Hydrodynamic modelling for simulating nearshore waves and sea levels: classification of extreme events from the English Channel to the Normandy coasts

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ORIGINAL PAPER

Hydrodynamic modelling for simulating nearshore waves and sea levels: classification of extreme events from the English Channel to the Normandy coasts

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Abstract
Assessing the vulnerability of coastal systems to storms often rely on an accurate modelling of extreme events and the identification of their impacts that depend on their physical characteristics. This requires the development of an exhaustive numerical downscaling of extreme hydrodynamics from deep to shallow areas to enhance our ability to predict the risks induced by these events, which is of fundamental importance for coastal managers. This work aims at investigating the nearshore dynamics of extreme events and their evolution from the shelf seas of the English Channel to the Normandy Coasts by developing a new numerical field of wave and sea level simulations during a period of 40 years. This dataset has been explored for the classification of extreme events considering their severity, direction, and duration. The overall results highlighted that more than 90% of the storms are coming from the Atlantic Ocean with a substantial change in their amplitude and their duration along the Channel: storms with Northern component are more severe while those coming from the South last longer with higher energy. A detailed monitoring of three different storm events exhibited that their impact depends on their travelling direction, being more significant for hydrodynamic events propagating following the orientation of the Channel, of about 70 degrees to the North, with lower diffraction. Extreme events coming from South Atlantic experience a stronger wave modulation when they arrive nearshore.

Keywords Extreme events · Numerical simulation · Coastal storm classification · Wave modulation · English Channel

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1 Introduction

Storms are one of the most powerful natural phenomena on Earth. They are controlled by strong meteorological and physical drivers induced by a violent atmospheric disturbance, with low barometric pressure, severe winds, and precipitation (Wallace and Hobbs 2006). From an ocean perspective they are described by high waves (Corbella and Stretch 2013) and when they have impact on the coasts they are known as coastal storms (Harley 2017). However, the definition of a storm has proven complicated given the dynamic and complex nature of oceanic systems. The intensity and duration of these phenomena can vary widely, making it difficult to establish clear criteria for what constitutes a storm (Harley 2017). Additionally, the specific conditions that give rise to storms are influenced by a range of factors, including atmospheric pressure, sea surface temperature, and ocean currents, all of which can be highly variable across different regions and time scales. Moreover, storms can occur in various forms, such as tropical storms, extra-tropical storms, and hurricanes, each with their own distinct characteristics that vary at different spatial and temporal scales over which they take place.

Nonetheless, coastal storms can have significant effects on coastal environments, including erosion of beaches (Jiménez et al. 2012; Mendoza and Jiménez 2006), coastal infrastructure damage (Bacopoulos and Clark 2021; Jiménez et al. 2011), flooding (Rouhaud and Vanderlinden 2022) among other impacts. These impacts will likely increase with climate change (IPCC, 2022; Switzer et al. 2015) and the increasing human pressure due to the overexpansion of urbanization and infrastructure that takes place in these areas.

Accurate wave data is crucial for the design of coastal structure development and the planning and management of coastal areas. This includes protecting vulnerable ecosystems and assessing coastal hazards to make well-informed decisions regarding coastal management and engineering design. Wave databases play a vital role in this process, as they provide various information, including the identification of storms and storm trends, and also serve as an essential element in validating numerical models. However, there are situations where in situ wave data is unavailable. In this situation, numerical models have proven to be a valuable tool for obtaining wave data (Appendini et al. 2014; Dee et al. 2011; Hersbach et al. 2020).

In the context of the English Channel, previous works have been focused on the dynamics of some energetic storms and their effects close to coastal zones, including marine submersion and coastal erosion. Wells et al. (2001) examined the extreme storm surges, produced during the events of 14–18 December 1989 within the English Channel, by the use of a shallow water hydrodynamic model to calculate the surge-tide interaction which reduces the peak heights of surges; their accurate estimation requires an adequate use of the wind stress parameter that improves the sea level modeling. The seiche oscillations induced by storms and their effects on the sea level changes have been investigated by Wells et al. (2005), they have shown the variation of such oscillations from their minimum in the central Channel and to their maximum in the Baie de Seine and the Golfe de St Malo.

Ozsoy et al. (2016) studied the high-frequency sea level variations and their coastal impacts during the extreme events of 28th October 2013 in the Solent, UK, a mesotidal estuarine strait located in the central English Channel. Recently, Bennis et al. (2022) used a 3D model to demonstrate that the flooding effects produced by storm Eleanor,in early Janu-

ary 2018 are strongly related to the angle between the wave-current direction leading to an acceleration or a reduction of the velocity.

The morphodynamic effects of storms on shoreline changes in the northern coast of France have been extensively studied in previous works by Anthony (2013) and Soloy et al. (2020, 2021; and 2022). Anthony (2013) investigated the impacts of storms on coastal dune morphodynamics and erosion in the southern North Sea. His study demonstrated that changes in the shoreline are influenced by various storm characteristics, such as wind speed, angle of incidence relative to the shore, and direct human intervention through beach management. In their recent works, Soloy et al. (2022) analyzed the temporal clustering of storms Ciara (December 1, 2019 - April 1, 2020) and Gareth (February 24 - April 1, 2019) along the Normandy coasts. Their research involved a combination of numerical models and remote sensing measurements to provide a comprehensive understanding of these storm events.

The non-stationary behavior and dynamics of historical storms in the South English Channel have been extensively studied over the past four decades by Turki et al. (2019, 2020a, b) using tide-gauge measurements. In their research, they employed stochastic approaches to develop novel probabilistic models that rely on global climate oscillations. These models were specifically designed to estimate extreme values and determine their corresponding return periods.

The aforementioned works have examined the behavior of individual storms and their impacts on coastal zones. The multi-timescale variation of storms and their evolution in the global context of climate change is still an issue under debate and is partly addressed in this research.

This research was carried out in the framework of the Surface Water and Ocean Topography (SWOT) program of the French National Centre of Space Studies (CNES) and focuses on gaining insight into the dynamics of storms and their hydrodynamic impacts on Normandy coasts under the time-varying climate and hydrometeorological drivers.

In this study, we examine the hydrodynamics of individual extreme events and analyze the temporal clustering of storms over a 40-year period in the English Channel and the Normandy Coasts. Here, we use a numerical approach to achieve the following objectives: (i) generating a comprehensive hindcast dataset of nearshore wave behavior in response to storms by integrating both temporal and spatial scales, (ii) classifying and identifying storm characteristics that have a significant impact on coastal zones, thereby identifying the most hazardous hydrodynamic scenarios, and (iii) assessing the effects of storms on flooding along the Normandy coasts, thus highlighting their impact on coastal areas.

2 The English Channel and the Normandy coasts

The English Channel is a sea basin located in Northwest Europe between the coasts of France and England. The Channel is one of the most impacted marine areas by human activities worldwide (Halpen et al., 2008). On the Eastern boundary, it is connected to the North Sea through the Strait of Dover, and in the Western limit, it is open to the Atlantic Ocean. The Channel lies far from the continental slope, considered as a shallow area with a decreasing depth from around 100 m on the West side to less than 30 m on the East.

The Channel, stretching approximately 560 km in length, boasts a varying width that gives rise to captivating hydrodynamic phenomena unique to this region. In the Strait of Dover, the French and English coasts stand a mere 20 km apart, gradually parting ways until reaching a separation of around 240 km near the Atlantic Ocean.

The shallowness of the English Channel along with the narrowing of the two sides eastwards and the intricate coastal morphology, defined by a complex system of capes and bays, generate the intense hydrodynamics of the basin. In the same way, the surrounding areas aggravate the situation due to the long fetches presented on the North Sea and, especially, on the Atlantic Ocean, with high exposure to storms and extreme events.

The Normandy coastal areas are very dynamic environments offering different services including wildlife habitat, erosion and flooding protection, tourism, economic and recreational activities. In the last decade, these areas have received additional interest for their high vulnerability to extreme climate drivers and anthropogenic activities inducing risks of flooding and erosion.

The study sites chosen for this research are situated North of the Seine estuary, in a region characterized by their pebble and gravel beaches, generated by the impact of the sea on the chalk cliffs that get eroded and produce this configuration on the coast. The selected sites were considered as the one of the most hazardous regions, historically exposed to marine submersion (Turki et al. 2020a, b; Soloy et al. 2021). Additionally, this area is strongly influenced by tides, which are semidiurnal and macro to mega tidal ranges, with up to 10 m at spring tides.

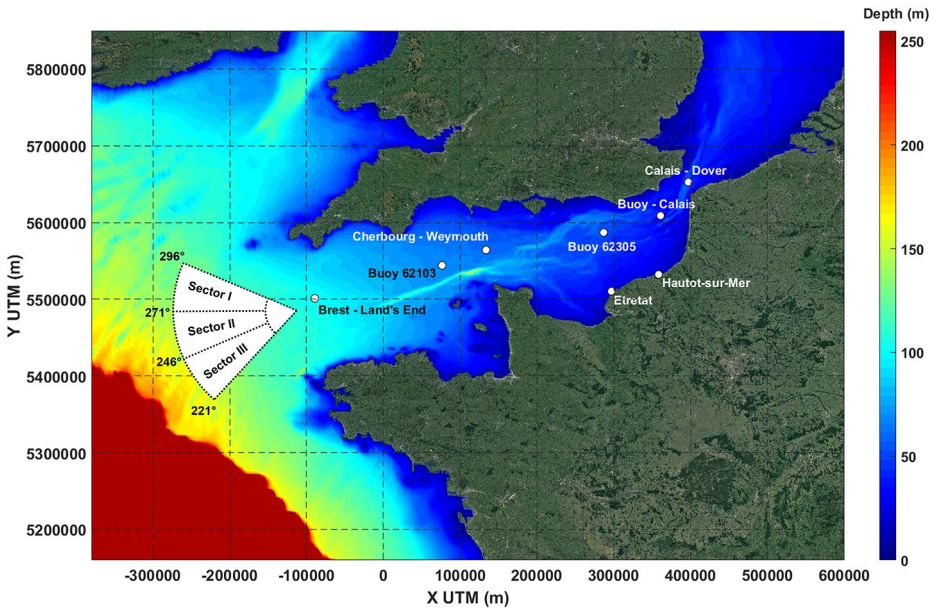

Fig. 1 Bathymetry map of the English Channel with the observation points used in the study, five in deep waters, located along the basin (Brest - Land's End, Cherbourg - Weymouth, Buoy 62,305, Buoy - Calais and Calais - Dover), and two nearshore in two representative sites on the Normandy coasts (Etretat and Hautot-sur-Mer). Buoy 62103 was used for validation and the three sectors considered for the study

3 Data and methods

3.1 Description of the databases: in-situ measurements and model forcings

Different databases have been used in this study with two central objectives: the main purpose has been the forcing of the numerical model, and the following point has been the validation of the results obtained after the simulations. The forcings used in the set-up include the wave parameters and the harmonic components of the astronomical tide defined on the open boundaries of the computational grid employed for the numerical simulations, and the wind and air pressure variables uniformly distributed over a grid defined in geographical coordinates. The bathymetry and topography information have been also specified for all the nodes on the computational grid.

Wave variables have been obtained from a particular database of the Copernicus Marine Service, the Atlantic-European North-West Shelf – Wave Physics Reanalysis. This product provides 3-hourly hindcast outputs from a wave model for the North-West European Shelf, with a temporal extent since January 1980. The wave model used for the simulations is WAVEWATCH III and the North-West Shelf configuration is based on a spherical cell grid mesh with a spatial extent from 46°N to 62.75°N of latitude and from 16°W to 13°E of longitude. The model is forced by lateral boundary conditions from a Met Office Global wave hindcast, and the atmospheric forcing is given by the ECMWF ERA-5 Numerical Weather Prediction reanalysis (O'Dea et al. 2012, 2017; King et al. 2018). The product is updated biannually providing a six-month extension of the time series. The variables selected for the simulations from this database include the spectral significant wave height, wave period at spectral peak, and mean wave direction.

The astronomical tide, used for the model set-up, has been generated from the simulation of the harmonic components, provided by FES2014 database. This model has been developed, implemented, and validated by the LEGOS, NOVELTIS and CLS, within a CNES funded project. The tide elevations, the tide currents and the tide loading grids were available for 34 tidal constituents distributed on 1/16° grids – amplitude and phase – for each tidal product (Carrere et al. 2016).

Wind and air pressure data has been extracted from the ERA5 on single levels database. ERA5 is the fifth generation ECMWF reanalysis for the global climate and weather. This product provides hourly estimates for a large number of atmospheric, ocean-wave, and land-surface variables, available from 1959 onwards. Data is presented in a regular spherical grid of 0.25 degrees for the atmospheric reanalysis (Hersbach et al. 2020). The atmospheric variables used in this study have been the 10 m u- and v-components of wind and the surface pressure, which correspond to the eastward and northward components of the speed of air at a height of ten meters above the surface, and the force per unit area of the atmosphere at the surface of the planet, respectively.

With the aim of defining the digital elevation model (DEM) in the computational grid of the numerical model, the bathymetry information has been obtained from the European Marine Observation and Data Network (EMODnet) Bathymetry Portal (EMODnet Bathymetry Portal, 2023). A detailed description of the EMODnet project, the digital terrain model (DTM), and the latest release can be found on the website.

In order to validate the accuracy of the water level predictions, sea level measurements from various tide gauges positioned along the coastlines of England and France were

compared to the model's outputs in corresponding locations. The tide gauge records from Weymouth, Newhaven, Dover, Calais, Dieppe, Le Havre, and Cherbourg were utilized for the validation process. The model performance is evaluated by calculating the Root Mean Square Error (RMSE, Eq. 1) and the Pearson's correlation coefficient (R, Eq. 2) with the observed and the predicted values of water level. The RMSE is useful to obtain an evaluation of the average distance between the observed data and the data obtained from the simulations.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{1}$$

Where n is the total number of coincident data and x_i and y_i represent the two sets of measured data and model estimation.

The Pearson's correlation coefficient can be used as an indicator of the trends of the measured and the modeled datasets. If the datasets analyzed tend to increase or decrease together is closer to 1, and if they disagree in their trends is closer to 0.

$$\mathrm{R} = \frac{\sum_{\mathrm{i}=1}^{\mathrm{n}}\left[\left(\mathrm{x_i} - \bar{\mathrm{x}}\right)\left(\mathrm{y_i} - \bar{\mathrm{y}}\right)\right]}{\left[\sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\mathrm{x_i} - \bar{\mathrm{x}}\right)^2}\sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left(\mathrm{y_i} - \bar{\mathrm{y}}\right)^2}\right]} \tag{2}$$

Where $\bar{\mathrm{x}}$ and $\bar{\mathrm{y}}$ are the mean values of coincident observed and simulated data, respectively.

The wave measurements employed in the validation of the wave outputs of the simulations have been obtained from stations 62103 – Channel Lightship and 62305 – Greenwich Lightship, in central locations on the English Channel (49° 54.00' N – 2° 54.00' W and 50° 24.00' N – 0° 0.00' E, respectively), owned and maintained by the UK MetOffice from June 1989 and June 1998. The data provided by the buoy is updated every 60 min, supplying wave height and wave period.

The performance of the model is evaluated by calculating the correlation coefficient, alongside the Scatter Index (SI, Eq. 3) and the normalized bias (NBIAS, Eq. 4). The scatter index (SI) is a normalized RMSE, and it provides information on the precision of the results of simulations with respect to the observations in percentage.

$$\mathrm{SI} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left[\left(y_i - \bar{y}\right) - \left(x_i - \bar{x}\right)\right]^2} \,/\, \bar{x} \tag{3}$$

The normalized bias (NBIAS) contributes to the validation giving information on the bias of the simulated data in relation to the measured data.

$$\mathrm{NBIAS} = \left(\bar{y} - \bar{x}\right)\sqrt{\frac{1}{n}\sum_{i=1}^{n}{x_i}^2} \tag{4}$$

3.2 Numerical approach

Simulations of waves and sea level have been made using the computer software suite Delft3D developed by Deltares, with the modules Delft3D-WAVE and Delft3D-FLOW, respectively. Delft3D is an integrated modelling suite, which simulates two-dimensional (in either the horizontal or a vertical plane) and three-dimensional flow, sediment transport and morphology, waves, water quality, and ecology and is capable of handling the interactions between these processes (Deltares 2020). In the current study, a two-dimensional hydrodynamics model on a Cartesian curvilinear grid has been used.

The computational mesh employed for simulating the propagation of waves and water levels from the Atlantic Ocean and the North Sea into the English Channel was constructed with spatial resolution that varies across the region. In deep waters along the western boundary, the resolution was set at approximately 4 km, gradually increasing to 1200 m near the Normandy coast. The mesh was comprised of quadrangles, forming a curvilinear grid consisting of 194 cells in one direction and 441 cells in the other, resulting in a total of 85,554 elements. The spatial reference utilized was the EPSG:32,631 WGS84/UTM zone 31 N projection system.

With respect to the forcings, 63 nodes for the astronomical tide generated by harmonic components and 76 nodes for the wave variables, distributed along the open boundaries on the North Sea, the Irish Sea, and the West and South limits of the grid on the Atlantic Ocean have been defined. For the atmospheric forcings, a rectangle covering the computational area has been extracted from the regular spherical grid, maintaining the spatial distribution of the ERA5 dataset. This spherical grid was converted into a curvilinear grid once the geographical coordinates were transformed into UTM coordinates.

By including the atmospheric forcing, the model is able to generate the storm surge if the extension of the computational grid is wide enough, which was considered when the grid was delimited. Likewise, the model is also able to include the interaction between the astronomical tide and the storm surge. The generation of a wave database in the central part of the English Channel and nearshore on the Normandy coasts is presumably necessary due to the lack of precision on this area of the currently available datasets, either for the bulk and the extreme conditions. In Fig. 2 the QQplots of significant wave height comparing the results obtained from a node of the reanalysis databases of ERA5 and NWSHELF in comparison to the measurements of the Buoy 62305, placed on the Greenwich meridian, are shown. As it can be appreciated, the bulk conditions of both datasets overestimate the real records of the buoy, and they slightly approach to the real values when taking higher values, finishing in a small underestimation of the extreme values. When the database obtained from the numerical model of the current study was originally generated, the same problem was found. Carrying and exhaustive analysis about the origin of this problem, the cause was found in the atmospheric conditions, more specifically, on the wind speed with which the model is forced, obtained from ERA5. Potisomporn et al. (2023) analyzed the wind speed of ERA5 onshore and offshore the UK, comparing the database with measurements. They determined that, generally, the wind data is accurate enough, but with the main discrepancies originate from short-term low speed episodes. However, they argue that ERA5 underestimates these events compared to the measurements, contrary to what seems to happen in this study. Thus, the problem is not on the wind data, but in an excessive transmission of the wind energy to

the waves inside the model. This issue becomes more important when the waves are lower and with less impact on the higher waves as these propagate through the English Channel.

To avoid overestimation in bulk wave height conditions, a calibration is performed based on the wind speed taking as a reference the measurements of wind intensity of the same buoy 62305. By considering the relationship between wave height and wind speed, it has been observed that the model can more accurately reproduce extreme wave events, typically produced by wind speeds exceeding 20 m/s. However, with intensities lower than that value, the model exhibits this excessive energy transmission. Therefore, it has been found that the most suitable way to calibrated the simulations is by decreasing the wind speed forcing in the model using a reduction factor proportional to the value measured by the buoy. This calibration method has not been previously documented in the literature; however, its effectiveness becomes clear when considering the relationship between wind speed and wave height. In Fig. 2 the QQplots of the results of wave height of the simulations of the model before and after calibration are presented in comparison to the measurements of the buoy. A constant overestimation, especially for the mean conditions, can be observed in the comparison of the outputs of the model and the measurements when the calibration is not applied. After the calibration, this situation is generally fixed except for the lowest values, which are not relevant for this study. When it comes to the extreme values, the underestimation of ~1 m shown before the calibration is reduced to less than 0.5 m after the calibration, coherent with the results obtained from the ERA5 and NWSHELF databases for this location. Therefore, the bulk conditions are ameliorated in comparison to the available datasets in a central part of the English Channel, with a similar or lesser error for the lowest and the most extreme values. The best performance among the four datasets illustrated in Fig. 2 is the QQplot of the calibrated results of the numerical model of the present study.

Once the grid and the forcings were defined, 40 years of data were simulated, from January 1983 to December 2022, with a time step of 10 min in terms of water level propagation, 20 min for the outputs of the model, and 3 hours in terms of waves for the propagation and the outputs.

The location of buoy 62,305 has been used as a control point for this study. The validation of waves has been assessed on this spot in the same way as a comparison to the outputs obtained in four more points equally distributed along the Channel (Fig. 1). One point has been designated between Calais, on the French coast, and Dover on the English coast for evaluating the influence of the storms coming from the North Sea, designated as "Calais – Dover" point. With the aim of estimating the evolution from the North Sea to the location of the buoy, a third point situated between the buoy itself and the second chosen point has been placed in a middle distance from these two other points, named as "Buoy – Calais" observation point. On the Atlantic Ocean, and due to the expectancy of a soft modification between the outer part of the Western English Channel and the central part, where the buoy is located, two additional control points were considered as enough, and have been defined. One of them on the most external part of the Channel, between Cornwall in England and Finistère in France, named as "Brest – Land's End" point, and an additional one on the North of the Cotentin Peninsula, between the cities of Weymouth and Cherbourg, situated on United Kingdom and France's shores respectively, designated as "Cherbourg – Weymouth" point.

Finally, and with the aim of defining the transformation of the extreme events when they approach the High Normandy coasts, two locations considered as representative of the

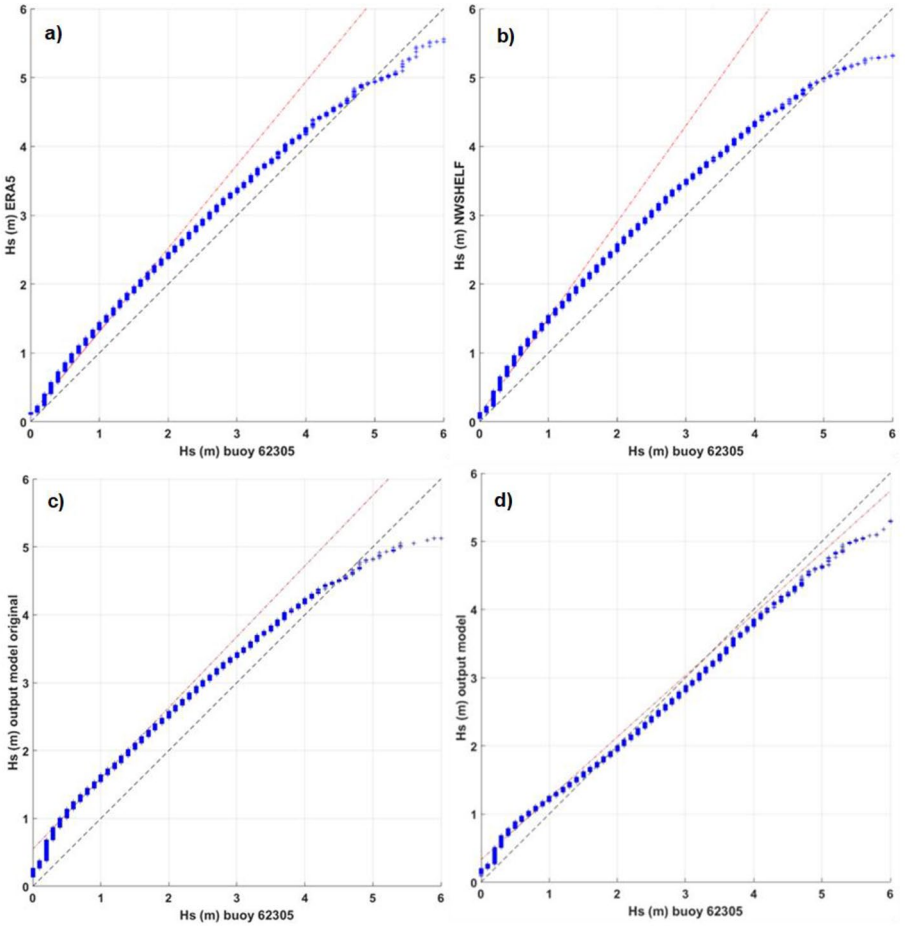

Fig. 2 QQplots of significant wave height (*Hs*) comparison of reanalysis or results of modelling versus obsrvations measured by buoy 62305: **a** reanalysis of ERA5, **b** reanalysis of NWSHELF, **c** results of the simulations from the Delft3D model forced with the original values of wind, and **d** results with the calibrated values of wind speed

morphology and composition of pebble beaches in this area have been studied too: Etretat and Hautot-sur-Mer.

3.3 Storm characterization

Coastal storms have been characterized following the methodology proposed by Mendoza et al. (2011) using the 40-year hourly wave height time-series mentioned above, considering three main variables: a wave height threshold, a duration threshold, and an independence criterion. The wave height threshold was obtained using the 95th percentile of the significant wave height datasets (Walker and Basco 2011; Castelle et al. 2015; Masselink et al. 2014).

From west to east, various wave height thresholds were established for specific coastal locations. The Brest – Land's End node had a threshold of 5.13 meters, while the Cher-

bourg – Weymouth point had a threshold of 3.60 meters. At the location of the buoy, the threshold was set at 2.54 meters, while for Buoy – Calais, it stood at 2.25 meters, and for Calais – Dover, it was 1.93 meters. Moving closer to the shore, the thresholds at the Etretat and Hautot-sur-Mer nodes were 1.70 meters and 1.15 meters, respectively. To determine the storm's duration threshold, factors such as local flooding, erosion processes, and tidal patterns in the area were considered. This involved analyzing a time-series of wave heights, with the storm duration defined as lasting at least 24 hours where the values remained above the designated threshold for each specific point.

For each observation point, considering the different thresholds associated to each one of them, a variable number of stormy events can be identified on their timeseries. For the Brest – Land's End point, 262 extreme events are determined, for Cherbourg – Weymouth, 254 storms, for the location of the buoy, 231 events, for Buoy – Calais, 236 and for Calais – Dover, 252. Nearshore, 252 and 258 storms have been identified in Etretat and Hautot-sur-Mer. As an example, the time-series of wave height alongside the threshold and the 160 storms identified for the Brest – Land's End point is shown in Fig. 3. Each storm is characterized by the significant wave height and the mean direction at the instant of the peak of the storm, the duration of the whole event and the random wave energy density since the objective of this study is also to focus on the impacts of the events on the coast. The wave energy is defined for the storm energy as the integral in time when the significant wave height surpasses a specified storm threshold for a minimum duration, i.e., the area limited by the line of the time-series of wave height and by the threshold throughout the duration of the storm, multiplied by the sea water density and the gravitational acceleration.

Following these characteristics, a storm classification has been carried out based on the offshore direction in the open sea, mainly focusing on the Atlantic Ocean, and the energy density of the extreme events on this point. This classification is explained alongside the evolution of the storms as they propagate through the English Channel and when they approach the Normandy coasts.

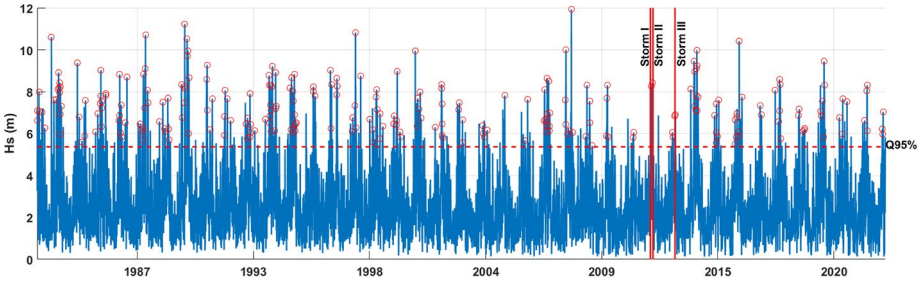

Fig. 3 Time-series of wave height in the Brest – Land's End observation point during the 40 years analyzed with the 262 storms identified over the threshold equivalent to the quantile 95. Storms selected as example are indicated: Storm Sector I (Joachim), storm Sector II (Andrea) and storm Sector III (designated as Storm 19)

4 Results

The dynamics of nearshore waves have been calculated during a period of 40 years, between 1983 and 2022. Results are presented in four parts: (1) the numerical simulations of waves by Delft3D and their validation by in-situ measurements; (2) the classification of the 262 stormy events and their physical evolution from regional to local scales; (3) the impacts of high energetic storms close to Normandy coasts; and (4) implications for coastal flooding.

4.1 Validation of results: sea level and waves

The results of sea level obtained from the simulations during the 40 years have been validated with in-situ measurements provided by different tide gauges, located along the coasts of England and France. A special focus has been given to the coasts of Normandy using tide gauges of Le Havre, Dieppe, and Cherbourg.

The comparison between the three tide gauges with the numerical simulations in the coincident period gave, as a result, a RMSE of ∼34 cm in Cherbourg, considering that there is a tidal range of around 7 m, an error of ∼50 cm in Dieppe with a tidal range of more than 10 m and a RMSE of ∼32 cm in Le Havre over a tidal range of slightly less than 9 m. Regarding the correlation coefficient, for Cherbourg a value of 0.9809 was obtained, for Dieppe it was 0.9803, and for Le Havre, 0.9901. These errors of some centimeters were mainly explained by the location of the observation points taken as close as possible to the coast in the computational grid, but still not in the exact same location as they are located in reality due to the limited spatial resolution of the model.

In Fig. 4 the time-series of the three tide gauges along with the output of the model in the closest location to each of them are shown in different short periods taken from the 40 years as an example.

Regarding waves, the simulated wave height has been compared to in-situ measurements, provided by buoy 62,103 and buoy 62,305, within the English Channel. The comparison between datasets highlighted that the correlation coefficient is 0.869 and 0.845 for the coincident years of buoy 62,103 and buoy 62,305, respectively, showing a good agreement in the results, having also a high precision proved by a scatter index of 36% and 45.2% and a normalized bias of 20.6% and 17.4%.

In Fig. 5 the scatter plot of significant wave height (Hs) for both the measurements of the buoys 62,130 and 62,305, and the results obtained from the simulations with Delft3D in the same output location are shown for the 40 years.

4.2 Classification and evolution of storms

The methodology for identifying and characterizing storms has been applied to all 7 observation points: Brest – Land's End, Cherbourg – Weymouth, the location of the buoy, Buoy – Calais, Calais – Dover, Etretat, and Hautot-sur-Mer. The different characteristics of storms selected and tracked down throughout the English Channel have conformed to a database that allows one to follow the evolution conditioned by the location of each node in the basin.

Looking at the main characteristics of the storms at first glance, two origins were highlighted: extreme events formed in the North Sea entering to the English Channel through

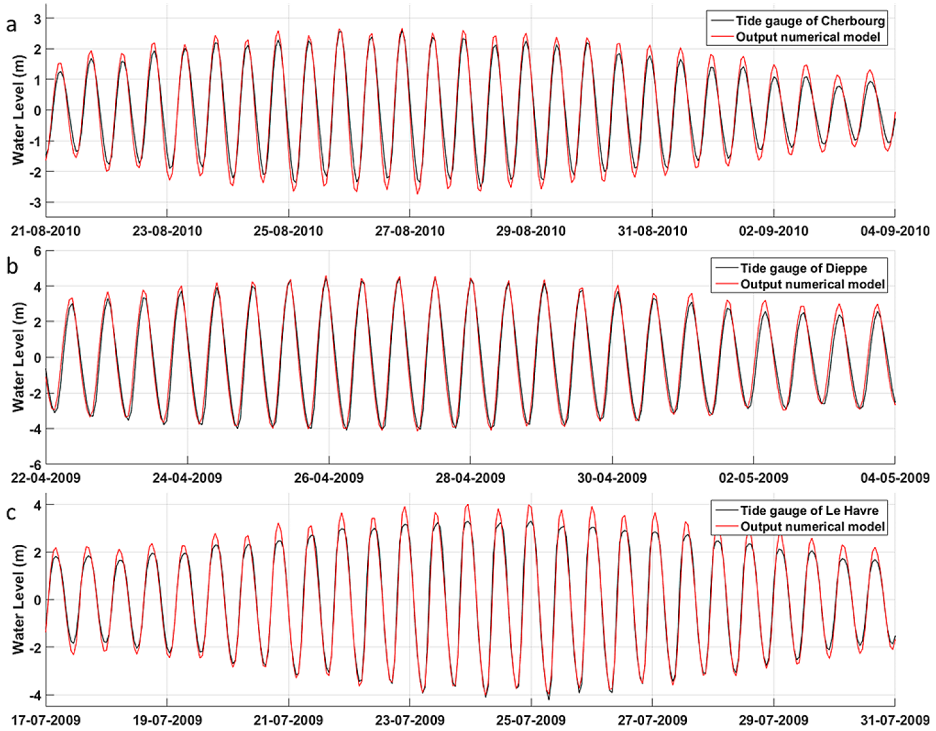

Fig. 4 (**a**) Water level measured by the tide gauge of Cherbourg in black and the output of the numerical simulations in the closest location in red for the period 21-08-2010 to 04-09-2010; (**b**) water level measured by the tide gauge of Dieppe in black and the output of the numerical simulations in the closest location in red for the period 22-04-2009 to 04-05-2009; and (**c**) water level measured by the tide gauge of Le Havre in black and the output of the numerical simulations in the closest location in red for the period 17-07-2009 to 31-07-2009

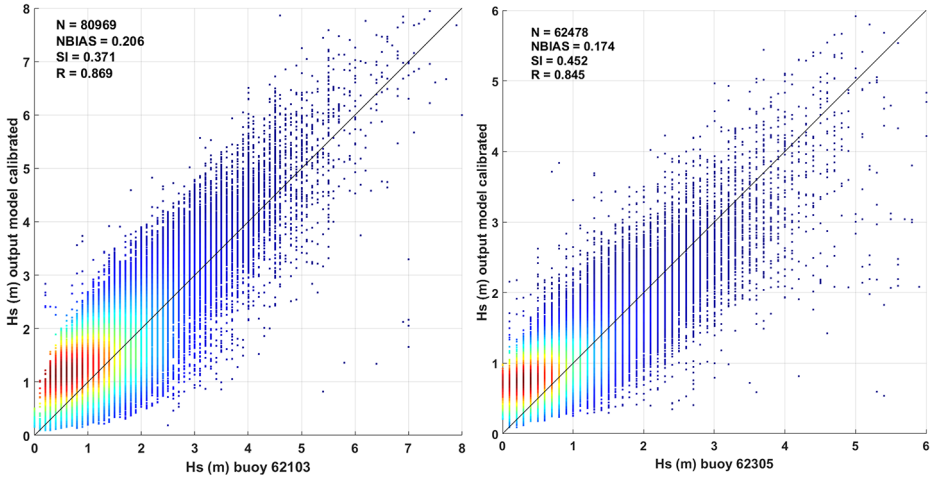

Fig. 5 Significant wave height (*Hs*) comparison of results of simulations from the Delft3D model versus observations measured by buoy 62,103 and buoy 62,305

the Strait of Dover in the Northeast, and storms produced in the Atlantic Ocean entering through the West.

Considering the North Sea as a node of origin of storms, only a few events were identified in comparison to the extreme events coming from the Atlantic Ocean. Moreover, these storms can only be found in the Calais – Dover observation point. By looking at the second point starting from the West, the Buoy - Calais node, these storms were not distinguished anymore.

Out of the 252 extreme events cataloged in the Strait of Dover, merely 18 had their origins in the North Sea, characterized by wave heights hovering around ∼2.5 meters and a duration spanning 26 to 37 hours. In contrast, the 262 storms that emanated from the Atlantic Ocean, impacting the Brest – Land's End node, exhibited varying characteristics in terms of wave height and duration. These storms, with directions ranging from 221° to 296°, were divided into three distinct sectors, each spanning 25°: the Sector I, spanning from 221° to 246°; the Sector II, encompassing the range of 246° to 271°; and the Southwest sector, extending from 271° to 296°. This division facilitated a comprehensive study of the storms' behavior within the region. The characteristics of these three sectors are shown in Table 1.

Out of the 262 storms analyzed, which exhibited an average directional bearing of 258 degrees, nearly half originated from the central sector. Approximately 17% of these storms were closely confined within the range of 258 degrees plus or minus 3 degrees, while 50% fell within the broader span of 258 degrees plus or minus 10 degrees. The storms that emanated from the central sector displayed the longest duration as an average, around 63 hours, but Sector II boasted the highest energy density, surpassing 4,700,000 J/m². Conversely, the most substantial wave heights, exceeding 11 meters, were observed in storms approaching from Sector I.

The relationships between energy density and wave height and duration are shown Fig. 6. It can be observed that the energy content is more sensitive to the duration of the storms, presenting an almost linear evolution between the two variables. The correlation with the wave height is apparently much more scattered.

One can observe a significant correlation between higher energy content and longer storm durations. This connection remarks the fact that storms, regardless of their wave height, can exhibit a substantial energy content, which is not solely contingent on the specific wave height value.

By adding the same analysis in the subsequent points along the English Channel, more specifically, the Cherbourg – Weymouth point, the location of buoy 62,305, and the two points studied nearshore, Etretat and Hautot-sur-Mer, it is possible to study how these 138 storms evolve when they propagate through the basin, getting diffracted, reflected, or dissipated.

Table 1 Main characteristics in terms of wave height at the peak of the storms (Hs), direction at the peak, duration of the storms and random wave energy density of the storms identified divided in the three sectors used in the study: I (271° to 296°), II (246° to 271°) and III (221° to 246°)

Brest – Land's End	Hs (m)		Dir (°)		Duration (hours)		Energy density (J/m^2)	
	Min	Max	Min	Max	Min	Max	Min	Max
I	5.415	11.927	271.078	296.07	24	168	448,590	2,902,879
II	5.506	10.811	246.052	270.576	24	212	408,664	4,752,552
III	5.595	11.232	221.932	245.977	24	250	604,156	4,224,517

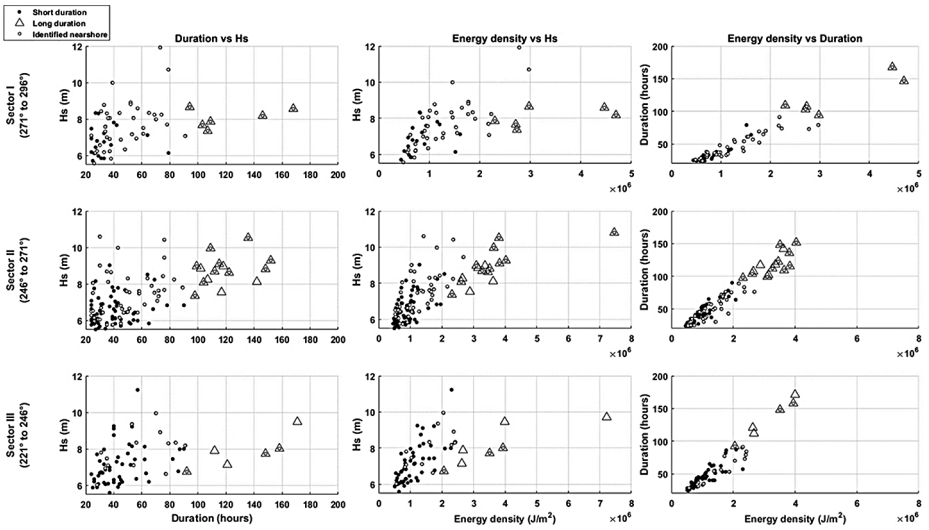

Fig. 6 Energy content versus wave height at the peak of the storms and every content versus duration of the storms for the three sectors used in the study: I, II and III

In terms of wave height and duration, 88% of the storms identified nearshore are contained in the range of 25–105 hours of duration and 6–9 meters of Hs. But this distribution is different for each sector: 64% of the storms coming from the Sector I arrive on the Normandy coasts, with 39% of the ones from the Sector II, and only 7% of the storms from the III. For the Sectors II and III, storms with longer durations, over 120 hours, are dissipated when they approach the coast.

Analyzing the decrease in the wave height through the different points along the English Channel, in the Cherbourg - Weymouth node there is a 30% decrease with respect to the first point, the same as in the third point in comparison to the second one. Once they have arrived at the location of the buoy, the decrease is reduced to less than 15% in the fourth with respect to the buoy and in the Strait of Dover in comparison to the previous. The distribution among the three sectors is equivalent throughout the points, except for the Calais - Dover node, where the Sector I suffers from a decrease in Hs of 30%, while the Sector II stays in the average of 13% and the storms coming from the III only a 5%.

The modification of the storms coming from the Sector III is the lowest among all the directions, between 1° and 3° from point to point. In the Sector II, on average, it is higher, from 1° to 10° and up to 16° in the point of Calais. For the Sector I, the diffraction ranges from 1° to 20°, notably higher, especially in the second and the last points.

In terms of modifications of the duration of the events, storms with lower wave energy density, independently of the sector, suffer from lower variation in their duration, from 30 to 60% lower than the storms with a higher wave energy density by comparing the storms with higher and lower energy of each sector.

4.3 Storms tracked throughout the English Channel

For each one of the three sectors corresponding to the Atlantic Ocean origin, a representative storm was chosen in order to track them along the English Channel and when they approach to the shore in the two main locations studied (Etretat and Hautot-sur-Mer):

- For Sector I, with a range of directions from 271° to 296°, the storm Joachim was chosen because it had the highest energy density in the most recent years. The date of the peak passing by the location of the Brest – Land's End point occurred on 15 December 2011 at 6 h.
- For Sector II, from 246° to 271°, the storm Andrea was chosen because it had the highest wave height nearshore in the most recent years. The date of the peak at Brest – Land's End was registered 3 January 2012 at 9 h.
- ForSector III, from 221° to 246°, a storm not identified by a name, simply called "Storm 19", chosen because it was the only storm from the SW that can be identified nearshore after 2008. The date of the peak at Brest – Land's End occurred on 29 January 2013 at 15 h.

Table 2 presents a summary of the characteristics on the point near the Atlantic Ocean and the two points nearshore.

As mentioned before, the highest energy density in the storm Joachim is explained by the duration of the extreme event, with a total time of 115 hours over the threshold defined in the point of Brest – Land's End. This duration evolves and it is kept throughout the English Channel until it reached the nearshore, where the storm lasts for 89 and 82 hours in Etretat and in Hautot-sur-Mer.

The time-series of wave height of these three storms in this point alongside the second and third nodes, and the two points nearshore can be seen in Fig. 7.

It can be noticed how the storms are modulated when they propagate through the English Channel. As an example, storm Andrea presented a conspicuous peak, especially when the storm is passing by the location of the buoy. Nevertheless, when the three storms arrive to

Table 2 Wave height at the peak (Hs), direction at the peak, duration and random wave energy density of the storms selected as example for the three sectors used in the study: Joachim for the I, Andrea for the II and the storm 19, identified from the III, in the Brest - Land's End observation point, and the two points nearshore, Etretat and Hautot-sur-Mer

Storm Joachim	Hs (m)	Dir (°)	Duration (hours)	Energy density (J/m^2)
Brest–Land's End	8.26	271.4	115	2,785,795
Etretat	2.51	271.3	74	167,315
Hautot-sur-Mer	1.54	298.6	100	89,274
Storm Andrea	Hs (m)	Dir (°)	Duration (hours)	Energy density (J/m^2)
Brest–Land's End	8.42	246.7	89	2,148,186
Etretat	3.82	288.6	74	293,313
Hautot-sur-Mer	2.78	305.0	78	149,317
Storm 19	Hs (m)	Dir (°)	Duration (hours)	Energy density (J/m^2)
Brest–Land's End	6.83	239.4	82	1,898,785
Etretat	1.61	268.2	73	110,678
Hautot-sur-Mer	1.08	294.4	73	51,902

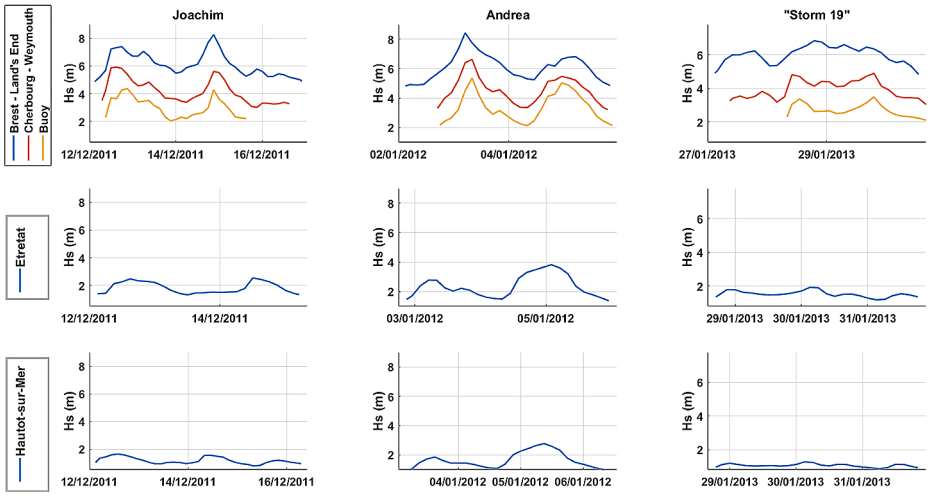

Fig. 7 Time-series of wave height for the three storms selected as example (Joachim, Andrea and Storm 19) in the Brest - Land's End, Cherbourg - Weymouth and Buoy observation points, and in the two nodes located nearshore

the coast they are completely modified, being more extended in time and with a less noticeable peak.

To track the storms through the English Channel, the contour maps of significant wave height (Hs) of 3 and 6 meters associated to these three storms are shown in Fig. 8.

Storm Joachim approached from the Sector I with a peak wave direction of 271°. A diffraction around a node defined by Land's End in the western limit of England can be appreciated in the 6 meters (Hs) contour line, where the storm is entering the Channel approximately with this direction of 270° and arriving to the central part of the basin with a direction of ~250°. It is also remarkable that the wave height remains lower in the shoreline of England in the central part of the English Channel due to the direction in origin of the storm and the resulting diffraction. When the storm approaches the coasts of Normandy, it takes a direction of 270° and 300° in Etretat and Hautot-sur-Mer, respectively. It arrives with a high energy to the initial control point, but its energy is quickly dissipated in less than 9 hours.

Since the English Channel basin is oriented at an angle of about 70 degrees to the North, the direction of storm Andrea closely aligned with the basin's orientation, resulting in minimal wave diffraction. Consequently, wave height experiences only subtle alterations. In the central regions of the Channel, where observation points are situated, Storm Andrea emerges as one of the strongest storms, although its strength may not rank as high when it initially enters the basin. This storm's arrival can be better understood by examining the contour lines of 3 meters of significant wave height (Hs), which extend even into the North Sea. The storm originates in a direction that causes it to diffract only after passing by the Cotentin Peninsula, resulting in a direction of approximately 290° at Etretat and 300° at Hautot-sur-Mer. This orientation is nearly perpendicular to the shoreline at both locations, and it elucidates the significant wave height's substantial impact on the coast. Storm 19 enters into the English Channel with a direction of 239°at the peak of the storm, a notably distinction as this extreme event impacts straight into the British shoreline. Unlike

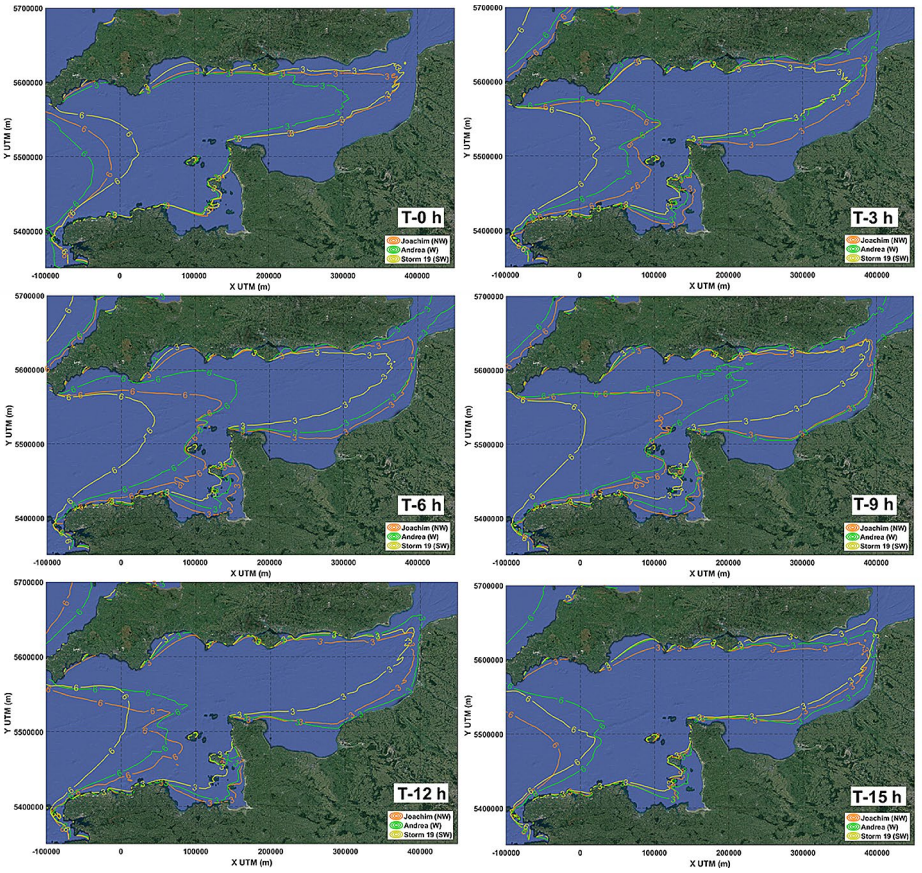

Fig. 8 Significant wave height contour map of Hs = 3 m and Hs = 6 m of three storms in consecutive instants propagating in the English Channel. The three storms (Joachim, Andrea and "Storm 19") correspond to each one of the three sectors in which the coming waves have been classified according to the direction of origin

the previous storms, it does not extend as far due to the diffraction in the western edge of France in Brittany. Consequently, it largely dissipates, resulting in lower wave heights at the subsequent observation points. Originating from the Sector III, the storm has suffered from a strong diffraction already when approaching to the Normandy coasts, causing it to arrive with a direction of 290° in Hautot-sur-Mer and just 260° in Etretat, impacting these locations more longitudinally than the previous storms analyzed. This difference is evident on the maps, with wave heights measuring below 3 meters upon arrival.

Furthermore, the maximum significant wave height has been tracked down throughout the channel in Fig. 9 to precisely trace the path of the three selected storms. At each time point, the maximum value of wave height has been identified within the limits of the English Channel following the x-coordinate. The figure clearly illustrates the diffraction of the three storms: storm Joachim and Andrea proceed from Sectors I and II and impact on the Southern side of the basin and, in a parallel way, Storm 19 proceeds from the Sector III and impacts on the Northern side of the channel.

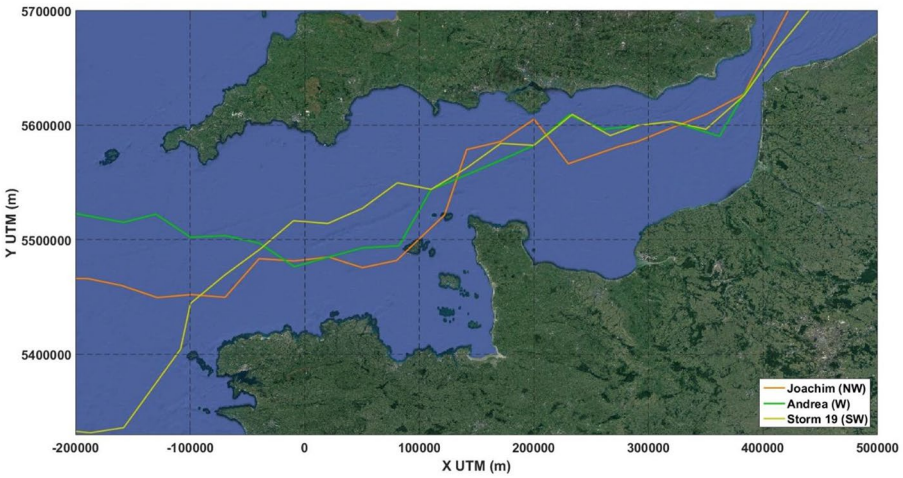

Fig. 9 Maximum significant wave height of the three selected storms, Joachim, Andrea and "Storm 19", tracked throughout the English Channel

5 Discussion

The validation of the numerical set-up carried out highlights a RMSE for the three tide gauges between ~32 cm and ~50 cm in tidal ranges between 7 m and 10 m, with correlation coefficients of 0.98 and 0.99. In terms of wave height, for the higher values measured by the buoy, over 4 m, there is an underestimation of ~20 cm, but with a SI of 18.5% and a correlation coefficient of 0.96. for similar configurations, the same statistical parameters for measuring the error are usually calculated in literature. For example, Ardhuin et al. (2012) obtained a SI for the wave height of 13.1% with a correlation coefficient of 0.96 using a model set up with no tides and a SI of 9.5% and a $r=0.98$ with tides. Boudière et al. (2013) generated a database and compared the outputs of their numerical modelling to numerous buoys along the coast, achieving an error ranging in the SI from 0.17 m to 0.37 m, not normalized in their study, and a correlation coefficient ranging from 0.89 to 0.97.

Such comparison confirms that the set-up of the numerical model considering the different maritime and atmospheric forcings is accurate enough to obtain reliable results and being able to use the outputs for this analysis and future studies.

For this study, storms have been defined in terms of wave height, duration and energy content, considering a threshold in wave height time-series fixed on the percentile 95%, a minimum time of exceedance of this threshold of 24 hours, and allowing the wave height to drop below this limit no more than 12 hours in order to quantify the independency of the extreme events. Although it is possible to identify storms in terms of other variables, such as the Beaufort scale (WMO, 2018), However, focusing on coastal areas, this study is interested in the potential impacts of storms. Therefore, we have used the two main statistical approaches to identify storms which are wave height and water level analysis as described in Harley (2017), in function of the local conditions. If they are wave-dominated coastlines, then it is appropriate to identify the storms in terms of wave height. If the presence of meteorologically driven increases in the water level beyond the usual tidal range has a

bigger impact, then an analysis of sea level measurements is required. This latter approach also implies the consideration of to which variable a threshold should be defined, since areas where the main objective is establishing a limit on the total sea level beyond which an inundation can be expected, it is indeed the total sea level the variable that should be used, as in Massalin et al. (2007). Instead, if the main interest is the meteorological effects of the increase of the sea level alongside the variability of storms over time, the non-tidal residual is the variable analyzed, eliminating the tidal signal from the measured total sea level. Studying this variable is analogous to examining wave height. In the work of Bromirski and Flick (2008), they established a threshold based on the 98th percentile with a minimum duration of 6 hours. However, in the context of the English Channel, the major impacts primarily stem from wave height rather than occasional sea level increases. This reinforces the rationale behind defining storms as peaks in the wave height time-series that surpass a specific threshold, along with a minimum duration above the threshold and a maximum allowable time below it, before considering it as a distinct storm event.

Storm characteristics are site dependent, therefore other studies have applied a similar description but taking different values instead. Shand et al. (2011) considered a threshold of either 5% of exceedance wave height or 10% exceedance wave height with minimum exceedance duration of three days, also including a minimum interval between storms of one day and applying it to different measurements of buoys on the Australian coast. This led to identify a range of between 12 and 27 storms per year, in contrast to the 6 storms identified as an average in the nodes of this study on the English Channel. In terms of thresholds, they take values between 2.43 and 4.56 m for the 10% exceedance and between 2.85 and 5.22 m for the 5% exceedance, similar values to the present analysis, with thresholds ranging from 2.03 to 5.37 m in deep waters. In a similar way, the average duration of storms defined in the Australian coast has been ∼46 hours, close to the mean of ∼50 hours in the English Channel. Biausque and Senechal (2019) also considered the percentile 95% for the definition of storms in SW of France, but, instead, they limited the duration to exceed just one tidal cycle, meaning 12 hours. However, for their study they have also contemplated the succession of storms, considering different storms as part of the same cluster when the period of 'calm' between events has been below 5 days. This is justified because they focused on the morphological response of a beach, while in this study, the main goal has been the characterization and the classification of storms in deep waters. In Jenkins et al. (2022), they considered the 99th percentile as the threshold and studied the succession of events over different points of the British coast, including the English Channel. They found several exceedances over that threshold that happened within 1 or 2 days, meaning that a duration of a storm of minimum 24 hours is necessary for identifying extreme events in this area.

As mentioned earlier, two origins can be identified in terms of classification of storms, the Atlantic Ocean, and the North Sea. Anthony (2013) analyzed the morphodynamics of the shoreface in response to storms in the southern North Sea. He described winds and waves in this region, also taking Calais as one of the study sites. Coinciding with the results obtained in the present study, he described dominant waves in that area as the ones originating from the English Channel, followed by waves generated in the North Sea.

In this work, the three storms mentioned above have been selected as examples, but other studies, have tracked down different storms throughout the Channel. Dhoop and Thompson (2021) have followed two exceptional swell events that took place between 30 January

and 1 February 2021 along the southern British coast by analyzing the wave and sea level records of tide gauges and buoys located nearshore. They gave a special focus to wave height and peak period, calculating the return periods associated to these events on the coastal locations, in contrast with the focus on direction and energy content used in the present study, due to the interest of their study on the footprint of the swell events rather than the modification when the extreme events enter into the English Channel. Muller et al. (2014) followed different storm surge events on the Western and Northern coasts of France, validating the numerical set-up with the measurements of the tide gauges of La Rochelle, Le Coquet, Saint-Malo, and Dunkirk. Within the different storms tracked down in this work, two were precisely Joachim and Andrea in the present work. Agreeing with the characteristics detailed in this section, in their study they described how Joachim presents a strong behavior in terms of surge when propagating from the Atlantic Ocean and when entering the English Channel but being almost negligible in the tide gauge of Dunkirk. Instead, they described how Andrea is barely recognizable in the time-series of the tide gauges of Le Coquet and Saint-Malo but grows in intensity when propagating within the English Channel, reaching almost 2 m of storm surge in the tide gauge of Dunkirk. These behaviors of the two storms are coincident in terms of wave height, as shown in Fig. 8, in the current study, arriving at an equivalent characterization of the extreme events.

6 Conclusions

This work provides a handful approach for the identification and characterization of the different storm events from the English Channel to the Normandy coasts. A 40-year wave database (from January 1983 to December 2022) has been simulated by the use of a numerical model, increasing the resolution of available reanalysis datasets, to be able to follow the behavior of storms from the regional scale of the basin to the local scale of the Normandy coasts. The characterization of the storms in 5 different observation points along the English Channel brings to light two origins of storms: the North Sea and, especially, the Atlantic Ocean. The direction of origin conditions the behavior of the storms when they propagate inside the Channel more than any other variable. Duration and wave height were used to obtain theenergy content. These three variables were examined and tracked along the English Channel, revealing modulation when they approached the Normandy coasts. This modulation was especially pronounced when the storms originated from either the Southern or Northern directions in the Atlantic Ocean.

The modeled nearshore wave and sea level data with the English Channel basin provide a relevant monitoring of hydrodynamics in response to various scenarios of extreme events driven by Atlantic and North Sea energetic conditions.

These findings present a handful of an integrative work highly useful as a the most relevant approach forward for understanding the dynamics of storms with a regional scale, case of the English Channel, and their physical mechanisms in nearshore areas.

Monitoring storms and understanding their behavior is relevant to investigate coastal flood risks that should be shaped by a series of adaptation strategies with the aim to reduce the coastal exposure and vulnerability at some cost.

A comprehensive analysis of extreme dynamics and their effects close to coastal areas is required, including additional works at local scales. Further investigations will explore this

work of long-term hydrodynamic dataset to examine the multi-time variability to coastal storms in relation with global climate oscillations and their impacts close to Normandy beaches.

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Declarations

Competing interests The authors have no relevant financial or non-financial interests to disclose.

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