Coastal Impacts of Storm Gloria (January 2020) over the Northwestern Mediterranean

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Abstract. The ocean component and coastal impacts of Storm Gloria, that hit the Western Mediterranean between January 20^{th} and 23^{rd} 2020 are investigated with a numerical simulation of the storm surges and wind-waves. Storm Gloria caused severe damages and beat several historical records such as significant wave height or 24-h accumulated precipitation. The storm surge developed along the eastern coasts of the Iberian Peninsula reached values up to 1 m, and were accompanied by wind-waves with significant wave height up to 8 m. Along the coasts of the Balearic Islands, the storm footprint was characterised by a negligible storm surge and the impacts were caused by large waves. The comparison to historical records reveals that Storm Gloria is one of the most intense among the events in the region during the last decades and that the waves direction was particularly unusual. Our simulation permits quantifying the role of the different forcings in generating the storm surge. Also, the high spatial grid resolution down to 30 m over the Ebro Delta, allows determining the extent of the flooding caused by the storm surge. We also simulate the overtopping caused by high wind waves that affected a rocky coast of high cliffs ($\sim 15\,m$) in the eastern coast of Mallorca Island.

1 Introduction

On 17 January 2020, a low-pressure system coming from the Atlantic made landfall in the northwestern part of the Iberian Peninsula. During the subsequent days, this low-pressure system evolved towards the southeast until reaching the Western Mediterranean Sea (Figure 1) on 19 January, where it intensified, severely affecting the northern and eastern regions of the Iberian Peninsula, including the Balearic Islands. This low-pressure system was named Gloria by the State Meteorological Agency (AEMET). However, the life-cycle of Gloria last approximately 24 h, since it was absorbed by a larger low-pressure system that was centred over the Alboran Sea and last until 26 January. For simplicity, in this study we refer to Storm Gloria as the most intense activity period of this low-pressure system which ranges between 20-23 January.

The northwestern and the central sectors of the Western Mediterranean are modulated during most of the year by northerly winds ~~(the so-called Tramontana and Mistral winds, from north and northwest, respectively)~~, resulting from gales developed over the Gulf of Genoa and the Gulf of Lions. These winds are the main source of sea storms along the Northwestern Mediterranean basin (Flamant et al., 2003) and generate wind-waves characterised by significant wave heights (H_s) between 0.1 – 1m and peak periods (T_p) between 3-6 s (Gómez-Pujol et al., 2019). In contrast, during the event of Storm Gloria, the synoptic situation was dominated by a deep low-pressure system located in the southern part of the domain that generated strong easterly winds (Figure 2). The event was initially dominated by a strong and negatively tilted upper-level ridge located over the Eastern Atlantic, where record-breaking pressure values of 1050 hPa (highest pressure value registered by the MetOffice since 1957) were registered in the north-western Europe, more specifically over the British Islands, followed by an intense upper-level trough centred over the Iberian Peninsula (Figure 2a). This upper-level trough was associated with cold air aloft, favouring potential instability over the mainland and the western Mediterranean Sea. During the following days this trough suffered a disconnection from the main westerly jet stream and as a result an intense cut-off low pressure system was developed over the Iberian Peninsula, enhancing a south-easterly flow at mid- and upper-levels (Figure 2b). At low levels, the initial low-pressure system (Figure 2c) moved towards the edge of the cut-off low, favouring the deepening of such surface low-pressure system and thus, enhancing the easterly winds, bringing unstable air (i.e., warm and moist) towards the eastern part of the Peninsula and the Balearic Islands (Figure 2d). This fact, together with the prominent orography associated with these regions, acts as a triggering mechanism for convection, which in this case resulted in heavy precipitations and flash floods. In addition, the prolonged coupling of the strong easterly winds together with the sea surface, generated wind-waves affecting coastal regions in the entire basin. According with the data from Mahon buoy ($39.71°N$ - $4.42°E$), these high waves reached maximum height of 14.77 m (January 21^{st} 12:00UTC) in deep waters, whereas winds also caused storm surges of up to 70 cm along the Spanish mainland (see the online report of the Spanish Meteorological Agency AEMET at http://www.aemet.es/es/conocermas/borrascas/2019-2020/estudios_e_impactos/gloria, in Spanish only). As a consequence many coastal sectors were flooded, coastal infrastructures were destroyed and strong erosion was reported in sedimentary coasts, with immediate economic losses of several millions of euros (e.g. only in the region of Valencia economic losses are estimated in up to 62.6 million € to the agriculture sector, according to the Valencian Association of Agricultural Producers (AVA-ASAJA)). According to the Copernicus Emergency Management Service (EMS) (http://emergency.copernicus.eu) the damages caused by the storm included lost of power supply, flooded areas and coastal erosion, as well as a total of 13 fatalities (https://emergency.copernicus.eu/mapping/sites/default/files/files/EMSR422_Floods_in_Spain_0.pdf).

Our focus here is on the marine effects of the storm. We concentrate on the shorelines of the eastern Spanish coasts and the Balearic Islands, where major impacts were reported. To quantify the impacts of Storm Gloria we numerically simulate the storm surges and wind-waves generated over the Western Mediterranean Sea. We apply near-real time atmospheric forcing fields of atmospheric pressure and surface winds to a coupled hydrodynamic and wave propagation models. Our purpose is twofold: the first part has a regional scope in which we aim to quantify the physical mechanisms at play along the different coastal areas in the basin, including the storm surges and the effect of waves, and to discuss their differences that ultimately led to coastal impacts. The model outputs allow identifying the main drivers of coastal hazards for areas differently exposed to the effects of the storm. Secondly, we focus on local case studies. We select locations with different characteristics (morphological and in terms of forcing) and simulate the impacts of the storm, accounting for the storm surge and wave setup at the local scale. The first site is the Ebro Delta (Figure 1), a low-lying region (with elevation ~ 1 m) of 320 km^2, of which around 77 km^2

corresponds to a protected natural area, being one of the most important aquatic habitats in the Western Mediterranean. During Storm Gloria, large parts of the delta were submerged. The second site corresponds to high-cliffs (~ 15 m) in Portocolom, a small town located in the eastern side of Mallorca Island (Figure 1), where very high waves were reported (see picture in Figure 8) that overtopped the cliffs severely damaging coastal assets.

The manuscript is organised as follows. We describe the oceanic and atmospheric observations and the implementation of the numerical models and their atmospheric forcing in section 2. This section also includes the model validation (in subsection 2.3). This is followed by the analyses of the results of the regional modelling (section 3) and the two case studies: the first one describes the coastal inundation in the Ebro Delta induced by the storm surges and waves (subsection 3.1) and the second addresses the wave impacts in the rocky coast of the eastern Mallorca Island (subsection 3.2). The final section discusses the results and provides the final remarks.

2 Data and Methods

2.1 Ocean and atmospheric observations

Sea level observations from tide gauges, wave measurements from *in-situ* buoys and remote sensing altimetry have been used to describe and quantify the effects of the storm over the ocean and also to evaluate the performance of the numerical simulations. Wind and atmospheric pressure records have also been recovered from weather stations on the buoys and compared to the atmospheric forcing used to feed the ocean models.

Wave parameters including significant wave height (H_s), wave peak period (T_p) and wave peak direction have been retrieved from four deep-water buoys and two coastal buoys (see Figure 3). All buoys provide near-real time hourly measurements. These observations have been complemented with along-track measurements of H_s from satellite altimetry on board of satellites SARAL/Altika, Cryosat-2, Sentinel 3A and B and Jason-3, with all missions homogenized with respect to the latter and calibrated on *in-situ* buoy measurements. All wave observations have been downloaded from the CMEMS data server.

Hourly tide gauge time series at five stations over the Northwestern Mediterranean basin are available in near-real time through the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu). Two more tide gauges providing near-real time sea-level measurements every minute have been obtained from the Balearic Islands Coastal Ocean Observing and Forecasting System (SOCIB, https:www.socib.es). See Figure 4 for location of these tide gauge stations.

2.2 Numerical modelling of storm surges and wind-waves

The storm surge and wind-waves generated by Storm Gloria over the Western Mediterranean have been simulated using SCHISM model (Semi-implicit Cross-scale Hydroscience Integrated System Model; Zhang et al. (2016)). We have used its dynamic core, which is a derivative product built from the original SELFE (v3.1dc; Zhang and Baptista (2008)), in 2DH barotropic mode fully coupled with the spectral wave model WWM-III (Roland et al., 2012). The two modules share the same triangular unstructured computational grid that covers the whole Western Mediterranean basin (Figure 1) with a total of

390113 nodes distributed in 771297 elements. Its horizontal grid resolution ranges from ∼15 km in open ocean down to 1-2 km along most coastlines and ∼30 m at the Ebro Delta. This small region covering the Delta and its surroundings contains around 75 % of the grid nodes. The Strait of Gibraltar, the region between Tunisia and Sicily and the Strait of Mesina were considered as closed boundaries. The model was implemented using the bathymetry 2018 version of the EMODnet digital terrain model (https://portal.emodnet-bathymetry.eu/), with a resolution of $1/16 \times 1/16$ arc minutes ($\sim 115\,m \times 115\,m$) over the European sea regions. In the Ebro Delta (upper-left panel in Figure 1) this bathymetry was combined with a high-resolution topography, provided by the Institut Cartogràfic de Catalunya, derived from LiDAR observations. The product covers an area of $24km \times 30km$ with a spatial grid resolution of 2 m. The modelled time period covered 9 days, from January 17^{th} to 26^{th} 2020. The computational time step was set to 10 minutes and the variables were saved every 30 minutes. The simulation took a total of 2 days and 19 hours and it run in a single core, what makes a performance of 3.2 times faster than the real time.

The atmospheric fields used to force SCHISM were retrieved from the high-resolution version of the deterministic ECMWF analysis (https://www.ecmwf.int/en/forecasts/datasets/set-i). These analyses are provided on a regular lat/lon grid and have the highest currently available ECMWF's horizontal grid resolution ($0.1° \times 0.1°$), which is roughly equivalent to 9 km in the mid-latitudes. In terms of temporal resolution, the outputs are available every 6 hours, i.e., at 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC. The atmospheric forcing terms correspond to the mean sea-level atmospheric pressure, the U-component and V-component of the wind at 10 m, spanning the period 6-27 January. We have compared point-wise modelled time series with measurements of the atmospheric parameters over the ocean at buoy locations (see the section above for details on the stations) in Figure S.M. 1. The results show ~~very~~ good agreement at every location and for all the forcing terms, thus confirming the reliability of the atmospheric forcing fields. Tides were not considered in the simulation since the Western Mediterranean is a micro-tidal environment.

In order to evaluate the contribution of the different forcings factors, namely atmospheric pressure, wind and wave setup, to the total water levels along the coasts, four different simulations were designed: 1) a fully coupled run between the hydrodynamic model and the wind-wave module that takes into account all the forcings as well as their coupling; 2) a run without wind-waves, using only the hydrodynamic module forced by wind and atmospheric pressure; 3) a hydrodynamic model run forced only by atmospheric pressure; and 4) a hydrodynamic model run forced only by wind. The total storm surge generated by Storm Gloria was evaluated using only the simulation #1; the effect of the wind-waves and the coupling with the dynamic effects was estimated by the difference between run #1 and #2; finally, the contribution of the atmospheric pressure (wind) was determined with the run #3 (#4). To quantitatively determine the individual effect as well as the synergistic effect between a set of different factors, a total of ($2^{\#forcings}$) simulations are required (Stein and Alpert, 1993), with all the possible combinations of switching on and off all the forcing terms. However, if the difference between the fully coupled run (#1) and the combination of the different forcings $[(\#1 - \#2) + \#3 + \#4]$ is computed, the median relative difference emerging from the simulations is around 0% and the maximum relative difference in one coastal point is around 3%. These small differences indicate that the interaction between the different forcings is small and justifies not to perform the additional numerical simulations. Note, that even in absence of strong interaction between storm surge waves and wind-waves, the coupled simulation is needed to account for the effects of the wave setup along the coasts.

To explore the impacts of Storm Gloria at the local scale, we focus on two cases under different forcing conditions. In the first one, we quantify the flooding induced by the joint effect of storm surges and waves on the Ebro Delta, taking advantage of the local very high grid resolution that allows an accurate representation of the local topographic features. In the second case, we evaluate the nearshore wave propagation and overtopping in Portocolom, located on the eastern coast of Mallorca Island (Figure 1 and upper panel in Figure 8), a rocky coast formed by high cliffs ($\sim 15\,$m) where numerous damages were reported by waves overtopping. Note that spectral wave models, such as WWM-III model used here, are unable to represent the overtopping generated by individual ocean waves; therefore, a set of 1D simulation were performed with the non-hydrostatic model SWASH~~In order to model nearshore wave propagation, a set of 1D SWASH model~~ (Zijlema et al. (2011); http://swash.sourceforge.net/) ~~simulations were performed~~ along a bathymetric profile with 1 m of horizontal resolution extracted from a nautical chart (1:5000) from the Spanish Army Hydrographic (IHM) Institute (the location of the profile is indicated by a red line in the upper panel in Figure 8; the profile is shown in the lower inset in the upper panel in Figure 8). The left side of the profile was artificially set as a downhill in order to account for all the water that overtops the cliff (upper inset in Figure 8). The Manning roughness coefficient was considered constant in all the domain with a value of 0.025. The wave forcing provided by the closest grid point of the regional model (extracted from simulation #1) was introduced in the eastern side of the 1D domain with a JONSWAP spectra. With this configuration, the simulation time was 60 minutes, with an initial ~~integration time~~computation time step of 0.05 s. Given that the comparison between modelled and observed H_s at the nearest buoy (Mahon) suggests that the model underestimates the magnitude of the waves (see section 2.3), instead of using the time series of wave parameters of the closest point, a set of values for H_s have been tested, ranging from 5 to 10 m, every 0.5 m, to determine the minimum significant wave height needed to have overtopping on the cliffs.. To minimize the inherent stochasticity when generating the wave forcing with a JONSWAP spectra, a total of 100 simulations with different seeds to generate the spectra were run for each H_s analysed.

2.3 Model validation

Modelled storm surges and waves have been compared to observations for the period 17-26 January 2020. The time series of the closest model grid point (the distance between model grid point and observation is indicated in Figure 3) was extracted for comparison with *in-situ* measurements. For the comparison to altimetry data, the closest model grid point in space, but also in time, to each altimetry track was used. Satellite observations with distance larger than 10 km from the closest grid point or with a time difference larger than 15 minutes between modelled time and observed time were discarded.

Figure 3 displays the comparison between modelled and observed wave parameters. *In-situ* measurements of T_p and wave direction are very well captured by the model output at both deep-water and coastal wave buoys. During the storm, T_p ranges between 10-12 s everywhere, with directions from the west ($\sim$ 90 degrees). Changes in these parameters are correctly simulated during the entire period with maximum differences in T_p of only 1 s. H_s significantly increases during the storm reaching values of up to 8 m, according to observations. The model underestimates H_s at all buoy locations, except in the two buoys near Tarragona (light blue curves in Figure 3). Differences between model and observations for H_s are between 1 m in Valencia (dark blue line) and 2.5 m in Mahon (red line) during the peak of the storm. This underestimation is also found consistently in the comparison to altimetry. The scatter plot of along-track altimetric observations and the corresponding model results displays a significant correlation of 0.73, although with a slope between observed and modelled H_s of 0.90, indicating that the overall underestimation is about 10% of H_s over the western Mediterranean basin. The possible causes of this underestimation include a poor energy transfer between the atmosphere and the ocean as simulated by the WWM-III wave model, a limited atmospheric forcing (either in terms of temporal or spatial resolution), and inaccurate bathymetry in some locations. To discard the role of the wave model in the H_s underestimation, we repeated the wave simulation with the same computational grid using SWAN model, a different spectral wave model developed at Delft University of Technology (http://swanmodel.sourceforge.net/) which led to equivalent results. As discussed above in the previous section, Figure S.M. 1 shows a good agreement between observations of atmospheric pressure and winds and the model forcing, with only small underestimations in wind velocity during the peak of the storm. Thus, we conclude that the likely causes of the H_s underestimation are related to limited bathymetry and small inaccuracies in the atmospheric forcing fields.

Coastal sea surface elevation is compared in Figure 4 to tide gauge observations. The sea level time series recorded by the tide gauges (represented in different colours in Figure 4 panels) have been detided (using the complete record of each station) and low-pass filtered using a Butterworth filter with a cutoff period of 30 minutes to remove the resonant modes of the harbors where the tide gauges are located. The filtered non-tidal residuals were compared to modelled outputs at grid points located within a radius of 5 km from the tide gauge. This approach seeks minimising the effect of local topographic features in the differences between modelled and observed records. We recall here that, since we run the coupled version of the model, sea surface elevation accounts for the storm surge and the effect of wave setup (every contributor is discussed and quantified below). Notably, observations indicate that sea levels have temporarily risen for up to 70 cm along the coasts in the mainland (sea level rises up 1 meter in Gandia prior to detiding and filtering - not shown). In contrast, values are much lower (around 20 cm) at tide gauges in the Balearic Islands. The similarities between modelled and observed extreme sea levels are remarkable at every tide gauge station: in Gandia, Sagunto and Valencia, the locations with larger increases, the model mimics both the intensity and the evolution of the sea surface elevation. Only in the tide gauge station in Tarragona, the model is found to significantly underestimate (~ 15 cm) observed sea levels; for the rest of the tide gauge records, the model results follow the oscillations and their magnitudes observed by the instruments. The underestimation of ocean surface elevation observed in Tarragona is likely related to inaccurate bathymetry at this location, a factor to which the storm surges are more sensitive at coastal locations.

3 Storm surges and wind-waves generated by Storm Gloria

The fully-coupled regional model (simulation #1) was run for the period 17-26 January 2020. The three days before the storm serve as spin up of the model to avoid starting the storm simulation from rest. The simulation is shown in S.M. Video 1, where frames are saved every 30 min. The video shows the evolution of the atmospheric pressure and wind fields (top figure) together with the ocean responses in sea surface elevation (middle figure) and waves (bottom figure). The intensity of wind fields increases rapidly on January 19 on the northern sector of the Western Mediterranean. This is followed by an immediate increase in H_s in the same area and direction; also visible is the accumulation of water along the coastal mainland resulting from the storm surge. On January 20, strong easterlies are developed in the centre of the basin, that generate waves of H_s around 5 m that reach the eastern coasts of the Balearic Islands. Contrary to the mainland, these waves hitting the Balearic Islands are not accompanied by significant storm surges. Note that the colorbars of both variables are saturated for representation purposes.

Maximum values of H_s and sea surface elevation during the storm at every grid point are mapped in Figure 5. Largest H_s are distributed in the area between the Balearic Islands and the mainland (Figure 5a), reaching values over 8 m in the region of Alicante and especially in the vicinity of Denia (see the map for locations). The high storm surge is concentrated along the coasts of the mainland, extending from the North at the Ebro Delta towards the South of the domain (Figure 5b) and with values larger than 40 cm. In contrast, around the islands the storm surge is negligible. This pattern is caused by the winds blowing towards the shallow waters along the mainland, as is clearly inferred in the video. Again, colorbars in both H_s and storm surge are saturated; the largest value of H_s and storm surges are around 7.5 m and 60 cm, respectively. Overall, the results of the simulation indicate that the coastal impacts in the mainland were originated by local wind-waves reaching the coastlines on top of an extremely large storm surge component; conversely, in the Eastern Mallorca island, the impacts were caused solely by the effect of waves travelling from the East.

The set of model runs described in section 2.2 allows the quantification of every forcing factor on total water levels. The contributions of atmospheric pressure, wind and wave setup are analysed separately in a coastal stripe along the mainland and represented in Figure 6. The coastal stripe is composed of sectors of size ∼5 km in latitude and ∼10 km in longitude, for which time series of total water levels and the three individual contributors corresponding to the grid points within each sector are grouped together. The values in Figure 6a correspond to the maximum total water levels in each sector. But to avoid any misrepresentation due to the limited bathymetry, the 90th percentile of the values of all time series is used. The corresponding values of every contributor are then identified at the same time step as the maximum in total water level. The major contribution to the storm surge is caused by the wind forcing (Figure 6d); maximum values reach 40 cm in the surroundings of Denia and are around 30 cm northwards up to the Ebro Delta. These quantities represent a contribution of approximately 70% of the storm surges along the entire coast, with the exception of the southernmost part of the coastal stripe where the surge does not exceed 10 cm. In this area the main contributor is the atmospheric pressure (Figure 6c). The effect of the atmospheric pressure is in general negligible where the storm surge is large, reaching values of 10 cm at most. The wave setup, computed as the difference in total water levels between the coupled simulation (simulation #1) and the simulation without the wind-wave module (simulation #2), is quantified in Figure 6b. Values larger than 20 cm are found near Denia, where the wind effects are also maximum, and in the northern part of the Ebro Delta. In these areas the wave setup accounts for up to 40-50% of the storm surge. as a result of the combination of forcings and the shoreline geometry. In these two spots there was a large wind contribution to the total surge (Figure 6d) allowing for more energetic waves reaching the coast; at the same time, particularly high waves hit the coast in a direction that is completely perpendicular to the shoreline (see the video of the simulation in the S.M.) maximising the accumulation of water due to the effect of the waves. This is particularly critical in the low-lying region of the Delta, as shown and discussed in the next section.

3.1 Coastal flooding in the Ebro Delta

Shortly after Storm Gloria, Copernicus EMS produced and published an image based on Sentinel-1 satellite observations of the flooded area in the Ebro Delta, one of the regions most impacted by the storm (image available at http://floodlist.com/europe/spain-storm-gloria-floods-january-2020). The satellite image maps the flooding during the days 20-22 January and shows the extensive and striking devastation over most of the Delta region. Note, however, that the image does not discriminate between coastal storm surge and rain-induced flooding, and that such discrimination is important to differentiate the parts flooded by salty water from those flooded by fresh water, as their impacts are very different especially for agricultural areas.

Our numerical simulation provides the total flooded area over the high-resolution Ebro Delta topography induced by the storm surge and waves. The results, mapped in Figure 7, show the maximum modelled flooding during Storm Gloria from January 17^{th} to 26^{th}, that reaches up to 4 km inland. This value is comparable to the 3 km extend reported by Copernicus EMS: "a storm surge also swept 3 km inland, devastating rice paddies and coastal features in the Ebro river delta ..." (at https://emergency.copernicus.eu/mapping/ems/copernicus-emergency-management-service-monitors-impact-flood-spain). ~~The qualitative comparison to the satellite image pointed out in the paragraph above suggests that the major part of the flooding in the Ebro Delta was caused by the heavy rains occurred during the storm rather than being linked to the storm surge, and hence to marine waters.~~The satellite image indicates that the extension of the flooding caused by the storm was larger than that obtained in our simulation. We explain this apparent discrepancy by the fact that we do not account for the flooding caused by the heavy rains that were reported in the area; instead, our results identify the extent of the flooding caused solely by the marine hazards. Notably, it is worth mentioning that our simulation reproduces the complete flooding of the Trabucador bar, which was swept out by the hazard.

We recall here that the validation of the model outputs indicated that the predicted storm surge in Tarragona tide gauge, the closest station to the delta, was underestimated (Figure 4). Therefore, our simulation could be considered as a lower bound for the flooded area.

3.2 Wave impacts in Portocolom (eastern Mallorca Island)

Another location that was severely hit by Storm Gloria was Portocolom, placed in the eastern coast of Mallorca Island (see Figure 1 for the location; top panel Figure 8). This section of the coastline, formed by high cliffs ($\sim 15\,m$), was impacted by large waves that overtopped the cliffs and whose spray reached up to 30 m high (see the inset picture in the low-panel in Figure 8). It caused damages to properties and temporal evacuation of the population.

Our regional simulation provides small storm surge values in the Balearic Islands (Figure 5b), in contrast to the large surges found along the coastline of the mainland. It also provides a maximum H_s of around 4.5 m in the vicinity of Portocolom during the storm (Figure 5a). The SWASH model has been implemented in 1-D in a section normal to the coast of Portocolom (red line in the upper panel and the insets from Figure 8), as described in the methodology in section 2.2. The initial tests indicated that the modelled H_s of 4.5 m is not high enough as to produce any overtopping. This is not surprising, since modelled H_s underestimates the maximum value recorded by the buoy at Mahon, located in the same area, by an amount of 2.5 m (January

21st at 12:00; red spot in Figure 3); thus, it is likely that the value in Portocolom is also biased low. Therefore, given that there is an amount of visual confirmations that overtopping was produced in this section of the cliffs (see the list in the Appendix, for example), we designed a set of SWASH simulations with values of H_s ranging from 5 m up to 10 m with a step of 0.5 m and fixing the peak period to 13 s (this is the value estimated by our regional simulation). For each value of H_s, we run 100 1-D SWASH simulations, of 60 min each, along the same bathymetric profile to account for the inherent variability in wave height. The averaged water flux over the cliffs and the number of waves that overtopped were computed in every run. These results are represented by the green and orange box plots, respectively, in the lower panel of Figure 8. It can be seen that the first set of 100 simulations that shows overtopping corresponds to a H_s of 7 m. This result suggests that our model is underestimating, at least, around 2.5 of H_s, in line with the comparison with observations in the buoy from Mahon (Figure 3). Then, as expected, the value of the flux and the number of waves that overtopped the cliffs increases with H_s. As an example, when H_s is 8.5 m, the amount of water over the 15m cliffs is $\sim$ 3600 litres per hour and meter. Note that our values do not account for the water input from the spray which, according to observations, was the most damaging to coastal properties, mostly related to the impact of wave water column against house roofs and balconies.

4 Discussion and conclusions

Storm Gloria has produced remarkably diverse impacts along the coasts of the Western Mediterranean. These include flooding of low-lying areas, mostly concentrated in the Ebro Delta (see section 3.1), destruction of coastal infrastructures and intense beach erosion due to the impact of waves. The storm surges and wind waves generated by Storm Gloria have been modelled with high resolution hydrodynamic and spectral wave models, both coupled and uncoupled. The outputs allowed to identify and to quantify the different physical mechanism acting on sectors of the coastlines that included the Spanish mainland (with the low-lying Ebro Delta) and the Balearic Islands. Along the coastline of the mainland, the simulated storm surges reached values up to 70 cm acting together with waves of significant wave height (H_S) up to 8 m. In contrast, the storm surge was negligible along the coasts of the Balearic Islands, where the reported impacts were mainly attributed to the high waves reaching the shore. Here, we have reproduced the overtopping of these waves over the high cliffs in the eastern coast of Mallorca Island using a non-hydrostatic model forced with the output of the regional wave model. In addition, by using a combination of different numerical simulations, we determined the role of each forcing factor (among atmospheric pressure, wind and ocean waves) in generating the total elevation of the storm surges and we conclude that the coupling between the hydrodynamic model and the spectral wave model is essential to account for the wave setup. Wave setup is particularly relevant in the Ebro Delta, where the model has predicted the flooding induced by the storm surge reaching up to 4 km inland and coincident with reports of monitoring services.

It is worth noting that Storm Gloria arrived after two relatively recent sea storms of lower intensity and return period of roughly 5 and 10 years, and before the complete recovery of the sedimentary coasts in the region was achieved. The frequency, and not only the intensity of the waves, have been shown to have an important effect on the eroded sediment in Mediterranean beaches during this type of events (Morales-Márquez et al., 2018). For instance, in January 2017 the basin experienced a mistral sea storm ~~that reach~~with maximum significant wave height values around 30 h, but in April 2018 there was an unusual sea storm event that maintain continuously maximum significant wave height values over more than 5 days. This sequence has very likely contributed to the large beach erosion induced by Storm Gloria in many places.

A major question arising with respect to the impacts of Storm Gloria is how rare this event has been and how it compares in intensity and extension with past events. Earlier works that have analysed the wave climate over the Western Mediterranean provide values of H_s that allow putting Storm Gloria into a historical perspective. Cañellas et al. (2007) used the HIPOCAS dataset (Soares et al., 2002), spanning the period 1958-2001, and estimated that 50-year return period in H_s is 11 m in the central part of the basin and has smaller values of 8 m along the eastern coast of the Iberian Peninsula and the southern part of the Balearic Islands. The same data base has shown that extreme wave heights over the Catalan and Valencia coast are significantly lower than those obtained in the north of the Balearic Islands due to the shadow effect of the islands over the intense north fetch produced by the Gulf of Lions and Ligurian sea storms (Ponce de León and Guedes Soares, 2010). These results indicate that, unlike Storm Gloria, extreme events are in most cases associated to northerly winds. The values extracted for maximum H_s using HIPOCAS data base are listed in Table 1 for two grid points located at the north and south of the Balearic Islands. At the northern point there are at least 11 events with H_s larger than 7 m during a minimum of six hours, being the most energetic the storms of December 1980 and January 2001, that reach respectively 13.9 m and 10.4 m in H_s and lasting for more than 3 days. At the southern point, in contrast, there are at least other 11 storm events with a significantly lower H_s. In this case, the most energetic storms correspond to December 1967 and December 1980, with H_s of 7.35 m and 8.93 m, respectively. In other words, the large waves generated by Storm Gloria of the order of 8 m in H_s are found among the largest events over the Western Mediterranean basin. The characteristics that have made Storm Gloria exceptional in terms of coastal impacts are, on the one hand, that while the largest waves are generally found in the northern sector of the Western Mediterranean, caused by northerly winds, during this event, the largest waves occurred in the western part of the domain and very close to the coast, increasing their potentially hazardous effects. This is further illustrated in Figure S.M. 2a, where maximum H_s for the period 2007-2017 is mapped. This output has been extracted from the Mediterranean Sea Waves Hindcast (CMEMS MED-Waves) available through Copernicus Monitoring Environment Marine Service (CMEMS) (Korres et al., 2019) and is the most recent, high-resolution wave hindcast in the region. Figure S.M. 2b shows the equivalent quantile of the maximum values of H_s reached during Storm Gloria and indicates that, while there have been other high values in the central and northern parts of the basin for the hindcasted period, the waves generated by the storm in the area between the Balearic Islands and the mainland are not found in these records (quantile values over 0.99). On the other hand, coastal impacts of Storm Gloria are mainly linked to the large storm surges occurred along the coasts of the mainland. Such temporarily high sea levels, reaching sustained values around half a meter during two days, have exacerbated the coastal hazards in this area to the extent of causing unprecedented damages (the appendix compiles a non-comprehensive list of reported damages published through official agencies as well as in the media). According to Kopp et al. (2014), this value of 50 cm corresponds to the median projected mean sea-level rise in the Mediterranean Sea by year $\sim$ 2080 under RCP4.5 and $\sim$ 2070 under RCP8.5. Thus, what is exceptional in the present-day climate, may become the average conditions later this century.

Appendix

A non-comprehensive list of websites with reports, images and videos of damages and impacts of Storm Gloria:

1. http://www.aemet.es/es/noticias/2020/01/Tres_temporales_mediterraneos_en_nueve_meses
2. https://beteve.cat/medi-ambient/platges-barcelona-estat-temporal-gloria/
3. http://www.caib.es/pidip2front/jsp/ca/fitxa-convocatoria/strongdesperfectes-i-pegraverdues-materials-als-ports-de-les-illes-balears-a-causa-de-la-borrasca-glograveriastrong
4. https://ib3.org/desallotgen-primera-linia-cala-marcal-mallorca-portocolom-ones-superen-altura-habitatges
5. https://www.diariodemallorca.es/mallorca/2020/01/22/temporal-mallorca-deja-balance-334/1479830.html
6. https://www.diariodemallorca.es/mallorca/2020/01/21/borrasca-gloria-mallorca-mejores-imagenes/1479528.html
7. https://www.20minutos.es/noticia/4126870/0/balance-muertos-danos-desaparecidos-borrasca-gloria-enero-2020/
8. https://lahoradigital.com/noticia/24641/sociedad/la-borrasca-gloria-la-peor-tormenta-de-levante-de-este-siglo.html
9. https://elpais.com/elpais/2020/01/20/album/1579518566_774901.html
10. https://www.elperiodico.com/es/tiempo/20200124/temporal-catalunya-cataluna-borrasca-gloria-ultimas-noticias-directo-7812567
11. https://www.infobae.com/america/mundo/2020/01/21/los-videos-que-reflejan-la-ferocidad-de-la-tormenta-gloria-en-espana-que-acumula-tres-muertes-apagones-y-escuelas-cerradas/
12. https://www.lavanguardia.com/vida/20200123/473082325223/temporal-gloria-balance-muertos-danos-espana-cataluna.html

Video supplement. A video of the numerical simulation is available in the supplementary material.

Author contributions. AA and MM conceived the work and designed the numerical experiments. DSC retrieved the atmospheric forcings. AA performed the numerical simulations. AA and MM analysed the outputs and all authors contributed to the outline and writing of the manuscript.

Competing interests. No competing interests are present.

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North ($H_s > 7m$)					South ($H_s > 6m$)				
Year	$H_s\,(m)$	$T_p\,(s)$	$D_p\,(°)$	$Dur\,(h)$	Year	$H_s\,(m)$	$T_p\,(s)$	$D_p\,(°)$	$Dur\,(h)$
1960	7,44	11,17	22	205	1960	6,45	10,15	68	48
1967	7,46	12,28	35	160	1961	6,23	9,33	75	64
1972	7,35	11,17	19	39	1965	6,04	11,13	83	88
1979	7,43	11,17	19	74	**1967**	**7,35**	**11,21**	**33**	**47**
1980	**13,87**	**14,86**	**25**	**121**	1971	6,56	9,23	113	69
1982	7,81	12,28	22	69	1973	7,14	11,15	106	85
1986	7,24	9,22	291	88	**1980**	**8,93**	**10,71**	**75**	**109**
1987	7,12	10,12	294	80	1992	6,84	10,11	108	83
1996	7,45	9,00	315	113	1993	6,36	10,15	103	135
1997	7,69	10,15	25	58	1997	6,89	10,21	115	87
2001	**10,44**	**12,38**	**29**	**204**	2001	6,13	8,26	79	85

Table 1. Characteristics of the events with maximum significant wave height H_s at two grid points north and south of the Balearic Islands, extracted from the HIPOCAS data base (Soares et al., 2002). Strongest events are highlighted in bold.

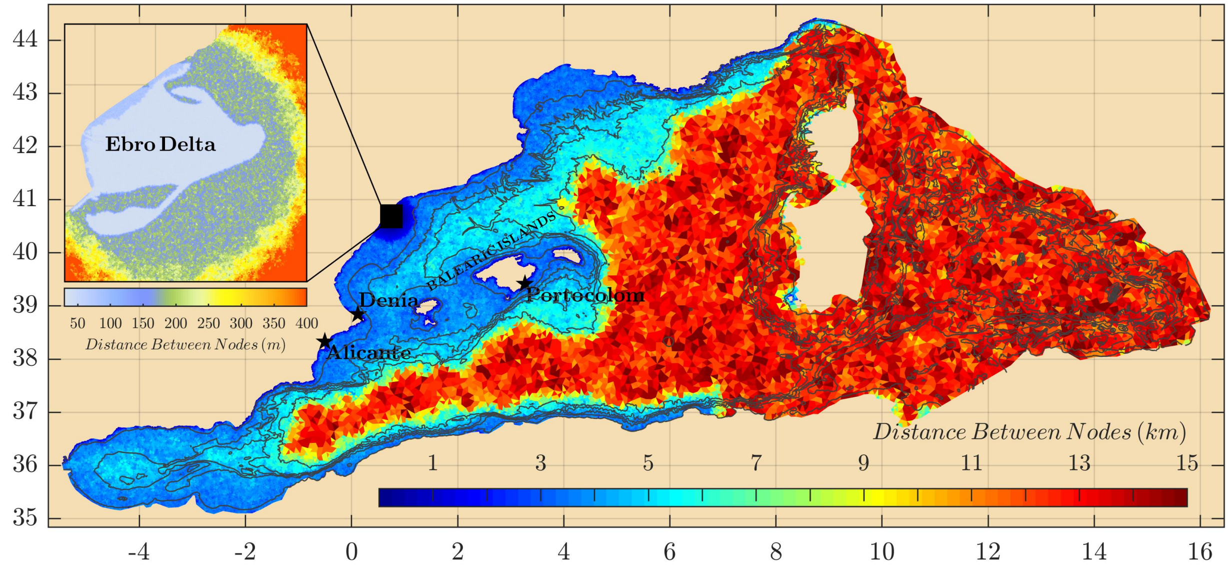


Figure 1. Map of the simulation domain with the element size indicated by colours. The contour lines indicate the 3000 m, 2500 m, 2000 m, 1500 m, 1000 m, and 100 m isobaths. The upper-left corner zoom shows the element size over the Ebro Delta river.

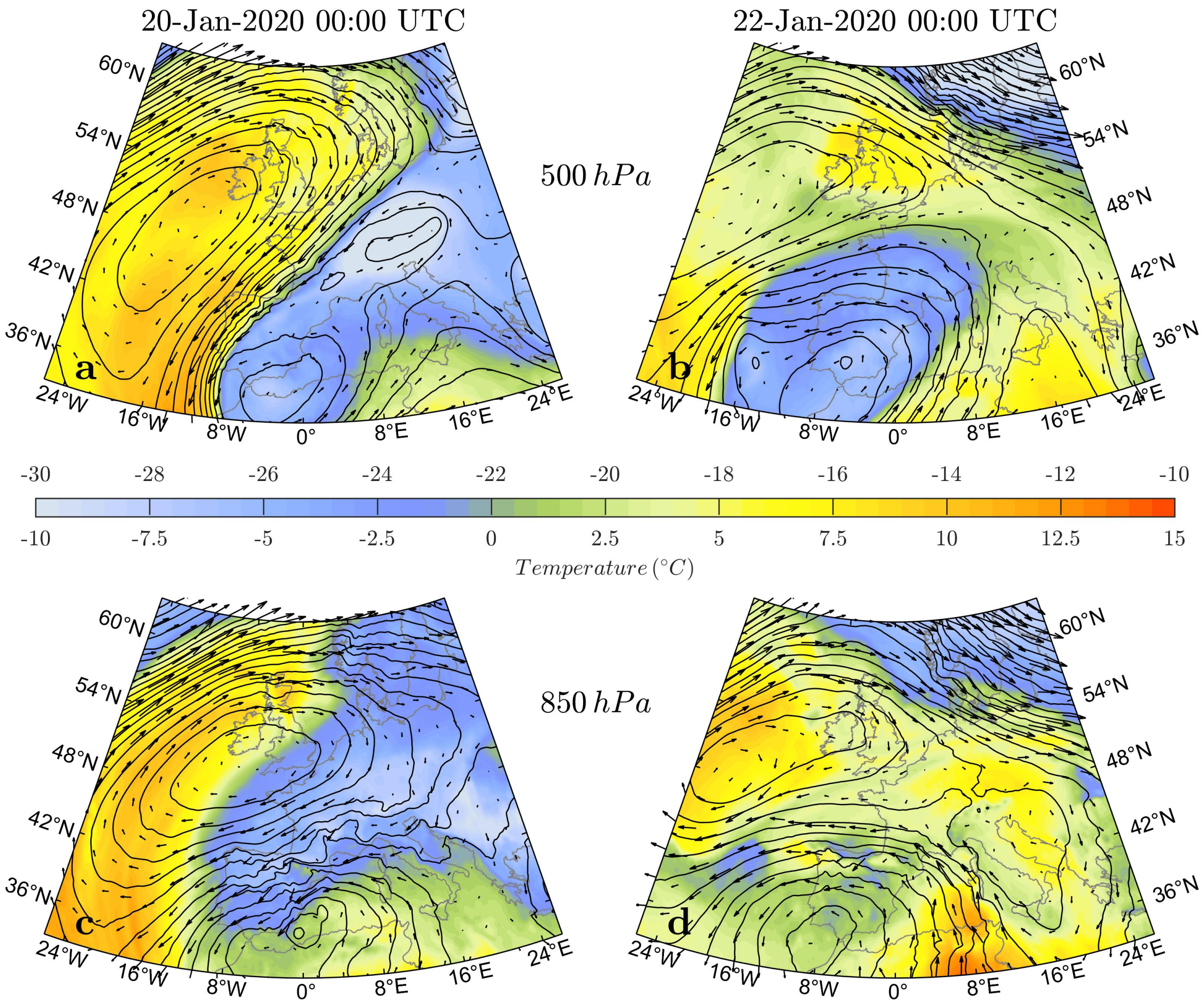


Figure 2. ECMWF analyses at 500 hPa (a and b) and 850 hPa (c and d) at 0000 UTC on January 20^{th} (a and c) and 22^{nd} (b and d) 2020. Black solid lines show the geopotential height, colours indicate the temperature and wind speed is represented by arrows. Note the different temperature ranges for the 500 hPa $[-30°C, -10°C]$ and 850 hPa $[-10°C, 15°C]$ fields.

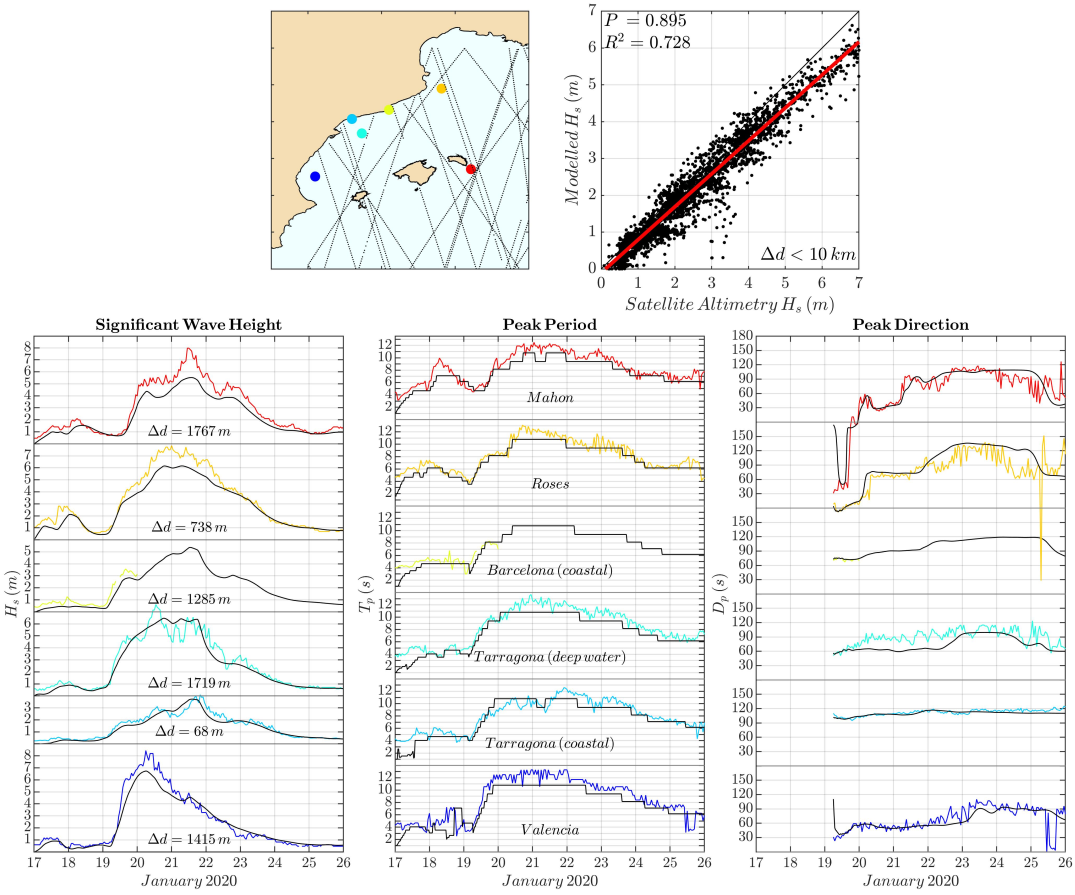


Figure 3. Comparison between modelled (black line) and observed (coloured lines; each colour corresponds to one location in the map) wave parameters during the storm. Note that wave direction before 19/01 is not used because of the low confidence with very small waves. The upper right panel shows the comparison between the modelled significant wave height and the satellite-measured at the same location (satellite tracks are indicated by black lines in the map) and time. Δd indicates the distance between observations and the closest grid point used for comparison.

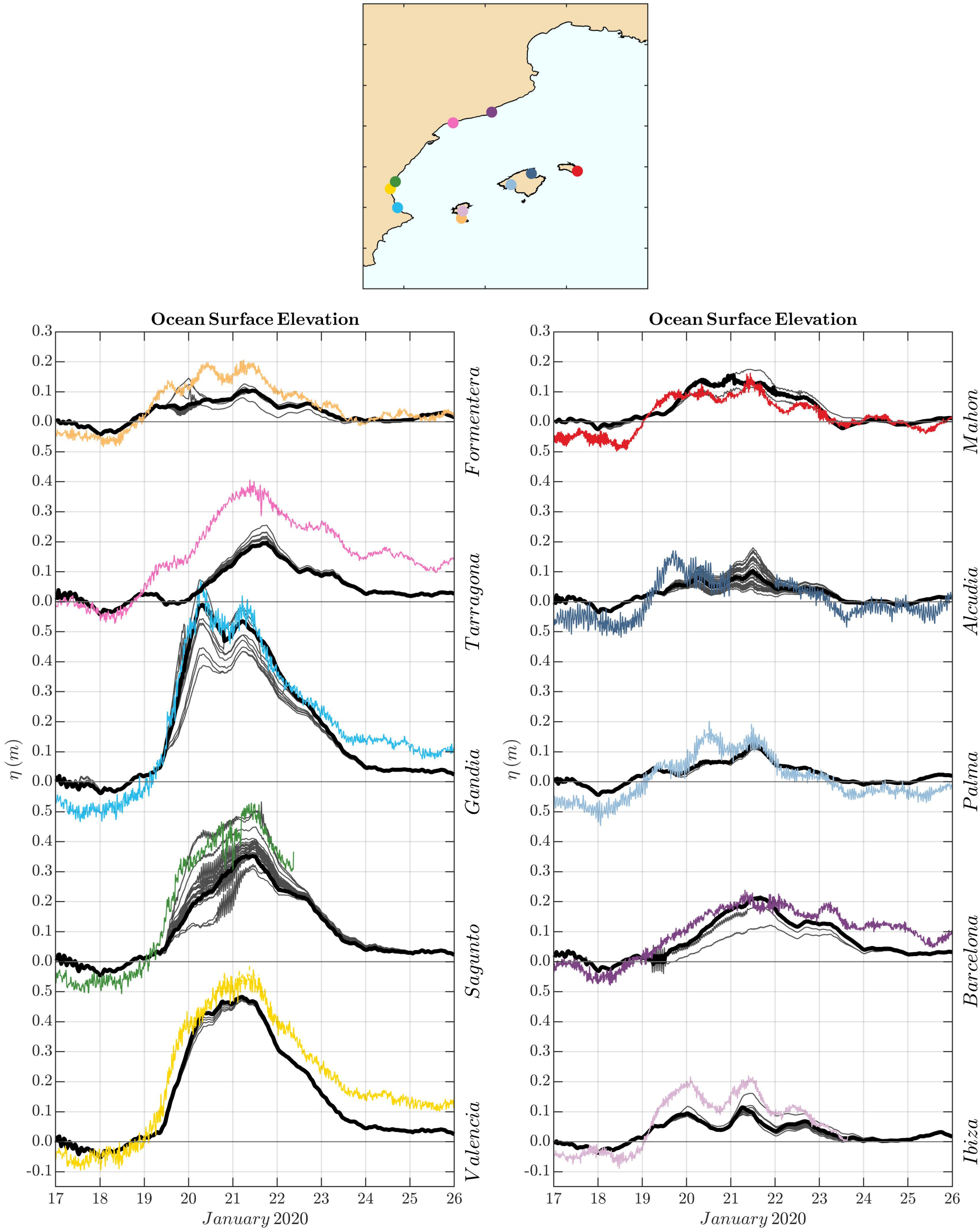


Figure 4. Comparison between modelled (black lines) and observed (coloured lines; each colour corresponds to one location in the map) storm surges by tide gauges. To avoid strong bathymetric dependencies, the time series of all modelled points closer to 2.5 km to the tide gauge location are shown. The closest modelled point to the tide gauge is indicated by a thick black line.

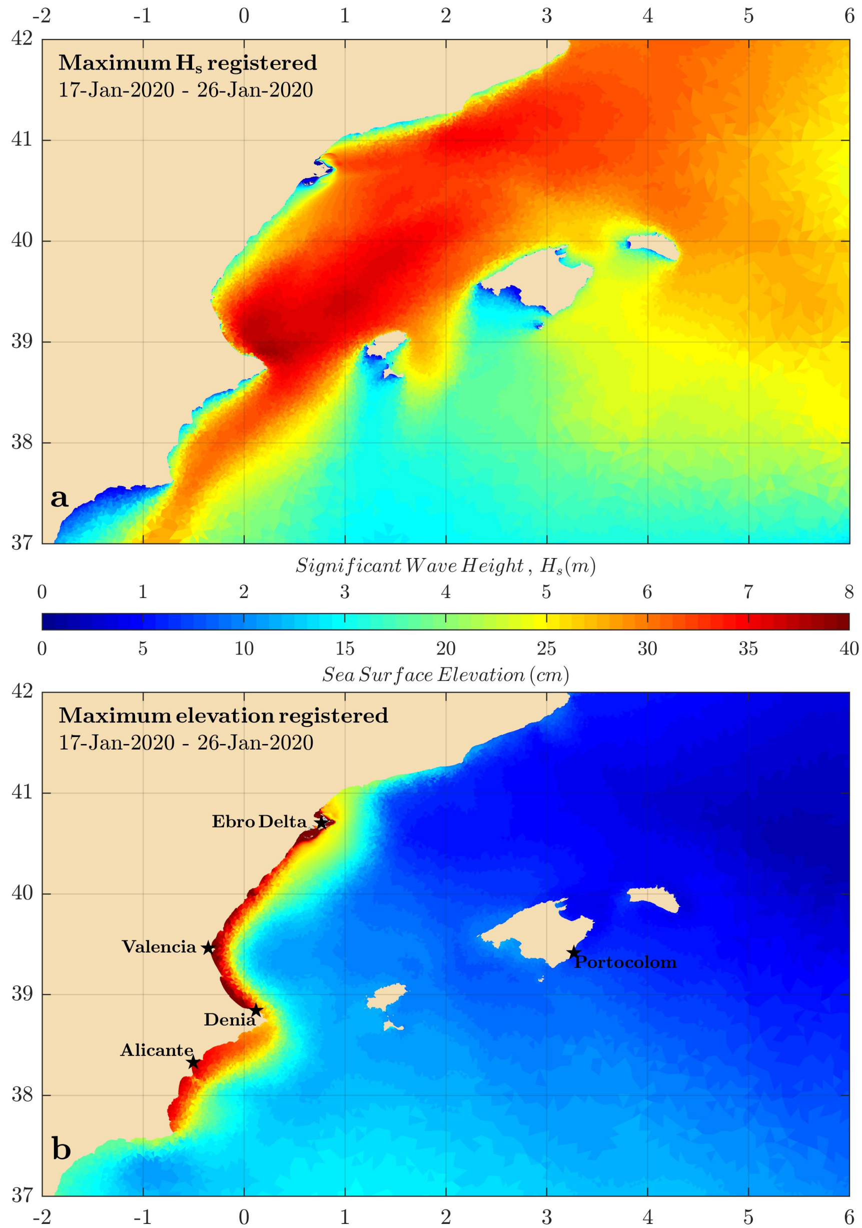


Figure 5. Maximum values of H_s (a) and sea surface elevation (b) during the simulation period.

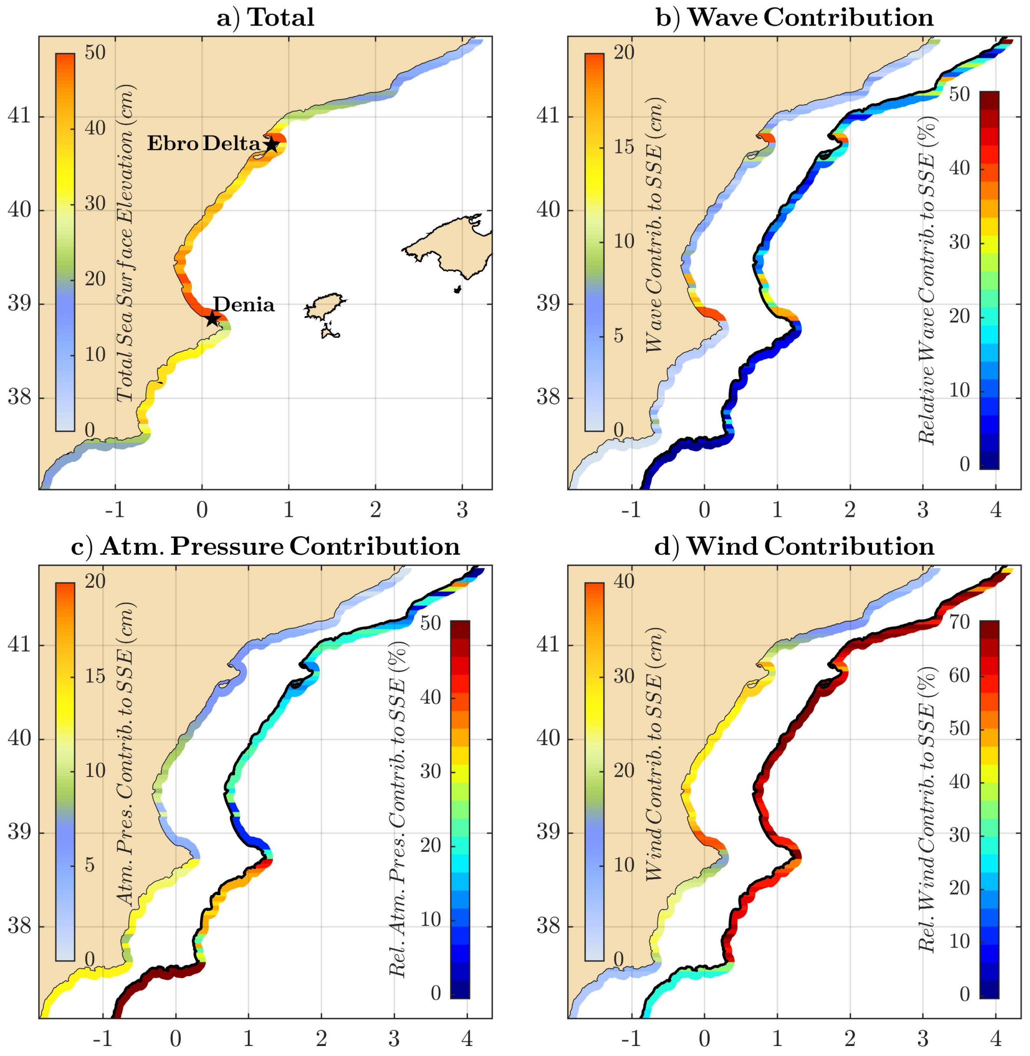


Figure 6. Maximum storm surge along a coastal stripe affected by Storm Gloria (a) and the contributors: wave setup (b), atmospheric pressure (c) and wind (d). In panels b, c and d, the absolute (relative) contribution is indicated by the profile in the left (right). Note that the colour scales for the wind have higher limits.

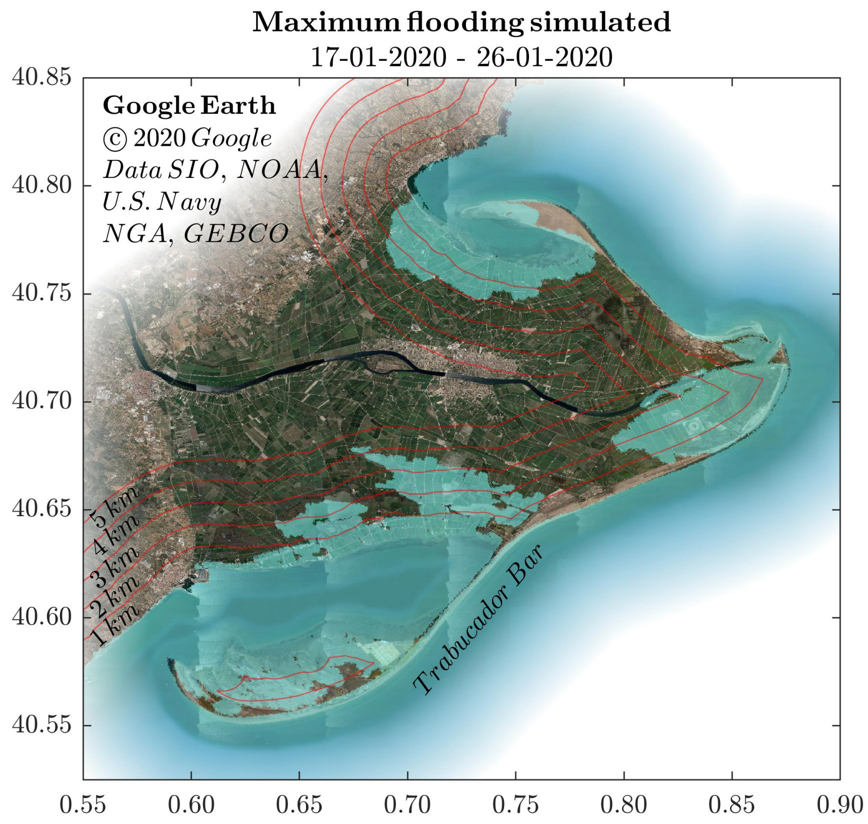


Figure 7. Simulated flooded area in the Ebro Delta caused by the storm surge. Red lines indicate distance from coast.

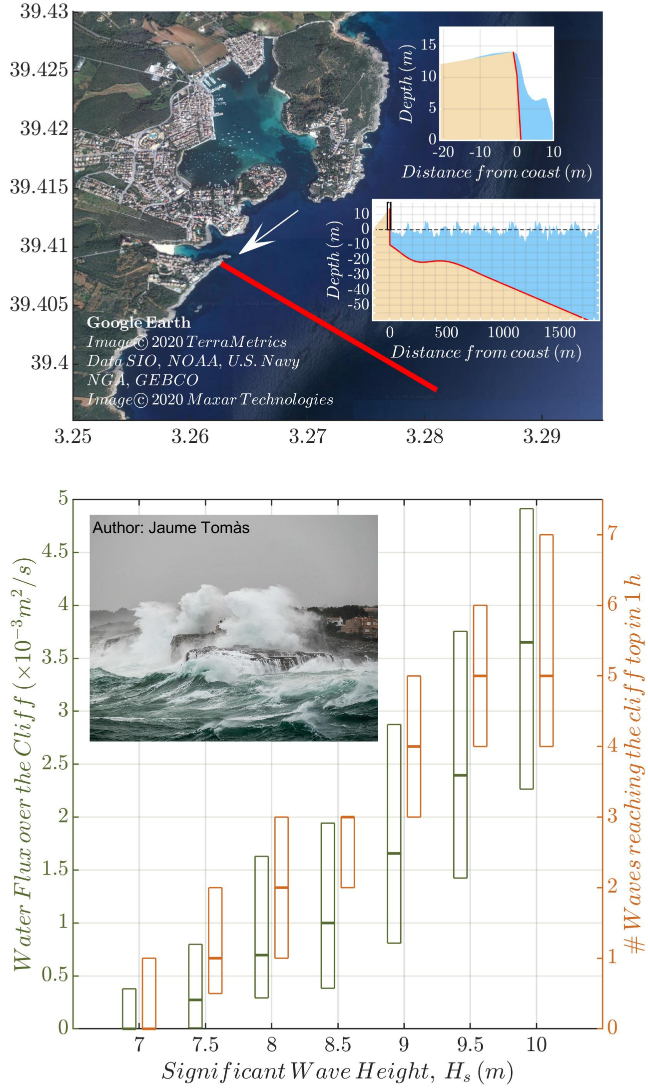


Figure 8. Upper panel: Satellite image of Portocolom area with the transect where the bathymetric profile was extracted in red. The lower inset shows one snapshot of one SWASH simulation in one moment where there is overtopping; the upper inset shows a zoom of the upper part of the cliff corresponding to the black box in the lower inset. Bottom panel: box plots of the water flux over the cliff per lineal meter (green boxes) and the number of waves reaching the top of the cliff (dark orange boxes) as a function of significant wave height. The thick line of the box plots indicate the median extracted from 100 different 1D SWASH simulations while the bottom and the top of the boxes show the quantile 0.25 and 0.75, respectively. The inset picture shows the waves hitting the simulated spot (white arrow in the upper panel) during the most intense time of Storm Gloria, Januaty 21st at 12:00 UTC.

Response to Referee #1 of our manuscript entitled **Coastal Impacts of Storm Gloria (January 2020) over the Northwestern Mediterranean** [nhess-2020-75] submitted to *Natural Hazards and Earth System Sciences*.

Angel Amores, Marta Marcos, Diego S. Carrió, and Lluís Gómez-Pujol

May 21, 2020

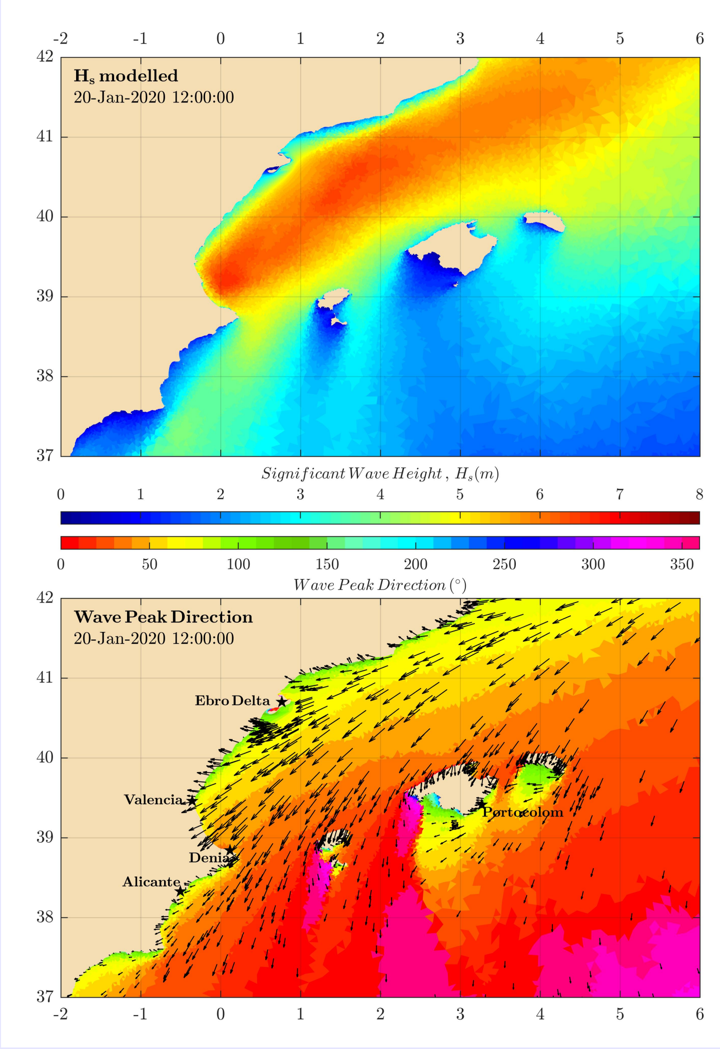
Author's response: We would like to thank the Reviewer for the comments provided. We have responded point by point to all the concerns raised below, with indication of the changes in the manuscript:

The reviewed manuscript "Coastal Impacts of Storm Gloria (January 2020) over the Northwestern Mediterranean" is a numerical study on storm surge, primarily using SCHISM for hydrodynamics and WWM-III for wave dynamics. A baseline 2D model was set up and validated considering the compound effects of wave, atmospheric pressure, and wind. The contribution from each effect were investigated individually by sensitivity tests. Locally high-resolution was implemented in the 2D mesh for a coastal site; a 1D non-hydrostatic model was implemented for another local region with high cliffs using SWASH. The simulation results of Storm Gloria were analyzed and then put into a historical context. The research is the earliest model study on Storm Gloria. The set up and validation of the numerical model are rigorous. The discussion on individual contributors of the total surge, spatial variabilities and historical context are of scientific and practical importance. I find the manuscript very well written. It generally meets NHESS's standard (attached in the previous page); only minor revisions are required.

Specific comments:

1) The authors should try to expand on the analysis of the spatially varying wave contributions to the total surge, specifically on why there are two hotspots (Ebro Delta and Denia in Figure 6b) along the coast. In Section 3 (Ln 194), Ebro Delta and Denia are found to differ from other alongshore regions in wave contribution ($>$ 20 cm, compared to mostly $<$ 7 cm elsewhere; 40-50% of the total surge, compared to mostly ¡10% elsewhere, as estimated from Figure 6b). Is this pattern related to shoreline geometry, topography/bathymetry, or forcing? Does mesh resolution have anything to do with it (seems not, since Denia is not refined)? Please elaborate either before or within Section 3.1; a short paragraph or 2-4 sentences will do.

Author's response: To illustrate our response we have produced the Figure below, that maps significant wave height (H_s, top panel) and wave peak direction (D_p, bottom panel) at the time that Storm Gloria hit stronger along the coast of the mainland (January 20^{th}, 2020). As the reviewer states the maxima wind-wave contributions to the total surge in Denia and the Northern side of the Ebro Delta is a physical effect linked to the wave direction. It is not related to the grid resolution since, as the reviewer noted, the area around Denia is not refined. These two spots were the areas where the waves hit the coast more perpendicularly and, consequently, the wave setup was larger. We thus conclude that the observed pattern in these two spots is a combination of the forcing (with large H_s and that direction) and the shoreline geometry, coinciding with the direction perpendicular to the forcing. We have added a paragraph explaining this fact just before section 3.1, following reviewer's advice.



2) A short paragraph needs to be added in Section 4, summarizing the major accomplishment and findings of the current work. Right now, the last paragraph (which I assume serves as the conclusion) only slightly touches the current work in the 2nd sentence.

Author's response: We have re-arranged the last section, now including a paragraph where we summarise the main findings of the present study.

Technical corrections:
1) Ln 55: consider adding some background for the two selected localities. Did you select them arbitrarily as long as they differ in morphology and forcing? Are they the most severely impacted area? Do they have any significance in agriculture, human residence, or wild life habitat? Some aspects are mentioned later, but a brief description here before delving into the modeling work would be nice.

Author's response: We selected these two locations based on a combination of two factors: differences in morphology and in the forcing, as stated in the text. In addition, for the local studies we needed high resolution topo-bathymetries to perform the local studies, that are not available everywhere but they were for these two areas.

We have included some background of these two spots in the introduction (second-to-last paragraph).

2) Ln 62: discusses the results and "provides" the final remarks.

Author's response: This change has been introduced.

3) Ln 86: More details should be provided on the model setup, e.g.: dt, bottom friction, etc. Also consider showing the computation speed, e.g., number/type of cores and the ratio of simulation time to real time.

Author's response: We have included more information about the model setup in the first paragraph of section 2.2

4) Ln 94: use the multiplication symbol instead of "x".

Author's response: This change has been introduced.

5) Ln 120: "m" should be in normal font.

Author's response: This change has been introduced.

6) Ln 121: provide a brief explanation on why a non-hydrostatic model is needed here in addition to the coupled SCHISM-WWMIII model, so that readers with less background can follow.

Author's response: We have included a sentence in lines 129-131 explaining the reason why a non-hydrostatic model is needed at this point (last paragraph of section 2.2).

7) Ln 135: because model results were not interpolated onto observation points, the authors should provide the maximum distance among all pairs of observation and model grid points.

Author's response: The distance between the location of the buoys and the closest model grid point has now been included in the Fig. 3 as insets in the panel of the H_s ($\Delta d =$...). The values range between 68 m and 1.7 km. This is referenced at the beginning of section 2.3.

8) Ln 141: Add one or two sentences, providing possible causes of underestimating Hs.

Author's response: Possible causes are a poor quality of the atmospheric forcing, a bad performance of the numerical model or inaccurate bathymetry. To test the model performance, we repeated the simulation with the SWAN wave model and obtained the same outputs, so this cause can be discarded. The atmospheric forcing slightly underestimates the wind during the peak of the storm (see Figure 1 in S.M), which might have an effect together with the possibly limited representation of the bathymetry. We have now included a brief discussion of these possible causes in section 2.3 (second paragraph).

9) Ln 158: "cm" should not be italic.

Author's response: This change has been introduced.

10) Ln 158: provide possible causes of underestimating elevation at Tarragona. Uncertainties in forcing, DEM, etc.?

Author's response: We believe that when approaching the coast the major source of error is the bathymetry, which is likely not accurate enough. We have included a sentence in this respect at the end of section 2.3.

11) Ln 197-202: [no corrections needed] If differentiating river flooding and storm surge is of interest to the authors, there are some recent publications on compound flood modeling using SCHISM and WWMIII.

Author's response: Thanks to the reviewer for the heads up. We will check these publications.

12) Ln 277: . . . a mistral sea storm "with" maximum significant wave height . . .

Author's response: This change has been introduced.

13) Figure 6: put the subplot labels (a,b,c,d) into the titles.

Author's response: This change has been introduced.

Response to Referee #2 of our manuscript entitled **Coastal Impacts of Storm Gloria (January 2020) over the Northwestern Mediterranean** [nhess-2020-75] submitted to *Natural Hazards and Earth System Sciences*.

Angel Amores, Marta Marcos, Diego S. Carrió, and Lluís Gómez-Pujol

May 21, 2020

Author's response: We would like to thank the Reviewer for the assessment on our manuscript and for the comments provided. We have responded to all the concerns raised below, with indication of the changes in the manuscript:

Suitability. The subject of the paper, i.e. the study of the Coastal Impacts of Storm Gloria (January 2020) over the Northwestern Mediterranean falls within the fields covered by NHESS.

Summary. The paper objective it twofold, concentrating on the shorelines of the eastern Spanish coasts and the Balearic Islands: (1) quantify at a regional scale the physical mechanisms at play along the different coastal areas in the basin, including the storm surges and the effect of waves, and discuss their differences, (2) at a more local scale (Ebro Delta and cliff of the eastern Mallorca Island), simulate the impacts of the storm, accounting for the storm surge and wave setup. The paper provides key results on the significant contribution of wind-induced storm surge at the regional scale along the mainland, and wave overtopping at Mallorca cliff site. It also provides flood modeling results on the Ebro delta. General comment.While the manuscript is very clear, well written and provides interesting insights in the knowledge of the Gloria storm marine forcings, the manuscript has some weaknesses which deserve to be tackled before publication: discussion (or integration?) on neglected marine forcing especially for the local flood investigation and for the regional model validation (tide, water level fluctuations induced by 3D circulations), the method used to validate the storm surge model, the validity of regional model to properly estimate wave setup with a grid resolution of 1-2km. In addition, the manuscript would benefit from a bit more physical interpretation of the results.

Major remarks:

1.Role of neglected processes? 3D Mediterranean circulation induce seasonal water level fluctuations of several centimeters to tens centimeters [Bouffard and Pascual; Larnicol et al., 1995]. For example, Larnicol et al. [1995] indicate variations of +/- 10 cm at the scale of the whole Mediterranean Sea and of each of the two basins. Such fluctuation is far to be negligible for flood issues in micro-tidal areas as the study sites. A bit of discussion on this water level contribution during the Gloria storm would be useful and could reinforce the confidence in the results, if, for instance, this contribution contributed for almost zero during Gloria storm.

Author's response: Seasonal sea level changes in the Mediterranean Sea range between 4 and 8 cm for the annual and 2 and 4 cm for the semi-annual signals, on average [*Marcos and Tsimplis*, 2007], in agreement with the magnitude pointed out by the reviewer. We have explored this baroclinic signal as illustrated in the figure below, corresponding to the tide gauge record in Barcelona. The time series has been demeaned and detrended. According to *Marcos and Tsimplis* [2007], in the western Mediterranean basin the sea level seasonal cycle peaks between September-November, and decreases afterwards. This is observed in the figure (lower panel). This panel also shows that mean sea level during Storm Gloria varies around the zero, which corresponds to the averaged mean sea level during the tide gauge period. Therefore, we conclude that seasonal mean sea level does not add any further effect that amplified or reduced the impacts of the storm.

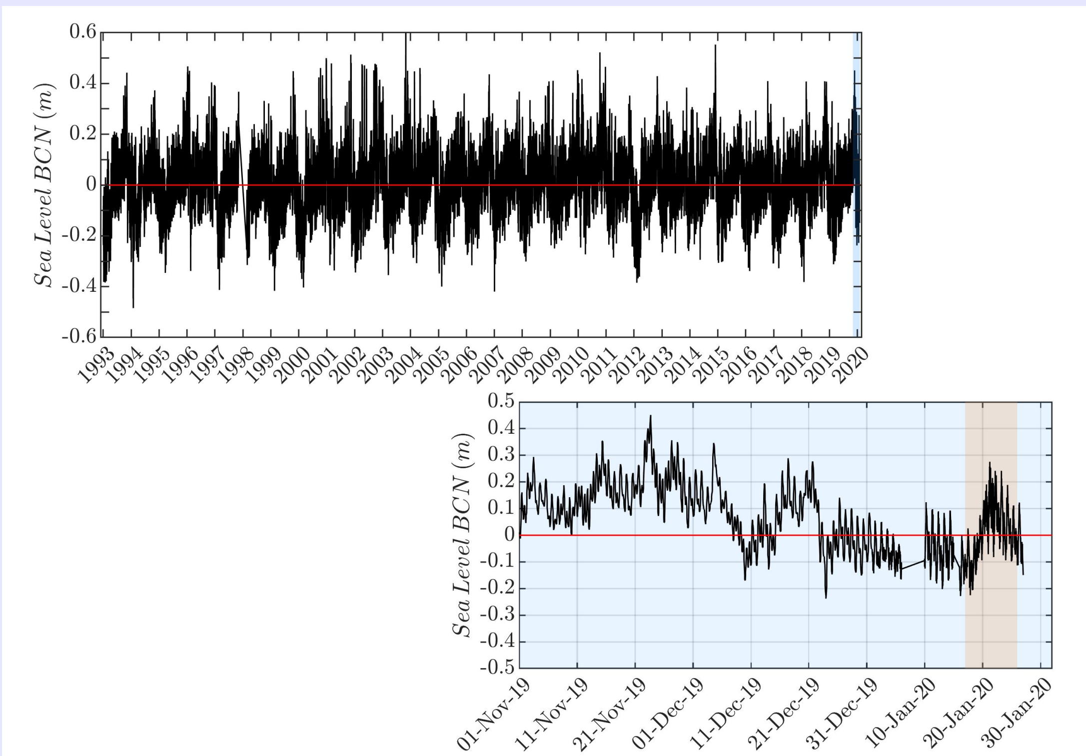


Figure 1: Sea level time series at Barcelona tide gauge (upper panel) and zoom of the most recent period (lower panel)

In addition, all the modeling experiment seem to neglect the tide. The authors should make more explicit that they neglect the tide and discuss the implications on the results for the flood investigations (Ebro Delta and Balearic rocky cliff). Indeed, for instance, the maximum tidal range seems far to be negligible (0.85 m in Barcelona after `http://www.portdebarcelona.cat/en/web/el-port/101#2`) in front of the Gloria storm surge. But what was the tide during Gloria storm?

Author's response: There seems to be an error in the tidal range at the site referenced by the reviewer. The tides in Barcelona, as in most of the Mediterranean Sea are much smaller. This is observed in the figure above of the previous response. Also, please check the table below, that has been extracted from the website of the Spanish Port Authority for the same tide gauge. It lists the tidal harmonics in Barcelona computed for the time period 1993-2018 (http://www.puertos.es/en-us/oceanografia/Pages/portus.aspx). The largest tidal constituent is the M2 with 4.60 cm of amplitude. Summation of all tidal constituents results in a total amplitude of 17.28 cm what makes a maximum tidal range of 34.56 cm, value that is far from the 85 cm stated by the authorities of the Barcelona harbour in which seems to be a typo.

In our simulation we did not consider the tides for the reason outlined above and also because the storm lasted 3 days and included all tidal phases. We have now specified this in the text. We have added a sentence in the manuscript indicating that the tides are not taken into account in the simulation (2nd paragraph in section 2.2).

Armónicos de Marea calculados sobre el periodo 1993-2018 / *1993-2018 Harmonic Constituents*

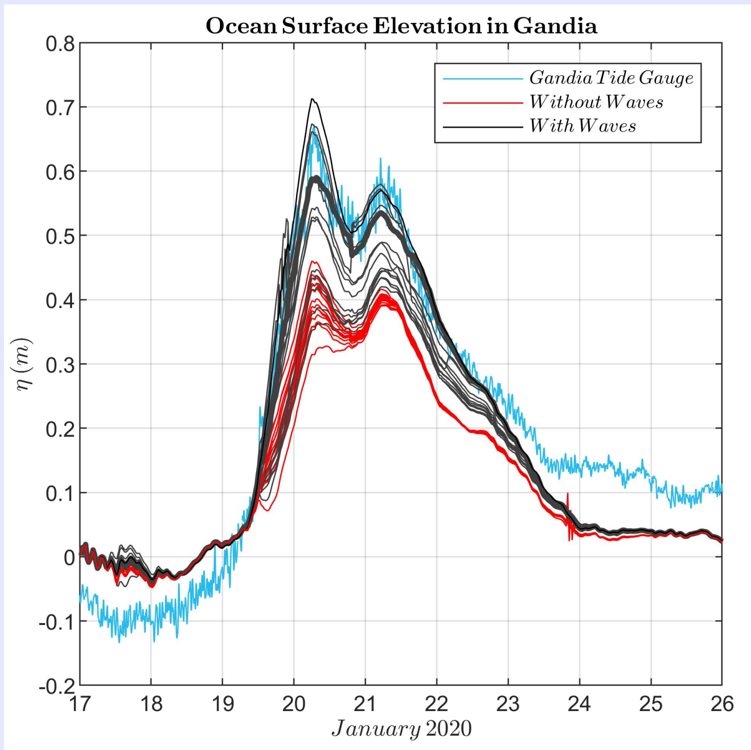
Armónico *Harmonic Id*	Frecuencia *Frequency* (ciclos/hora)	Amplitud *Amplitude* (cm)	Fase *Phase* (°)	Armónico *Harmonic Id*	Frecuencia *Frequency* (ciclos/hora)	Amplitud *Amplitude* (cm)	Fase *Phase* (°)
Z0	0.000000	30.05	0.00	S2	0.083333	1.65	230.58
Q1	0.037219	0.32	53.01	K2	0.083561	0.48	228.54
O1	0.038731	2.36	102.80	M3	0.120767	0.14	158.85
P1	0.041553	1.25	160.81	MN4	0.159511	0.21	303.21
K1	0.041781	3.68	168.03	M4	0.161023	0.52	346.81
2N2	0.077487	0.15	190.35	SN4	0.162333	0.05	4.38
MU2	0.077689	0.16	177.26	MS4	0.163845	0.33	51.23
N2	0.078999	0.98	201.44	MK4	0.164073	0.10	58.78
NU2	0.079202	0.18	202.60				
M2	0.080511	4.60	213.38				
L2	0.082024	0.12	220.89				

Data extracted from: http://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx

Tabla generada por Puertos del Estado/*Generated by* **Puertos del Estado** **Fecha actual**/*Today is* **05 May 2020**

2.Model resolution for the wave setup quantification Without more justification, a coastal resolution of 1-2km is probably too coarse to capture the local wave set-up contribution. Either I am wrong, then the authors should prove that this resolution is enough for their study site. Or I am true, and then, I am afraid that the authors should remove the analysis of the wave setup contribution (at the regional scale). But they could probably discuss it for the Ebro Delta, where the grid resolution falls to 30 meters (and thus is probably fine enough to capture the wave setup).

Author's response: We would like to highlight that the comparison between modelled and observed sea level as measured by tide gauges (Figure 4 in the manuscript) shows a good agreement, suggesting that our simulation correctly captures the most relevant processes that are taking place during Storm Gloria. In order to prove this, we are going to focus our response in the two sites where the wave setup has significantly contributed most to the total water level modelled along the Mediterranean coast of the Iberian Peninsula, i.e. the northern side of the Ebro Delta and the region around Denia (see Figure 6 of the Manuscript). Since the high grid resolution of the Ebro Delta could explain by itself the good agreement, we are discussing here the results and comparison between model and observations at Gandia tide gauge which is the closest one to Denia (Figure 4). In the figure below we show the same comparison as in Figure 4 for Gandia tide gauge, but we have added the ocean surface elevation time series of the simulation without taking into account the waves (red lines) to the coupled simulation (grey lines). Not accounting for the wave setup (red lines) underestimates by around 20 cm the observed sea level (blue line), whereas including the effect of waves (grey lines) decreases this bias. Indeed, the closest grid point (thick grey line) mimics the amplitude of the observed storm surge. We thus conclude that the spatial resolution that we are using is enough to, at least partially, capture the effects of the wave setup.



3.Model validation. First, regarding the wave model results, the manuscript would benefit from explanations for the Hs underestimation.

Author's response: This was also a query from Reviewer #1. Possible causes are a poor quality of the atmospheric forcing, a bad performance of the numerical model or inaccurate bathymetry. To test the model performance, we repeated the simulation with the SWAN wave model and obtained the same outputs, so this cause can be discarded. The atmospheric forcing slightly underestimates the wind during the peak of the storm (see Figure 1 in S.M), which might have an effect together with the possibly limited representation of the bathymetry.

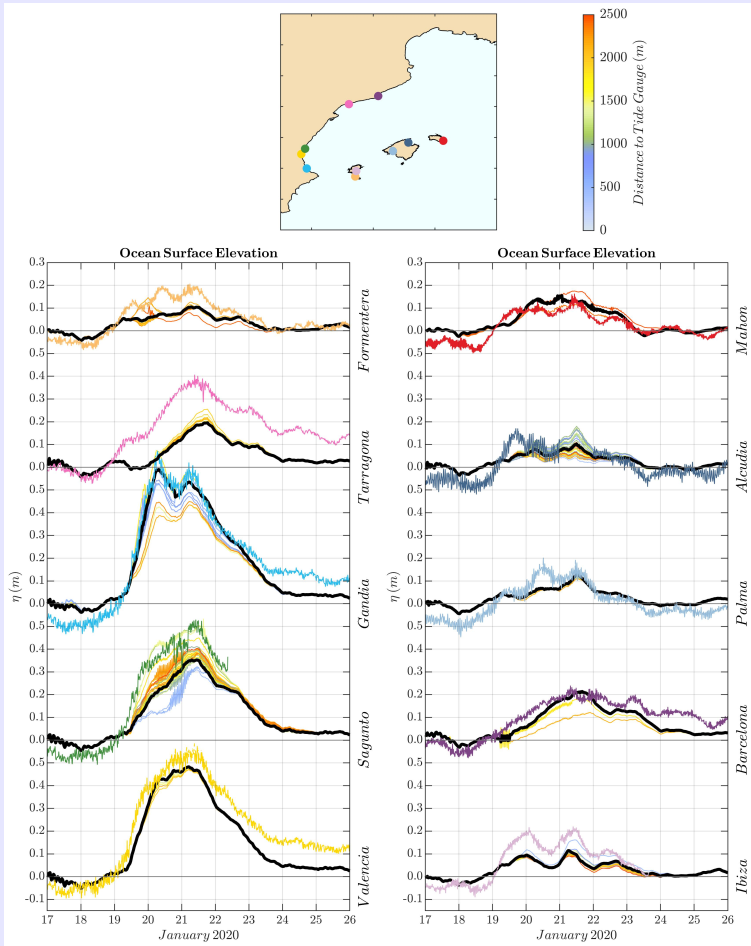
We have added a discussion on the possible causes of the underestimation of H_s (section 2.3, 2nd paragraph).

Second, and more importantly, I have some doubts with the method which consists in comparing the water level model outputs in the 5km radius to the local tide gauge measurements. Indeed, depending on the grid points, some points may include a part of the wave setup (probably less than the reality due to the too coarse resolution of the model, except close to the Ebro delta area), others not. As illustrated in Figure 4, there is a strong variability in the model outputs in the 5km radius, which makes not fully convincing the conclusion of a model providing satisfactory prediction compared to the tide gauge measurements. I would suggest at least to add the model outputs of the nearest point to the tide gauge (simulation #1 and #2). In theory (if the grid resolution is high enough to capture the wave setup), the tide gauge measurements should be comprised more or less between the results of simulation #1 and #2, for the nearest point. If there are discrepancies, the authors could discuss the location and resolution of the model close to the tide-gauge (with maps) and also discuss the local knowledge of wave setup contribution to the tide gauge measurements. To contribute to provide a clearer validation and keep the 5km radius, another idea could be to plot all the model outputs for simulations #1 (first) but with a colorscale (on the time series of model outputs) indicating the distance of the model outputs to the tide gauge, and put in thick line the closest point (together with the tide gauge observation of course). The same figure could be done with the simulations #2 (together with the tide gauge observation of course). Of course, the authors are free to follow other ideas, as long as it makes the validation clearer by at least showing results on the closest point. I think this an important issue. Refining the validation could also help identifying to which extend the seasonal water level fluctuations induced by 3D circulations are negligible or not during the Gloria storm.

Author's response: We have explored different options to meet the reviewer requirements and we decided that the best one is to represent the time series of the modelled points within a radius of 2.5 km to the tide gauge location and indicating the closest grid point with a thicker line (see the new Figure 4).

We also produced alternative figures following reviewer's recommendations, including a different color lines depending of the distance for grid point (see the figure below). This format is, in our opinion, less clear and hinders its interpretation. In addition, we also produced a figure merging the results of simulations #1 and #2 (not shown here) but again it looked too messy. We hope that the reviewer's concern about the ability of the model in resolving the wave setup was satisfied with the answer to the question #2. The results showed essentially the same conclusions as in our example for Gandia tide gauge discussed above.

We hope that the new Figure 4 is more satisfactory for the reviewer.



"On-line" Remarks:

- Title: for me, the main focus of the paper is not on providing information on coastal impacts, but more on investigating the relative forcing contributions. I would suggest to modify the title to better illustrate the paper content.

Author's response: We have carefully considered reviewer's criticism regarding the title of the manuscript. We understand the reluctance to focus on the impacts, since we interpret that the reviewer associates the term "impacts" to only our two case studies. However, to our view, coastal impacts refer to the effects that the storm had on the physical mechanisms acting along the coast and that included the storm surges and waves. In this sense, and this was our initial purpose, we want to highlight the marine impacts along the coasts of the Western Mediterranean of Storm Gloria. We have been trying to figure out a not too long title that accounts for regional as well as local effects, but without success (our best approach is the first sentence of the abstract). Among all the alternatives, our preferred is the current title and we would like to keep it as it is.

- Abstract: The abstract could be a bit more informative regarding the key results.

Author's response: We are limited here by the maximum allowed length of the abstract, between 100 and 200 words. We are currently using 209 words which makes it impossible to extend without removing some of the major results that are highlighted.

- Line 38: please provide the geographical coordinates of the Mahon buoy.

Author's response: The coordinates have been introduced in the text.

- Line 72: Figure 4 is called before Figure 3 $->$ reorder the figures?

Author's response: Thanks for spotting this error. We have decided to switch the order of the text instead of the figures (change in 2nd and 3rd paragraph in section 2.3)

- Line 85: "contains" $->$ "contain"

Author's response: The whole sentence is: *This small region covering the Delta and its surroundings contains around 75% of the grid nodes.*; as the subject is "This small region", the verb should be contains.

- Line 104-107: Test 3 & 4 are done with the 2DH hydrodynamic model or with the coupled model? If the first case, the authors should make it more explicit, and then in Lines 107-108 stress that these tests 3 and 4 are used to estimate the contribution of Patm and wind on the atmospheric storm surge.

Author's response: The simulations #3 and #4 are done with the 2DH hydrodynamic model (i.e. uncoupled). It is written in lines 112-113 that the simulation #3 is "a hydrodynamic model run forced only by atmospheric pressure" and that the simulation #4 is " a hydrodynamic model run forced only by wind". Moreover, in lines 115-116 it is indicated that "the contribution of the atmospheric pressure (wind) was determined with the run #3 (#4)".

- Line 110-112: not clear if the 0% and 3% come from theoretical analysis or from the modeling results. Please clarify.

Author's response: This values come from the modelling results. We have modified the text in line 119 to clarify this issue.

- Line 121-132: it seems that steady forcing conditions (for SWASH) are used in terms of wave spectrum and still water level. More justification/explanation of this choice and its implication would be welcome.

Author's response: We have used the steady conditions because we aim at determining the minimum significant wave height needed to have overtopping on the cliffs. So we have used a range of values of H_s. This is now explained in the manuscript (last paragraph, section 2.2).

- Line 129: “an initial integration time of 0.05 s” – > “an initial computation time step of 0.05 s”.

Author’s response: This change has been introduced.

- Line 131: “0,5 m” – > “0.5 m”

Author’s response: This change has been introduced.

- Line 149: explain/justify why the tide gauge data have been low-pass filtered using a Butterworth filter with a cutoff period of 30 minutes. I guess this is due to some local physical reasons, but some justification would be welcome.

Author’s response: The reviewer is right. We low-pass filtered the time series of the tide gauges to remove the signal of the resonant modes of the harbours which are usually less than 30 minutes. We have included a sentence clarifying the reason of this filtering (last paragraph, section 2.3).

- Line 161: add a subsection title?

Author’s response: We did not add a subsection on purpose. We first describe the regional results of the model runs and then use subsections only for the two case studies.

- Line 164: not sure the authors can use “ocean” for the Mediterranean Sea – > reformulate?

Author’s response: In this case we use ocean as a synonym of sea, since it is used very closed to the word sea: ”...together with the ocean responses in sea surface elevation”.

- Line 174-175 / “This pattern is caused by the winds blowing towards the mainland”: I do not fully agree. Indeed, for me, the results are also strongly influenced by the bathymetry. I remind that the analysis of the 2DH shallow water equations show that wind-induced storm surges increase with decreasing water depth (see e.g. Flather [2001]). I think the authors could easily check it using their simulation results (by having a look on 2D spatial maps of simulation #4). This remark leads also to the suggestion to add a bathymetric map in the paper. This will support the analysis of the forcing contributions.

Author’s response: We agree with the reviewer. The shallow waters along the coasts of the mainland play a role in the magnitude of the storm surges. We have added a line in this respect to clarify the sentence (2nd paragraph, section 3). We have also followed reviewer’s recommendation and we have modified Figure 1 to include bathymetric lines that will facilitate the interpretation of the new sentence.

- Line 207-210: these sentences are not clear to me. Please clarify.

Author's response: We have rewritten the sentence, that now reads:"The satellite image indicates that the extension of the flooding caused by the storm was larger than that obtained in our simulation. We explain this apparent discrepancy by the fact that we do not account for the flooding caused by the heavy rains that were reported in the area; instead, our results identify the extent of the flooding caused solely by the marine hazards."

- Line 204-214: the comments on the validation/comparison of the model results in terms of flood are not really clear to me. Indeed, when I compare the Copernicus map and the model results, the model seems to provide a larger flooded surface, but predict no flood in one of the N-E area, while there was flood. This this is not clear to me why the authors seem to think that the model underestimates the flood. The manuscript would probably benefit from quantitatively comparing the Copernicus map and the model results, for instance with a map showing the following classes: Copernicus and model predict no flood; Copernicus and model predict flood; Copernicus indicates flood, but the model predicts no flood; Copernicus indicates no flood, but the model predict flood ; Copernicus and the model predict no flood. If not accessible, the Copernicus map could be digitized. In addition, at the Ebro scale, this could be interesting and relevant to investigate the spatial variations relative contribution of wave set-up, pressure induced and wind induced storm surges (more in details that in figure 6).

Author's response: We would like to remark that, according to the reports, part of the flooding in the Ebro Delta during Storm Gloria was caused by heavy rains. These are not included in our simulation and therefore a direct quantitative comparison would not make sense. Our purpose here was to estimate as accurately as possible the marine-induced flooding. We added the comparison to the satellite image to argue that the extension of the modelled flooding was realistic. In this respect, we feel that we have achieved our goal with the map we have represented in Figure 7 that shows the areas that, for sure, were flooded by salty water.

- Legend of Figure 2: "c and c" should be "a and c"?

Author's response: This change has been introduced.

References

Bouffard, J., and A. Pascual (), A review of altimetry Applications over European Coasts (invited talk), *Second Coastal Altimetry Workshop, Pisa, Italy.*

Flather, R. A. (2001), Storm surges, *Encyclopedia of Ocean Sciences, edited by: Steele, J. H., Thorpe, S. A., and Turekian, K. K.*, p. 2882–2892.

Larnicol, G., P.-Y. Le Traon, N. Ayoub, and P. De Mey (1995), Mean sea level and surface circulation variability of the Mediterranean Sea from 2 years of TOPEX/POSEIDON altimetry, *Journal of Geophysical Research: Oceans*, *100*(C12), 25,163–25,177, doi:10.1029/95JC01961.

Marcos, M., and M. N. Tsimplis (2007), Variations of the seasonal sea level cycle in southern Europe, *Journal of Geophysical Research: Oceans*, *112*(C12), doi:10.1029/2006JC004049.