Characteristics and coastal effects of a destructive marine storm in the Gulf of Naples (Southern Italy)

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Abstract. Destructive marine storms bring large waves and unusually high surges of water to coastal areas, resulting in significant damages and economic loss. This study analyses the characteristics of a destructive marine storm on the strongly inhabited coastal area of Naples Gulf, along the Italian coasts of the Tyrrhenian Sea. This is highly vulnerable to marine storms due to the accelerated relative sea-level rise trend and the increased anthropogenic impact on the coastal area. The marine storm, which occurred on the 28th December 2020, was analyzed through an unstructured wind-wave coupled model that takes into account the main weather-marine components of the coastal setup. The model, validated with in-situ data allowed to establish threshold values for the most significant marine and atmospheric parameters (i.e., wind intensity and duration) beyond which an event can produce destructive effects. Finally, a first assessment of the return period of this event was evaluated using local press reports on damage to urban furniture and port infrastructures.

1 Introduction

Impacts of storm-driven erosion and flooding are the most serious hazards being faced by coastal systems worldwide, due to the strong urbanization of these areas, especially because ca. 50% of the world’s coastline is currently under pressure from excessive human development. Furthermore, according to the recent IPCC report (IPCC, 2021), global mean sea-level rise is expected to rise 1.1 m by 2100, enhancing the effects of extreme marine events that, in the future, will probably hit increasingly-wide coastal areas (Antonioli et al., 2020; Bamber et al., 2019; Aucelli et al., 2017b). Other relevant physical drivers are changes in storms and hurricanes characteristics such as wave height and tracks (Buccino et al., 2020; Di Luccio et al., 2019). In the last years, additionally, global climate changes have increased the intensity and frequency of coastal flooding observed in the Mediterranean due to severe storms and relative surges and often in response to the occurrence of extra tropical-like cyclones, better known as Medicane (MEDIterranean hurriCANE) (Scicchitano et al., 2021; Bakkensen, 2017; Portmann et al., 2019). Climate change related impacts, such as shoreline changes, under these conditions and their prediction are essential for integrated coastal zone management (Di Paola et al., 2020).

Impacts of storms on coastal areas induce relevant economic and human losses that demand better knowledge of coastal exposure and oblige to reflect on the adoption of measures to reduce the impacts of these events (Costas et al., 2015). Erosive effects on the coasts are controlled by the interplay between storm characteristics and coastal geomorphology (Lionello and Scarascia, 2020). Moreover, coastal damage, strongly related to storm-induced processes (i.e. flooding or erosion), can be exacerbated by the presence of intensive human activities or other developments in residential localities such as ports or touristic infrastructures (Godschalk et al., 2000; Esnard et al., 2001; Jiménez et al., 2012).

Storm impact assessment on urbanized coastal areas in the Mediterranean Sea (Sanuy et al., 2018; Lira-Loarca et al., 2020; Amores et al., 2020; Cavaleri et al., 2019; Jiménez et al., 2018; Amarouche et al., 2020; Anfuso et al., 2021) has become an issue of high scientific and social interest due to the alarming effects related to the climate changes observed over the last decades (Young and Ribal, 2019; Lionello and Scarascia, 2020; Gulev and Grigorieva, 2004), not only in the form of an increasing trend in significant wave heights (H_s) and wind speed (W_s) (Dobrynin et al., 2012; Reguero et al., 2019; Vieira et al., 2020; Meucci et al., 2020), but also due to the accelerated relative sea-level rise.

The examination of the behaviour, evolution, and consequences of the coastal storm disasters is necessary to assess their danger and the population's ability to adapt and mitigate their effects (Tsai and Chen, 2011). In this respect, many Authors (Van Westen, 2013) recognized the relevance of a risk analysis based on its estimation, identification, and understanding.

To this aim, this paper deals with the characterization of a significant storm that occurred in the Gulf of Naples (Italy) that was reconstructed by analyzing weather and marine data obtained from in-situ instruments and numerical simulations. These simulations, based on WRF and WW3 wind and wave models, have been configured by University of Naples "Parthenope" in the Gulf of Naples since 2006 (Benassai and Ascione, 2006), and have been successfully validated with in situ and satellite data (Benassai et al., 2015, 2013, 2012).

The study area exhibits a seasonal wave climate as observed along the whole coastal area of the Tyrrhenian Sea (Morucci et al., 2016; Saviano et al., 2020). Low H_s (in the order of a few tens of centimeters) are measured during the summer (from June to August) and significant waves up to 3 m during winter and autumn (from November to February). However, coastal effects of the most intense winter events on a specific coastal sector not only depend on wave height and period but also storm groupies and interaction of the storm waves to the bathymetry and the shoreline. Consequently, a precise assessment of the parameters that characterize a storm event is a significant challenge to better understand final effects on the coast associated with potential damages (Biolchi et al., 2019; Ferrando et al., 2021; Anfuso et al., 2016).

Therefore this paper focuses on defining and interpreting the dangerousness of the extreme storm waves that occurred in the Gulf of Naples on 28th December 2020. The numerical assessment of the storm surge on the most impacted coastal sector was carried out through a procedure, validated with in-situ data, which took into account the main weather–marine components of the coastal setup. The aim of this paper was twofold: on one hand to characterize the event, by applying a large-scale evaluation of the weather-marine variability during the maximum peak; on the other, to define a fast procedure able to establish threshold values for the most significant marine and atmospheric parameters (i.e. wind intensity and duration), beyond which an event can produce destructive effects on human activities and coastal infrastructures. This procedure, coupled with the high-precision marine-weather forecasting, provided by the network in the Gulf of Naples belonging to the University of Naples "Parthenope", might be intended as a tool for civil protection and coastal damage prevention purposes. The approach proposed in this study can be efficiently used to define the level of sensitivity of urbanized coasts to storms (Williams et al., 2018; Molina et al., 2019, 2020).

The paper is organized as follows: Section i. introduces the thematic, Section ii. details the study area characteristics, Section iii. describes the methodologies, Section iv. presents the reconstruction of the storm event on the framework of historical wind events, Section v. discusses the coastal effect of the storm surge, and Section vi. concludes.

2 Study area

The Naples Gulf (Figure 1), Tyrrhenian Sea, is one of the most populated Italian areas, with 3.016.762 inhabitants and a medium density of 2.672 inhabitants/km^2. The urban territory includes 92 municipalities on a surface of 1.171 km^2, with a 60% of small municipalities (surface <10 km^2) and an 11% of big ones (surface >25 km^2). The lasts include the coastal cities of Naples, Torre Annunziata, and Pozzuoli. The urbanized area in the Gulf occupies only 32.54% of the total surface, and consequently, the population density in this area is more than 8000 inhabitants/km^2. Its coasts, with an extension of 153 km, have a high cultural and natural value as demonstrated by the presence of several protected areas under different legal coverages, such as marine protected areas (Marine Protected Areas of Punta Campanella and Regno di Nettuno) and archaeological parks (Underwater archaeological parks of Baia and Gaiola). However, the numerous submerged archaeological sites scattered along the coasts are significantly vulnerable to coastal processes (Mattei et al., 2019). Under these circumstances, the urbanized coasts of the Gulf can be certainly considered highly sensitive from both a socio-cultural and economic point of view to severe marine storms. On the other hand, main cities are located in narrow coastal plains, with commercial activities and infrastructures located only a few meters above sea level (Ascione et al., 2020). In fact, the present coastal morphology in the Gulf (Figure 1) is characterized by an alternation of articulated seacliffs with sheltered pocket beaches, and narrow coastal plains, often strongly urbanized (Ascione et al., 2020; Aucelli et al., 2017a). In particular, the high-coastal sectors in the Gulf can be divided into seacliffs made of volcanic deposits typically bordered by wide shore platforms (often of polycyclic origin), and plunging cliffs in hard limestones located along the eastern side of the Gulf (Aucelli et al., 2016a, b; Pappone et al., 2019; Aucelli et al., 2019; Mattei et al., 2020). The main coastal plains in the Gulf, that are Fuorigrotta, Chiaia, Sebeto and Sarno plains (filled by successions of volcanoclastic deposits) host the most populated cities in the Gulf, i.e. Naples and Torre Annunziata (Romano et al., 2013; Vacchi et al., 2016; Cinque, 1991).

From a geological point of view, the Gulf of Naples is an active peri-Tyrrhenian basin extending for about 1000 km^2. It is characterized by physiographic features typical of a passive continental margin sector, with a continental shelf between -140 and -180 m of depth (Milia and Torrente, 1999, 2003). The structure of the Gulf of Naples is controlled by numerous Quaternary fault systems, NE–SW trending SE-dipping and NW–SE trending SW dipping, linked to the last stages of the opening of the Tyrrhenian Sea (Fedele et al., 2015; Milia, 2010). Between the Middle and Upper Pleistocene, the fault systems were responsible for the development of the half-graben of the Gulf of Naples and Sorrento Peninsula fault block ridge (Milia and Torrente, 2003). The landscape of this area is strongly influenced by the presence of two active volcanos: the Campi

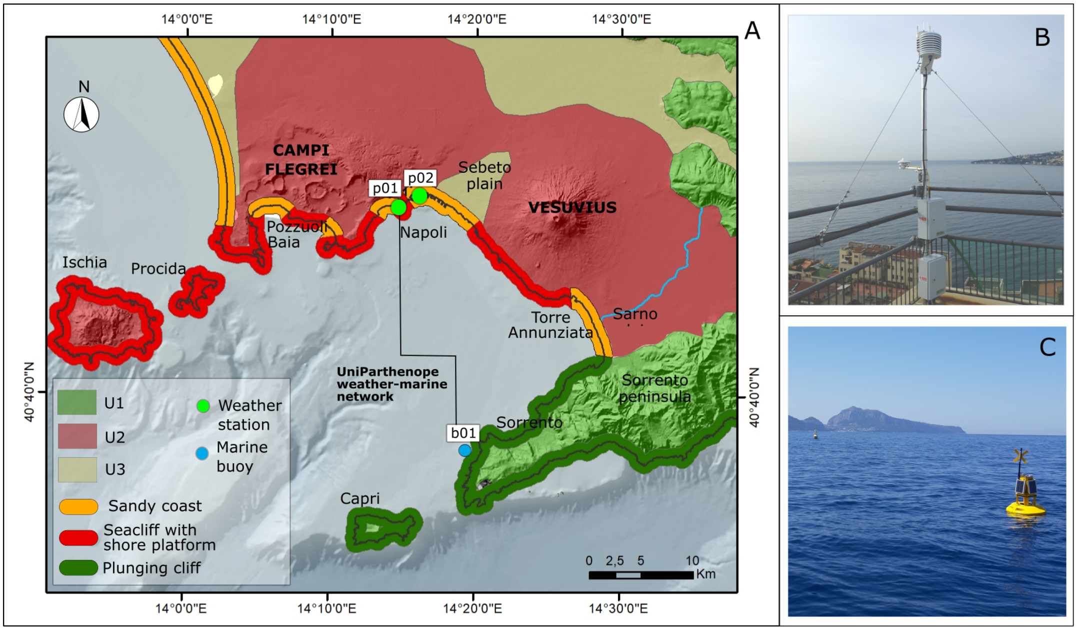

Figure 1. A) Geological and geomorphological sketch of the study area: U1 - Limestones, dolomites, and marls of carbonate platform units (Meso-Cenozoic); U2 - Volcanoclastic deposits (Quaternary); U3 - Alluvial, coastal, palustrine-lacustrine, and slope deposits (Quaternary). The DTM of the emerged area was downloaded from ISPRA webGIS (http://www.sinanet.isprambiente.it); the DTM of the emerged area was downloaded from GEBCO website (www.gebco.net). Photos of the B) weather station and C) ondameter belonging to the Parthenope University network.

Flegrei poly-caldera on the west and the Vesuvius stratovolcano on the east (Figure 1), that interfered with its Late Pleistocene – Holocene evolution (Iannace et al., 2015; Isaia et al., 2018; Santacroce et al., 2003).

During the Holocene, the morpho-evolutive trends of the coasts of the Gulf of Naples have been characterized by sudden coastal changes strongly related to the interplay between glacio-isostatic sea level rise and volcanic forcing (Cinque et al., 2011; Aucelli et al., 2020, 2019, 2018a, b; Mattei et al., 2020). The latter was driven by the combined effects of volcanic eruptions with consequent landscape mantling by pyroclastic products, and vertical ground movements of a metric entity related to sudden uplift for inflating and subsidence for deflating of the magmatic chamber. Since Historical times, the anthropic impact started interfering with these natural forcing often producing permanent modifications of the original coastal landforms (Aucelli et al., 2021; Pappone et al., 2019; Mattei et al., 2018), through mining activities and construction of port structures and infilling. However, the major forcing factor to be taken into account as the main cause of the recent coastal changes in the Gulf certainly is the local wave climate. In detail, main stormy events (Menna et al., 2007) with wave height values up to 4.8 m, are associated with atmospheric low-pressure systems and occur during winter (December - February). According to Saviano et al. (2019), high-frequency radar (HFR) data shows that the highest waves mainly approach from 180°N to 210°N this confirming a marked South – West directionality, as expected from the local morphology of the Gulf.

On the contrary, in late spring and summer periods, the main wind regime is represented by breezes, with SSW direction and maximum speed values of 8 m/s (Menna et al., 2007), that produce low wave height values ranging from 0.4 to 0.6 m (Benassai et al., 1994; Buonocore et al., 2003; Saviano et al., 2019).

Considering the seasonal surface circulation, during winter, cyclonic and anticyclonic circulation systems alternate in the Gulf due to the interaction between the local wind forcing and the large-scale circulation of the Tyrrhenian Sea. In spring, when a shallow and sharp seasonal thermocline is present, coastal upwelling is recorded and generates internal waves that propagate along the coast causing relevant mixing processes (de Ruggiero et al., 2018). In summer, the breeze forcing induces a relatively regular diurnal current oscillation (de Ruggiero et al., 2016). In this last season, surface currents typically rotated clockwise under the effect of land and sea breeze over an entire day (Uttieri et al., 2011). In autumn, the circulation is similar to the one recorded in winter.

3 Materials and methods

The fast procedure proposed in this paper aims to analyze marine and atmospheric parameters (i.e. wind intensity and duration) during a marine storm to establish a threshold beyond which an event can produce destructive coastal effects (Fig. 2), according to the following steps:

1. detecting the most-exposed coastal sectors during the peak of a meteo-marine event by calculating the total effect of the meteo-marine agents;
2. calculation of the wind set up in the coastal sketches where the total effect was highest;
3. calculation of the coastal setup only along with the urbanized coastal sketches with maximum values of wind setup.

The storm intensity was analyzed based on historical weather-marine data coupled with the spatial modeling of barometric pressure, wind speed, and wave height and direction. This severe event strongly impacted the coast of Naples city, flooded wide areas, and greatly damaged the promenade and restaurants, although the significant wave height measured by the wave buoy in the Gulf did not exceed 3.5 m. The examination of the duration, degree of severity, assessment of damages, and losses, reported in the local press, were compared with those of local historical chronicles, to demonstrate the high return period of the event analysed in this study.

3.1 Wind observations

Data from different facilities, devoted to meteorological in situ observations, were consulted to provide a historical analysis of the wind event that affected the study area in the last ten years, and to evaluate the accuracy of the simulation results. The following weather stations located in the Naples city were considered (see Figure 1):

- p01 (14°14’41.78”E - 40°49’55.16”N) is managed by the University of Naples "Parthenope" (Fig. 1a). From 2015, this Vaisala Weather Transmitter (WXT520) measures barometric pressure, humidity, precipitation, temperature, and wind

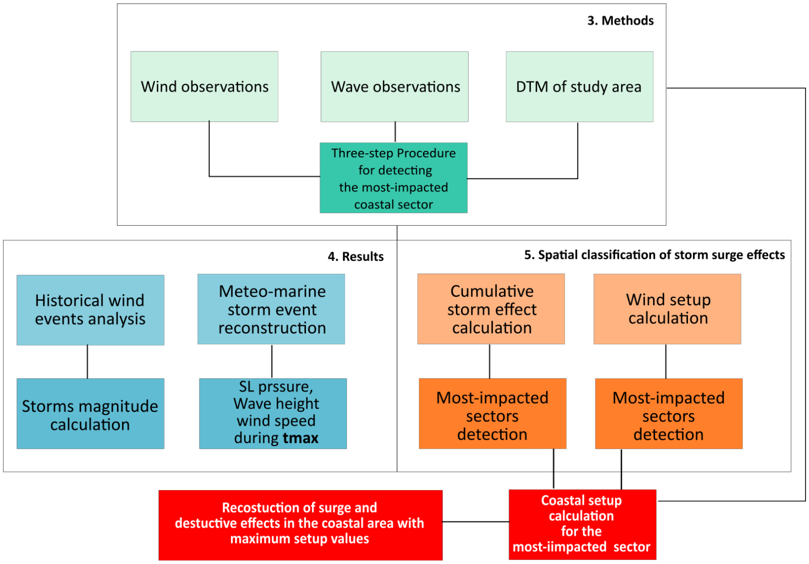

Figure 2. Workflow of the procedure applied in this study to evaluate the most impacted coastal sectors in the Gulf of Naples during the 2020-December storm.

speed and direction. The Vaisala WINDCAP sensor uses ultrasound to determine horizontal wind speed and direction with an accuracy of ±0.3 m/s and ±3°, respectively.

- p02 (14°16'30.63"E - 40°50'24.46"N) is part of the National Tidegauge Network, and it is managed by the Italian Institute for Environmental Protection and Research (ISPRA). The weather station is located in the port of Naples at the Diaz pier.

Considering such databases, an analysis of wind events was applied to 2010-2020 wind records to evaluate and classify the storms that approached SW in the last 10 years. Therefore, the dataset was filtered for events coming from 202°-242° directions, highlighting those with a velocity higher than 13.9 m/s (the lower limit of the "near gale" class in the Beaufort scale) and duration > 6 hours (according to Allen (1981)). Subsequently, for each of the selected events, the magnitude (M) was evaluated according to the following equation:

$$M = h * v^2 \tag{1}$$

where h is the event duration in hours and v is the wind speed in m/s (modified from Allen (1981)).

3.2 Wave observations

The in-situ sea waves observation was carried out with the wave recorder b01 (14°19'24.60"E - 40°37'07.82"N), managed by the University of Naples "Parthenope" (Fig. 1a,c). The buoy is located in the Gulf of Naples near the Vervece islet, and it is operative since July 2020. It is equipped with a BRIZO-X directional GNSS wave height sensor to record wave statistics as significant wave height (H_s), maximum wave height (H_m), peak wave period (T_p), mean zero upcrossing period (T_m), mean wave direction(D_m), wave spread (D_s), and wave spectra.

A subset of the dataset was used to evaluate the accuracy of the offshore wave simulations during the considered 2020-December storm event.

3.3 Atmospheric-marine numerical workflow

To characterize the meteo-marine scenario during the 2020-December storm event, an high spatial resolution model chain (Sánchez-Gallegos et al., 2021; Di Luccio et al., 2020b; Sánchez-Gallegos et al., 2019b, a) was configured using the workflow orchestrator DagOnStar (Montella et al., 2018) to manage and run the community numerical models Weather Research and Forecasting (WRF) (Skamarock et al., 2001; Powers et al., 2017) and Wavewatch III (WW3) (Tolman et al., 2009).

The first workflow component is the atmospheric model WRF which computes the 10 m wind fields and other atmospheric parameters needed to drive the WW3 offshore wave model.

The weather pattern (e.g. 10 m wind field, sea level pressure, etc.) during the 2020-December storm was reconstructed with the WRF model with the following two-way nested computational domains: a coarser domain (25 km) covering the whole of Europe, an intermediate domain (5 km) on the Italian peninsula, and a finer domain (1 km) on the Southern Thyrrenian Sea. The WRF model initial conditions were provided by the Global Forecast System (GFS) owned by the National Center for Environmental Prediction (NCEP).

A similar telescopic configuration was used in the case of WW3 wave model with a ground resolution of 0.09° on the whole Mediterranean Sea, an intermediate resolution of 0.03° for seas surrounding Italy, and a finer resolution of 0.01° for the southern Tyrrhenian Sea. In this case, the weather conditions provided by WRF were used to drive the marine dynamic in the Mediterranean Sea closed geographical domain, so no wave boundary condition was necessary. Moreover, an offline coupling approach between the atmospheric model WRF and the wave model WW3 was applied. The simulation results were provided with a 1-hour timestep in NetCDF format.

This configuration of WRF and WW3 numerical models had been already tested in other applications involving, among others, the beach run-up calculation (Di Luccio et al., 2018a, 2020b), the rip-current identification (Di Luccio et al., 2018b), the reconstruction of weather (Di Luccio et al., 2020a, 2021; Montella et al., 2019) and marine (Castagno et al., 2020) patterns.

In the present application, the simulated wind speed (WS_s) and direction (WD_s), the sea level pressure (SLP_s), the significant wave height (Hs_s), and the mean wave period (Tm_s) and direction (Dm_s) were analyzed to characterize the 2020-December storm along the whole Gulf of Naples, using the maximum resolution dataset available for WRF and WW3 models.

3.4 Set-up evaluation

The reconstruction of the main erosive effects of the maximum water level time interval (t_{max}) that occurred during the 2020-December storm in the study area, was performed with the following methodological steps.

Class	Wind speed [m/s]	Wave height [m]	Sea level pressure [hPa]	Cumulative effect
1	<10.8	<1.25	>1013	Very low
2	10.9-13.1	1.25-2.5	999-1013	Low
3	13.2-15.5	2.5-3.5	998-999	Medium
4	15.6-17.8	3.5-4.5	997-998	High
5	>17.9	>4.5	<997	Very high

Table 1. Classification in five classes of the three weather-marine parameters, WS_s,Hs_s, and SLP_s, and classification of their cumulative coastal effects.

1) The first step is aimed to detect the most-impacted coastal sectors in the Gulf of Naples during t_{max}. To do this, each weather-marine parameter WS_s, Hs_s and SLP_s was classified taking into account the 5 classes of intensity and/or impact on the coasts summarized in Table 1. Wind intensity was classified according to the Beaufort scale, considering also the range of wind variability in the Gulf in the last 10 years. In particular, class 1 corresponds to a fresh breeze, class 2 is a strong breeze, classes 3 and 4 are near gale and class 5 is gale or higher than a gale. The wave height was classified according to the Douglas scale, where class 1 is from calm to slight wave, class 2 is a moderate wave, class 3 is a rough wave, classes 4 and 5 from rough to very rough. Atmospheric pressure was classified in equal intervals, starting from class 1 corresponding to high-pressure conditions, up to class 5 corresponding to low-pressure ones.

The total effect of the three classified parameters was evaluated by calculating the average values between the above-mentioned classes and, consequently, classified in five classes according to Table 1.

2) The second step was the calculation of the wind set up in the coastal sketches where the total effect was high, according to the following equations (Reeve et al., 2018):

$$i_w = C_w \left(\frac{\rho_a}{\rho_w}\right) \frac{U_w^2}{gh} \tag{2}$$

where U_w is the wind speed (m/s), h is the water depth, ρ is the density of air (a) or water (w) and C_w = air/water friction coefficient.

The maximum set-up at the downwind coast is

$$\eta_w = i_w \frac{F}{2} \tag{3}$$

where F is the fetch length in meters and η_w is the wind set-up in meters.

3) The last step provided the calculation of the coastal setup as the sum of wind, wave, and barometric setup, along with the urbanized coastal sketches with maximum values of wind setup. The aim was to evaluate the flooding during t_{max} only where

the storm had destructive effects on anthropic structures. In the surf zone, the rise of the mean water level at mean depth d_x was calculated as following (Dean and Dalrymple, 1991):

$$\bar{\zeta}(x) = \bar{\zeta}_b + \frac{3\gamma_b^2}{8}\left(1 + \frac{3\gamma_b^2}{8}\right)[d_b - d(x)] \tag{4}$$

where $\bar{\zeta}_b$ is the wave setdown at the breaking depth, given by:

$$\bar{\zeta}_b = -\frac{1}{16}\gamma_b H_b \tag{5}$$

where H_b is breaking wave height and γ_b is the breaker index.

For spilling type breakers on dissipative beaches the assumption commonly employed is that γ_b remains a fixed ratio throughout the entire surf zone:

$$\gamma_b \approx \left(\frac{H}{d}\right)_b \tag{6}$$

where d_b is the mean depth at breaking. The breaking index was calculated by various Authors. According to Kamphuis (1991), the significant breaking index is given by:

$$\gamma_b = 0.56e^{3.5m} \tag{7}$$

where m is the slope of the seabed.

The barometric setup was calculated as follow:

$$\Delta\zeta = \frac{\Delta P_a}{\rho g} \tag{8}$$

where ΔP_a is the pressure variation during the event.

4 Results

The 2020-December storm came from SW, between 202°N and 242°N. As described in the following sections, the event was characterized by anomalous wind conditions that strongly influenced effects on the coast.

4.1 Historical wind events analysis

A historical analysis of wind events coming from SW between 2010 and 2020 was applied to data recorded in p01 and p02 weather stations to classify the event investigated in this paper. The results reported in Figures 3 and 4 show that the most

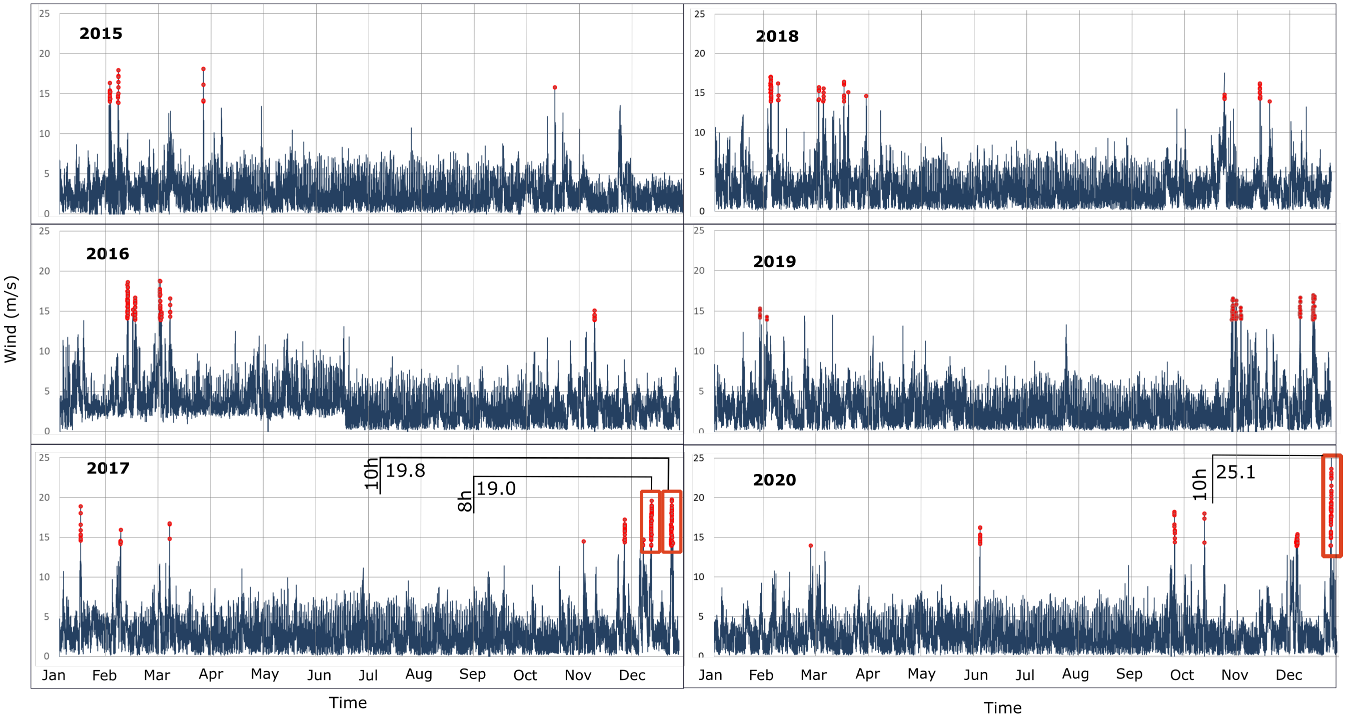

Figure 3. Graph of wind speed (m/s) between 2015 and 2020 measured by the P01 weather station, red points highlight storms from 202°-242° with velocity > 13.9 m/s.

intense events with a duration higher than six hours (red points in the figures) come from the NW sector during winter months, confirming previous studies (Menna et al., 2007; Saviano et al., 2019, 2020).

The calculation of the storm magnitude (Figure 5) shows that these events frequently occurred in December (7 out of 10). Moreover, the 2020-December storm is the most intense event that occurred in the observed period, both in terms of maximum wind speed measured by p01 station (25.1 m/s) and maximum duration (11 h) of wind speed > 13.9 m/s ("near gale" in Beaufort scale).

4.2 Meteo-marine storm event reconstruction

The scientific workflow described in Section 3.3 supported the reconstruction of the 2020-December storm event. As shown in Fig. 6, the study area was characterized by a low-pressure front with a minimum SLP_s value equal to 995 hPa at $t_{max} \pm 1h$ during 28 December 2020.

On the same day, this intense atmospheric low-pressure system was accompanied by widespread rainfall and strong winds coming from SW (WS_s > 20 m/s) with gusts > 25 m/s, as shown in Figure 7.

Moreover, the sea state at $t_{max} \pm 1h$ was characterized by high waves (about 4 m as recorded by the wave recorder b01).

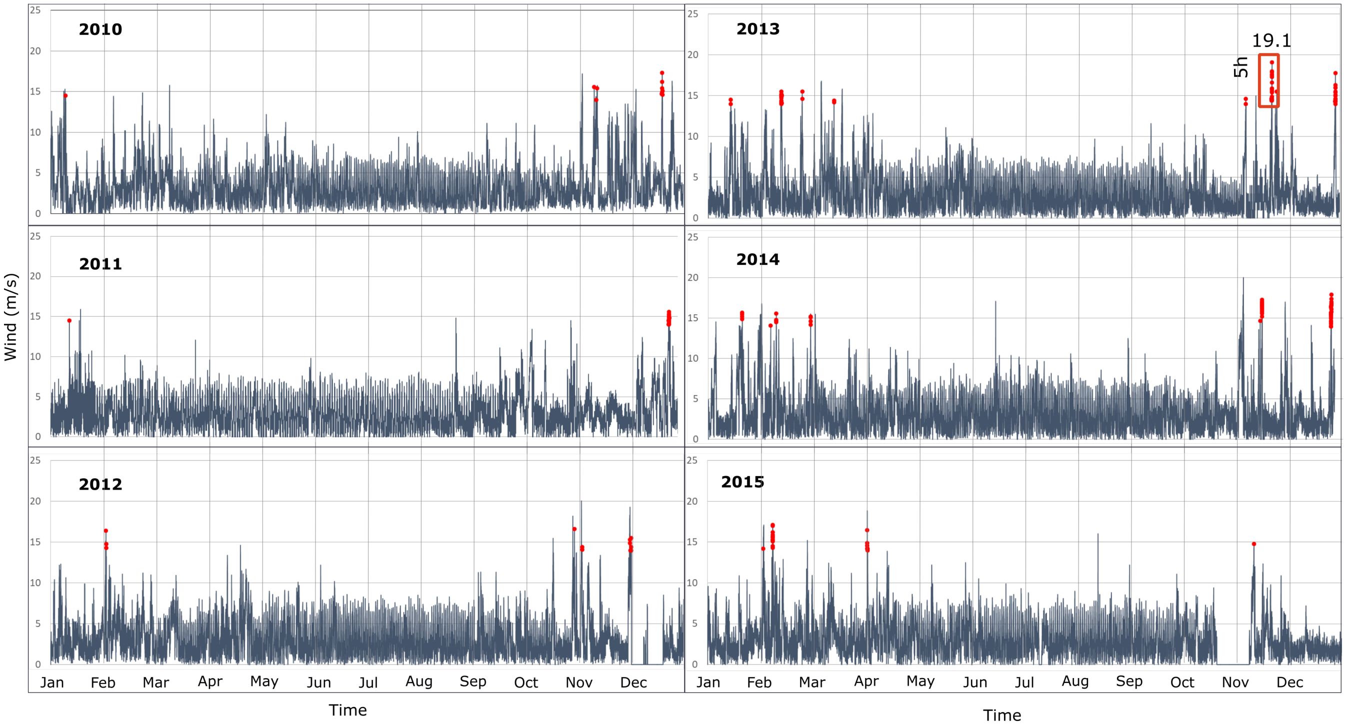

Figure 4. Graph of wind speed (m/s) between 2010 and 2015 measured by the P02 weather station, red points highlight storms from 202°-242° with a velocity higher than 13.9 m/s.

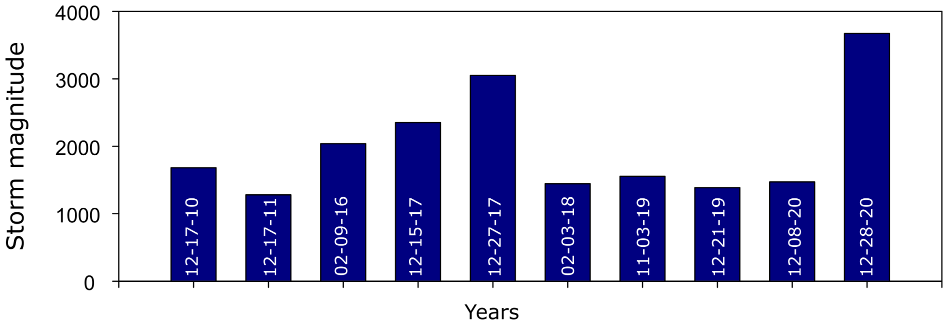

Figure 5. The magnitude of storms lasting more than 6 hours during the observation period (2010-2020) from 202°-242° directions with a velocity higher than 13.9 m/s.

The combination of these and other (eg. tide level) coastal dynamic agents caused a violent storm surge in Naples that strongly flooded the city's waterfront overnight.

The validation of the accuracy of WRF and WW3 models was done through the comparison between the hourly numerical results in the time interval 27-30 December 2020, and the data recorded by the weather and wave recording stations (p01, p02,

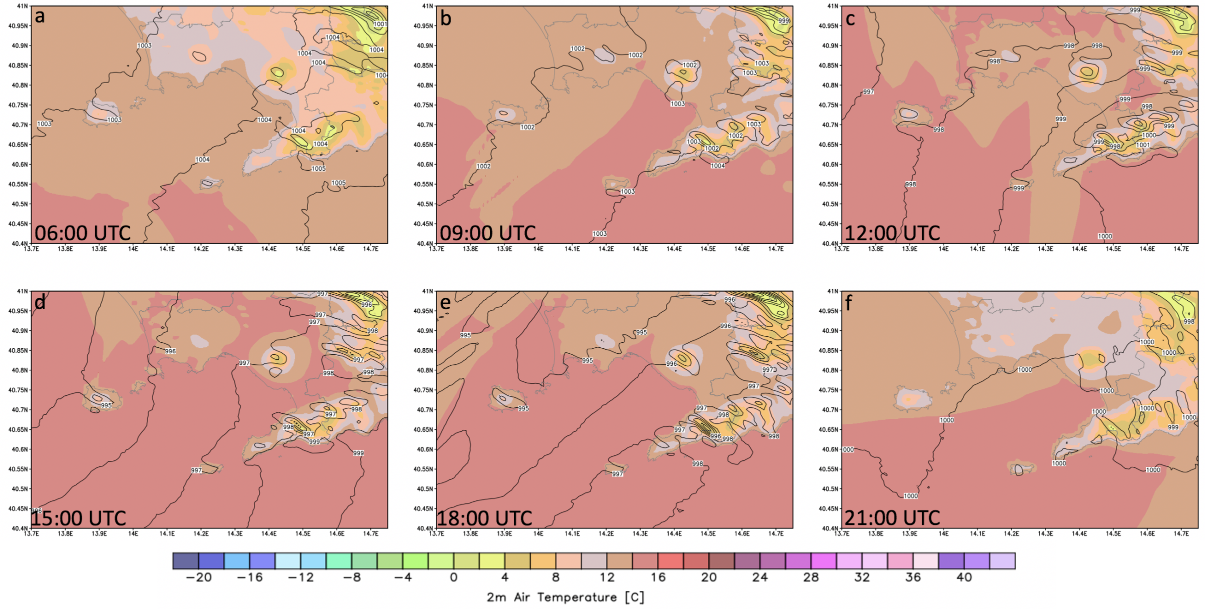

Figure 6. Sea level pressure and 2 m air temperature simulated with WRF model on 28 December 2020 at 06 UTC (a), 09:00 UTC (b), 12:00 UTC (c), 15:00 UTC (d), 18:00 UTC and 21:00 (UTC).

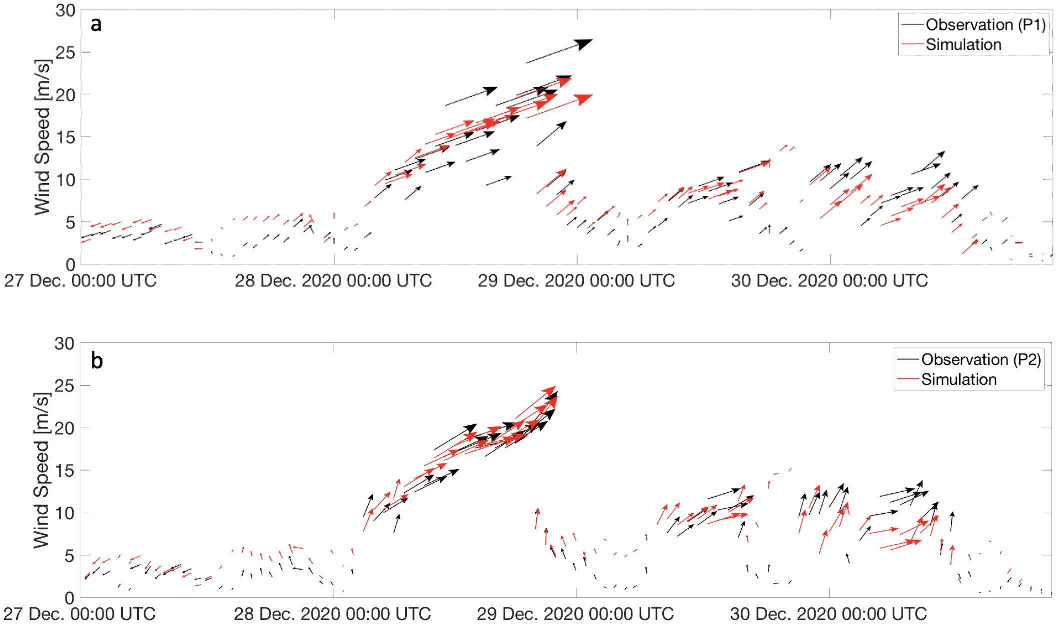

Figure 7. Comparison between wind speed and direction in-situ observations in p01 (a) and p02 (b) with the simulation results.

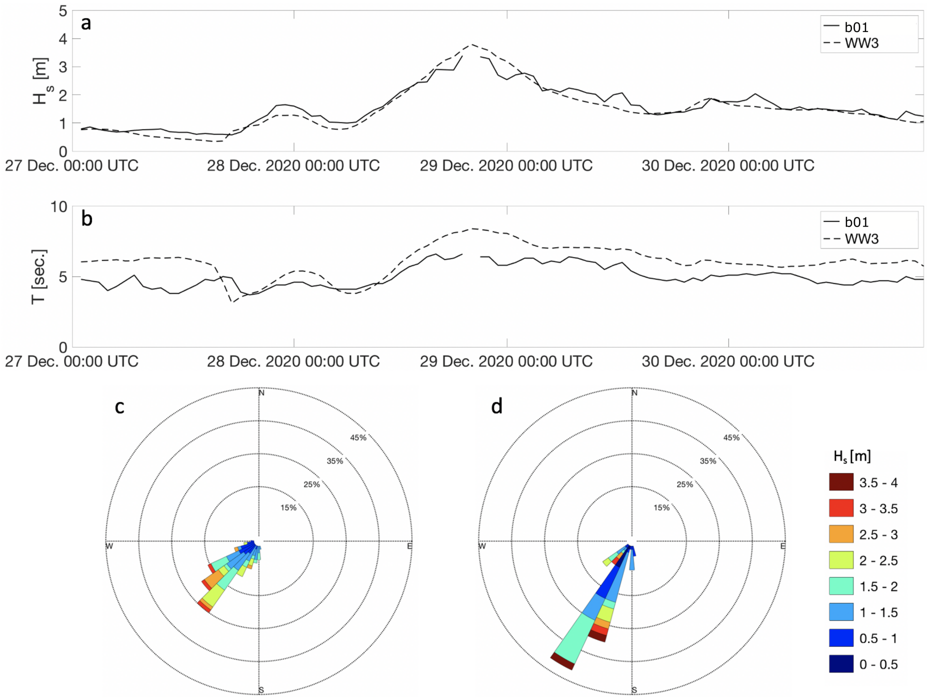

Figure 8. Comparison between in-situ wave observation and simulation about significant wave heights and period (a, b); directional distribution of the significant wave heights occurrence (c, d).

and b01). The results evidenced that the numerical models were in good agreement with the observations. In particular, the root mean square error (RMSE) was about 0.23 m for the significant wave height in b01 and about 3.06 m/s and 3.35 m/s in case of wind speed in p01 and p02, respectively

5 Discussion of the spatial classification of storm surge effects

The results of the spatial classification of the cumulative storm surge effects show that it was highest (red class) along with three cliffed urbanized sectors (Ischia, Capri, and Sorrento Penisula) and three strongly anthropized urban low-coastal areas (Posillipo, Port of Naples, and Torre Annunziata), as shown in Figure 9d.

This result can be explained through the analysis of the wind and wave spatial distribution during the 28th December event in the Gulf of Naples. The wind speed in the western part of the Gulf (Figure 9a) is lower than that in the Central-Eastern part. On the contrary, the significant wave height was maximum in the proximity of the islands (Capri and Ischia) with values higher than 5 m and between 4 and 5 m along with the other urban exposed sectors. The spatial fetch distribution of the coastal areas, coupled with the wind speed variation, was such that the cumulative effect of the storm surge was maximum among the urbanized areas exposed to NW storms that is Naples coast (Posillipo and Port sectors) and Torre Annunziata.

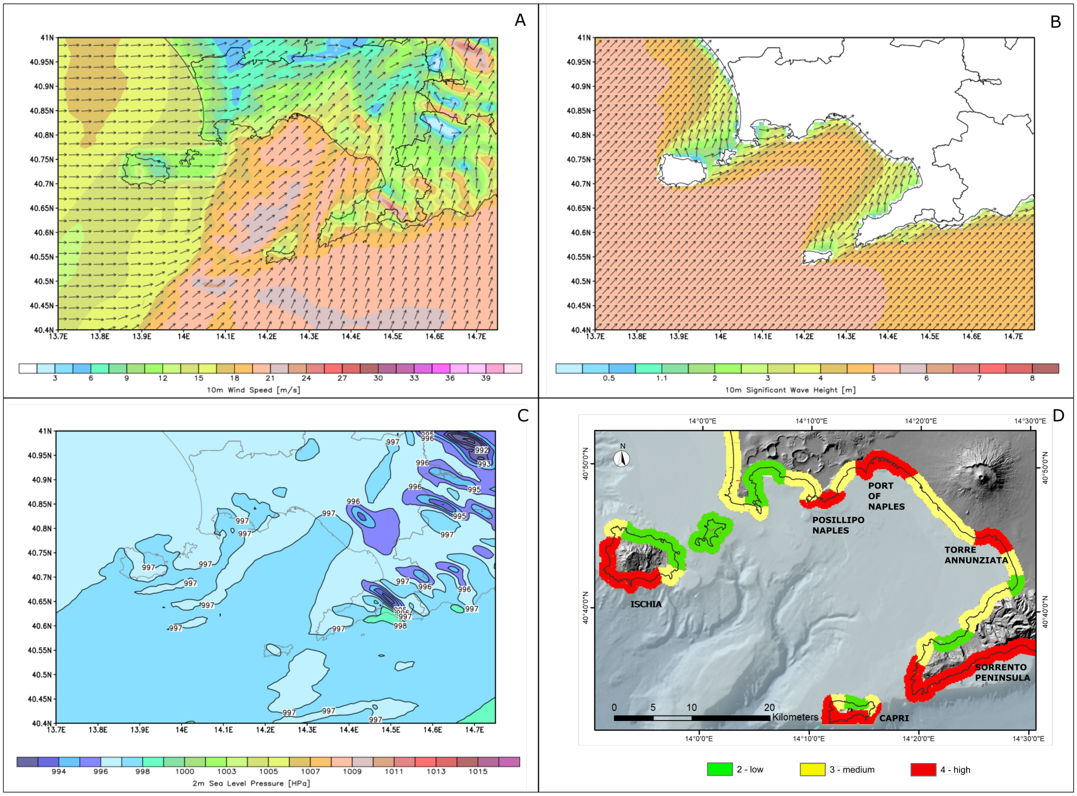

Figure 9. Maps during t_{max} of: A) wind speed; B) Significant wave height; C) Sea level pressure; D) the cumulative effect of the three-modeled parameters - the DTM of the emerged area was downloaded from ISPRA webGIS (http://www.sinanet.isprambiente.it); the DTM of the emerged area was downloaded from GEBCO website (www.gebco.net/data_and_products/gridded_bathymetry_data).

However, the Naples coast (sectors 5 and 6 in Figure 10) was the most exposed to the wind effects, as the wind setup calculation demonstrated. Consequently, the mean coastal setup was evaluated only in this sector, according to the procedure described before. In particular, the wave setup was calculated (equation 2) by using the high precision submerged bathymetry, obtained from a Multibeam survey of the Neapolitan area, from which the slope in shallow waters was measured.

As a result of the calculation (step 3 in Section 3.4), the time-averaged water-level elevation at the coastline (coastal setup) during t_{max} in the most exposed area of Naples waterfront was 1.6 m, resulting from the sum of wind setup (0.8 m), wave setup (0.3 m), barometric setup (0.2 m) and water level (0.3 m).

The fast water level increase during t_{max} produced a twofold effect on the coast, as evidenced by video- and photo reports (Figure 12). On one hand, total flooding of the coastal area took place (Figure 11), on the other, wave breaking processes took place on the coastal promenade (Figure 12).

The flooding produced several destructive effects that interested the whole coastal sector, as shown in Figures **??**, including a XIV century castle (Castel dell'Ovo, Figure **??**i,n). In the touristic city area between via Caracciolo and Castel dell'Ovo, the

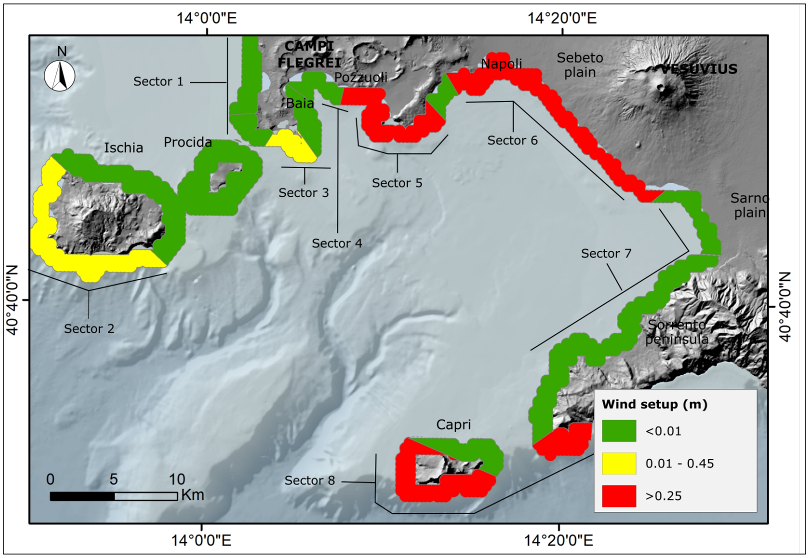

Figure 10. Wind set up along the coast of Gulf of Naples during t_{max}. The DTM of the emerged area was downloaded from ISPRA webGIS (http://www.sinanet.isprambiente.it); the DTM of the emerged area was downloaded from GEBCO website (www.gebco.net).

main damages concerned both commercial activities and archaeological structures. In particular, a part of the promenade was dismantled, together with the bungalows of some restaurants, and some shop windows (Figure **??**h). Regarding the cultural heritage, the destruction of the Bourbonic pier occurred (Figure **??**m) and the dismantling of the nineteenth-century pavement on the outside of Castel dell'Ovo. The main damages to the Port were related to the military infrastructures located on the San Vincenzo pier.

The return period of this event was evaluated through the analysis of historical archives of local newspapers. According to the last 100 year chronicles, based on similar damage records, the 2020-December storm surge is a weather-marine event with a very high return period. The only past event with similar destructive effects occurred on 28th December 1927, as described by local newspapers (Figure 13).

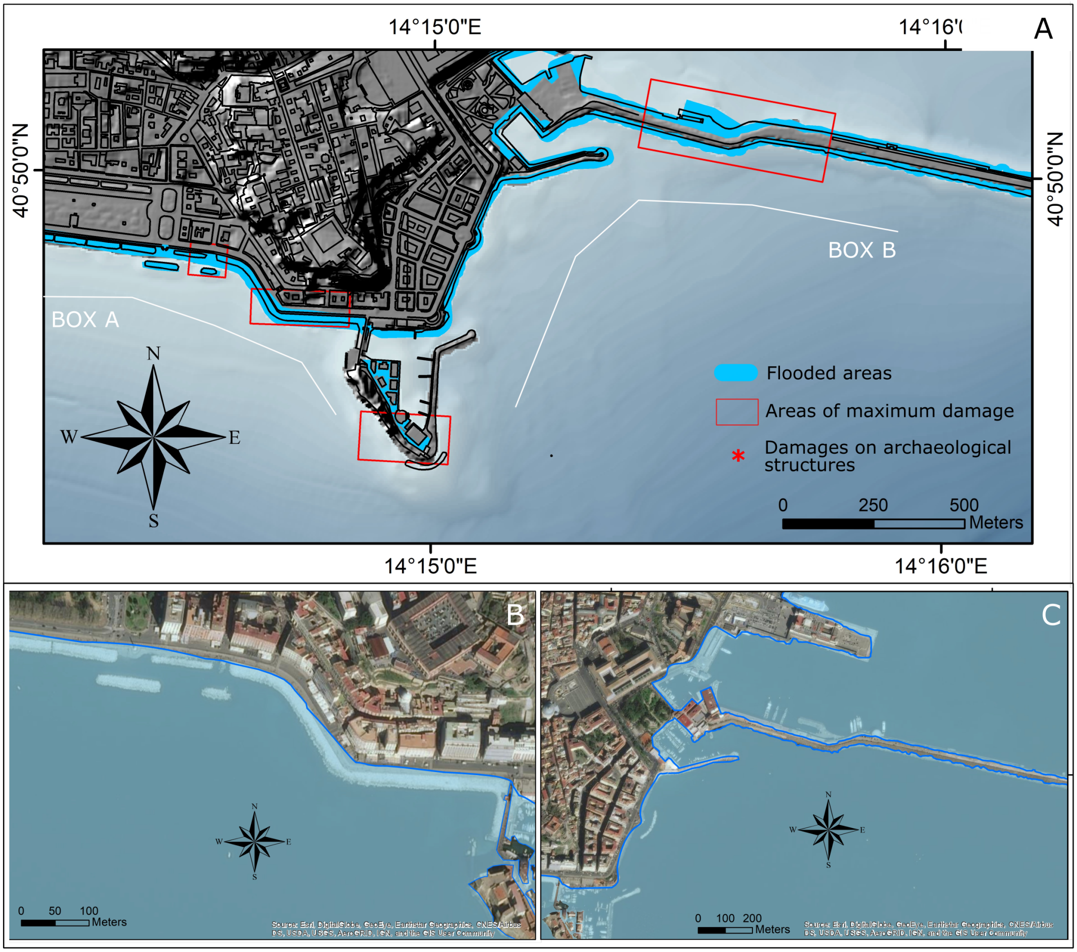

Figure 11. A) The surge in the coastal area with maximum setup values (Naples city center) during the storm event (the onshore DTM from Lidar data was provided by Ministero dell'Ambiente; the offshore DTM derive from bathymetric data provided by Regione Campania); Zoom of flooded areas in B) W sector and C) E sector (Google Maps).

6 Conclusions and future investigations

The marine storm of 28th December 2020 that affected the Gulf of Naples represented an outstanding storm associated with the persistence of wind speed up to 90 km/h and low-pressure conditions (997 hPa). This caused a significant surge with a local increase of about 1.6 m during the peak of the event. The anomalous water level rise provoked the flooding of wide coastal areas of Naples city, with catastrophic effects on port infrastructures, urban facilities, and cultural heritage. The very high intensity of this event was testified also by the analysis of historical chronicles that identified only one storm with similar destructive effects in December 1927. The numerical characterization of this SW-storm, based on the high spatial resolution model, allowed the detection of the most-exposed coastal sectors in the Gulf, according to the first step of the proposed procedure. On the other

Figure 12. Photos of: A), B), C) and D) Storm surge in the coastal area with maximum setup values (Naples city center); E) and F) Damages on structures during the event; G) promenade destroyed with collapsed parapet; H) shattered shop windows; I) and N) Castel dell'Ovo after the event; L) and M) Bourbon pier after the event; H) Bourbon pier before the event. In the map, the onshore DTM from Lidar data was provided by Ministero dell'Ambiente; the offshore DTM derive from bathymetric data provided by Regione Campania.

Figure 13. Historical photo of 1927-storm that impacted and destroyed via Caracciolo, Naples (from Il Mattino newspaper).

hand, this expedited procedure resulted in an efficient way to measure the effects of this event on the urbanized areas among the most-exposed sectors. The main result was the definition of threshold values for wind speed and duration, coupled with atmospheric pressure and medium wave height, which could be used as an alert for future similar events coming from the fourth quadrant. This fast procedure applied to data from the weather-marine forecasting networks can become an operative tool for local authorities asked to apply protective actions to human activities. Consequently, the approach proposed in this study has the aim to limit the damages of extreme events, through the two following actions, that is the preliminary detection of the destructive storms in time and space and the implementation of fast procedures for alerting. In the context of global warming, this issue is highly topical due to the recent and continuous increase in sea surface temperature (SST) that is having the effect of exacerbating the intensity and frequency of extreme marine events both on a global and Mediterranean scale. Considering also the recent acceleration of sea level rise, urbanised and natural coastal areas are likely to be increasingly flooded. In the framework of reducing the flood risk in the coastal area, two alternative strategies can be assessed. On one hand, it is mandatory to enhance the actual poor information on the way in which local stakeholders counteract flood risks, for which local shop owners are held responsible. On the other hand, community disasters management is currently limited to closing off the waterfront at high water levels. The creation of high-resolution databases of the main weather-marine characteristics of extreme events sounds strategic for improving information and take precautionary measures. The second strategy is to improve the resilience of the urban waterfront. This can be achieved by enhancing flood resilience into existing shops, e.g. by rising the topographic level of the shops entrances and incorporating wet-proof technologies and infrastructures on the open air utilities.

Data availability. The weather and marine numerical model results are available at http://meteo.uniparthenope.it (last accessed 7 October 2021).

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