant offshore wave height $H_{so}$>5.5 m and total duration of 22 hours (Fig. 7a) is classified as "class III: significant storm" (Table 2). The highly energetic character of the Lefkada storm ($H_{so}$=5.5 m, $T_p$=9.5 s) is also indicated by the more recent classification of sea storms in the NW Mediterranean by Mendoza & Jiménez (2008) (see Table 2 and Figure 7b), as it has reached the wave characteristics (peak $H_{so}$ and $T_p$) of a "severe" to "extreme" storm (class IV to V) in less than 12 hours.

The rarity of the November 2007 storm event (Hs=5.5 m, T=9.5) is also shown by the fact that during the 40 years of operation of the nearby meteorological station at Aktion, there is only one more observation of NW winds >40 knots and that event had a short duration (<6 hours as opposed to >12 hours of winds exceeding 40 knots during the November 2007 storm).

**Table 1**. Morphological, textural and sediment volume changes (in $m^3$/m of shoreline) of the beach zone during the extreme storm event of November 9-11, 2007.

| | Profile | | | | Average |
|---|---|---|---|---|---|
| | A | B | C | D | |
| **Morphological / textural characteristics** | | | | | |
| Coastline retreat (m) | 0.9 | 1.3 | 2.2 | 1.0 | 0.9-2.2 |
| Slope of beach face (°) | 8.9⇨3.7 | 10.4⇨9.0 | 3.6⇨1.2 | 7.5⇨4.5 | 7.6 ⇨4.6 |
| Average beach slope (°) | 4.5⇨4.7 | 4.3⇨4.5 | 2.7⇨2.8 | 3.7⇨4.0 | 3.8⇨4.0 |
| Texture of surficial sediments | gS⇨sG | sG⇨G | gs⇨G | gS⇨sG | coarser |
| **Volumetric change** | | | | | |
| $V_1$, from 4/2007 to 11/2007 ($m^3$/m) | -9.0 | -8.5 | -10.2 | -10.6 | -9.6 |
| $V_2$, during the storm event ($m^3$/m) | -7.9 | -8.1 | -8.2 | -7.8 | -8.0 |
| $V_2$ as percentage (%) of $V_1$ | 87.8 | 95.2 | 80.4 | 73.4 | 84.2 |

Key: gS: gravelly Sand; sG: sandy Gravel; G: gravel (after Folk, 1974).

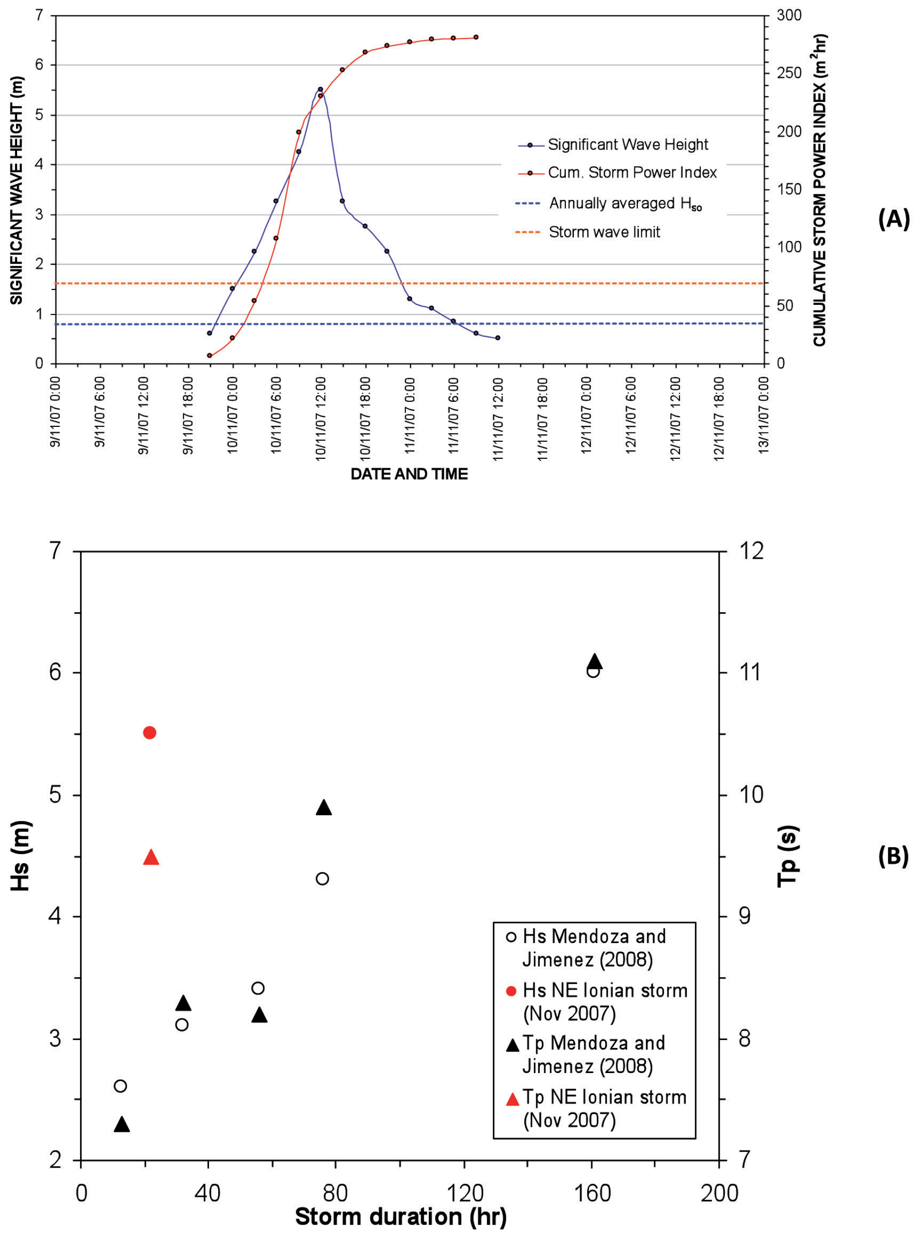



***Fig. 7:*** (A) Significant wave height and corresponding cumulative wave power index during the storm event of November 2007; (B) Comparison of the characteristics of the November 2007 storm in NE Ionian Sea to the class-averaged characteristics of the Mendoza & Jiménez (2008) classification.

**Table 2.** Comparison between the Lefkada (NE Ionian Sea) storm characteristics and the storm classification schemes for the USA Atlantic coast (Dolan & Davis, 1992) and the NW Mediterranean coast (Mendoza & Jiménez 2008). $H_{so}$ and $T_p$ are the offshore significant wave height and period at the peak of the storm, respectively, and t is the duration of the storm.

| **Storm Class** | | ***USA Atlantic coast*** | ***NW Mediterranean*** | | |
|---|---|---|---|---|---|
| | | ***Power Index (P)*** ($m^2$hr) | $H_{so}$ (m) | $T_p$ (s) | ***t*** (hr) |
| I. | Week | P≤71.63 | 2.6 | 7.3 | 13 |
| II. | Moderate | 71.63<P≤163.51 | 3.1 | 8.3 | 32 |
| III. | Significant | 163.51<P≤929.03 | 3.4 | 8.2 | 56 |
| IV. | Severe | 929.03<P≤2322.58 | 4.3 | 9.9 | 76 |
| V. | Extreme | P>2322.58 | 6.0 | 11.1 | 161 |
| ***Present study*** | | | | | |
| NE Ionian storm | | P=271.62 | 5.5 | 9.5 | 22 |

The overtopping of the barrier, mostly at its WNW-facing part, was the result of the combined effect of the storm-induced sea surface elevation rise and the wave run up, which together exceeded 2.5 m. Similar coastal sea level elevations induced by storms have been reported by Poulos *et al.* (2013) for the case of the Ammoudara beach (North Crete, Greece), where a strong Etesian wind event ($H_s$=1.9 m) together with the presence of an alongshore offshore reef has caused a sea surface elevation of 44 cm at the shoreline; Eliot *et al*., Travers, & Eliot (2006) for the Como Beach (Western Australia) have reported analogous non-tidal water level fluctuations being associated with storm surge.

Barrier overtopping events in the vicinity of Point Gyrapetra and along the Aghia Mavra barrier beach, the Phoukias sand spit and the Aktion headland have been identified and reported by May *et al.* (2008, 2011) and Vött *et al.* (2007, 2008, 2010). They attribute the formation of the identified washover fans to extreme waves of tsunamigenic origin. In a recent publication, May *et al.* (2012) suggested that part of the coarse clastic sediment layers on the nearby Akarnanian coasts may be related to high energy storm waves instead of tsunami impacts. They also suggested that the extreme storm waves of the November 2007 event, as reported by Ghionis et al. (2008), may be related to the dislocation and accumulation of beachrock fragments (up to ~40 cm length) along the Aghia Mavra barrier beach.

Eight months after the storm, it is obvious from the examination of the topographic profiles that the WNW-facing part of the barrier beach, which was hit most severely by the NW storm of November 2007, had not recovered. According to Benavente *et al*. (2013), in low-energy environments, sandy barriers that are affected by energetic storm events take years to recover, while Costas *et al*. (2005) studying a low-energy beach in the NW Iberian peninsula (west Mediterranean) have pointed out that the morphology of these low-energy beaches is inherited from high-energy events and reveals a non-equilibrium state with the prevailing mean hydrodynamic conditions. Hence, extreme storms, like the November 2007 event, have the potential to erode beach sediment and transport it offshore, to water depths where it cannot be remobilized by the ordinary wave activity of the area. In this way, part of the sediment that is eroded during extreme storms is permanently lost for the sub-aerial beach and the inner nearshore zone. If it is not replenished, either artificially or by longshore sediment transport (from the SW in this case), the barrier beach will continue to erode (especially during severe storm events). The same adverse effects may result from the combination of insufficient sediment supply and frequent sequences (groups) of moderate storms (*e.g.,* Del Río *et al*., 2010; Lee *et al*., 1998).

Analysis of the wind records of the meteorological station at Aktion revealed a significant change in the frequency and direction of severe storms with wind speeds exceeding 40 knots (Table 3). The number of S, SW and W storms, which induce a northward sediment transport along the western coast of Lefkada and supply sediment to the north beaches (Verykiou *et al*., 2008b), has decreased from seven storms in the decade 1971-1980 to one in the next two decades and none in the decade 2001-2010. At the same time, the number of NW and N and NE storms, which erode sediment from the north beaches and transport it offshore (as in the case of the November 2007 storm), has increased from none in the decade 1971-1980 to two storms in the decade 1981-1990 and one in the next two decades. Similar changes were recorded by the meteorological station at Andravida, located 115 km to the SSE, indicating a more or less uniform trend in the Ionian Sea.

These significant changes in storm frequency and direction coincide temporally with the appearance of the first signs of erosion along the northwest beaches of Lefkada in the mid-1980s. In addition to the above, the November 2007 storm event was far more energetic than any previous storm from the north sector that has been recorded during the forty years of operation of the Aktion meteorological station.

It is not clear at the moment, whether the above changes in severe storm direction, frequency and intensity are due to climate change or to a decadal variability in the wind regime of the Ionian Sea, that may be related to the North Atlantic Oscillation (NAO) and the Mediterranean Oscillation (MO). Poulos *et al.* (2015) found

**Table 3.** Number of severe storm events (wind speeds >40 knots) recorded by the meteorological stations at Andravida (115 km to the SSE) and Aktion (15 km to the NE) during their periods of operation.

| PERIOD | ANDRAVIDA (682) | | | AKTION (643) | | |
|---|---|---|---|---|---|---|
| | S, SW, W | NW, N, NE | Total | S, SW, W | NW, N, NE | Total |
| 1961-1970 | 3 | 0 | 3 | | | |
| 1971-1980 | 4 | 2 | 6 | 7 | 0 | 7 |
| 1981-1990 | 1 | 3 | 4 | 1 | 2 | 3 |
| 1991-2000 | 1 | 0 | 1 | 1 | 1 | 2 |
| 2001-2010 | 0 | 1 | 1 | 0 | 1 | 1 |
| Total | 9 | 6 | 15 | 9 | 4 | 13 |

that changes in the relative frequencies of occurrence of NW and SW waves, with $H_s$ in the range of 2 - 4 m, correlate well with the inter-annual fluctuations of the NAO index, with negative NAO index values coinciding with increased frequencies of NW waves. Further research is underway, including analysis of the wind records of all the meteorological stations operated in the Ionian Sea by the Hellenic Meteorological Service, to investigate the extent and the causes of these climate changes.

However, if the current shift in severe storm direction from southerly to northwesterly directions continues in the future, regardless of its causes, it constitutes a severe threat not only for the north beaches of the island, but also for the existence of the Lefkada lagoon as it may lead to breaching of the barrier beach.

## Conclusions

Extreme storm events, like the event of November 2007 in the NE Ionian Sea, with NW winds with speeds reaching 20 $m \cdot s^{-1}$ and resulting in waves with offshore significant heights >5 m, occur very rarely (annual frequency <0.01%).

The run-up potential of the November 2007 storm waves, enhanced by storm surge, led to overtopping of the ~2.5 m high barrier beach (average width of approximately 100 m), an even more rare event, as it had not been observed for at least the past 50 years. The morphological impact of this storm on the Lefkada beach barrier was the removal of approximately 8 $m^3$ of sediment per meter of shoreline, which accounts for almost 88% of the total sediment loss observed between March 2007 and June 2008. This reveals the important role of severe storm events in the stability and evolution of coastal landforms formed by the accumulation and redistribution of marine sediments.

Recent meteorological data show evidence of an increase in the frequency of occurrence, as well as a shift in severe storm direction from S-SW-W to NW-N-NE, resulting in decreased longshore sediment supply. Hence, any future increase in the frequency or intensity of severe NW storm events combined with the anticipated sea level rise during the 21$^{st}$ century, and especially the frequent repetition of overtopping, may be detrimental for the stability of the barrier beach and, consequently, for the existence of the Lefkada lagoon.

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