Research Paper

Title

# Comparing impact effects of common storms and Medicanes along the coast of south-eastern Sicily

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## Abstract

The coastal vulnerability along the Mediterranean coasts is increasing, especially in response to the occurrence of tropical-like cyclones, known as Medicanes, which have become more intense than in the past. A peculiar case was the impact of Medicane Zorbas in September 2018 along the coasts of south-eastern Sicily, where it caused inland flooding and damages to the socio-economic activities. Here, Zorbas effects are reconstructed through post-event geomorphological surveys, interviews with direct witness and analyses of video recorded by surveillance systems or found in social media. These data allowed us to assess the flooding extent on seven coastal sectors located between Thapsos Peninsula and Marzamemi. Flooding caused by

Zorbas appears to be greater than those produced by the main seasonal storms affecting the areas from 2015 to 2019; nevertheless, it is comparable with the flooding generated by Medicane Qendresa that impacted south-eastern Sicily in 2014. Wave propagation and extreme water level modelling, performed for the main storm events that occurred in the area since 2005, and analyses of data recorded by tide gauges of Catania, Porto Palo di Capo Passero and Malta since 2008, showed that Medicanes generate greater flooding than seasonal storms because they can induce higher and longer surge along the coastline. Collected data indicated that the surge generated by Zorbas reached a maximum value between about 0.8 m and 1.2 m above mean sea level (msl) along the coast of southeastern Sicily. Results highlighted the need to better evaluate the coastal hazard related to the propagation of Medicanes, especially in the context of future climate change when these events will probably be characterized by longer duration and greater intensity than at the present.

Keywords: coastal flooding; storm wave; storm surge; tropical-like cyclone; vulnerability.

# 1. Introduction

Faced with global climate change, special attention is paid to coastal vulnerability issues because most of the coasts are interested by the presence of urban settlements and economic activities. Under ongoing global warming, a global mean sea-level rise is expected for the 21st century with a likely range between 0.61-1.10 m at 2100 (IPCC, 2019) or even greater (Bamber et al., 2019; Jevrejeva et al., 2014; López-Dóriga and Jiménez, 2020; Rahmstorf, 2007; Rahmstorf et al., 2012). This could enhance the effects of extreme marine events that, in the future, will probably impact on the coastal landscapes currently emerged (Antonioli et al., 2020, 2017; Anzidei et al., 2021; Aucelli et al., 2017; Bonaldo et al., 2019; Marsico et al., 2017; Scardino et al., 2020; Scicchitano et al., 2018). In combination with the geomorphological coastal features, flooding connected to extreme marine events is commonly conditioned by tide excursion, storm surges, and storm waves. The combined effect due to tide height and storm surge determines a rise of the water column that enhances the storm wave inundation throughout the coastal landscape (Chaumillon et al., 2017; Holman, 1986; Stockdon et al., 2006). While the tidal oscillations are deterministic, storm surges and storm waves are driven by meteorological variations, usually related to tropical and extra-tropical cyclones (Chaumillon et al., 2017). Several studies considered the general cyclones' effects and related flooding in coastal areas, such as: the Gulf of Mexico during Hurricane Katrina in 2005 (Dietrich et al., 2010), the Bay of Bengal during cyclone Bhola in 1970 (Karim and Mimura, 2008), the United States with Hurricane Sandy in 2012 (Valle-Levinson et al., 2013), the Philippines with Typhoon Haiyan in 2013 (Shimozono et al., 2015). Some evidence of cyclone impacts were observed during storm surges in phase with spring tides, as the historical case of January 1953 that caused extensive flooding on the low-lying coastal zones of the Netherlands, Belgium, and United Kingdom (Wolf and Flather, 2005). Recently, in winter of 2018, the combination of storm surges with astronomical tides, enhanced by rain and river download, induced large flooding in Venice, Italy (Ferrarin et al., 2020).

Over the last century, global climate changes have increased the intensity of coastal flooding observed in the Mediterranean, mostly in response to the occurrence of extra tropical-like cyclones, better known as Medicane (MEDIterranean hurriCANE) (Bakkensen, 2017; Cavicchia et al., 2014a; Fita et al., 2007; Miglietta et al., 2013; Moscatello et al., 2008; Nastos et al., 2015; Portmann et al., 2019a). Medicanes are tropical-like cyclones that develop and determine convective cloud bands wrapped around a cloud-free central eye, with a typical size of their associated cloud clusters on the order of 300 km in diameter (Emanuel, 2005). These events produce a very low-pressure system with a cyclonic wind pattern that generates severe storms and relative surges, inland flooding and intense rainfalls, causing casualties and harmful destruction. Over the last decades, a decrease of the Medicane frequency was observed even though their intensity appears to be increasing (Marcos et al., 2011; Bakkensen, 2017), as for the cases of Medicane Qendresa in 2014 and Zorbas in 2018 (Bouin and Lebeaupin Brossier, 2020a; Scicchitano et al., 2020). The storm event connected to the Medicane Zorbas showed its effects on southern Greece and in southern Italy, especially in south-eastern Sicily (Scicchitano et al., 2020) where low pressure and wind generated a lot of waves and induced a storm surge able to flood large coastal areas. In this study, the impact effects of Medicanes and common seasonal storms are compared through: i) reconstruction of the coastal flooding due to the impact of the Medicane Zorbas in seven areas located along the coast of south-eastern Sicily (Fig. 1), ii) modelling of the storm surge, tide heights and wave propagation along the studied area for Zorbas and for other Medicanes and seasonal storms, iii) analyses of data recorded by tide gauges of Catania, Porto Palo di Capo Passero and Malta during the occurrence of Medicanes and storms.

Fig. 1 – Sites surveyed in south-eastern Sicily in response to the impact of Medicane Zorbas; A) Geographic location of the study area; B) Geological framework of the areas impacted by extreme marine events; C) Seven areas affected by Zorbas impact (yellow dots represent the zones with interviews of Zorbas effects, purple dots represent the zones described by official reports; light blue dots represents the zones monitored by videos, red dots represent the zones surveyed through direct witnesses and field evidence).

### 1.1 Seasonal storms and Medicanes in the Mediterranean Sea

The Mediterranean Sea is a semi-enclosed basin, connected with the Atlantic Ocean through the Gibraltar Strait and with the Black Sea through the Dardanelles Strait (Anzidei et al., 2014; Lin-Ye et al., 2020; López-Dóriga and Jiménez, 2020; Moatti and Thiébault, 2018). The Mediterranean climate is conditioned by the interaction between air masses and the orography (Lionello, 2012; Lionello et al., 2006). This interaction usually determines dry summers, with associated southern regional winds (Sirocco, Sharav, Khasmin etc.), followed by winter rainfall events and cold dry northern regional winds (Mistral, Tramontane, Bora, etc.) (Giorgi and Lionello, 2008; Moatti and Thiébault, 2018). The combined action of air pressure and wind stress causes the occurrence of baroclinic instability (Lionello and Sanna, 2005) that determines the common seasonal storms. These storms are characterized by a temporary rise of the sea level due to the inverse barometric effect (Doodson, 1923) and by wind stress that pushes horizontally the water column (Lionello, 2012; Lionello et al., 2006) with annexed coastal flooding. Sometimes, the seasonal storms can reach extreme values of storm surge and wave height and cause extensive coastal flooding, such as for the storm event of 28th October 2018 in the Northern Adriatic Sea (Ferrarin et al., 2020). During this event, significant wave heights were recorded at the *Piattaforma Acqua Alta* station (property of Council National of Research, Italy), 15 km off-shore of the Venetian littoral (wave height of 6 m) and near the city of Rovinj, Istrian coast of

Croatia (wave height of 4.7 m). However, other extreme events are related to the Medicanes (Cavicchia et al., 2014b; Portmann et al., 2019b). Medicanes are characterized by a development driven by convection and air-sea interaction rather than baroclinic instability of seasonal storms, assuming features similar to those of tropical cyclones (Bouin and Lebeaupin Brossier, 2020b; Cavicchia et al., 2014b; Portmann et al., 2019b; Tous and Romero, 2013). Although these events showed significant wave heights, comparable to the seasonal storms, they caused greater coastal flooding respect them. A peculiar case was observed in south-eastern Sicily, in September 2018, when Medicane Zorbas determined significant coastal flooding and boulders transportation on the rocky platform (Scicchitano et al., 2020). Furthermore, the sea-level data and wave height recorded close to Catania (Fig. 2) revealed that Medicanes have hydrodynamic features similar to the common storms even though field observations showed greater flooding.

Fig. 2 – Sea-level (source of ISPRA-Istituto Superiore per la Protezione e Ricerca Ambientale) and wave data in off-shore (source: RON—Rete Ondametrica Nazionale; www.idromare.com) recorded in the proximity of Catania (Sicily); yellow dots indicate the occurrence of Medicanes.

## 2. Geomorphological settings

Coastal areas of south-eastern Sicily (Fig. 1A, Tab. 1) are located on the emerged portion of the Pelagian Block, the foreland domain of the Neogene-Quaternary Sicilian collisional belt (Grasso and Lentini, 1982). The whole area lies at the footwall of a large normal fault system that runs along the off-shore of south-eastern Sicily (the Malta Escarpment, Fig. 1B; Bianca et al., 1999; Cultrera et al., 2015; Gambino et al., 2020). During the Late Quaternary, this coastal area has been affected by a slow vertical deformation that, combined with sea-level changes, generated several orders of marine terraces and paleo-shorelines (Bianca et al., 1999; Di Grande and Raimondo, 1982; Dutton et al., 2009; Meschis et al., 2020; Scicchitano et al., 2018, 2008; Spampinato et al., 2011; 2012). Notwithstanding this, according to Anzidei et al. (2018; 2021), GPS permanent stations and interferometric data locally show current weak subsidence at rates close to 1 mm/yr. This is relevant considering that the whole area is undergoing a heavy coastal retreat and it is exposed to severe storms.

The studied coastal area, characterized by an alternance of small rocky promontories and low-lying beach systems often bordering coastal lagoons, has been affected by several marine extreme events in historical times. Effects of several tsunamis have been reconstructed from the analyses of boulder accumulation (Scicchitano et al., 2012, 2007), high-energy deposits (Scicchitano et al., 2010; Smedile et al., 2011) and cores performed inside lagoons (De Martini et al., 2012, 2010). The analyzed area experienced also the effects of several storms that occurred over the last decades, mainly represented by boulders and cobbles dislocation along the coastal area (Barbano et al., 2010; Cama et al., 2015; Scicchitano et al., 2020). This suggests that, as described in other Mediterranean coastal areas (Biolchi et al., 2019b, 2019a, 2016), storms can produce effects comparable to other marine extreme events.

Studies of the meteo-marine regime performed by previous authors (Scicchitano et al., 2020, 2007), which analysed data recorded by the wave buoy of Catania (RON—Rete Ondametrica Nazionale; www.idromare.com), indicated that the strongest storm occurred in south-eastern Sicily since 1990 was characterized by significant wave height ($H_0$) of about 6.2 m and peak period Tp of 11.3 s (Fig. 3A). This is consistent with the analyses of wave data performed by Inghilesi et al. (2000) that considered possible for the area a maximum significant wave height of about 6.24 m with a return period of 50 years. Analysis of RON data also reveals that seasonal strongest storms are characterized by a maximum $H_0$ranging between 4.5 and 5 m (Fig. 3A), mostly from ESE although storms from ENE are frequent (Fig. 3B).

Several Medicanes impacted the coasts of south-eastern Sicily (Tab. 2) and in the last decades, these events have become more intense than in the past. Between 2014 and 2018, two strong Medicanes, called Qendresa and Zorbas respectively, occurred. Qendresa formed on the 5th November 2014 and rapidly intensified two days later, reaching peak intensity on the 7th November 2014. It directly hit Malta in the afternoon and then crossed the eastern coast of Sicily on the 8th November 2014. Later, the Medicane Qendresa weakened significantly and dissipated over Crete on the 11th November 2014. Measurements performed by the wave buoy of Crotone and Catania (RON—Rete Ondametrica Nazionale, “www.idromare.com,” 2009), during the passage of Qendresa, showed values of significant wave heights of about 4 m. The Medicane Zorbas generated in the Aegean Sea, moved westward until it reached the centre of the Ionian Sea, then reversed its track moving over north-western Turkey. Although Zorbas did not affect south-eastern Sicily directly, as in the case of Medicane Qendresa, its impact determined similar features, as recorded by satellite data in the off-shore (about 4.1 m) (source AVISO satellite altimetry, credits CLS/CNES, Scicchitano et al., 2020).

Fig. 3 – Meteo-marine regime of south-eastern Sicily: A) Data of significant wave heights recorded by wave buoy of Catania (1986 – 2014); B) Frequency distribution of wave height of Catania buoy (source: RON—Rete Ondametrica Nazionale; www.idromare.com).

Another important effect induced by Zorbas was a temporary sea-level rise detected by the tide gauges located inside Catania harbour (property of ISPRA, *Istituto Superiore per la Protezione e Ricerca Ambientale*) and in Porto Palo di Capo Passero (property of INGV, *Istituto Nazionale di Geofisica e Vulcanologia*) and observed in the video recorded at the Maddalena Peninsula by a surveillance camera of the Marine Protected Area of Plemmirio (Scicchitano et al., 2020).

Tab. 1 – Features of the coastal areas affected by Medicane Zorbas during the 28th September 2018.

## 3. Material & Methods

In order to describe the effects of Zorbas, we performed post-surveys through the use of Global Positioning System Real-Time Kinematic (GPS RTK) techniques. This allowed us to assess, with centimetric accuracy, the flooding limits reached by marine inundation on seven coastal areas of south-eastern Sicily (Fig. 1C). Flooding limits have been identified in the field, soon after the impact of Zorbas, detecting: i) debris and deposits carried out inland by waves, ii) erosion effects on the beaches, iii) overwashed sediments inside coastal lagoons, iv) effects on civil structures located along the coast.

In order to monitor the effects of common seasonal storms, systematic surveys were performed between 2015 and 2019 in two specific areas located along the coast of south-eastern Sicily, Arenella and Fontane Bianche (Area 3 and 5, respectively, Fig. 1C). Field evidence was integrated with video acquired by surveillance cameras or by people that observed the impact of Medicane Zorbas. In addition, interviews were conducted among the witnesses in order to detect reference points in the field, submerged by the flooding, which were subsequently measured through the GPS RTK. From the analyses of the videos, it was possible, in the same case, to detect the rise of the water column determined by tide height and storm surge on the coastal landscapes. Tide height and storm surge were assessed considering the elevation of reference points, as in the case of the temporary submersion of Milocca and Ognina Islands and Marzamemi square (Tab. 1). Where it was not possible to perform a survey through GPS RTK, the elevation of reference points was measured using orthophotos and Digital Terrain Model (DTM) provided by Regional Authority and surveyed by means of airborne photogrammetric and LiDAR (Light Detection And Ranging, 2x2 m cell width) techniques. The video frames showed wave inundation enhanced by the combined effect of storm surge and wave propagation, determining gradually inland flooding and involving the back-dune and residential areas. To assess and compare the wave heights of storm and Medicane events, wave data were recorded by satellite altimetry (AVISO CNES, "MSS: Aviso+," 2020), in off-shore for Medicane events (e.g., Zeo 2005, Qendresa 2014, Zorbas 2018, Trudy 2019, Ianos 2020) and main seasonal storms (e.g., events occurred in December 2009, October 2015, October 2016, December 2017). These data were used to reconstruct the wave propagation along the near-shore zone in Delft3D environment. Coupled simulations have been performed by means of Delft3D-WAVE with Delft3D-FLOW to incorporate wave-current interaction. Delft3D-FLOW was used to assess the hydrodynamic flow, and Delft3D-WAVE was used to simulate the wave propagation, based on the SWAN (Simulating WAves Nearshore) model (Lyddon et al., 2019; Whitham G.B., 1974).

With the aim to modelling the wave propagation in Delft3D, we reconstructed morpho-topography and morpho-bathymetry of the seven studied areas. LiDAR data and orthophoto (0.3 m resolution), provided by *Regione Sicilia* and acquired in 2008-2009, have been used to define the morpho-topography. Bathymetric data have been extracted by *Istituto Geografico Militare* (IGM) nautical maps or, as in the case of the Ognina site, surveyed through Multi-Beam Echosounder System (MBES) techniques in previous studies (Scicchitano et al., 2016). Topographic and bathymetric data were interpolated following different grid resolutions in order to homogenize the different data sources. Grids were built with a resolution of 2x2 m cell width on the shoreface and a resolution of 8x8 m cell width on the near-shore zone.

Temporary sea-level rise induced by storms and Medicanes was assessed through records of the tide gauges located in Catania (property of ISPRA – *Istituto Superiore per la Protezione e Ricerca Ambientale,* time-series 1987-2020), Porto Palo di Capo Passero (property of INGV – *Istituto Nazionale di Geofisica e Vulcanologia,* time-series 2015-2020), and Malta (property of University of Malta, time-series 2019-2021). A spectral analysis was performed on tidal signals through a Continuous Wavelet Transform (CWT), using the Wavelet "Morlet" (Bogusz and Klos, 2010; Cohen, 2019), to identify the frequency of occurrence of storm surges, and to filter the tide phases during the recorded events reported in Tab. 2.

The spectral analysis (Fig. 4) reports the tidal signals together with the scalograms. The scalograms represent the percentage of energy for each wavelet coefficient. The highest percentage of energy is attributed to the surge that occurred during the Medicane and storm events. Based on the frequencies reported in the scalograms, a high-pass filter was applied to highlight the surge values in Tab.3.

Fig. 4 – Spectral analysis performed through CWT on the tidal signals; colour bar on the scalograms represents the percentage of energy for each wavelet coefficients; cones of influence of the scalograms are reported in white lines.

## 4. Results

Flooding due to the Medicane Zorbas was assessed for seven specific areas located along the coast of south-eastern Sicily: Thapsos Peninsula, Siracusa, Arenella, Ognina, Fontane Bianche, Avola and Marzamemi. Each one of these sites, mainly represented by beaches, marsh environments and low-lying rocky coasts (Tab. 1), was affected by the impact of Zorbas in different ways.

In the Thapsos Peninsula (Area 1 – Fig. S1 Supplementary Material), characterized by a low-lying sandy beach protecting a lagoon in the back, flooding showed minimum value (about 30 ± 2 m) in correspondence of the isthmus and maximum one (about 95 ± 2m) in correspondence of the lagoon. However, the flooding did not reach the marsh probably because the dried season sensibly decreased its level. All along the sandy beach, several bathhouses were active during the period of impact of Medicane Zorbas; alongside, a power plant is connected to the sea through a pipeline pumping saltwater in special pools for cooling purpose. Zorbas surge flooded the main road all along the coastal area depositing, at the border wall of the power plant, a coarse sand deposit up to 30 cm thick (Fig. S2 Supplementary Material).

Interviews performed with several employees and managers of the bathhouses, revealed that during the occurrence of the largest flooding (28th September 2018 at 14:33 UTC), the tidal level appeared to be 0.6 – 0.8 m higher than under normal weather conditions (estimated along with specific structures of the bathhouses such as walls or tiled track). This value was constrained and better defined by the witnesses of several professional fishermen. They reported that, during the occurrence of the storm-induced by Medicane Zorbas, sea level was raised for about three hours, submerging the concrete structures posed to protect the pipelines of the power plant, up to a height of 0.8 ± 0.1 m above the msl. Wave propagation modelling performed by Delft3D, shows that during the Zorbas occurrence, waves impacted the south-eastern corner of the Thapsos Peninsula with greater energy than in the northern part, not directly exposed to the waves. On the other hand, wave heights modelled at the shore of the southern sector range between 0.8 m and 1.2 m (Area 1, Fig. S1-S2 Supplementary Material), not explaining the wide flooding reached by the Medicane Zorbas.

The Area 2 is located inside the natural harbour of Siracusa and it is mainly represented by a marshy coastal environment protected by the Natural Reserve of Ciane River and Siracusa Saline (Fig. S3 Supplementary Material). The abundant remains of *Posidonia oceanica* significantly contribute to the formation of a sandy coastal barrier system that has isolated the lagoon from the sea. In this area, Zorbas flooding was surveyed the day after the impact, when we also collected some interviews with local professional fisherman. Flooding values ranged between 15 ± 2 m, mostly in the areas where the reeds were particularly dense, and 123 ± 2m, measured in the proximity of Ciane River mouth. Flooding overwashed the marsh in several areas depositing a wide layer of marine sediments up to 40 ± 5 cm thick (Fig. S4 Supplementary Material). Employees and managers of a boat storage centre located on the mouth of Ciane river reported a msl raising of 0.7 – 1 m. The seawater flooded their mooring structures for about 3 hours, on 28th September 2018 at 16:20 UTC.

The Delft3D modelling showed the refraction of the waves, evident in the proximity of the entrance of the harbour, and a strong decrease of the wave height values inside the natural bay (Fig. S4 Supplementary Material). Along the coastal area, Delft3D modelled waves approaching the shore with a height value ranging between 0.65 ± 0.2 m and 0.42 ± 0.2 m. In the proximity of the Ciane river mouth, the coastal topography and bathymetry probably determined an interaction between refracted and diffracted waves.

Area 3 is located about 6 km south of the Siracusa harbour, between the Milocca Island and the Asparano Promontory (Fig. 5 and Fig. S5 Supplementary Material), and it is represented by a low-lying rocky coast, in its north-eastern sector, and a long sandy beach in the south-western sector.

Fig. 5 - Map of Marine Protected Area of Plemmirio, between Milocca Island and Asparano Promontory (Area 3) showing: the reconstructed limit of flooding during the Medicane Zorbas (blue line), points surveyed in the field (red Points), locations of the points for which witnesses reported in the interviews (yellow points); A) and B) tiles displaced by storm waves; C) reeds bordering the lagoon damaged by the storm.

The worst effects in terms of flooding occurred in the south-western sector, where it reached values of 120 ± 2 m heavily hitting the bathhouse located alongside the Arenella beach, in the proximity of the Asparano Promontory (Fig. S5 Supplementary Material). In this site a tiled track was present, connecting the bathhouse with a beach resort located about 2 km to the south, composed of singular tiles of about 5 kg. Zorbas flooding was able to displace several tiles inside a small lagoon present at about 120 m from the beach towards the hinterland (Fig. S6 A-B Supplementary Material). Reeds bordering the marsh have been heavily damaged by the storm (Fig. S6 C Supplementary Material) that deposited sediments and garbage inside the lagoon.

In the northern sector of Area 3, technicians of the Marine Protected Area of Plemmirio reported that on 28th September 2018 the Milocca Island (Fig. S5 Supplementary Material), which reaches an elevation of 1.5 ± 0.3 m above msl, resulted totally submerged for about 3 hours, from 15:00 UTC to 18:00 UTC. This temporary rise in sea level has been also confirmed by videos collected by a surveillance camera of the Marine Protected Area of Plemmirio (Scicchitano et al., 2020) and by interviews with employees and managers of the bathhouse located in the southern sector, who described a water level increase of 1.2 – 1.5 m along the coast. Although, the Delft3D wave propagation highlights a continuous impact of waves along the eastern portion of the Arenella beach, again the waves were too small to produce flooding effects.

Area 4 (Ognina area, Fig. S7 Supplementary Material) is formed by a small promontory that delimits a bay where a channel harbour about 600 m long occurs. In front of the harbour entrance, there is a flat island that, in historical times, was connected to the mainland by a narrow rocky isthmus, which is now submerged (Scicchitano et al., 2016). A detailed survey was performed the day after the impact of Zorbas and integrated with interviews conducted among the owners of the houses damaged by the storm and the owners of a Diving Center located on a side of the harbour channel.

In the northern sector of the area, the flooding induced by Medicane Zorbas overtopped the rocky coast, reaching the main road, and pulled a border wall located about 55 m from the shoreline (Fig. S8 A Supplementary Material). In some cases, the water broke down property gates depositing coarse sands and pebbles in the backyards (Fig. S8 B Supplementary Material). Close to the harbour entrance, the waves hit the Guard of Finance barracks causing severe damages (Fig. S9 Supplementary Material). Along the channel harbour, the flooding eradicated an ancient milestone transporting it further inland (Fig. S9 Supplementary Material). In the inner part of the channel, on 27th September 2018 at 05:30 UTC, the surveillance camera of the Diving Center recorded for about 3 hours a sea level of about 0.8 – 1.0 m above the msl, measured along the dock.

The Delft3D wave propagation modelling for the Ognina area highlights the interference of the waves and an increase of wave height at the distal extremity of the channel. Along the channel axis, wave height becomes higher and faster than in the near-shore zone, determining extended flooding at the entrance of the channel, according to field evidence.

Area 5 (Fontane Bianche, Fig. S9 Supplementary Material) is located about 5 km southward of the Ognina site and it is mainly represented by a long sandy beach often bordered on the back by large housing complexes, bathhouses and beach resorts. In this area, Zorbas flooding ranged between a minimum value of 15 ± 2 m and a maximum of 125 ± 2 m, as reconstructed by a post-event survey performed the day after the event, interviews with house owners and bathhouse managers and analyses of media reports. In the southern sector of the area, Zorbas generated wide flooding that caused damages on the wall of a drainage artificial channel (Fig. S10 A Supplementary Material) and displacements of several wood structures of the bathhouse up to 125 ± 2 m inland (Fig. S10 B Supplementary Material). In the central part of the area, the flooding pulled down a property wall located about 65 m from the coastline (Fig. S10 C Supplementary Material). Interviews and media reports documented that, during the stroke of Zorbas, the sea level increased up to 0.9 -1.2 m with respect to the msl.

About 30 km south of Siracusa, along the Avola seafront (Area 6, Fig. S11 Supplementary Material), several docks were flooded by the marine ingression, as reconstructed by interviews and by the analyses of videos uploaded on social media by witnesses (https://youtu.be/easN5yFIwic) (Fig. S12 Supplementary Material).

In the harbour of Marzamemi (Area 7, Fig. S13 Supplementary Material), the main effect of storm impact, reconstructed by several media reports and by the analysis of several interviews, was a sudden and durable storm surge that flooded most of the structures.

Analyses of video uploaded on youtube (https://youtu.be/XvKfWczzqr8) and recorded by news media allowed us to accurately reconstruct a storm surge of about 0.85 m (Fig. S14 Supplementary Material) that hit all the natural embayment of Marzamemi, flooding the infrastructures along the seafront.

The model shows an effect of diffraction due to the harbour and to the islet “Isola Piccola”, determining a wave propagation able to rapidly reach the coast and to flood the emerged surface up to 66 m landward.

In order to compare wave heights on the shoreface related to Medicanes and storms, Delft3D has been applied to model the wave propagation for all the events reported in Tab 2. Results show a reduction in height of about 83% between the waves recorded in the off-shore (by satellite altimetry and buoy) and those estimated on the shoreline by the model, both during the Medicanes and the common storms. Wave heights reconstructed in the proximity of the coastline for the area of Arenella (Area 3) and Fontane Bianche (Area 5), during the impact of Medicanes and storm events (see Tab.2), show very similar values for both typologies. The highest wave height value is about 0.72 ± 0.1 m and it is related to the Medicane Zeo (2005) and to the storm occurred in February 2015. Medicanes Zorbas (2018) and Trudy (2019) produced wave heights of 0.65 ± 0.2 m and 0.6 ± 0.05 m, respectively, as well as the 2017 seasonal storm.

Tab. 2 – Wave heights for the Medicanes and storm events over the last decades.

Tidal signals recorded by the gauges of Catania and Porto Palo di Capo Passero showed a significant rise of the water column during all the events reported in Tab 2. We performed a spectral analysis of the tide gauge data to define the storm surge contribution filtering the tidal excursion. Results show that greater surge values were observed during Medicanes rather than common storms (Tab. 3, Fig 6). This analysis reconstructed for Medicane Zorbas a storm surge of 0.23 ± 0.03 m and a tide height of about 0.42 ± 0.02 m. On the other hand, field evidence, video and reports allow us to reconstruct a significant rise of the water column during Zorbas of 1 ± 0.3 m, resulting in a surge value much higher than those defined by tidal analysis (applying the tide excursion previously calculated).

Tab. 3 – Rise of the water column observed in the tide gauge and values of storm surge obtained by filtered tidal signal.

Fig. 6 - Filtered tidal signals of the storm events, dark blue indicates the Medicanes while light blue indicates the common storms.

## 6. Discussions

The impact of extreme marine events determined significant flooding along the coastal stretches of south-eastern Sicily. Two main kinds of flooding were observed over the last decades: (ì) coastal flooding related to the common storm events and (ìì) coastal flooding related to the Medicanes. Medicane Zorbas impacted along the coasts of south-eastern Sicily determining extensive flooding that were reconstructed through a joint analysis of direct surveys, interviews and videos reported on social media. In order to compare flooding extension during Medicanes and storm events, we selected two specific areas of the seven studied: Area 3, including the Arenella beach, and Area 5, including the Fontane Bianche beach (Fig. 7). These two areas have been subject to intense monitoring since 2014, when, after the storm-related to Medicane Qendresa (see Tabs. 2 and 3), post surveys have been performed with the aim of reconstructing the flooding limits. Other surveys were performed over these years also after the impact of the strongest seasonal storms (occurred in 2015, 2016, 2017, 2019).

Fig. 7 – Flooding limits surveyed in two specific areas during different Medicanes and storm events; A – flooding on Arenella beach (Area 3); B- flooding on Fontane Bianche (Area 5).

In Fig. 7 the flooding limits surveyed in Area 3 and Area 5 after the impact of Medicane Qendresa (2014) and Zorbas (2018) and after the impact of the seasonal storms that occurred between 2015 and 2019 are showed. Results show that the flooding related to Medicane events are wider than those related to the storms. Zorbas and Qendresa generated flooding that penetrated up to 120 – 130 m landward, while storms normally did not exceed 50 - 60 m of inland inundation. Flooding generated by Medicanes seems to be characterized by high energy flows able to destroy and dislocate structures located along the coastal area. Flooding connected to extreme marine events is commonly conditioned by the tide phase, storm surges, and storm waves.

In order to verify if the difference between Medicanes and seasonal storms flooding extension may be connected to a different wave setting along the coast, we modelled in Delft3D the wave propagation for all the events reported in Tab.2. Results show a general homogeneity in wave height values (Tab. 3): the highest value measured in the proximity of the coastline, of about 0.96 m, was reached by Medicane Zeo in 2005 and by a storm occurred in 2015. A storm occurred in 2017 reached a wave height of about 0.86 m that resulted to be higher than those modelled for Medicane Qendresa and Zorbas. This result highlights that the wider flooding generated by Medicanes cannot be explained by the largest values of wave height impacting the coastal areas, and it should be attributed to the effects of surge and tide. The combined effect of tide height and storm surge determines a rise of the water column, which enhances the storm wave ingression throughout the coastal landscape (Chaumillon et al., 2017; Höffken et al., 2020; Holman, 1986; Stockdon et al., 2006; Woodruff et al., 2013). Considering that the coasts of south-eastern Sicily are characterized by microtidal excursion (Anzidei et al., 2018; Braitenberg et al., 2011; Palma et al., 2020; Tsimplis et al., 1995), it is reasonable to consider storm surge as a major component of water level rise.

In the studied events, storm surge is defined as a positive deviation from the sea level (see also Carter, 1997) and it can be assessed by filtering the raw tidal signals. During a storm event, raw signals in the tide gauges are conditioned by components of the tide height and perturbation of water level due to the storm surge. Our analyses of the tide gauges of Catania and Capo Passero during the propagation of Medicane Zorbas, provided a storm surge value of about 0.23 ± 0.03 m that appears very low with respect to that obtained by analyses of field evidence, which suggest a surge value of about 0.60 m. This difference can be probably attributed to local amplification processes that, in areas particularly exposed to the storm impact, can generate a strong effect of flooding along the coasts.

This study shows that the Medicanes generated stronger effects, especially in terms of flooding, than common seasonal storms along the coast of south-eastern Sicily. This difference is probably attributed to a higher raising in water level column that Medicanes can induce along the coastline, and imply that coastal hazard of areas prone to Medicanes occurrence should be better assessed maybe throughout the definition of specific numerical modelling. Furthermore, in the near future, other processes could increase the Medicane effects, such as i) the relative sea-level rise and vertical land movements (Antonioli et al., 2020, 2017; Anzidei et al., 2018; 2021¸ Aucelli et al., 2018, 2017; Vecchio et al., 2019), ii) changing in sedimentary balance and annexed shoreline movements (Brunel and Sabatier, 2009; Rosskopf et al., 2018; Sabatier et al., 2009; Scardino et al., 2020), iii) anthropogenic influence along the coasts (Anthony et al., 2019; Caldara et al., 2006; Di Stefano et al., 2013).

## 7. Conclusions

Medicane Zorbas impacted along the coasts of south-eastern Sicily determining extensive flooding that has been reconstructed, for seven areas, by coupling analysis of direct surveys, interviews and videos reported on social media. Comparing the flooding limits reached by two distinct Medicanes (Qendresa and Zorbas) and several seasonal storms in two specific areas (Area 3 and Area 5) and analyzing wave propagation models and tidal gauge data, we reached the following conclusions:

- Medicanes generally are able to generate wider flooding than to the seasonal storm. Although the models of wave storm propagation provide similar values of wave height for both typologies of event, surface flooded by Medicanes is double to those flooded by common storms.
- The difference in flooding between Medicanes and storms have to be attributed to the combination of storm surge and tide height. Analyses of the raw signal recorded by tide gauges of Catania and Capo Passero, revealed that high rise of the water column were detected during the passage of the Medicanes.
- Storm surges reconstructed from tide gauge data analyses appear underestimates when compared with field evidence detected during the impact of Medicane Zorbas along the coast of south-eastern Sicily. This is probably due to the local effects of amplification.

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# Data Availability

Datasets related to LiDAR data were provided by WMS service of Regione Sicilia at https://sif.regione.sicilia.it (accessed on 21 January 2021).

Datasets related to tide gauge for the sea-level station are freely available at www.mareografico.it (accessed on 21 January 2021) and http://www.ioc-sealevelmonitoring.org/ (accessed on 21 January 2021).

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Fig.1

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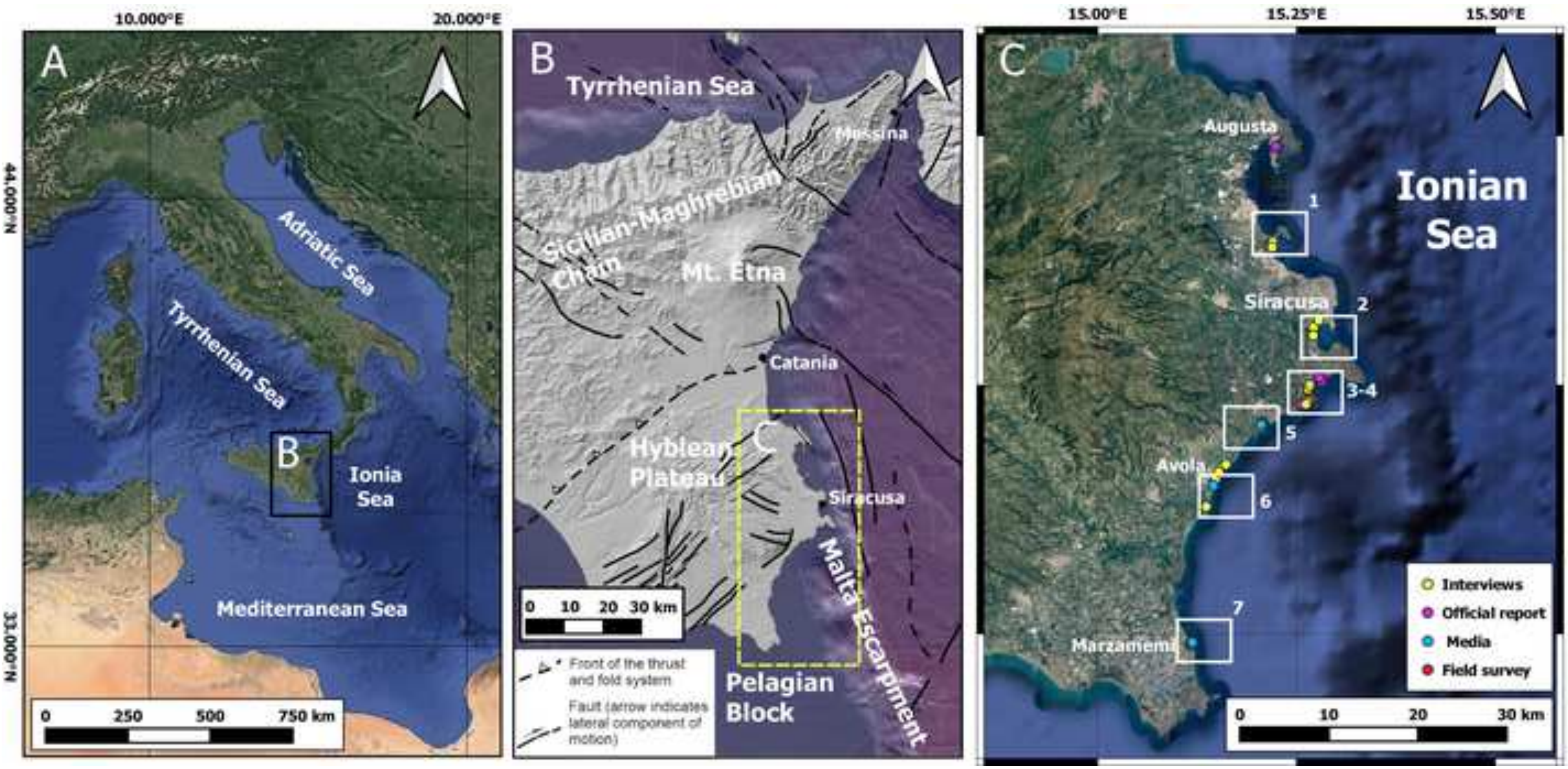

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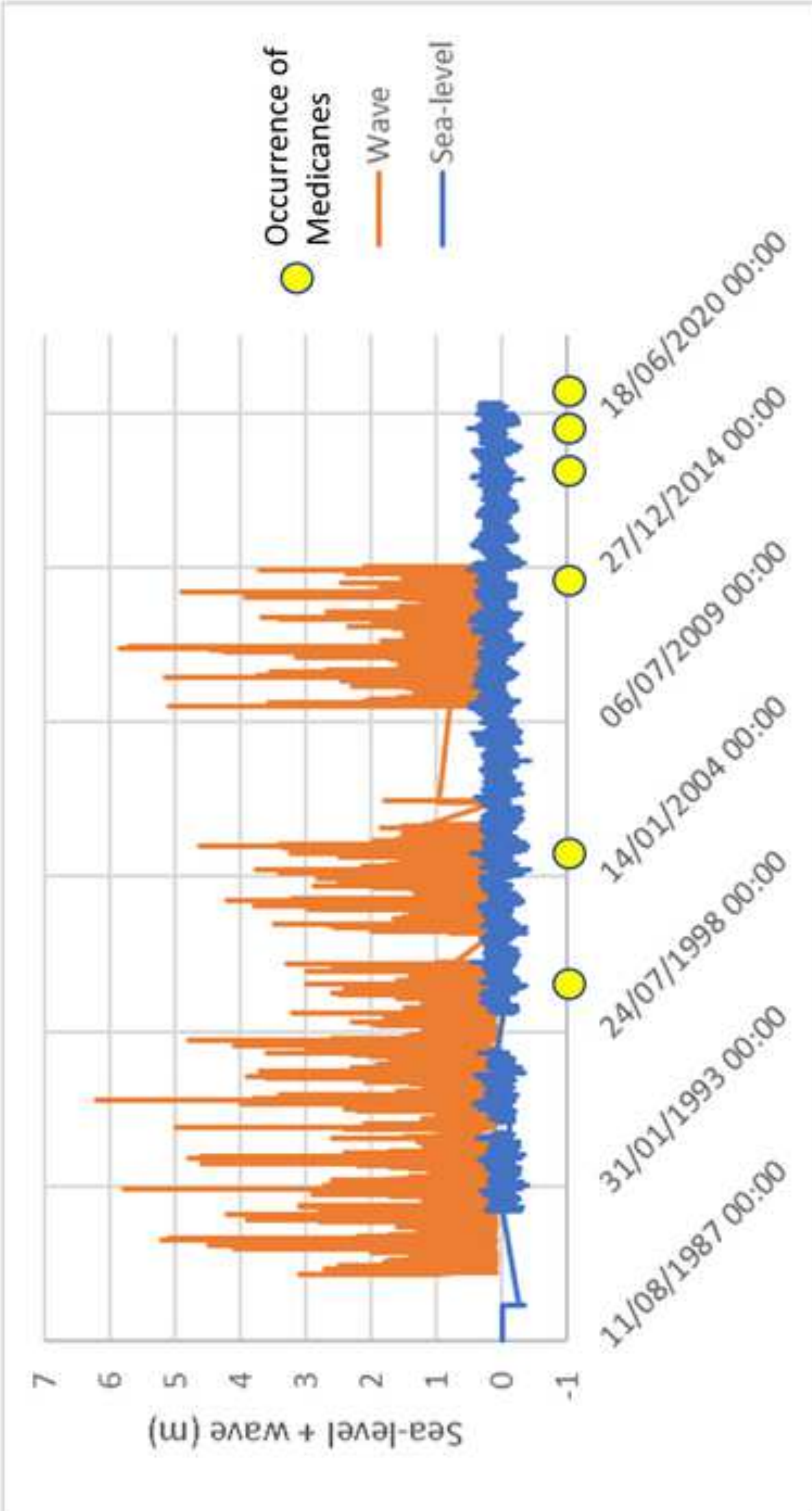

Fig.3



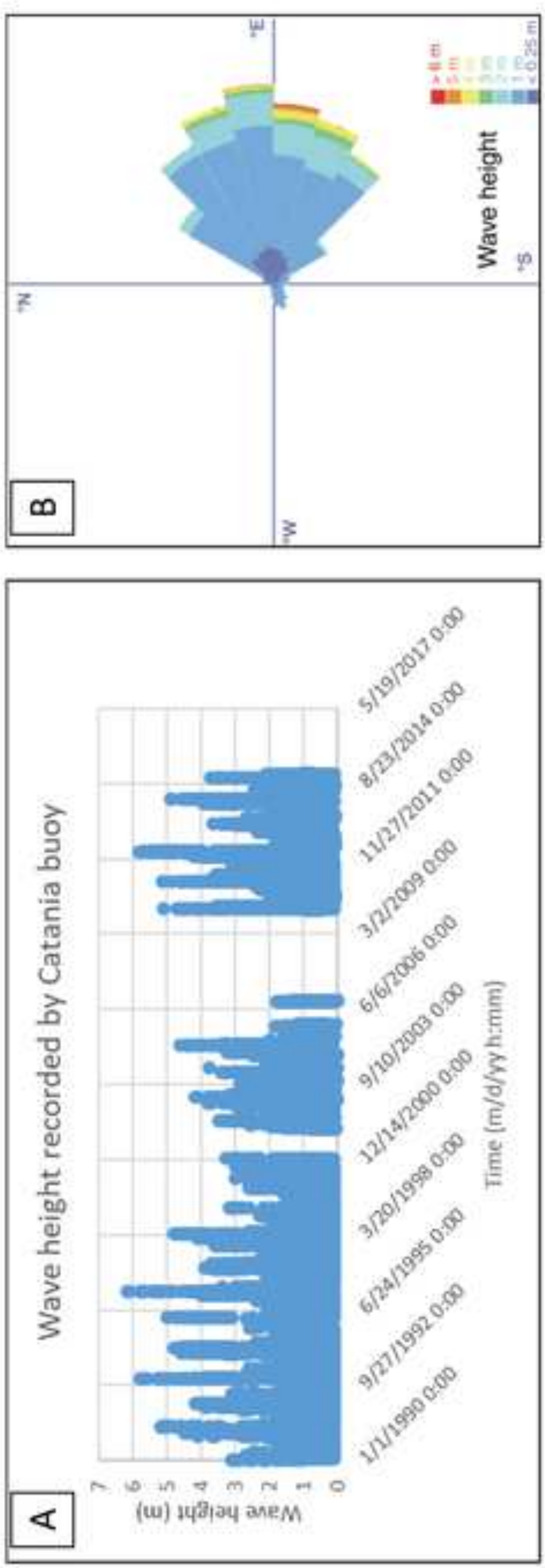
A
Wave height recorded by Catania buoy
Wave height (m)
0
1
2
3
4
5
6
7
1/1/1990 0:00
9/27/1992 0:00
6/24/1995 0:00
3/20/1998 0:00
12/14/2000 0:00
9/10/2003 0:00
6/6/2006 0:00
3/2/2009 0:00
11/27/2011 0:00
8/23/2014 0:00
5/19/2017 0:00
Time (m/d/yy h:mm)
B
N
E
S
W
Wave height

Fig.4

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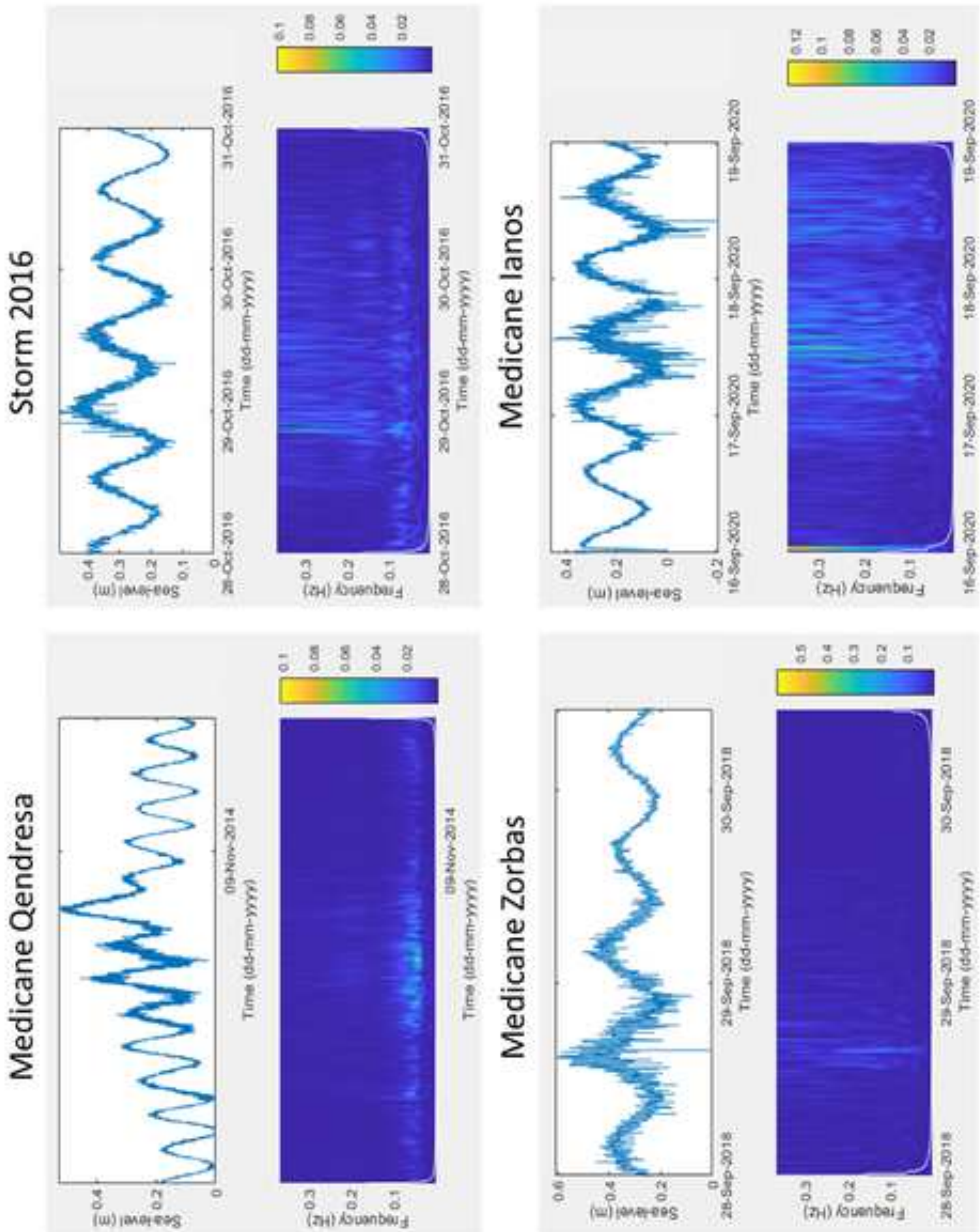


Fig.5



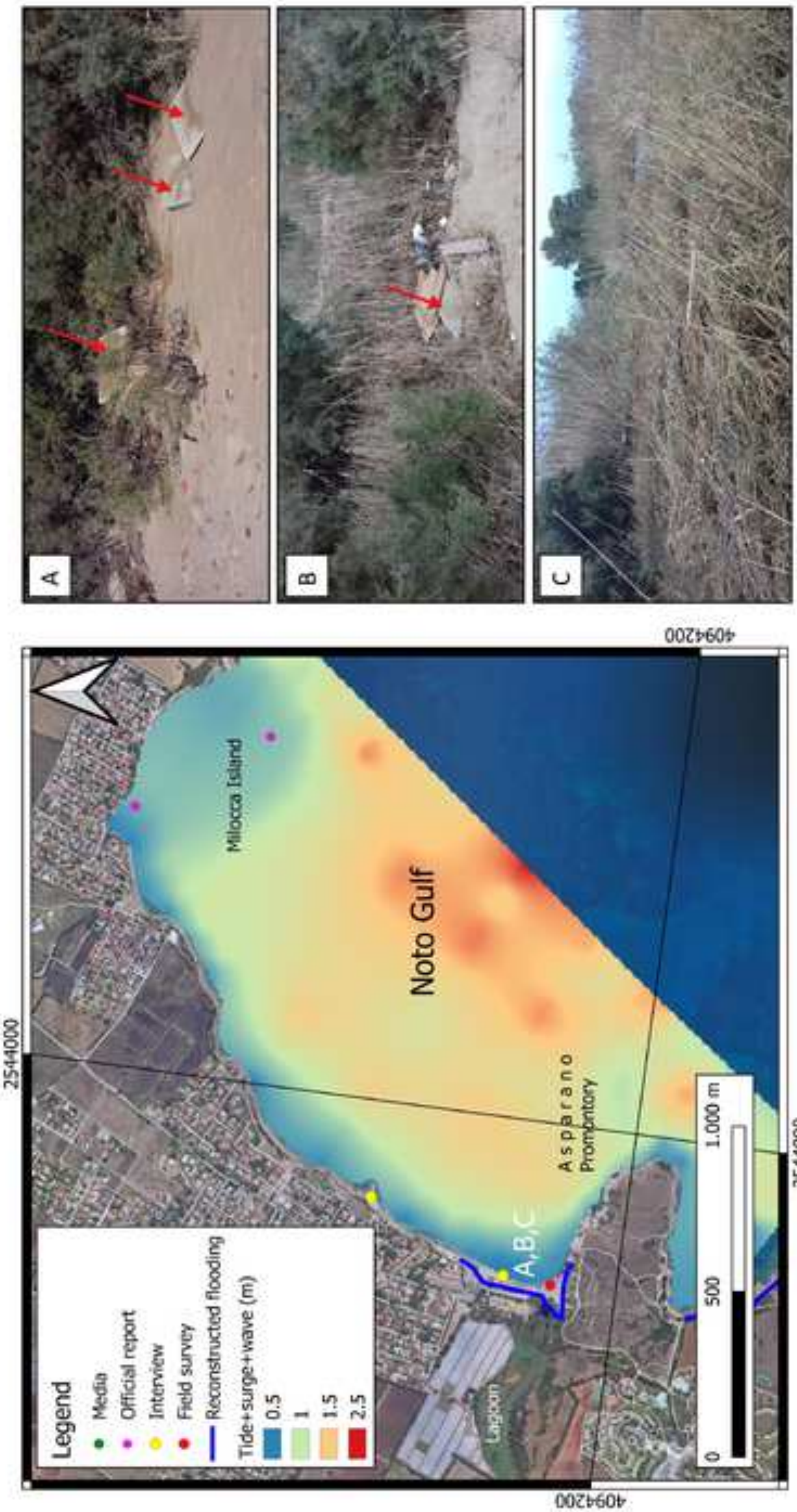

A
B
C
Legend
Media
Official report
Interview
Field survey
Reconstructed flooding
Tide+surge+wave (m)
0.5
1
1.5
2.5
Noto Gulf
Milocca Island
Asparano
Promontory
A,B,C
Lagoon
0
500
1.000 m
2544000
4094200

Fig.6



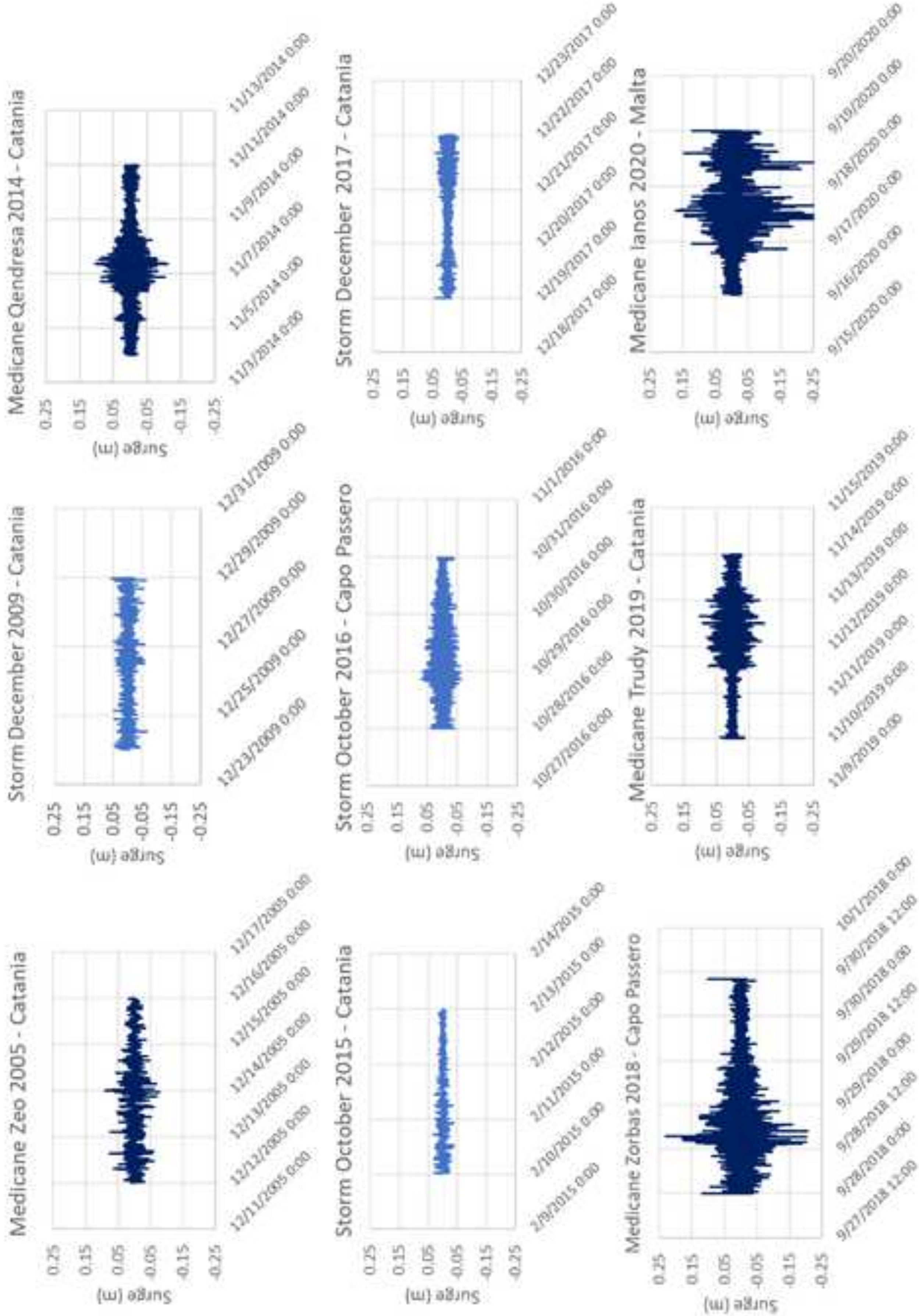
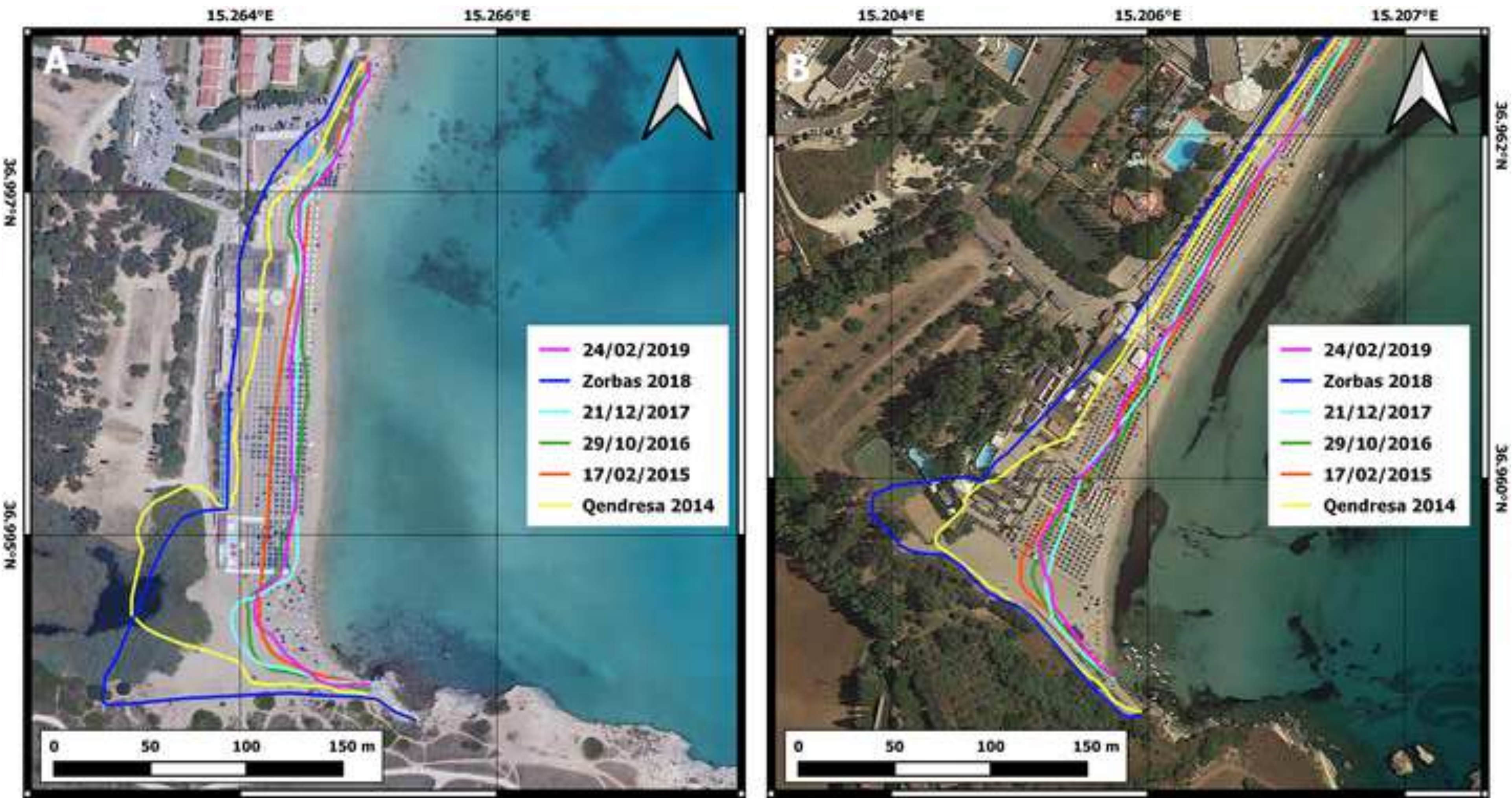

Medicane Qendresa 2014 - Catania
Storm December 2009 - Catania
Medicane Zeo 2005 - Catania
Storm December 2017 - Catania
Storm October 2016 - Capo Passero
Storm October 2015 - Catania
Medicane Ianos 2020 - Malta
Medicane Trudy 2019 - Catania
Medicane Zorbas 2018 - Capo Passero
Surge (m)

Fig.7





15.264°E
15.266°E
36.997°N
36.995°N
A
24/02/2019
Zorbas 2018
21/12/2017
29/10/2016
17/02/2015
Qendresa 2014
0
50
100
150 m
15.204°E
15.206°E
15.207°E
36.962°N
36.960°N
B
24/02/2019
Zorbas 2018
21/12/2017
29/10/2016
17/02/2015
Qendresa 2014
0
50
100
150 m

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Fig.S2

Fig.S3

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Fig.S9

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Fig.S12

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Fig.S13

Fig.S14

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