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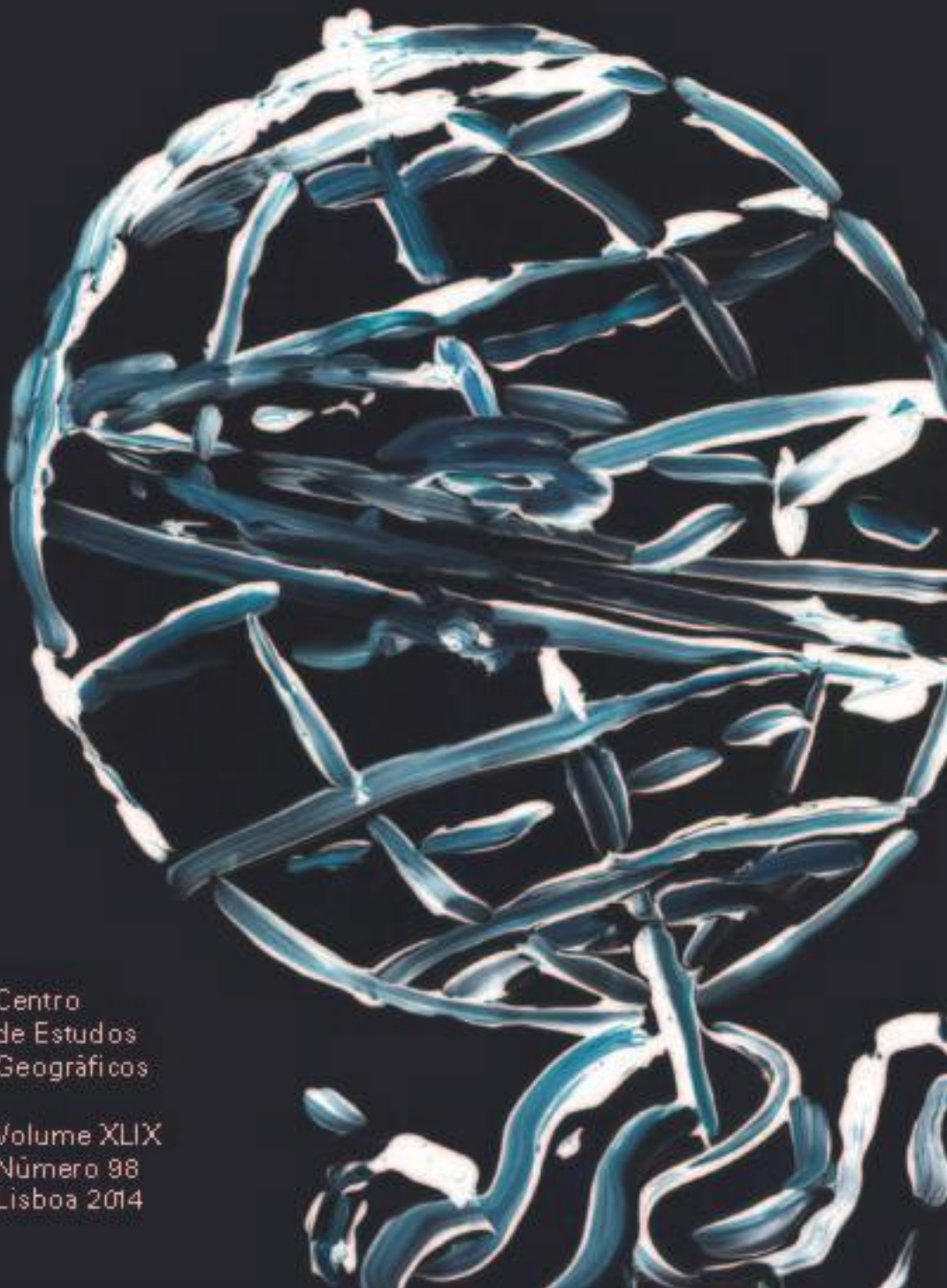

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IMPACTS OF THE STORM *HERCULES* IN PORTUGAL

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Abstract –The aim of this study is to analyse the impacts of the *Hercules* storm in Portugal. The storm occurred from January 5th to 7th, 2014. A brief characterization of the storm was conducted and the witnesses' accounts were compiled, complemented with field survey before and after the storm. The results show that this event had origin in a strong system of low pressure that hit Portugal. The system triggered strong sea waves with long periods, run-ups between 6 to 9 m, and inundation depths mostly under 1 m. The effects on the Portuguese coastline showed some weaknesses in the spatial planning management: (i) the fact that a wave train restricted to the beaches, front streets, ports and marinas caused significant damage; (ii) some people ignored the emergency management authorities, putting themselves in a risk situation.

Keywords: *Hercules* storm, media, witnesses' accounts, field survey, risk awareness.

Resumo – Impacto da tempestade *Hercules*, em Portugal. Neste estudo, analisam-se os impactos da tempestade Hércules, que atingiu Portugal entre os dias 5 e 7 de Janeiro de 2014. Caracteriza-se brevemente a tempestade, e apresentam-se os relatos das testemunhas e os resultados do trabalho de campo anterior e posterior à tempestade. Este evento teve origem num forte sistema depressionário que provocou forte agitação marítima, ondas de longo período, *run-ups* de 6 a 9 m, com profundidades de inundação em geral inferiores a 1m. Os efeitos no litoral português ilustram algumas fraquezas no ordenamento e gestão do território: (i) o facto de um conjunto de ondas, mesmo restringidas às praias, marginais, portos e marinas, ter causado elevados prejuízos materiais; (ii) a circunstância de os avisos das autoridades da gestão da emergência terem sido ignorados por indivíduos, que assim se colocaram em situação de risco.

Palavras-chave: Tempestade Hércules, comunicação social, testemunhos, trabalho de campo, sensibilização ao risco.

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Résumé – IMPACTS DE LA TEMPÊTE *HERCULE* AU PORTUGAL. La tempête “Hercule” a touché le Portugal du 5 au 7 janvier 2014. Pour analyser ses conséquences, on l’a sommairement caractérisée, on a recueilli divers témoignages et on a observé le terrain, avant et après la tempête. Ce système dépressionnaire accentué a provoqué une forte agitation maritime, avec des vagues de longue période et de 6 à 9 m d’amplitude. Les dégâts enregistrés révèlent certaines faiblesses de gestion de la part des autorités : i) Il est anormal que des vagues n’ayant touché qu’une étroite bande littorale aient provoqué de tels dégâts matériels; ii) Les avis de danger émis par l’organisme chargé de gérer les situations périlleuses ont été ignorées par certaines personnes, qui ont ainsi couru des risques.

Mots-clés: Tempête “Hercule”, média, témoignages, travail de terrain, enquête de terrain, sensibilisation aux risques.

آثار العاصفة هرقل في البرتغال. ضربت العاصفة "هرقل" البرتغال في شهر يناير 2014. ومن أجل تحليل نتائجها، تم وصفها بشكل موجز وجمع العديد من الشهادات، وتمت ملاحظة الميدان قبل العاصفة وبعدها. تسبب هذه الزيادة في الضغط في هيجان بحري قوي، بموجات طويلة تراوحت بين 6 و 9 أمتار. و أظهرت الأضرار المسجلة ضعفا في إدارة السلطات: فمن الغريب أن موجات أثرت فقط على لإنذارات الخطر الصادرة عن الهيئة المسؤولة عن إدارة شريط ساحلي ضيق تسببت في مثل هذا الضرر؛ كما تم تجاهل بعض الناس الحالات الخطرة ، وبالتالي عرضوا أنفسهم للمخاطر.

كلمات البحث: العاصفة "هرقل" وسائل الإعلام ، الشهادات، العمل الميداني، المسح الميداني، التوعية بالخطر

I. INTRODUCTION

Portugal has been experiencing atmospheric events that caused severe damage and fatalities, such as the floods of 1876, 1967 and 1997 (Zêzere *et al.,* 2014). However, scientific studies focusing on observational perspective are scarce (Sousa *et al.,* 2013) and even fewer studies deal with post-disaster field surveys. Pereira, *et al.* (2014) pointed out that newspapers are good data providers regarding temporal information about the natural disaster events that caused damage including direct injuries on the populations, as well as economic damage. Thus, field surveys, carried out by the first author, are the best approach to obtain spatial inventories. In 2011 a storm destroyed the sand dunes at the south of *Vagueira* (fig. SM 1, Supplementary Material, available online), damaged a road and reached the *Aveiro Ria*, which is about 200 m inland. The field survey showed the fast reconstruction of the sand dune, and a scouring of about 0.8 m on the road. Also in 2011, a very rare episode of hail occurred in Lisbon (Fragoso *et al.,* 2011), where data was also collected *in situ*. Another storm that occurred in 2013 generated waves that reached at least 5 m high in *Cova*, *Figueira da Foz*. The debris line was still visible at the base of *Cova*’s sand dune (fig. SM 2). At that time, there was also large debris deposited on the *Cova*’s south spur. Although this storm did not cause any damage on the area, evidences were found that a section of the sand dune was collapsing.

Between January 5th and 7th, 2014 a low pressure system approached Portugal from the Atlantic Ocean. It was named "*Hercules*" by The *Weather Channel* (http://www.weather.com/news/weather-winter/winter-storm-names-2013-2014-20131001), which is a media company. However, the official name of this winter storm is "Christina" by the University of Berlin (http://www.met.fu-berlin.de/adopt-a-vortex/tief/). In this paper the "*Hercules*" name was selected because most of the information related to its impacts was provided by the media. Its passage left significant damage due to strong winds, long period waves and intense precipitation. The most significant impacts occurred on the evening of Monday, January 6th and in the early morning of Tuesday January 7th.

Long sea waves generated by atmospheric disturbances can be caused by atmospheric gravity waves, storm activity, pressure jumps, frontal passages and squalls (Rabinovich *et al.,* 2009; Vilibic and Sepic, 2009). These waves are similar to ordinary tsunami waves and can affect coasts in a similar way. They are usually called *meteotsunamis* or meteorological tsunamis. Thus, the features of *Hercules* storm fits well in this type of natural hazards.

The emergency management authorities provided several storm warnings to the general population (Civil Protection, IPMA and the Maritime Authority). The warnings were disseminated to the public by the media. In fact, the role of media has been increasing in the dissemination of the information related to natural disasters (Vasterman, *et al.* 2005; Barnes *et al.,* 2008) not only live, but especially on online archives (Tschoegl *et al.,* 2006; Santos *et al.,* 2007; Santos, 2011; Santos and Queirós, 2013). The media also played an important role in the dissemination of the witnesses' accounts by providing videos, photos and reports online. The witnesses' accounts are very important because among other data allows a comprehensive analysis of a natural disaster (Levine *et al.,* 2004; Tinti *et al.,* 2005). For example, Vucetic *et al.* (2009) compiled the witnesses' accounts of the 1978 *meteotsunami*, in order to put together that event.

Although the *Hercules* storm caused damage in the interior of Portugal, the objective of this study was to investigate the impact of the storm on coastal areas of Portugal (fig.1), with the aim of pointing out the damages on natural systems, structures and infra-structures, as well as fatalities.

In the next section, the methodology is presented, followed by the storm characterization. In section IV, the witnesses' accounts are collected, complemented by the results of the field survey. Finally, the discussion and conclusions are presented.

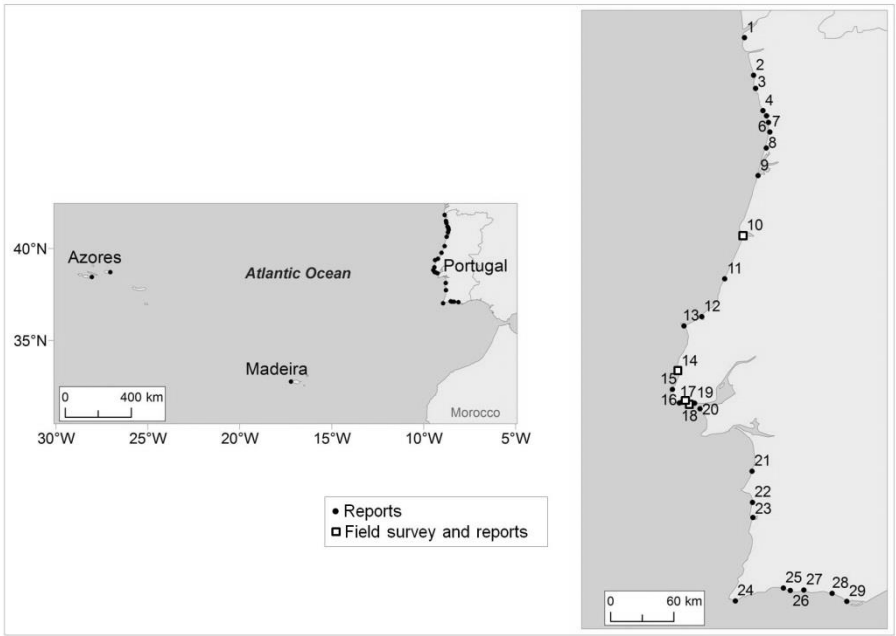

Fig. 1 – Points with witnesses reports on the storm impact and the field survey. See text for details.
Fig.1 – Locais com testemunhos dos impactes da tempestade e trabalho de campo.

II. METHODOLOGY

The methodology applied to this study was based in the following methods: the storm characterization, the compilation and interpretation of the witnesses' accounts and a post-tsunami field survey. The storm characterization was carried out by the collection of satellite images, forecasted weather maps and tide gauge data.

The witnesses' accounts were compiled from the media, reporting damages all over the Portuguese coastline that occurred in the evening of January 6th. Most of the reports were broadcasted live on the Portuguese TV channels, on Monday evening (January 6th) and on Tuesday morning (January 7th), and later posted on online archives. The major sources of information used in this study were *RTP Notícias* online (www.rtp.pt), *Sic Notícas* online (www.sicnoticias.sapo.pt), *Porto Canal* online (www.portocanal.sapo.pt) and *TVI24* online (www.tvi24.iol.pt). In addition, daily newspapers also provided important data on their websites: *Correio da Manhã* online. (www.cmjornal.xl.pt), *Diário de Coimbra* online (www.diariocoimbra.pt) and *Região Sul* online (www.regiao-sul.pt). The *Rádio Renascença* radio station also posted online information about the storm's impact at *Rádio Renascença* online (www.rr.sapo.pt). Furthermore, many videos and photos were posted online by the witnesses themselves, which also provided important valuable data.

As a complement to the witnesses' accounts, a field survey was conducted on some coastal areas. The selection of the studied points were based on existing previous research and field surveys, as well as on availability of post-storm photos. The *Hercules* storm generated waves of unusual long periods (section III), fitting in the definition of a *meteotsunami*, causing its behaviour on the coastline as "tsunami like". Therefore, post-tsunami field survey techniques (Borrero, 2005; Imamura *et al.,* 2005; Dominey-Howes *et al.,* 2012) were applied by the first author with the aim of: i) documenting damages on camera, ii) measuring longitude, latitude and height using GPS iii) pointing out features of the storm, and iv) measuring maximum water level height and inundation depths on the affected coastal areas.

III. STORM CHARACTERIZATION

On January 5th, 2014 the North Atlantic was under the influence of a deep depression, in the lower troposphere, with a closed nucleus above 40ºN, between the longitudes of 0 to 40ºW, to which was associated an occluded frontal system with a cold front to the West of the Iberian Peninsula extending north, to the UK. At the centre of the depression, located at 50ºN, 30ºW, the pressure at the surface (12:00 UTC) was lower than 940 hPa. The system extended to the south till 30ºN as a cold long wave in the mean sea level pressure field; the associated winds were strong, especially north of 35ºN. The deep vertical structure of the system was associated with wind values that increased with altitude Portugal was under the influence of a shortwave high pressure ridge with advection of warm air. A cold low was located at the Gulf of Genoa in the Mediterranean Sea.

Then, from January 5th to 6th, all the depressionary structure moved to N-NE. The cold frontal surface was (12:00 UTC) on the north and centre of Portugal. The entire country was under the influence of warm air from SW and positive advection of relative vorticity. Also, from January 5 th to 6 th, an intensification of the wind was observed, both at surface and aloft; at the 500 hPa level the wind intensity was higher than 50kt.

On January 7th, the cold frontal surface mentioned above, was already influencing the south of Portugal, by moving from NW to SE. In the middle troposphere, at 500 hPa, over Portugal, an intense positive advection of relative vorticity was associated to wind intensities of 60 to 70 kt. The high pressure ridge that on January 5th was located over Portugal two days later was influencing the Gulf of Genoa. The above mentioned cold low was observed to move to the North of Africa. Furthermore, from January 5th to 7th, over the Atlantic Ocean, the fetch length was large with strong winds from SW. The propagation of this low-pressure system was very well identified by the Global Forecast System (GFS) analysis displayed in figures 2 and 3.

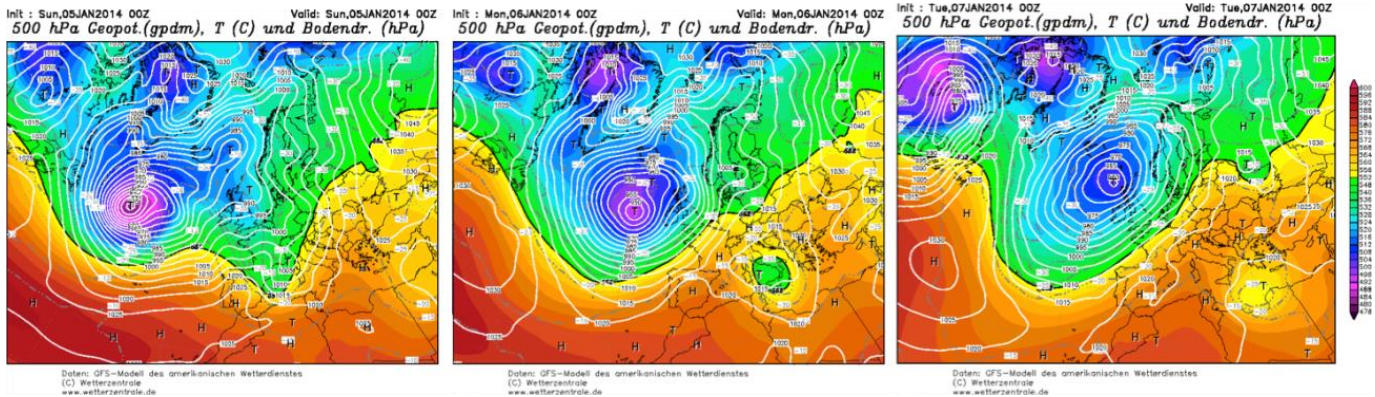

Fig. 2 – GFS forecasts maps of 500 hPa geopotential (colour contours) and temperature (grey contours), and surface air pressure (white contours), January 5th to 7th at 00UTC (*www.wetterzentrale.de*).

Fig. 2 – Mapas de previsão do GFS dos campos do geopotencial (a cores) e da temperatura (cinzento) aos 500hPa, e da pressão atmosférica à superfície (branco), 5-7 de Janeiro às 00UTC.

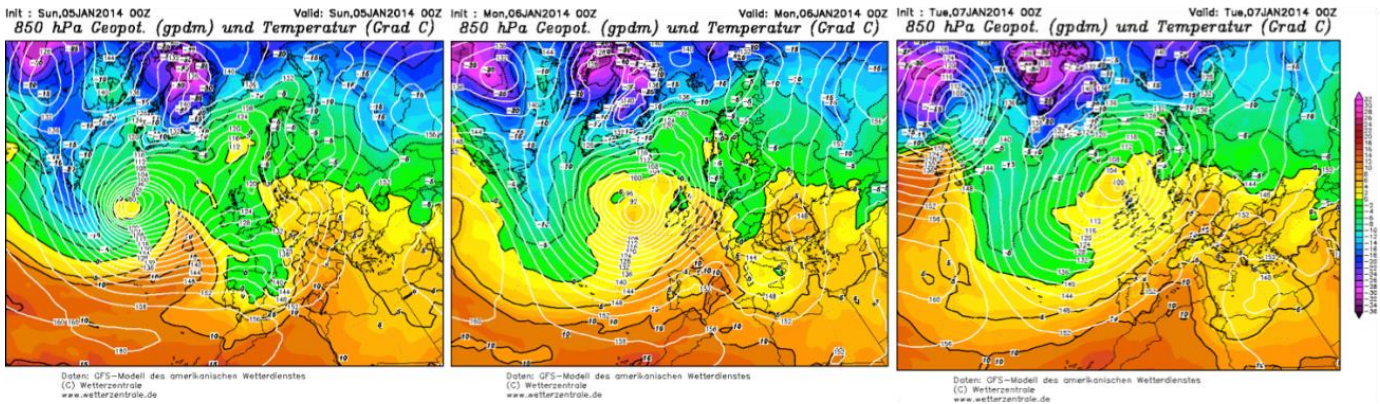

Fig. 3 – GFS forecasts maps of 850 hPa geopotential (white contours) and temperature (colour and black contours), January 5th to 7th at 00UTC *(www.wetterzentrale.de).*

Fig. 3 – Mapas de previsão do GFS dos campos do geopotencial (a branco) e da temperatura (a cores e preto) aos 850hPa, 5-7 de Janeiro às 00UTC.

Finally, on January 8th all the cyclonic structure was in the lower troposphere, over the Atlantic Ocean fragmented. A high pressure ridge of long wavelength between 20ºW and 40ºW was observed. Above Portugal, at the surface, the wind was weak from south, and a new frontal surface was now influencing the country from the NW. At 500 hPa, the long wavelength trough was still observed with warm air advection and positive advection of relative vorticity at 850 hPa and 500 hPa. Although the *Hercules* storm had completely vanished on January 8th, Portugal still remained under the influence of rainy weather conditions, although not stormy.

The most significant impacts occurred on the evening of January 6th and in the early morning of January 7th during the high tides. Figure 4 shows the available tide gauge stations that recorded the *Hercules* storm (www.ioc-sealevelmonitoring.org) in mainland Portugal. Due to the evident unreliability displayed by the data registered at Lagos station, the authors decided to rely on the *Cascais* data set. The *Cascais* tide gauge station clearly shows that the maximum water level corresponded to the high tide of the January 6th, about 18:40 (UTC), and in the early morning of January 7th. Data also show clearly long period waveforms of about 10 minutes, a feature also observed in *meteotsunami* events.

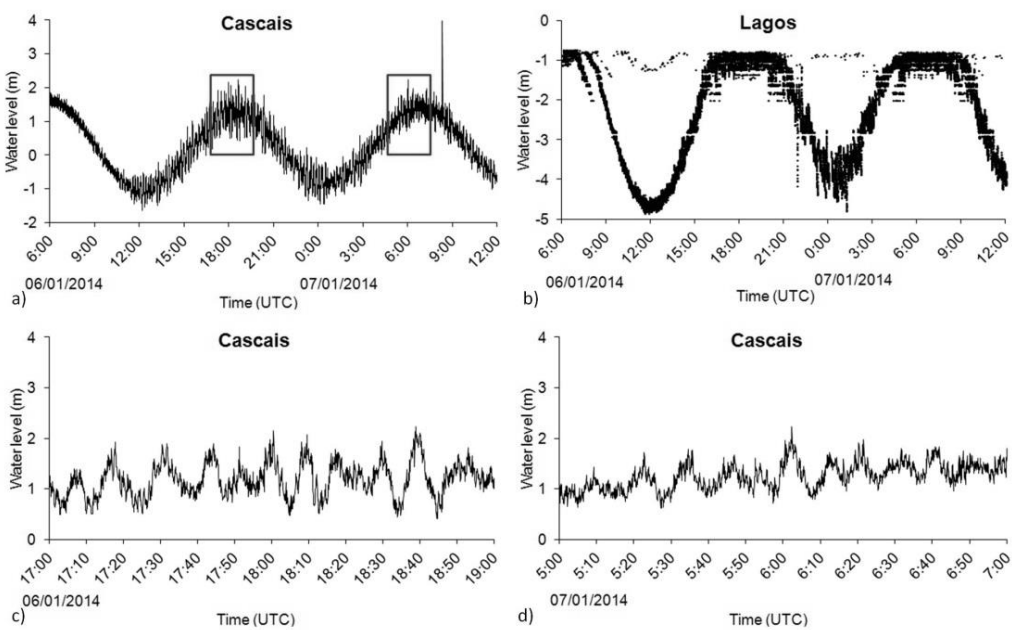

Fig. 4 – Tide gauge recordings during the *Hercules* storm: a) Cascais; b) Lagos; c) and d) zoom of Cascais data: second high tide on of January 6th (c) and first high tide on January 7th (d).
Fig. 4 – Registo dos marégrafos referentes à tempestade Hércules: a) Cascais; b) Lagos; Ampliação do gráfico de Cascais: segunda maré alta de 6 de Janeiro (c) e primeira maré alta de 7 de Janeiro (d).

Table I – Summary of the impacts.
Quadro I – Resumo dos impactos.

Points	Storm parameters	Damage		Fatalities
		Natural features	Structures and property	
1-*Vila Praia de* Âncora	---	- Coastal areas of the *Caminha* municipality flooded - Sand and trash dragged away (Carmo and Paiva, 2014)	- Warehouse damaged (Carmo and Paiva, 2014)	---
2-*Esposende*	---	- 15 m of sand dunes were destroyed (Carmo and Paiva, 2014)	- Walls collapsed (Carmo and Paiva, 2014)	---
3 - *Póvoa de Varzim*		- Sand deposited on roads (Fernandes and Ribeiro, 2014)	- at least 3 shopping malls damaged - bar severely damaged and with sand inside (Fernandes and Ribeiro, 2014)	- woman caught by a wave (rescued) (Fernandes and Ribeiro, 2014)
4 - *Matosinhos*	- 0.5 m of inundation depth at the residential areas - 4 waves, the 2nd and the 4th being the largest (PC, 2014a; PC, 2014b; PC, 2014c)	- residential areas of *Pescadores beach* flooded in *Angeiras, Lavra, and Antune*s Av. (*Leça da Palmeira)* - Streets full of debris and sand (PC, 2014c)	- "Severe damage" on the beach structures (bars and surf schools) - Damage on the beach structures of *Angeiras Norte*, *Paraíso* and *Leça da Palmeira* beaches (TVI24, 2014c)	---
5- *Oporto*	- Two major waves, one of them inundated the coastal area, within 10 to 15 sec (PC, 2014a)	---	- 20 cars (including a tourist bus) dragged inland on the *Foz do Douro*, - On the *Ourigo* beach the restaurant "Chis" was completely destroyed with rubble scattered all over the beach (PC, 2014a)	- 4 people injured, and many more caught by the wave on the *Foz do Douro*. 1 man almost drowned stuck under a car (PC, 2014a)

6- *Gaia*	---	---	- About 6 km of sidewalk damaged (Ferreira and Silva, 2014)	---
7- *Espinho*	---	---	- 2 beach bars flooded (RTPN, 2014a)	---
8- *Ovar*	- Waves higher than 9 m high at *Furadouro*, *Ovar*. (Ribeiro *et al.,* 2014)	- Sand, mud and concrete stones dragged inland at *Furadouro, Ovar (*Bessa and Valentim, 2014)	- Levees destroyed (Bessa and Valentim, 2014)	- One man injured while walking near the shoreline (RTPN, 2014e).
9- *Ilhavo*	- Waves higher than 8 m high (Ribeiro *et al.,* 2014)	- Sand dunes destroyed on the *Barra* beach (Ribeiro *et al.,* 2014)	- Restaurant destroyed on the *Barra* beach (Ribeiro *et al.,* 2014)	---
10-*Figueira da Foz*	- Waves 7 m high and winds of about 100 km/h (Carmo and Paiva, 2014)	- Uncovered about 100 m of an old rocky structure that supported the artificial sand dune of the *Cabedelo* beach (Carmo and Paiva, 2014) - At the south of *Cova*, overtopped the sand dunes and reached the pine trees. (Cruz, 2014)	- Parking lot overtopped at *Cabedelo,* damaging walls, fishing port and all the sidewalks. - Destroyed the sidewalks of *Costa de Lavos*. (JN, 2014) - Market gardens of *Leirosa* flooded and several sidewalks destroyed (Carmo and Paiva, 2014)	- No fatalities reported, but the populations of *Buarcos* and *São Pedro* were in danger (DC, 2014)
11-*São Pedro de Moel*	---	- *Afonso Lopes Vieira Square* flooded (Carmo and Paiva, 2014)	- Houses and restaurants flooded and damaged. - Public infrastructures destroyed (Carmo and Paiva, 2014)	---
12- *Caldas da Rainha*	-One major wave flooded the *Mar Avenue* . 19:00 (TVI24, 2014i)	---	- Dragged away 4 cars (TVI24, 2014i)	---
13-*Peniche*	---	---	- Parking lot flooded, near the marina - 8 vessels and several structures at the marina damaged (TVI24, 2014g)	- A male kitesurfer was rescued at the *Baleal* beach by the fire-fighters and the Coastal Guard (TVI24, 2014g)

14-*Ericeira*	Waves were 8 m high, period of 20 sec (Carmo and Paiva, 2014)	---	- Restaurant and 2 bars destroyed at the *Algodio* beach (North) - Destroyed about 10 vessels at the fishing port - Coffee shop and naval club flooded. - Sidewalk and walls damaged at Praia do Sul and *Foz do Lizandro* (Carmo and Paiva, 2014)	- Two men were caught by the waves, but only 1 was injured. The water level reached their necks (Carmo and Paiva, 2014)
15-*Sintra*	- Waves 8 to 9 m high, reaching 15m, around 18:00 (Ramalhinho, 2014)	- Flooded the beaches of *Praia Grande* and *Praia das Maçãs* - Parking lot of *Adraga* beach flooded (TVI24, 2014b)	- Damage on some roads. - At *Praia Grande* beach the stone benches were ripped away and the walls were damaged; deposits of sand and debris on the roads - The bridges that provide access to *Magoito* beach were destroyed - Damages at *Azenhas do Mar* beach. (TVI24, 2014b)	---
16-*Cascais*	---	---	- Damage on a restaurant and on 2 bars (RTPN, 2014d)	---
17- *Tamariz* beach, *Estoril*	- Waves were 5 m high, reaching 9 m -(Sousa, 2014)	---	- Stone sidewalk ripped away - Bars and restaurants damaged - Several promenades washed away, debris scattered all over the beach and sidewalk (Sousa, 2014)	---
18-*Carcavelos*		---	- Significant damage on the restaurants and bars at *Carcavelos* beach (TVI24, 2014a)	---
19-*Paço de Arcos*	---	---	2 vessels sank and at least 12 were damaged (SICN, 2014a)	---

20-*Costa da Caparica*	- At the high tide of 07/01/2014, between 6:00 and 7:00, the waves were 6 – 7 m high (TVI24, 2014e).	- *São João* and *Fonte da Telha* sand dunes washed away (TVI24, 2014e)	- The sea overtopped the levees at the urban area of Costa da Caparica, causing significant damage on the restaurants close to the shore (SICN;2014c; TVI24, 2014d). - Damage on 3 or 4 vessels at Cova do Vapor and debris was deposited on the road. (TVI24, 2014e)	---
21-*Santiago do Cacém*	---	---	- Damages on the *Melides* and *Santo André* beaches (TVI24, 2014f)	---
22- *Porto Covo, Sines*	---	---	- A vessel destroyed at the *Porto Covo* pier (TVI24, 2014f)	---
23-*Vila Nova de Milfontes, Odemira*	---	---	- Restaurant at the *Farol* beach damaged - 2 vessels damaged and fishing materials were washed away at the fishing port (TVI24, 2014f)	---
24-*Sagres*	---	---	- Damages on coffee shops, bars, and other annexes, at *Beliche, Tonel* and *Martinha*l beaches, and on the *Baleeira* port (RS, 2014a)	---
25-*Portimão*	---	---	- Restaurants and bars were damaged - A pier of the marina was damaged at the *Rocha* beach (RTPN, 2014b)	---
26-*Lagoa*	---	- The low areas of *Carvoeiro, Lagoa* were flooded (RTPN, 2014b).	- Damages on restaurants, a bar and the Scouts headquarters (SICN, 2014b). - Damages in *Ferragudo* restaurants, public areas and beach annexes (RS, 2014b).	---

27-*Armação de Pêra*	---	---	- Fishermen facilities were destroyed (RTPN, 2014b)	---
28-*Quarteira*	--	- *Quarteira Av.* flooded (RS, 2014a)	---	- 12 young tourists went swimming, unaware of the danger and had to be rescued by the maritime authorities (RTPN, 2014f; SICN, 2014b)
29- *Praia de Faro, Faro*	---	- Sand dunes overtopped by waves that reached *Ria Formosa* (RS, 2014a).	---	
Azores	---	---	- Significant damages on the ports *of Vila Nova* and *Biscoitos*, *Terceira Island.* The waves overtopped the breakwaters and concrete blocks were dragged inland Fisherman could not go out to sea for a week (Neves *et al.,* 2014) - Maritime transportation was suspended between *Terceira* and other islands. - Damages on the beach structures of *Piedade (Ribeirinha)* and *Prainha do Norte, Pico* Island (Carmo and Paiva, 2014)	---
Madeira	- Waves were 6 – 9 m high at *Porto Moniz* (Fernandes *et al.,* 2014).	- Waves inundated streets and promenades at *Porto Moniz*. - Waves overtopped the levees at *Paul do Mar* (Fernandes *et al.,* 2014)	---	- Several tourists were caught by the waves, and one woman was injured at Porto Moniz (Fernandes *et al.,* 2014)

IV. WITNESSES' ACCOUNTS

The location of the points described by the witnesses is presented in figure 1, and table I summarizes the reports. The places are ordered from north to south. The witnesses reported several storm parameters, damages that were separated between damages on natural landscapes, structures and properties, and fatalities.

In Matosinhos (Point 4), four waves were observed, the second and the fourth being the largest ones (PC, 2014c). However, one major wave was responsible for the flooding on the coastal areas of *Porto* (Point 5), *Caldas da Rainha* (Point 12) and *Tamariz* beach, *Estoril* (Point 17). The witnesses also reported the wave heights, estimated based on their knowledge about the local areas. The wave heights ranged between 5 m in *Tamariz* beach, *Estoril* (Point 17) and 9 m height at *Furadouro*, *Ovar* (Point 8).

Significant damage was observed along most of the Portuguese shoreline, including Azores, as presented in table I. Exceptions occurred in *Cortegaça, Ovar* (Point 8) where there were no damage or injuries, but the *Cortegaça* camping site was in danger of being flooded (Bessa and Valentim, 2014). In Madeira, although the waves overtopped the levees, no damage was reported (Fernandes *et al.,* 2014). Although sand dunes are natural barriers these structures did not stand the sea onslaught in several coastal areas such as in *Esposende* (Point 2), in *Ilhavo* (Point 9), in *Figueira da Foz* (Point 10), *Costa da Caparica* (Point 20), and *Praia de Faro*, *Faro* (Point 29).

In some places streets were closed down: at *Matosinhos* (Point 4) the sea front streets were full of sand and debris, and the traffic was cut between the *Liberdade Avenue* (Av) and *Antunes Guimarães Avenue* in *Leça da Palmeira* (near the new Port authorities of *Douro* and *Leixões*) and the *Almeiriga Norte St*., between the *Paraíso* and *Memória* beaches, in *Perafita* (TVI24, 2014c). At *Porto* (Point 5), the authorities had to progressively increase the safety perimeter (RTPN, 2014d) because people would not stay away from the coastline; in *Caldas da Rainha* (Point 12) one major wave flooded the *Mar Avenue*, at the *Foz do Arelho* beach, dragging away four cars although no injuries were reported. This happened soon after 19:00 hours. Following this, the beach bars and streets were closed to traffic (TVI24, 2014i).

There were no fatalities in Portugal, however around 20 people needed to be rescued in *Póvoa do Varzim* (Point 3), *Porto* (Point 5), *Furadouro, Ovar* (Point 8), *Peniche* (Point 13), *Ericeira* (Point 14) and *Quarteira* (Point 28). In Madeira, several tourists were caught by the waves (Fernandes *et al.,* 2014) while at *Paul do Mar*, the local population took safety measures.

Although no further incidents were reported, many witnesses adopted a risky behaviour: in *São Pedro de Moel* (Point 11), several photos and videos taken by witnesses and reporters (e.g., TVI24, 2014c, 2014) showed local people running at the last minute from the waves. At *Cascais* (Point 16) videos and photos also showed locals adopting risky behaviour patterns by taking photos too close to the

coastline. In *Costa da Caparica* (Point 20), a video showed a man running away at the very last minute. Being caught by the wave, he was able to escape and was later evacuated by car.

Disaster prevention measures were taken by stakeholders: in *Matosinhos* (Point 4), three families were evacuated; in *Gaia* (Point 6) an elementary school with 52 children was evacuated (Ferreira and Silva, 2014); in *Espinho* (Point 7) the *Regimento de Engenharia de Espinho* had been building sand bars for the past several weeks (RTPN, 2014a). As a consequence, only two beach bars were flooded and no further consequences occurred; in *Peniche* (Point 13) the sea flooded the parking lot near the marina. There was no further damage in the area because it had been closed to traffic several days before the storm (TVI24, 2014g). In *Sintra* (Point 15) the roads were closed to traffic because the waves were reaching them (Ramalhinho, 2014).

V. FIELD SURVEY

The field survey was conducted on several places displayed in table I and in figure 1: *Figueira da Foz* (Point 10), *Ericeira* (Point 14), *Tamariz* (Point 17), *Carcavelos* (Point 18). At the *Poça* beach*, Estoril* no witnesses' accounts were available, showing that field surveys are indeed fundamental work. The field survey results are presented in table SM I.

A field survey had been conducted at *Cabedelo, Figueira da Foz* (Point 10.1) before this storm on April 18th, 2012 (fig. 5b and SM 3b). Photos after the storm show that the waves overtopped the parking lot which is 5.67 m high (table SM I), inundating it and depositing sand and small boulders. It partially destroyed a wall near the road. The sand dune is 9.13 m high (point 10.2), and did not suffer significant damage.

The *Cova*' sand dune showed to be a natural barrier (fig. SM 3d, Point 10.3), reaching a height of 13.84 m. In 2013 part of the sand dune was showing signs of collapsing (fig. SM 2) being almost as the same level as Point 10.4 (5.10m). Although there were no structural damages on the area, the collapsed sand dune allowed the water to penetrate inland till the pine trees (fig. 5d, e).

The field survey conducted on *Costa de Lavos* on June 13th, 2013 shows that the sea front of *Costa de Lavos* (fig. 5f, Point 10.9) is located on high ground at 10.91 m, as is the south spur (Point 10.6, is 9.13 m). The storm did not damage any building or important infrastructure, but it completely destroyed the wooden sidewalk (figs. 5g and SM 3e) which is between 7.34 m and 8.77 m high (Points 10.7-9).

Fig 5 – Field survey conducted at *Figueira da Foz*: a) Framework; b) and c) Point 10.1 before and after the storm; d) Zoom of *Cova* sand dune; e) *Cova* sand dune photo; f) and g) Point 10.9 before and after the storm. c, d, g: Photos taken by Pedro A. Cruz.
Fig 5 – Trabalho de campo na Figueira da Foz: a)Enquadramento; b) e c)Ponto 10.1 antes e depois da tempestade; d) Duna da Cova- ampliação de a; e)Fotografia da duna da Cova; f e g) Ponto 10.9 antes e depois da tempestade; c,d,g: Fotografias tiradas por Pedro A. Cruz.

Ericeira (Point 14) was surveyed on several occasions, both before and after the storm. At the *Norte* beach, the sea waves moved several large boulders, caused a landslide and significant destruction on a concrete stair at Point 14.2, located at a height of 8.12 m (fig. SM 4 b, c, d). The waves also ripped away the concrete bricks of the sidewalk (fig. SM 4i), and completely destroyed all the beach bars (figs. 6b, c and SM 4e, f) except one that remained standing. The "Algodio" bar is located about 7 m above mean sea level (Point 14.4). The first author measured an inundation depth of 2.7 m on the bar (fig. 6 c), giving a local run-up of 9.7 m. Furthermore, the waves ripped away about 75 m of the concrete sea wall (fig. SM 4 g), which was deposited on the road. The cleaning operations started on January 7th and about 2 months later, on March 8th the road was clear of the debris (fig. SM 4 h). The beach was about 5 m high before the storm. However, figure SM 4j shows the erosion of the beach close to 2 m, and the access to the beach (Point 14.5) could not be used.

From the *Norte* beach, the waves propagated into the *Ericeira* fishing port. The naval club, located at a height of 5.19 m (Point 14.6), was completely destroyed (fig. SM 5 b, c), and on March 4th 2014 it was completely renovated (fig. SM 5 d). Two men trapped inside the club said the water level reached their necks (table I). The breakwater is 6.57 m high (Point 14.8), and the witnesses also reported that the waves passed over it. The difference in heights is 1.38 m which confirms the witnesses' accounts. On the other hand, photos taken during the storm (fig. SM 5e) and in the evening of January 7th (fig. SM 5 f) show the waves hitting the breakwater and passing over it, validating the reports (table I). In addition, photos taken before and after the storm at the fishing port (fig. 6 d, e) showed a significant deposition of sand (fig. SM 5 g) that most likely originated from the *Norte* beach. The maximum inundation level was 4.51 m (Point 14.11) whereas the ground has a height of 3.9 m (Point 14.12), which shows that the breakwater had an important role in decreasing the waves' impact on the fishing port because the inundation depth was 0.61 m only. Since the fishermen's warehouses are located on elevated ground (fig. SM 5 h) the waves did not cause significant damage inside the facilities, but the wave currents were strong enough to destroy several vessels, and ripping away a bench and the civil protection sign (fig. 6 e).

Fig. 6 – Field survey at *Ericeira*: a) Framework; b) Algodio bar destroyed; c) Bar and road cleaned from debris; d) and e) Point 14.13 before and after the storm; f) Damage at *Sul* beach.
Fig. 6 – Trabalho de campo na Ericeira: a) Enquadramento; b) Bar Algodio destruído; c) Bar e estrada limpos de detritos; d) Ponto 14.13 antes da tempestade; e) Ponto 14.13 depois da tempestade; f) Estragos na Praia do Sul.

The *Sul* beach also suffered significant damage from the waves that ripped awaythe concrete floor and seawall, scattering debris and stones and leaving a hole on the ground (fig. SM 6 f and 6 b, f, g). Although by March 7th the sand and debris had been cleared from the sidewalk (fig. SM 6 c), damage was still visible. The waves hit the sidewalk, breaking and increasing significantly in height (fig. SM 6 d). Photos taken after the storm showed sand deposited on the sidewalk and broken windows in a restaurant (fig. SM 6 d, e). The sidewalk is located at about 6 m high (Point 14.14, Point 14.15, and Point 14.16); the windows are located about 2 m above the ground, giving a run-up of more than 6 m. The swimming pools of the hotel, at the same level as the sidewalk, were also very damaged (fig. SM 6 h). In addition, a fishing vessel was recovered from the sea. It was found around 8 m deep, about 2 km south of *Ericeira* and about 500 m from the beach, as reported by professional divers of NDivers.

The January 7th survey showed a similar situation at *Tamariz* beach, *Estoril* (Point17), with sand deposited on the sidewalk and stones ripped away from it (fig. 7 b and SM 7 b). The witnesses and owners of the promenade's restaurants and bars also reported damage (table I). On March 8th, 2014 everything was cleaned and repaired (fig. 7 c and SM 7 c), and one restaurant was already opened for business. Point 17.1 and 17.2 were 5.59 m and 5.00 m high, indicating the waves were at least 5.6 m high.

The media did not report any damage on the *Poça* beach, *Estoril*. Nevertheless, the first author found significant damage (fig. SM 7 d and 7 e). The inundation mark was at 6.12 m (Point Pb1). The sidewalk is 5.40 m high therefore the local inundation depth was 0.72 m, enough to scatter the sea walls stones on the sidewalk. On March 8th, 2014 the protection bars were still missing (fig. SM 7 f), but new stones were already available on site to rebuild the area.

At *Carcavelos* (Point18), the inundation marks (fig. 8 b) left on the sidewalk showed that the waves reached a maximum of 5.56 m (Point 18.1). The stones were displaced (fig. 8 c,) at a height of 3.85 m (Point 18.3). The bars, restaurants and surf school (Point 18.4), located at a height of 5.35 m, suffered significant damage (fig. SM 8d); in the same area there was sand erosion on the stairs and sand deposited on the ramp (fig. SM 8 b and c). On March 8th 2014, all shops were opened for business (fig. SM 8 e). The bar "Surf" (Point 18.5) which is located at 6.43 m did not suffer any damage (fig. SM 8 f), and in the evening of January 7th it was opened for business. The sand reached 6.01 m (Point 18.5), showing the waves did not inundate the sidewalk. The most significant damage was observed at the eastern part of *Carcavelos* beach (fig. SM 8 d, e, f, g, h, i): a kiosk was torn apart (Point 18.7), being located at 4.19 m height, as well as the bar "Fizz", located at 4.25 m (Point 18.8). The protection bars were ripped away on several places (Points 18.9, 18.10 and 18.11) showing the waves were higher than 5.40 m. The bar "Moinho" suffered significant damage, despite being located at a height of 6.85 m (Point 18.12). On March 8th it was opened for business.

Fig. 7 – Field survey at *Estoril*: a) Framework; b) Sand deposited on the sidewalk and stones ripped away on Point 17.2; c) Point 17.2 cleaned; d) Damage at the *Poça* beach; e) New flagstones available.
Fig. 7 – Trabalho de campo no Estoril: a) Enquadramento; b) Areia depositada no passeio e pedras arrancadas no Ponto 17.2; c)Ponto 17.2 limpo; d) Os estragos na Praia da Poça; e) Novas pedras colocadas.

Fig. 8 – Field survey at *Carcavelos* beach: a) Framework; b) Inundation mark; c) Stones from the ramp were dragged away; d) Kiosk ripped away; e) Restaurant completely destroyed; f) Point 18.12 shows the maximum inundation area.

Fig. 8 – Trabalho de campo na praia de Carcavelos: a) Enquadramento; b) Marca da inundação; c) Pedras da rampa arrastadas; d) Quiosque totalmente destruído; e) Restaurante totalmente destruído; f) O Ponto 18.12 mostra o local de máxima inundação.

VI. DISCUSSION AND CONCLUSION

The storm was very well documented by the witnesses who posted news, articles, videos and photos on online archives. Most witnesses described one or two waves, around 6 - 9 m high (table I). In most coastal areas, the waves completely flooded the sand beaches, and overtopped the levees and breakwaters on the evening of January 6th and early morning of January 7th. These reports were validated by the *Cascais* tide gauge station. The flooded areas were not significantly large being restricted to the beaches, sea fronts, marinas and ports, and on some streets of the low coastal areas, including both commercial and residential buildings. A preliminary report revealed that the *Hercules* storm caused more than 16 million Euros in damages (Pinto *et al.,* 2014). The witnesses' accounts also showed that the authorities were able to correctly forecast the storm and to warn the coastal populations in time. The immediate response of local authorities was commendable, not only in the emergency response but also in assessing damages and cleaning operations. However, the Portuguese population did not gain significant experience from previous disasters, and the "culture of risk" had not being completely assimilated. Hence, some locals and tourists did not take the warnings seriously, moved into dangerous areas too close to the shoreline to film or take photos of the event. As a consequence, several people were caught by the waves. Some were able to escape by themselves, but others needed assistance (about 20 people).

Previous involvement in hazard incidents is important in the risk perception (Queirós *et al.,* 2007; Momani and Salmi, 2012), and after this event the Portuguese population was more aware of coastal dangers. Nevertheless, a new incident happened on March 3rd, 2014 (Sol, 2014) in which a 60 year old woman was caught by a wave at *Poça* beach (fig. 10) and died (Rodrigues *et al.,* 2014). In order to prevent similar situations in the future it is necessary to develop strategies of spatial planning that involve the implementation of safety awareness, dissemination of disaster prevention measures and mitigation strategies to the general public. These strategies involve organization of drills and evacuation exercises (Queirós and Santos, 2013), as well as the distribution of informative pamphlets (Santos *et al.,* 2013). At *Ribeirinha, Pico* Island, Azores, the beach structures will not be reconstructed on the same place because it is clearly unsafe (Carmo and Paiva, 2014). Most likely those structures will be rebuilt on higher ground.

Still, the *Hercules* storm showed the weaknesses of the coastal areas to a maritime extreme event, showing that coastal protections need serious evaluation and urgent mitigation actions are necessary. The problem of coastal erosion in Portugal has been addressed in the past (Paixão 2013, Trindade and Ramos-Pereira, 2013), but no practical solutions have been found yet. Although sand dunes offer a natural protection, they are not reinforced material. The construction of spurs and breakwaters offer some protection but other engineering solutions should be considered, e.g. all breakwaters and sea walls should be reinforced and elevated at least by 0.5 m.

The *Hercules* storm was characterized by long period waves, causing its behaviour on the coastline as "tsunami like". This phenomenon is designated by scientific

literature as *meteotsunami* or meteorological tsunami. Therefore, post-tsunami field survey techniques were used in order to study the impacts of this storm. The field survey confirmed the witnesses' accounts of wave heights of 6 to 9 m and confirmed the deposition of sand reported by the witnesses. It showed scouring and erosion nearby those areas. The inundation depths were less than 1.0 m in most areas, being restricted to the sea fronts, marinas and ports. Photos taken before and after the storm allowed a better comprehension of the coastal impact of the storm. The field survey also showed that the Portuguese coastline has high ground nearby the beaches and ports allowing the users to escape safely and in time to higher ground.

APPENDIX A. SUPPLEMENTARY MATERIAL

Supplementary material related to this article can be found at http://revistas.rcaap.pt/finisterra/article/view/6468

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Appendix A. Supplementary material

IMPACTS OF THE STORM *HERCULES* IN PORTUGAL

ÂNGELA SANTOS
SUSANA MENDES
JOÃO CORTE-REAL

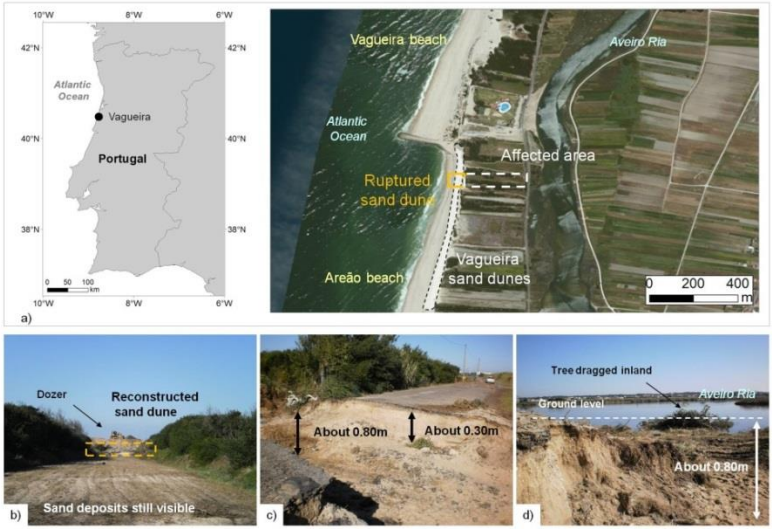

Fig. SM 1 – The impact of the November 2011 storm at south of Vagueira: a) Framework; b) Reconstruction of the sand dune was almost complete; c) Scoring of the road; d) Tree deposited at the Aveiro Ria.

Fig. SM 1 – Impacto da tempestade de Novembro de 2011 a sul da Vagueira: a) Enquadramento; b) Trabalhos de reconstrução da duna quase concluídos; c) Estrada destruída; d) Árvore arrastada para a Ria de Aveiro.

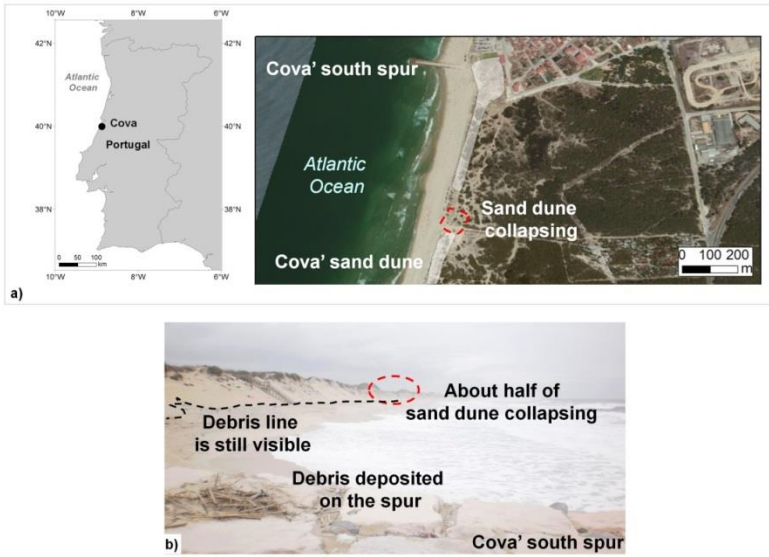

Fig. SM. 2 – The impact of the May 2013 storm at south of Cova, Figueira da Foz: a) Framework; b) Debris deposits show evidence of waves more than 5 m height.

Fig. SM. 2 – Impacto da tempestade de Maio de 2013 a sul de Cova, Figueira da Foz: a) Enquadramento; b)Depósitos de detritos mostram evidências de ondas de mais de 5m de altura.

Table SM I – Field survey results.
Quadro SM I – Resultados do trabalho de campo.

Place	Surveyed points	Lon (ºW)	Lat (ºN)	Height (m)
10-Figueira da Foz	10.1 Cabedelo – south spur, parking lot	8.86344	40.14061	5.67
	10.2 Cadedelo – sand dune	8.86223	40.13896	9.13
	10.3 Cova – sand dune top	8.863770	40.122995	13.84
	10.4 Cova – sand dune bottom	8.862691	40.123179	5.10
	10.5 Costa de Lavos - street	8.876304	40.090072	10.91
	10.6 Costa de Lavos - spur	8.876392	40.089660	9.13
	10.7 Costa de Lavos – sand dune sidewalk1	8.876366	40.088461	8.77
	10.8 Costa de Lavos – sand dune sidewalk2	8.876570	40.088487	7.57
	10.9 Costa de Lavos – sand dune sidewalk3	8.876613	40.088321	7.34
14-Ericeira	14.1Norte beach – parking lot	9.420776	38.969662	21.05
	14.2Norte beach – stairs	9.420776	38.969662	8.12
	14.3 Norte beach – sidewalk	9.419778	38.967238	7.47
	14.4 Norte beach – “Algodio” bar	9.419778	38.968093	7.01
	14.5 Norte beach – access to beach	9.419580	38.966891	5.28
	14.6 Fishing port – Naval club1	9.419750	38.965806	5.19
	14.7 Fishing port – Naval club2	9.419756	38.965595	4.34
	14.8 Fishing port – breakwater	9.420235	38.965627	6.57
	14.9 Fishing port – street1	9.419039	38.964451	14.47
	14.10 Fishing port – street2	9.418304	38.964827	28.27
	14.11 Fishing port – inundation mark	9.418410	38.964640	4.51
	14.12 Fishing port – information board	9.418579	38.964458	3.90
	14.13 Fishing port – street3	9.417953	38.964233	28.82
	14.14 Sul beach – sidewalk1	9.416233	38.959793	6.10
	14.15 Sul beach – sidewalk2	9.416112	38.959701	6.13
	14.16 Sul beach – sidewalk3	9.415923	38.959405	6.39
17- Tamariz beach, Estoril	17.1 Tamariz beach – sidewalk1	9.399848	38.703054	5.59
	17.2 Tamariz beach – sidewalk2	9.399251	38.702971	5.00
Poça beach, Estoril	Poça beach – inundation Mark (IM)	9.392524	38.702283	6.12
	Poça beach – Damage1 (D1)	9.392120	38.702228	5.40
18-Carcavelos	18.1 Carcavelos beach - inundation mark	9.339021	38.681145	5.56
	18.2 Carcavelos beach – sidewalk1	9.339051	38.681143	5.15
	18.3 Carcavelos beach – dragged stones	9.339132	38.681099	3.85
	18.4 Carcavelos beach – bars and surf	9.337991	38.680930	5.35

	school			
	18.5 Carcavelos beach – bar “surf”1	9.334921	38.680049	6.43
	18.6 Carcavelos beach – bar “surf”2	9.334868	38.680015	6.01
	18.7 Carcavelos beach - kiosk	9.330620	38.677995	4.19
	18.8 Carcavelos beach – bar “fizz”	9.330297	38.677839	4.25
	18.9 Carcavelos beach – sidewalk2	9.328197	38.676670	5.46
	18.10 Carcavelos beach – sidewalk3	9.327715	38.676582	5.41
	18.11 Carcavelos beach – sidewalk4	9.327437	38.676695	5.49
	18.12 Carcavelos beach – bar “Moinho”	9.327195	38.676733	6.85

Fig. SM 3 – Field survey at Figueira da Foz: a) Framework; b) Cabedelo sand dune before the storm; c) Cabedelo sand dune after the strom. Photo taken by Pedro A. Cruz; d) Cova sand dune; e) Damage at Costa de Lavos. Photo taken by Pedro A. Cruz.

Fig. SM 3 – Trabalho de campo na Figueira da Foz: a)Enquadramento; b)Duna do Cabedelo antes da tempestade;c) duna do Cabedelo depois da tempestade. Fotografia tirada

por Pedro A. Cruz; c) Duna do Cova; e) Estragos na Costa de Lavos. Fotografia tirada por Pedro A. Cruz.

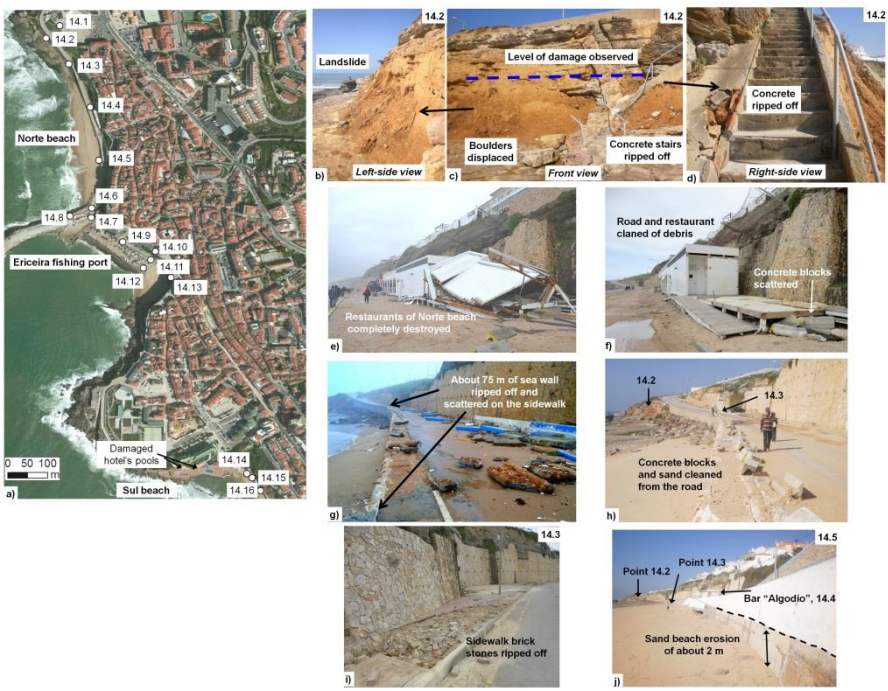

Fig. SM 4 – Field survey at Norte beach, Ericeira: a) Framework; b) Landslide at left-side view of Point 14.2; c) Front view of Point 14.2; d) concrete ripped off at stairs at right-side view of Point 14.2; e) Destruction of the Algodio restaurant. Photo by AZUL; f) restaurants and road cleaned; g) sea wall destroyed. Photo by AZUL; h) Sea wall concrete blocks removed from the area; i) Part of the sidewalk destroyed; j) Erosion of the Norte beach.

Fig. SM 4 – Trabalho de campo na praia do Norte, Ericeira: a) enquadramento; b) Deslizamento, visto do lado esquerdo do Ponto 14.2; c) Vista de frente do Ponto 14.2; d) cimento arrancado das escadas na vista do lado direito do Ponto 14.2; e) Destruição do restaurante Algodio. Fotografia tirada por AZUL; f) restaurantes e estrada limpos de detritos; g) Murete destruído. Fotografia tirada por AZUL; h) Blocos de cimento do murete removidos da área; i) Parte do passeio destruído; j) Erosão na praia do Norte.

Fig. SM 5 – Field survey at Ericeira fishing port: a) Framework; b) Naval club being inundated. Photo by AZUL; c) Naval club completely destroyed. Photo by AZUL; d) Naval club reconstructed; e) Waves hitting the fishing port breakwater. Photo by AZUL; f) Weaker waves hitting the fishing port breakwater; g) cleaning operations at the fishing port. Photo by AZUL; h) fishing port cleaned.

Fig. SM 5 – Trabalho de campo no porto da Ericeira: a) Enquadramento; b) Clube Naval a ser inundado. Fotografia tirada por AZUL; c) Clube Naval totalmente destruído. Fotografia tirada por AZUL; d) Clube Naval reconstruído; e) Ondas atingindo o quebra-mar. Fotografia tirada por AZUL; f) ondas mais fracas ainda atingindo o quebra-mar; g) operações de limpeza no porto. Fotografia tirada por AZUL; h) porto limpo de detritos.

Fig. SM 6 – Field survey at Sul beach, Ericeira: a) Framework; b) damages on the Sul beach sidewalk. Photo by AZUL; c) sidewalk cleaned from debris; d) Sea waves hitting the Sul beach. Photo by AZUL; e) Damage on a restaurant. Photo by AZUL; f) Sea wall ripped off; g) Concrete structures ripped off; h) Damage on the hotel's pools. Photo by AZUL.

Fig. SM 6 – Trabalho de campo na praia do Sul, Ericeira: a) Enquadramento; b) Estragos no passeio. Fotografia tirada por AZUL; c) Passeio limpo de detritos; d) ondas atingindo a praia do Sul. Fotografia tirada por AZUL; e) Estragos num restaurante; Fotografia tirada por AZUL; f) Murete arrancado; g) Estruturas de cimento arrancadas; h) Estragos nas piscinas do hotel. Fotografia tirada por AZUL.

Fig. SM 7 – Field survey at Tamariz and Poça beaches, Estoril: a) Framework; b) Sand deposited on the sidewalk; c) Sidewalk cleaned; d) Inundation mark; e) Protection bars ripped off; f) damage still visible.

Fig. SM 7 – Trabalho de campo nas praias do Tamariz e Poça, Estoril: a) Enquadramento; b) Areia depositada no passeio; c) Passeio limpo; d) Marca da inundação; e) Barras de proteção arrancadas; e) Estragos ainda visíveis.

Fig. SM 8 – Field survey at Carcavelos beach: a) Framework; b) Erosion at the base of stairs; c) sand and boulders deposited; d) restaurants damaged; e) sidewalk cleaned, but damage was still visible; f) inundation marks at the beach; g) Protection bars still missing; h) Protection bars still missing and tiles ripped off; i) Tiles of the sidewalk ripped off.

Fig. SM 8 – Trabalho de campo na praia de Carcavelos: a) Enquadramento; b) Erosão na base das escadas; c) Depósitos de areia e pedras; d) Estragos nos restaurantes; e) Passeio limpo, mas estragos ainda são visíveis; f) marcas da inundação na praia; g) Barras de proteção ainda não repostas; h) Barras de proteção ainda não repostas, e predas arrancadas; i) pedras no passeio arrancadas.