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Impact of an extreme storm event on a multiple intertidal barred coastal system

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Abstract

In December 2021, the British Isles experienced Storm Barra, an exceptionally intense storm event, categorised as the second most energetic event on the east coast of Northern Ireland in the past 25 years. Dundrum Bay (Co. Down) on the Irish Sea coast features a Multiple Intertidal Bar (MITB) system, with an additional subtidal sandbar. Here, we examine the direct coastal impact of this event on the MITB system, focusing on (1) the morphological response of beaches, and (2) the role of the multiple sandbars in dissipating wave energy at different tidal stages. Topographic profiles showed high variability in morphological response. Distinct erosional, accretional and transitional zones were evident that reflect complex interactions between the local geology, pre-storm profile shape and the impact of previous events. Accretion occurred on profiles that were depleted by previous storms. Erosion was prevalent on profiles where the MITB features were poorly developed. Cross-shore sediment transport was dominant in the NE (Ballykinler), while sediment was transported alongshore in the SE sector (Newcastle to Murlough). Analyses of wave height and wave energy dissipation illustrate the key role of sandbars in dissipating extreme storm energy at different water levels. The storm peak occurred on a falling tide stage, and most of its energy was dissipated by the subtidal bar. Following the peak, at high tide and under moderate energy conditions, part of the wave energy bypassed the subtidal and seaward intertidal bars but was fully dissipated on the landward intertidal bars. Consequently, even though Storm Barra generated high-energy waves, the effectiveness of the sandbars in dissipating the wave energy at different tidal stages prevented severe impacts on the shoreline. This work demonstrates the important role of sedimentary bedforms in buffering storm energy before it reaches the shoreline. Additionally, the work shows the crucial role of coincidence or otherwise between storm peak and tidal stage on energy dissipation across the nearshore.

KEYWORDS
beach, extreme event, sandbars, sediment transport, SWAN, water level

1 | INTRODUCTION

Multiple Intertidal Bars (MITB) are complex morphological systems composed of a succession of sandbars parallel to the shore, confined within the intertidal area. Initially defined by King and Williams (1949), they are described as long-term stable morphological structures (e.g., Cooper & Navas, 2004; Miles et al., 2019). Even though their genesis is still poorly understood, multiple models and theories have been discussed in the literature (e.g., Biausque et al., 2020; King, 1972; King & Williams, 1949; Kroon & Masselink, 2002; Simmonds, O'Hare, & Huntley, 1997; Simmonds, Voulgaris, & Huntley, 1995). To date, the model combining the influence of both surf and swash processes, proposed by Carter (1988), prevails. These processes appear to be key forcing leading the formation, short-term evolution and long-term stability of MITB systems (Houwelingen, 2005; Kroon & Masselink, 2002; Masselink, 2004; Masselink & Anthony, 2001).

MITB features are broadly located in areas submitted to wind waves with limited fetch, meso- to macrotidal conditions (tidal range >3 m) and dissipative intertidal beach profiles (low-angle beach slope) (e.g., Houwelingen, Masselink, & Bullard, 2006; Kroon & Masselink, 2002; Scott, Masselink, & Russell, 2011). Ideal conditions for MITBs development and stabilisation are however a combination of three main factors defined by the following thresholds: a tidal range between 3 and 10 m, a wave peak periods between 3 and 8 s and a beach slope lower than 0.02 (Biausque et al., 2020).

Relatively stable under specific conditions of tidal range, wave peak period and beach slope (described above), MITB features are however the result of a 'dynamic equilibrium' driven by seasonal morphodynamics. Indeed, under energetic winter conditions, intertidal sandbars can display cross-shore migrations and morphological changes, such as modifications of bar crests' elevation, bar shape and width, distance between bars and runnels' depth (Biausque et al., 2021; King & Williams, 1949; Mulrennan, 1992; Ruiz de Alegria Arzaburu, Ilic, & Gunawardena, 2007; Wright, 1976). Moreover, MITB features are split by cross-shore drainage channels; during high-energy periods, drainage channels migrate alongshore driving longshore bar dynamics (Anthony et al., 2005; Biausque et al., 2023; Isla et al., 2024; Montreuil et al., 2022; Reichmüth and Anthony, 2008a & 2008b; Sedrati & Anthony, 2006 & 2007). Even though MITBs' morphological changes have been studied worldwide and can be attributed to seasonal hydrodynamic conditions and energetic periods (e.g., Masselink, 2004; Masselink & Anthony, 2001; Mulrennan, 1992), impacts of extreme events and the role of the different intertidal bars in dissipating the wave energy are still poorly understood. In a context of climate change, an increase of the severity of storms could be expected (Feser et al., 2015; Seneviratne et al., 2021). Therefore, a better understanding of interactions between extreme events and MITB features is needed for more sustainable coastal protection and management planning.

The overall aim of this paper is to investigate the morphological response of a MITB system located at Dundrum Bay, Co. Down (Northern Ireland), to an extreme event—storm Barra—including a detailed analysis of the role of multiple sandbars in dissipating extreme events' energy at different tidal moments. To this regard, DGPS surveys were conducted in December 2021, just before and after the storm, to investigate the morphological signature of Barra on two meso- to macrotidal adjacent mixed beaches. Additionally, SWAN simulations were run to better understand interactions between intertidal sandbars and nearshore hydrodynamics, including the role of storm surge and tidal cycles, before, during and after storm Barra.

2 | STUDY SITES, METHODS AND DATA

2.1 | Study sites

Dundrum Bay is located on the east coast of Northern Ireland, Co. Down. The Bay is confined between two headlands, isolating Murlough and Ballykinler sandy beaches, respectively, located on the western and eastern side of the bay and separated by a 4-m-deep inlet channel and an active ebb delta (Navas et al., 2001; Pye & Blott, 2017; Figure 1C). The system is backed by a wide Holocene sand dune system (Biausque et al., 2023; Grottoli et al., 2021; Orford, Murdy, & Wintle, 2003). Murlough (National Trust) and Ballykinler (Ministry of Defence) beaches are both classified as dissipative environments due to their low-angle intertidal beach slope and exhibit a succession of up to six intertidal sandbars, defining a MITB system (Biausque et al., 2021 & 2023; Navas et al., 2001), associated with a nearshore subtidal bar. The intertidal beach sediment is composed of medium to fine sand, with a sediment gradient decreasing towards the Irish Sea (Figure 1d2 and 3). In contrast, the upper beach is made of coarse sand to cobbles (Figure 1d1), occasionally covered by a finer sand layer, in which beach cusps are observed (Cooper & Navas, 2004; Navas et al., 2001).

Dundrum Bay opens into the Irish Sea and thus the restricted fetch (<200 km) induces low to moderate energy waves propagating into the bay. Typical mean wave height (Hs) is around 1 m for a wave period about 6 s (Cooper & Navas, 2004; Jackson et al., 2022; Navas et al., 2001; Orford, 1989). Occasionally, the bay can however get hit by energetic events and related oceanic swell (Pye & Blott, 2017). The tidal regime is semidiurnal (Jackson et al., 2022) and macrotidal, associated with a mean spring tidal range of about 3.9 m and a maximum astronomical tidal range up to 5.5 m (Navas et al., 2001; Pye & Blott, 2017). Murlough and Ballykinler beaches are therefore tide-dominated systems. Even though the wind direction may vary locally due to the beach/dune orientation and the presence of rocky headlands, low to moderate winds are generally southeast-oriented, while dominant high-energy winds come from south to south-west direction (Biausque et al., 2021).

In recent years, Murlough beach has experienced increased erosion and in response different management strategies have been deployed along the beach (Grottoli et al., 2023). For instance, old unmaintained groynes are still visible at the western end of the beach (Figure 1d3). Further east, wooden poles were installed to trap sediment and cobbles in the upper beach (Figure 1d1), and a sea wall has been built to protect the golf course located at the top of the dune (Figure 1d2 and 3). The eastern end of Murlough beach, the inlet and Ballykinler beach are, however, unmanaged areas and therefore governed by natural processes (Biausque et al., 2023).

2.2 | Geomorphological dataset

A total of 37 topographic surveys were recorded, in total, from April 2019 to March 2022. Surveys were conducted monthly at low spring tides, using quadbikes mounted with Trimble R10© RTK-GNSS

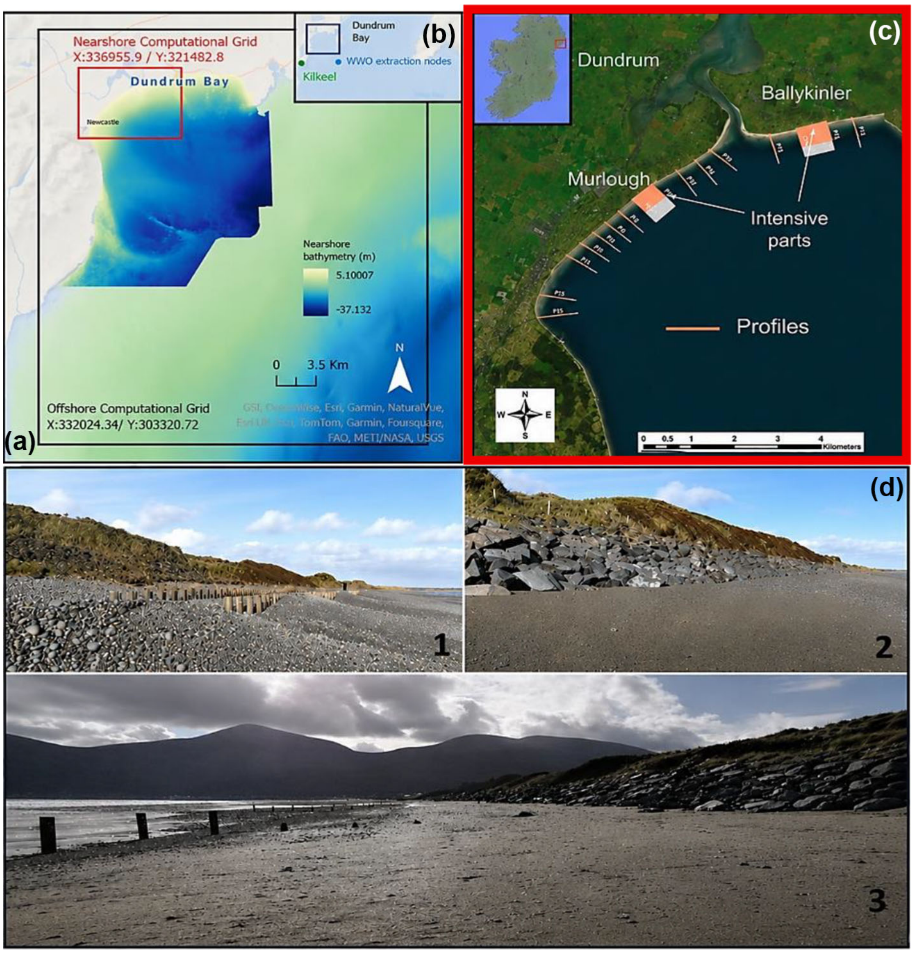


FIGURE 1 (a) SWAN computational grids: offshore grid (black) and nearshore grid (red); (b) location of WW3 extraction node; (c) location of Dundrum Bay, Co, Down, NI; location of Murlough and Ballykinler beaches with DGPS profiles measured during fieldwork and 'intensive' areas where profiles are closer;
(d) Murlough beach: gravel (upper beach, d1) and sand sections (intertidal beach, d3), and sea defences (sea wall (d2; d3) and wooden poles: old groynes (d1; d3)).

systems. Surveys consisted of 10 cross-shore profiles at Murlough beach and four profiles at Ballykinler beach. In addition, smaller areas at both beaches were intensively surveyed by 15-m spaced profiles covering respectively 600 and 700 m alongshore for Murlough and Ballykinler, respectively (referred to as intensive areas in the following text; Figure 1c). For further details about topographic surveys, please refer to Biausque et al. (2021).

The focus of this study is however the morphological impacts of storm Barra on Dundrum Bay. Therefore, to identify the signature of this specific event, pre- and post-storm Barra surveys were additionally conducted the 7th and 9th of December 2021, respectively. Both cross-shore profiles and interpolated 'intensive areas' were used to analyse morphological changes after the storm. Moreover, isolines representative of the different beach areas (dune foot, supra- and intertidal areas) were extracted to identify cross-shore sediment transport during the event. According to the methodology presented by Biausque et al. (2023), the lower limit of the supratidal beach is defined by the mean high-water level reached at spring tide (MHWS = 2.15 m), and the seaward boundary of the intertidal beach by the mean low-water level reached at neap tide (MLWN = −1.45 m). Additionally, surveys of November 2021 and January 2022 were here respectively considered to identify the pre-Barra beach profile and state and the post-storm recovery.

2.3 | Hydrodynamic dataset

Multiple hindcast datasets were used in this study for the SWAN model (Booij, Ris, & Holthuijsen, 1999) to simulate the nearshore hydrodynamic conditions and evolution of wave behaviour in the bay during storm Barra. Tides were extracted from the POLTIPS3 model (https://noc-innovations.com/services/tide-prediction-software/coastal-software/), developed by the National Oceanography Centre (NOC), in the United Kingdom, who also provided the surge and the total water level (TWL) datasets. Nearshore wave computations at Dundrum Bay (latitude: 54.2007, longitude: −5.5779) accounted for TWL; therefore, combining storm surge and tide levels.

Offshore waves were computed using the Wave Watch III model (WW3) and provided by Ifremer (https://marc.ifremer.fr/) every 3 h during the storm. WW3 data were extracted at a node located about 15 km offshore Dundrum Bay (54°N 5.5°W) and validated against waves measured by the M2 buoy. Offshore wave climate extracted from WW3, such as the significant wave height (Hs), peak period (Tp) and peak direction (Dp), are presented in the following section (Figure 3). Initial offshore boundary conditions simulated were for 7th December 00:00, Hs: 1.148 m, Tp: 5.15 s, Dp: 241, Tide: 2.53 m.

Nearshore wave conditions were modelled using the shallow water wave simulation model SWAN (Booij, Ris, & Holthuijsen, 1999) in a third-generation mode. SWAN is a third-generation spectral wave model widely applied and validated for simulating wave propagation and spatial patterns of wave energy under storm conditions (De Swart et al., 2020). These capabilities make SWAN particularly suitable for investigating the spatial variability of wave forcing and identifying potential areas of enhanced sediment mobilisation across the study site. Simulations were run using default parameters for linear wave growth and white capping dissipation, and the bottom friction dissipation model (JONSWAP) following Hasselmann et al. (1973). The wave frequency and directional space were discretized in 33 logarithmic

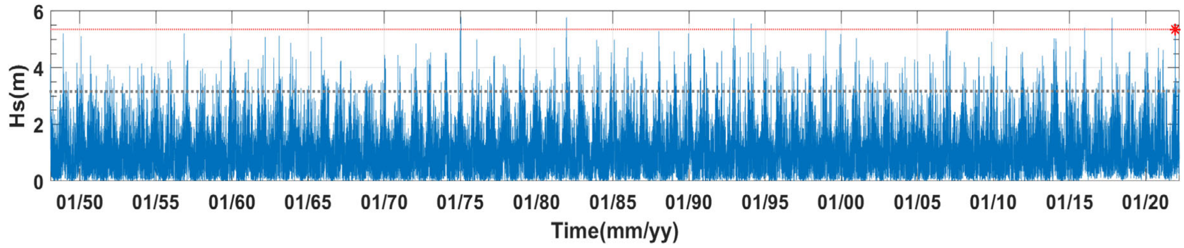


FIGURE 2 Time series of significant wave height (Hs) since 1950; the dashed red line represents the mean Hs calculated for the entire period; the red line represent the maximum Hs reached during storm Barra (red dot).

distributed bins from 0.03 to 1.00 Hz and 36 regular-distributed bins, respectively (Guisado-Pintado, 2020). A nested approach of simulations was implemented in which a first step involved offshore simulations over a 100-km bathymetric grid extracted from the General Bathymetric Chart of the Oceans (GEBCO) (Figure 1a, 'offshore grid').

Storm Barra was propagated using a nonstationary approach (i.e., the full development of the storm was modelled) in which wave conditions were run at 3-h interval using parametric data from the offshore WW3 node (i.e., Hs—significant wave height, Tm—mean wave period; Dir—mean wave direction) and Tides (TWL). Further, resulting wave spectra was applied uniformly to the offshore boundaries of the nested computational grid (Figure 1.A, 'nearshore grid'). For this propagation, a nearshore bathymetry (2-m resolution) from two combined datasets was used. The offshore part of the nearshore bathymetry is a multibeam data acquired in 2012 provided by the Agri-Food and Bioscience Institute (AFBI). The shallower part of the nearshore bathymetry is a bathymetric LiDAR acquired in summer 2021 provided by the Department of Agriculture, Environment and Rural Affairs (DAERA). As a result, nearshore simulations for the whole storm period were obtained from the 5th (06:00 AM) to the 12th of December 2021 (18:00 PM), and the following outputs extracted for each timestep (at 5-m resolution): significant wave height (Hs, m), wave energy dissipation (Dissip, W/m2), defined as wave energy dissipated due to white capping, depth-induced-wave breaking and bottom friction, and direction of wave energy transport (Dir, degrees).

3 | RESULTS

3.1 | Storm Barra characteristics

To place storm Barra into a global context, a hindcast long-term dataset (over 70 years) modelled by IHCantabria, Spain (https://ihdataprot-a.ihcantabria.com/wave-data/) in which time series of significant wave height are plotted (Figure 2) was analysed. Results showed that Storm Barra was the sixth most energetic event since 1949 to strike the east coast of Northern Ireland, and the second highest in the past 25 years (Figure 2). That exceptionally high-energy storm event crossed the United Kingdom on the 7 December 2021.

At the peak of Storm Barra, the significant wave height (H_s) reached 5.5 m, associated with a peak period (T_p) of 10 s (Figure 3). The peak wave direction was around 179°N with waves from the south-southeast for the entire duration of the storm. Offshore waves were therefore perfectly aligned to propagate inside Dundrum Bay and impact both Murlough (western) and Ballykinler (eastern) beaches.

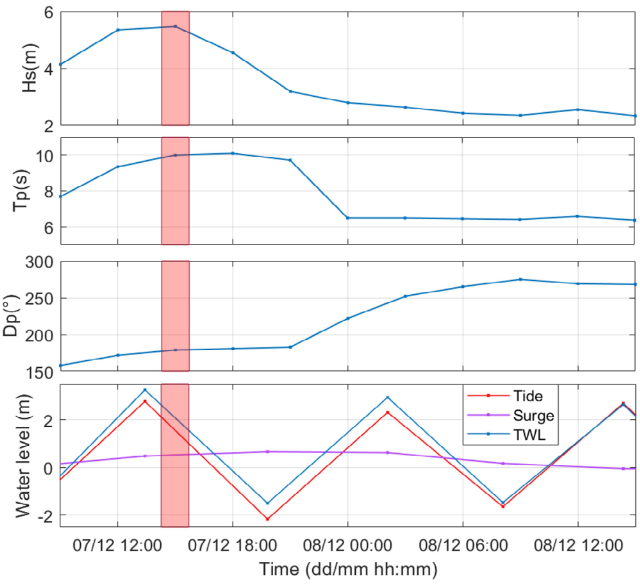


FIGURE 3 Time series of significant wave height (Hs), peak period (Tp), peak direction (Dp) and water levels (tide in red, surge in purple and Total water level [tide + surge] in blue) during Storm Barra. Red patches highlight the peak of the storm.

However, just after the storm (post-7th December 21:00), the wave period dropped from 9 to 6 s and the orientation of the waves suddenly shifted from south-southeast to west.

The TWL, that includes both the tide and the surge, reached its maximum few hours before the peak of the storm. Indeed, the peak of Barra corresponded to a falling tide period and therefore lower water levels. The maximum surge (0.7 m) occurred after the peak of the storm and coincided with low tide. After the storm, the amplitude of the TWL signal tends to progressively decrease following the reduction of the Hs and the associated storm surge.

3.2 | Nearshore hydrodynamics

Figure 4 presents a series of maps illustrating significant wave heights at Dundrum Bay during Storm Barra, at different tidal moments (every 6 h, starting at low tide) on December 7th and 8th. Results show that preceding the storm peak (7th December, 6:00 AM Figure 4a, low tide Figure 3), wave heights are moderate across most of the bay, with values around 1–2 m reflecting the buildup phase of the storm, where wave energy is progressively increasing but has not yet reached peak intensity. In this phase, the most significant waves height exceeding

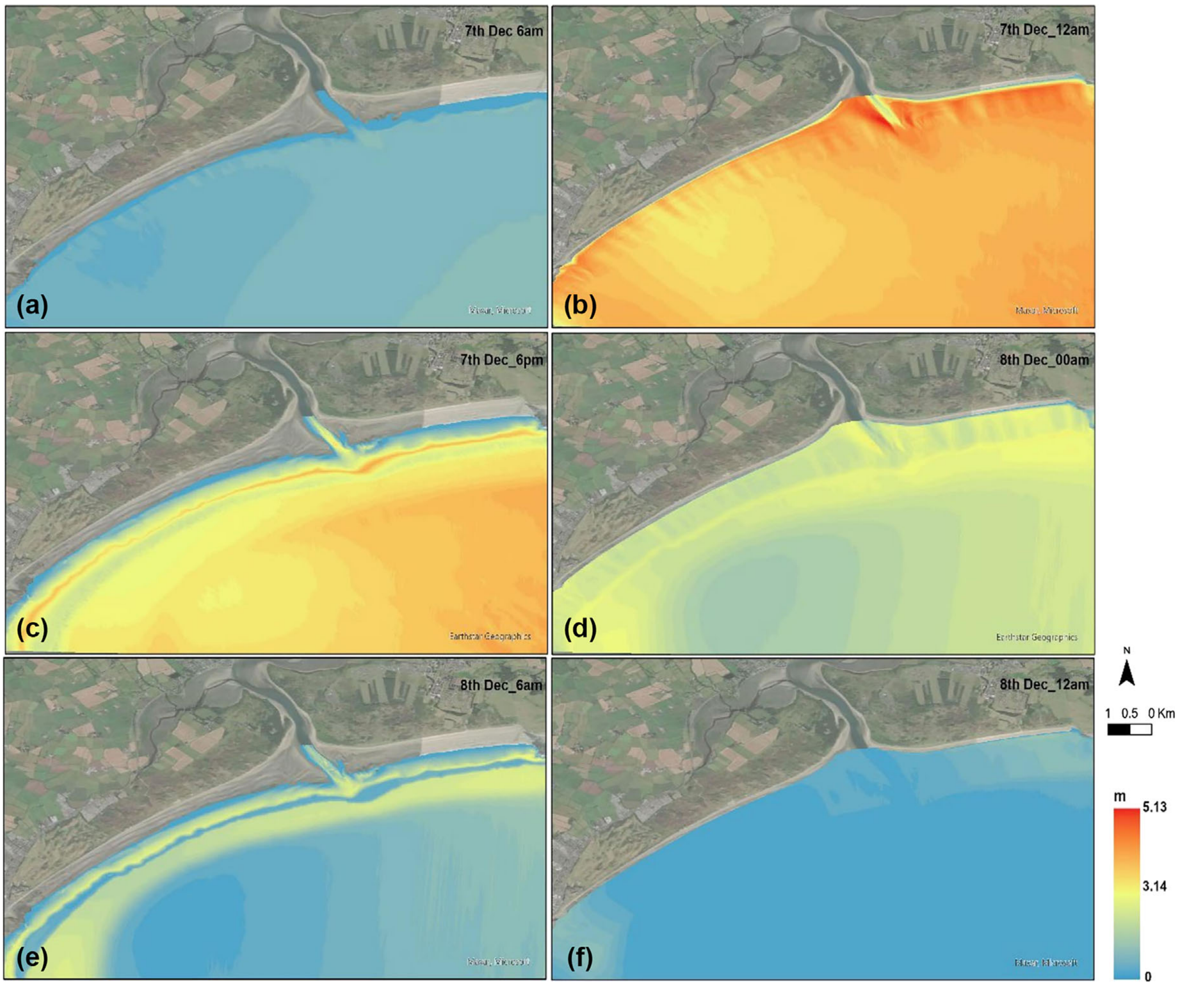


FIGURE 4 Significant wave height (Hs) during storm Barra simulated every 6 h (a to f) using SWAN.

1.5 m are observed in the offshore region, while waves of around 0.8 m occur in the nearshore areas of Ballykinler and Murlough. As the storm starts (7th December, 12:00 AM, Figure 4b), wave heights continuously increase until reaching a maximum H_s around 5 m driving maximum storm surge conditions. At this stage, deeper water over the nearshore bars (at high tide, Figure 3) allows large waves to propagate towards the bars, with maximum H_s located on each side of the inlet. At the following low tide and after the storm peak (7th December, 6:00 PM, Figure 4c), the maximum Hs, and associated wave energy, is concentrated at the limit of the intertidal area, in the shoaling zone. The energy driven by the incoming waves is therefore focused around the subtidal bar, outside of the MITB system and the DGPS profiles area. Finally, post-storm transition (8th December, 12:00 AM to 6:00 AM Figure 4d,e), wave heights continue to decrease as the storm subsides, dropping to 2–3 m by 12:00 AM and below 2 m by 6:00 AM. During this phase, the nearshore environment transitions back to normal conditions, with significant waves mainly located outside the bars and MITB system at low tide.

The figure also highlights the significant wave height variation during the storm, significant wave heights increase during high tide, coinciding with the starting of the storm's peak (12:00 AM, 7th December) reflecting the combined effect of increased storm energy and deeper water levels, which allow larger waves to form and propagate. As the tide falls (6:00 PM, 7th December) significant wave heights decrease as shallower water depths limit wave growth due to interaction with the seabed.

Figure 5 presents the wave energy dissipation during storm Barra, computed every 6 h to integrate the role of tidal cycles as well as storm surge. At low tide and for moderate waves (7th December at 6:00 AM, Figure 5a), the energy dissipation is localised offshore of the MITB system and values are lower than 0.1 W/m^2. At high tide and increasing wave energy, the dissipation of the wave primarily occurs on the upper beach of Ballykinler (7th December at 12:00 AM, Figure 5b). For high-energy waves and low tide, the wave energy dissipation reaches maximum value (up to 0.51 W/m^2) just offshore the intertidal area (e.g., limit of the DGPS profiles), on the offshore-most sandbar (subtidal bar). However, despite the dissipation mostly taking place over the bars (subtidal and seaward intertidal bars), some residual energy still seems to reach the shoreline (western part of the bay around profiles 3 to 6) at peak stage (6:00 PM, December 7th, Figure 5c), though significantly reduced. At the following rising tide stage (Figure 3), the decreasing in wave energy translates into a less intense dissipation (lower values) provided by the system. The bars, however, still effectively dissipate the wave energy closer to the shore, at the MITB intertidal area, therefore protecting the shoreline from residual waves' impact following extreme storm conditions. At post-storm stage (December 8th, Figure 5e,f), waves are effectively dissipated outside the intertidal area at high tide, and as wave height

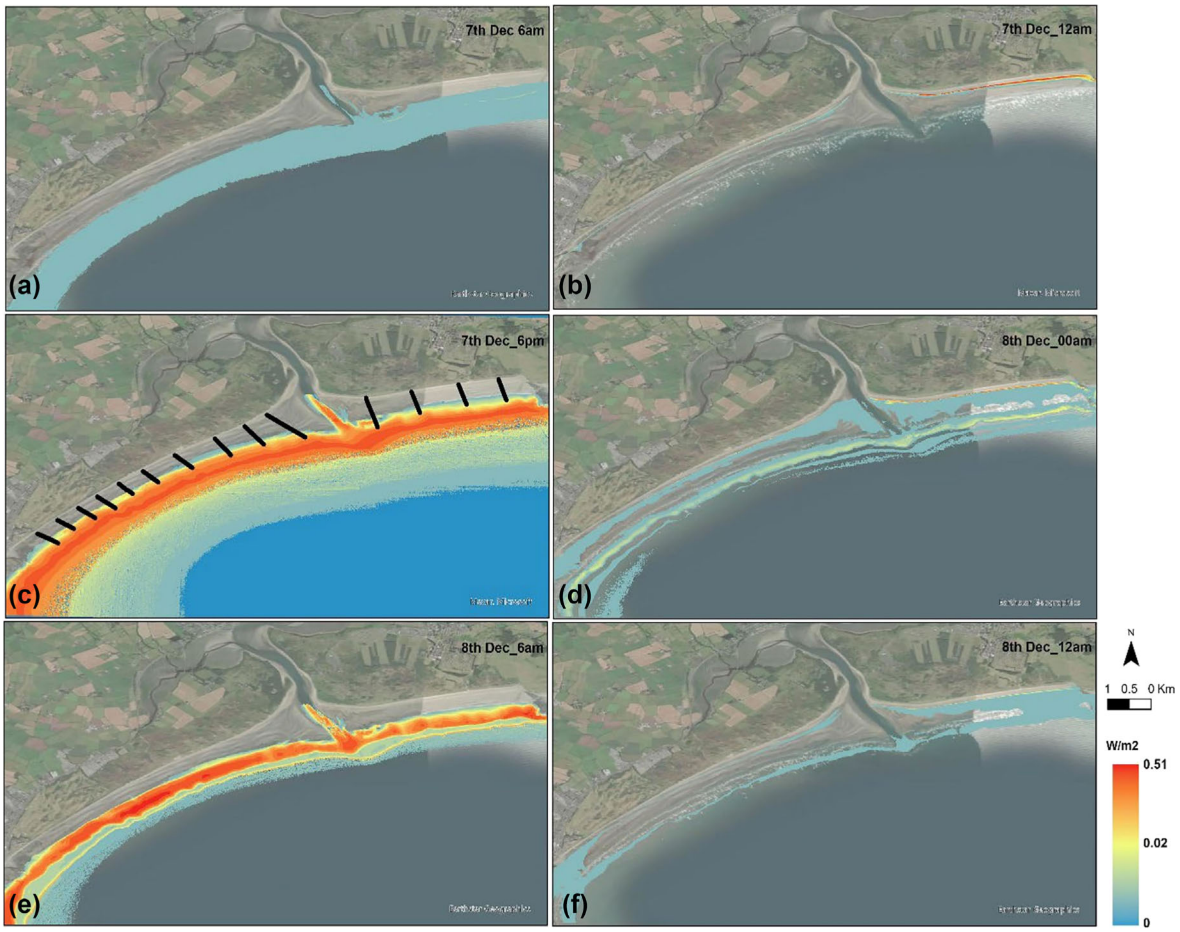


FIGURE 5 Wave energy dissipation over the duration of storm Barra, simulated every 6 h (a to f).

continues to decrease, the need for dissipation diminishes, and the nearshore system transitions back to regular low-energy conditions.

The wave energy dissipation and significant wave height figures collectively reveal a strong relationship between tidal states, wave height and dissipation efficiency. At the storm's peak (falling tide), both wave height and energy dissipation peak, underscoring the bars' role in managing extreme conditions. At high tide, while wave height drops, the dissipation remains concentrated over the bars, albeit with less overall energy to manage.

Finally, Figure 6 shows a timestamp of main directions of wave energy transport between the 7th December 6 AM and 8th December 12 AM. The sediment transport direction can be inferred from the direction of wave energy transport, as sediment is, in Dundrum Bay, typically mobilised and carried in the same direction as wave energy (Biausque et al., 2021). Before Storm Barra (7th December, 6:00 AM), the direction of wave energy transport, covering two thirds of the bay, is primarily onshore with a southeast direction. The eastern end of the bay (P3 to P9) is, however, dominated by east-southeast directions. At the early stage of the peak of the storm (7th December 12:00 AM) the direction shifts slightly eastward (splitting the bay in two), showing more concentrated and intense wave energy transport towards the west and central areas of Murlough beach. On the 7th of December at 6 PM, post-peak, a slight easing in wave energy concentration is observed, but wave energy transport remains predominantly in the same direction. At the following tidal cycle (8th December 00:00 AM and 6:00 AM), the wave propagation patterns maintain a similar direction. Moreover, localised patterns show that, in the western section of Murlough, the wave arrows point from a slightly north-east direction, suggesting a potential wave-induced sediment transport along the coast. After the storm (8th December 12:00 AM), the arrows seem to shift towards a more southern direction (from ESE to SE) indicating a possible increase in the cross-shore component of wave forcing, although its effect would likely be less pronounced due to the lower wave energy conditions.

Overall, the figure shows that the induced-wave energy transport is predominantly oriented onshore, with vectors indicating a southeast-to-east-southeast variation along the coast. The oblique incidence of waves, together with the spatial distribution of wave energy dissipation, suggests potential longshore sediment transport towards the western end of the bay and possible sediment movement along the coast rather than directly offshore or onshore. At storm's peak (7th December 12:00 AM–6:00 PM), the directional consistency of wave energy combined with maximum H_s indicates conditions that could have enhanced sediment mobilisation, particularly along the central to western sections of the coast.

3.3 | Water level and beach zones

Using both the intensively surveyed areas and the profiles, isolines representing the limits of the dune foot (green), supratidal beach (red), mean sea level (MSL, yellow) and the intertidal area (blue) were

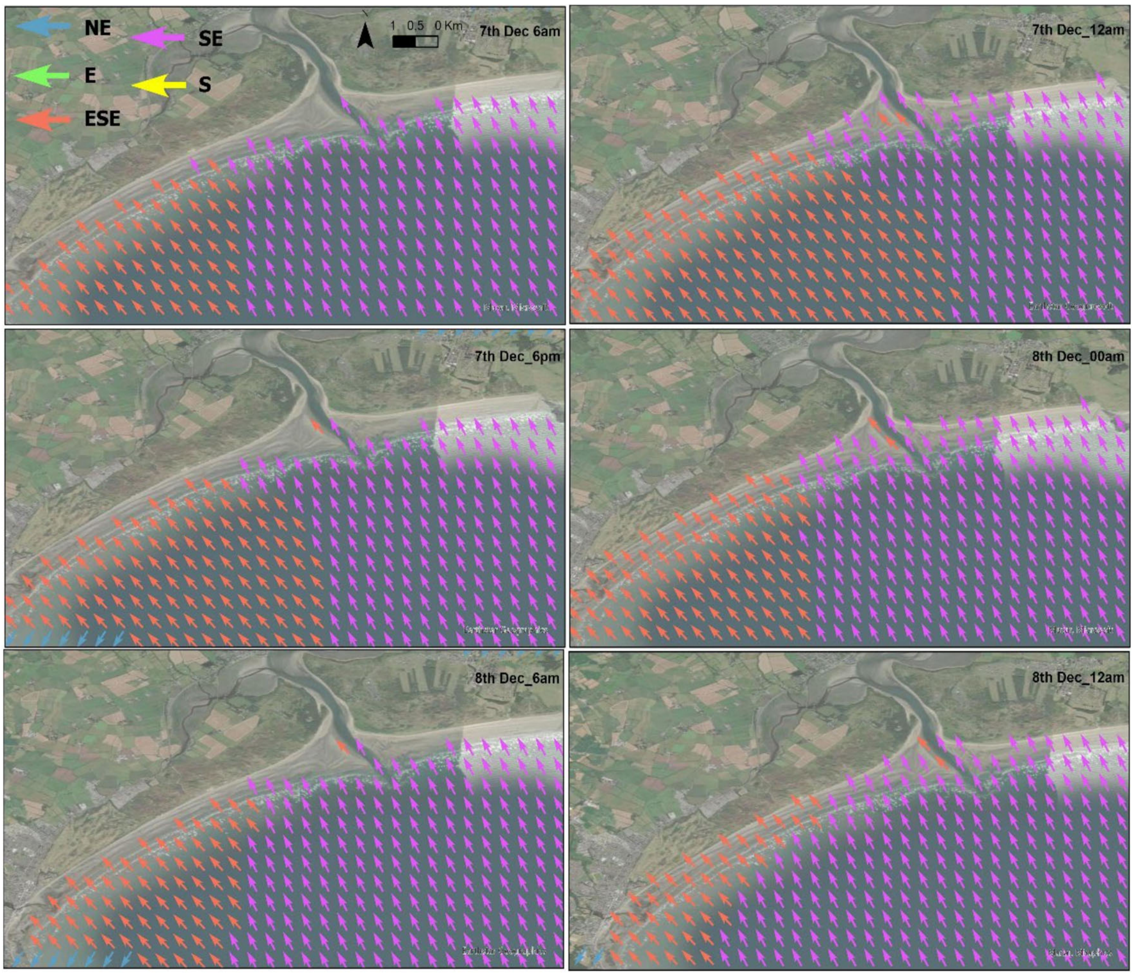
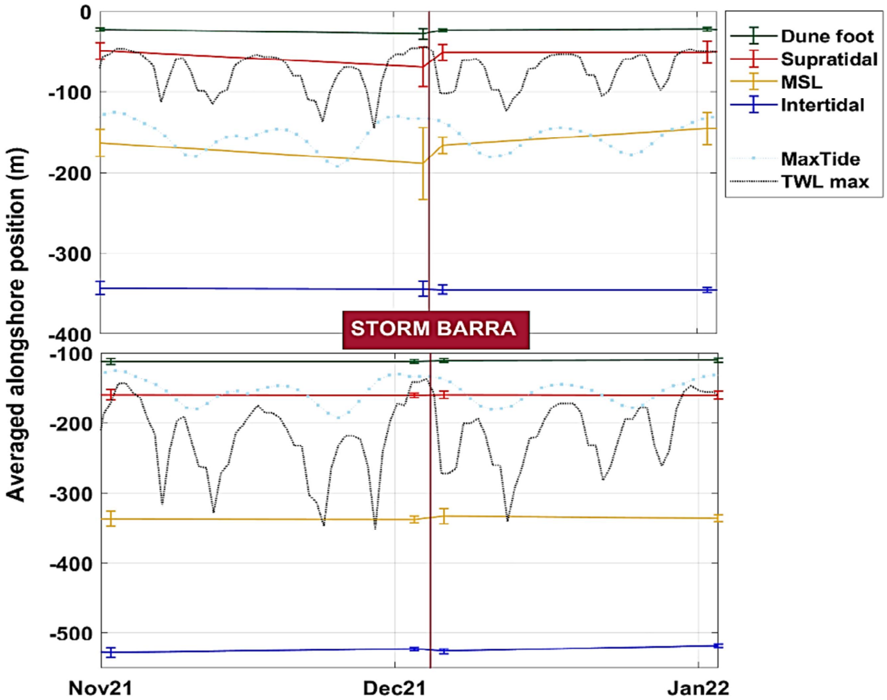


FIGURE 6 Direction of wave energy transport at several stages of Storm Barra (every 6 h).

FIGURE 7 Cross-shore position evolution of various isolines at Murlough (top) and Ballykinler beaches (bottom): the limits of the dune foot (green), supratidal beach (red), mean sea level (MSL, yellow) and the intertidal area (blue). The dashed light blue line represents the maximum tide level; the black line represents the total water level (TWL).



extracted and averaged alongshore. Figure 7 presents the cross-shore position evolution of those isolines in time, from November 2021 to January 2022, at Murlough and Ballykinler beaches (respectively top and bottom panels). The maximum tide level and maximum TWL are also plotted to analyse the beach areas reached by the maximum water elevation.

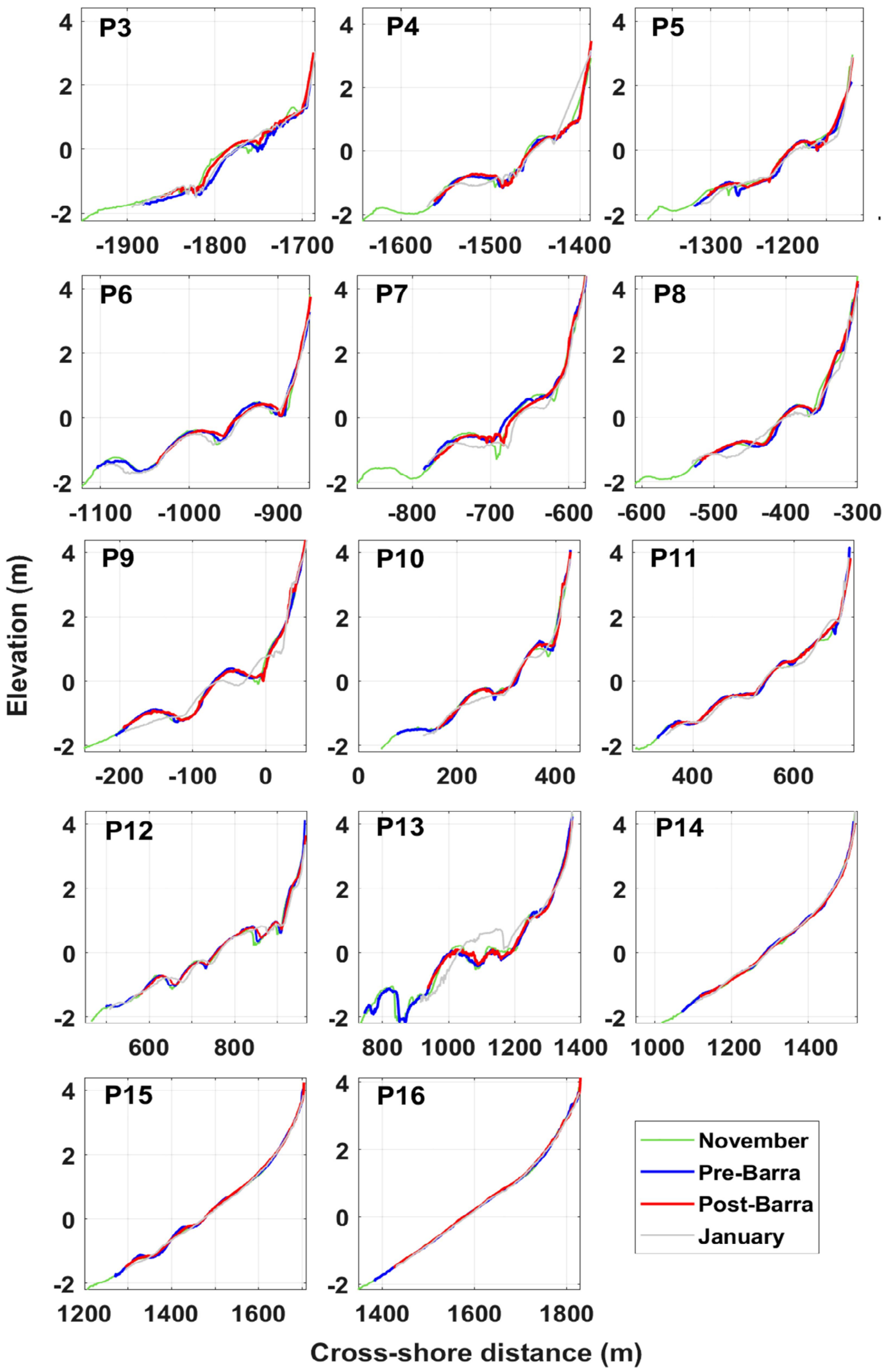


FIGURE 8 Cross-shore profiles recorded at Murlough (P3 to P12) and Ballykinler (P13 to P16) beaches, pre- (in blue) and post-storm Barra (in red). Profiles from surveys conducted in November (in green) and January (in grey) are also plotted for context: pre-storm conditions and post-storm recovery.

Before storm Barra (in November), the isolines representing Murlough's supratidal beach boundary and MSL tend to migrate offshore, while the intertidal limit shows no significant change. Murlough's supratidal area seems therefore slightly wider, while the intertidal area is proportionally reduced. After the storm, both the MSL and the supratidal boundary retreated (>20 m), decreasing the supratidal area back to its initial width in November's (from 50 m to about 30 m wide). In January, even though the supratidal and intertidal zones seem stabilised, the MSL keeps migrating onshore.

In contrast, no significant changes are noticeable between November and pre-storm Barra surveys at Ballykinler beach. After the storm, a slight offshore migration (<5 m) of the intertidal zone limit associated with a minor retreat (<10 m) of the MSL is visible. Those changes however look negligible compared to the variations observed at Murlough beach.

At both sites, the TWL is maximal during storm Barra and exceeds the supratidal area limit for a short period of time. The maximum water level induced by tides (MaxTide level, Figure 7) however never reaches the supratidal area at Murlough beach, suggesting a significant role of the storm surge. The opposite pattern is notable for Ballykinler beach. Indeed, the maximum tide level often reaches the supratidal area as before, during and after storm Barra. Consequently, Murlough seems mostly influenced by the maximum TWL, which includes the storm surge and is therefore limited in time (to the storm duration), while Ballykinler beach seems primarily driven by tidal levels and not as much by storm Barra.

3.4 | Storm-induced profile changes

Profiles measured during the surveys of November 2021 (4th and 5th, in green), pre- (December 6th and 7th 2021, in blue) and post-storm Barra (December 9th, in red) and January 2022 (5th and 6th, in grey)

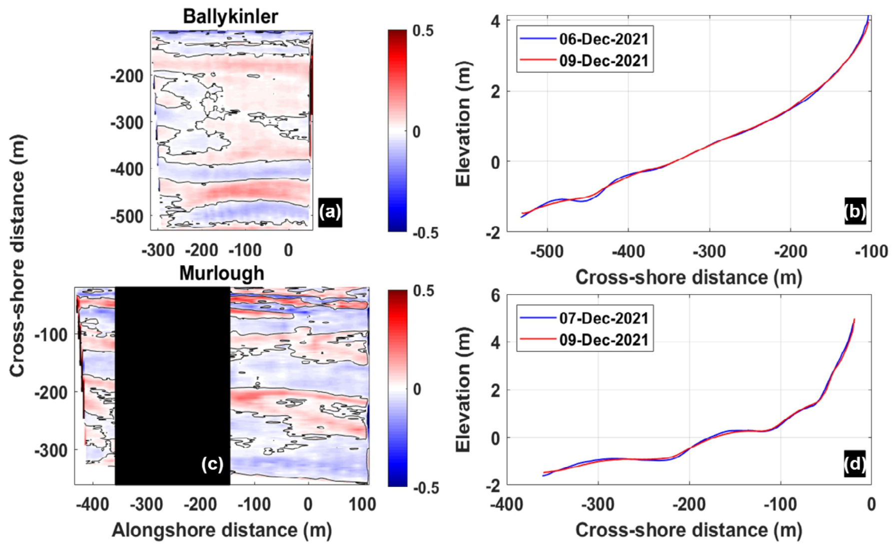


FIGURE 9 (a) DEM of elevation differences (DoD) due to Storm Barra at Ballykinler beach, blue (resp. red) colours show areas of erosion (resp. accretion); (b) alongshore-averaged cross-shore profiles pre- (blue) and post-Barra (red) at Ballykinler beach; (c) DEM of elevation differences due to storm Barra at Murlough beach, blue (resp. red) colours show areas of erosion (resp. accretion); (d) alongshore-averaged cross-shore profiles pre (blue) and post-Barra (red) at Murlough beach.

are plotted in Figure 8. Profiles 3 to 12 and 13 to 16, respectively, represent Murlough and Ballykinler beaches.

P3, located at the western end of Murlough beach, evolved from an erosion of the profile between November and pre-Barra, to a post-Barra accretion of the profile reaching its November's position, towards another erosion in January. P4 also displayed a limited accretion of the profiles after the event; however, this was associated with a slight onshore migration of the bars (<15 m). The crest of the second bar appears eroded in January. Even though P5 and P6 follow the same pattern of onshore bar migration (up to 20 m) after storm Barra, they present a different profile in January. Indeed, an erosion of the bars' crest is visible at P5 (up to 15 m), while P6 changes are driven by an offshore migration of the bars (up to 30 m). P7 is marked by an erosion of the offshore side of the bars during storm Barra. An enhanced erosion of the bars (up to 15 m) and their crests is noticeable on January's profile. Profiles 8, 9, 10 and 11 show no significant morphological changes between November and December, nor after storm Barra. Erosions and cross-shore migrations of the different bars are nonetheless visible on January's profiles. P12 and P13 are located on each side of the tidal inlet and exhibit the highest number of bars. During storm Barra, the sandbars are migrating onshore at both locations; those migrations carried on after storm Barra and are still in evidence in January. P14 and P15 are recorded at Ballykinler beach; those profiles differ from Murlough's profiles as the amplitude of the intertidal bars is much smaller. Storm Barra, however, induced an erosion of the sandbars that persisted in January, smoothing entirely the profiles. P16 is at the eastern end of Ballykinler, just in front of the rocky headland. The profile was already linear before storm Barra (no morphological structures) and did not change during or after the event.

3.5 | Morphological evolution: An overview

Data were collected pre- (6th and 7th December) and post-Storm Barra (9th December) at Ballykinler and Murlough beaches (respectively). Profiles recorded along both intensive areas were interpolated to generate the Digital Elevation Models (DEMs); DEMs of differences (DoDs) were then calculated by subtracting elevations pre- to post-storm Barra and are presented in Figure 9 (A for Ballykinler and C for Murlough). Red colours highlight areas of sediment accumulation (accretion), while, in contrast, blue colours represent loss of sediment (erosion). The black area covers the section of the beach where the collected data were too inaccurate to be used in this study due to some equipment failure. Panels B and D show plots of the alongshore-averaged cross-shore profiles (mean profiles) pre (in blue) and post-Storm Barra (in red) for Ballykinler and Murlough, respectively.

The DoD of Ballykinler displays a cross-shore alternance of blue and red areas, highlighting succession of erosion/accretion patterns. Those observations are in adequation with mean profiles plot. Indeed, two bars are visible in the intertidal zone of the pre-Barra blue profile. The post-event red profile, however, is flattened, suggesting cross-shore sediment transport. Further, Murlough beach also shows alternance of erosion and accretion areas, but this time the patterns are more complex. The faded colours of the DoD, however, suggest changes $<+/-0.4$ m. In contrast with Ballykinler, the averaged profiles exhibit a well-developed intertidal bars system defined by higher wavelengths and amplitudes of the sandbars. Despite a slight erosion of the crests and deposition within the runnels, the bars were, however, maintained after storm Barra.

Figure 10 illustrates the alongshore variability in the morphological response of Dundrum bay to Storm Barra, highlighting distinct zones of coastal behaviour. In the south-west area, profiles P3–P4 are characterised by an increase in beach level (dark blue lines) and slight onshore migration of the intertidal bars (light blue lines). This transitions into a zone extending from P5 to P7, where onshore bar migration is accompanied by erosion of the offshore side of the bars (dark yellow line). In contrast, profiles P8–P11 show little or no measurable morphological change (green lines). Around the inlet, profiles P12 and P13 exhibit renewed onshore bar migration on either side of the channel. Further north-east, at Ballykinler, profiles P14 and P15 are characterised by profile linearisation (red lines), while profile P16 shows no significant change.

In addition, representative elevation change plots for selected profiles (P3, P6, P7, P11, P14 and P16) illustrate the range of morphological responses observed across the bay. Overall, the results reveal a clear alongshore transition from beach accretion and onshore bar

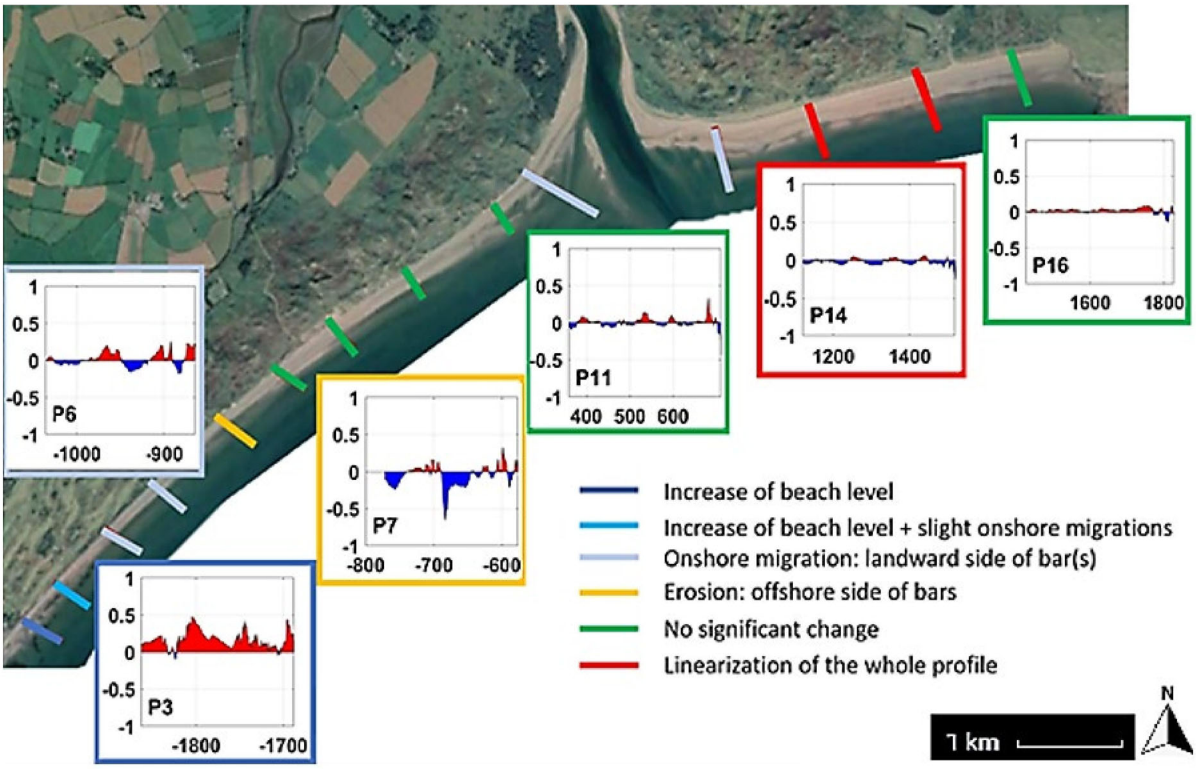


FIGURE 10 Summary of the alongshore variability of Dundrum Bay's response to Storm Barra. Plots show the elevation differences in metres (*x*-axis) along chosen profiles (P3, P6, P7, P11, P14 and P16; *y*-axis being the cross-shore distance in metres).

migration in Murlough to a stable central sector, followed by a localised response associated with the inlet. East of the inlet, the beach response shifts towards profile linearisation at Ballykinler before becoming relatively stable again at the easternmost profile.

4 | DISCUSSION

4.1 | Role of water levels and intertidal bars

Dundrum Bay is a macrotidal environment primarily driven by tidal processes. However, SWAN simulations show that during Storm Barra, the morphological response to the event was the result of a combination of multiple physical factors.

The maximum wave heights during the peak of Storm Barra occurred during a falling tide period (Figure 3). Therefore, as the storm peaked (7th December around 3:00 PM), the falling tide stage and corresponding shallower water levels increased the bottom friction, thereby naturally dissipating more wave energy within the nearshore zone (Lavaud et al., 2022; Putnam & Johson, 1949). However, the reduced water depth and high-energy waves also allowed some energy to overtop the offshore bars, leading to moderate wave action along the intertidal area (Carter, 1983). The MITB system, through the bars located in the lower intertidal area, assumed a dissipating role by absorbing the remaining energy and helping to protect the upper beach. The TWL during the event was limited, occasionally reaching the supratidal beach, and thereby approaching the front dune (Figure 7). Consequently, the dissipation of the wave energy was mostly focused seaward of the intertidal area and driven by the nearshore subtidal bar. The combination of the subtidal and seaward intertidal bars therefore acts as an efficient natural barrier, absorbing most of the wave energy before it can propagate further towards the shoreline, thus preventing impacts on the aerial beach and the landward MITB system at the peak of the storm. The occurrence of low tide and limited storm surge helped minimise the impact of storm Barra on beach morphology. After the peak of the storm, the wave height and energy dropped dramatically; the wave energy, however, remained relatively high for the area. Together, lower waves and higher water levels induced a maximum bottom shear stress localised on the subtidal bar yet associated with more overtopping than previously observed, primarily linked to the high tide stage. The wave energy was then fully dissipated along the intertidal area by the MITB system. The subsequent low tide is again characterised by the dissipation of wave energy by the outermost sandbar. The decrease in both wave height and water levels halted any overtopping of the bar, and the energy was fully dissipated outside the intertidal area. Therefore, the energy dissipation pattern changes directly with the tidal stage. At low tide, limited wave energy overtops the offshore bars and reaches the shore, while at high tide, the intertidal MITB features dissipate most of the energy.

Consequently, even though Storm Barra was an extreme event that induced high-energy waves rarely reported in the area, the effectiveness of the hybrid system of subtidal and intertidal sandbars in dissipating the energy dramatically reduced any severe impacts at the shoreline. Indeed, at both low and high tide, the nearshore subtidal bar and MITB system acted as an effective buffer against storm alteration of the upper beach and dune, only occasionally allowing water inundation at those areas. Variations in water levels and wave height, however, did influence the location of active physical processes along the topo-bathymetric profile. The relatively short duration of the storm, coupled with a rapid decrease in wave height and relative energy, also played a key role in mitigating the impact of Storm Barra on the shoreline. More significant coastal impacts would likely have occurred if the storm had lasted longer and had coincided more with high tide stages.

Although the dataset provides valuable insights into the short-term morphological response of the study area, its restricted temporal coverage limits the ability to fully disentangle the relative influence of individual forcing mechanisms, such as storm-induced hydrodynamics and tidal processes, on the observed morphological changes. In addition, while the SWAN model provides a robust representation of the nearshore wave field, it has inherent limitations in the swash zone and close to the shoreline, where waves transform into bores and run up processes become dominant. This limitation is particularly relevant in the macrotidal setting of the study area, where rapidly changing water levels continuously shift the zone of wave action, reducing the time during which storm waves can effectively rework the upper intertidal bars. Therefore, the relationship between the simulated wave conditions and the observed morphological changes should be interpreted with caution, particularly in the upper intertidal zone, where swash processes are not explicitly resolved by the model.

4.2 | Alongshore variability of Dundrum Bay's response to Barra

Even though water levels and interactions between hydrodynamics and sandbars (subtidal and intertidal) are key parameters in Dundrum Bay's response to storm Barra, a strong alongshore variability is observed (Figure 10). Ballykinler beach is, for instance, characterised by onshore bar migrations near the inlet and erosion of the bars along the beach. Before Barra, the intertidal bars were already of low amplitude, to non-existent for the headland-side profile. The dissipation of pre-storm wave energy by the bars was already poorly efficient, and water levels were able to reach the upper beach (Figure 4, 7th December, 12:00 AM), allowing sediment to move along the beach profile. Additionally, the direction of wave energy transport (Figure 6) was uniform over the entire storm episode and southeast oriented, thereby driving cross-shore sediment transport and potential erosion.

Our study indicates that maximum tidal levels often reach the supratidal area, allowing tidal processes to activate sediment transport for longer periods of time and not only during storm surge maximums. Antecedent events and local geology also played a key role in the response of the bay to this extreme event. Smaller previous winter storms (three events according to Biausque et al., 2023) already fully linearised the P16 profile by interacting with the beach and the headland (Biausque et al., 2021), leading to its winter equilibrium (e.g., lowest winter profile) and explaining the lack of morphological change after storm Barra.

In contrast, the MITB system is much more developed at Murlough beach with stable, more pronounced intertidal bars of higher amplitude. A longshore response gradient at Murlough to storm Barra is, however, observed. The western end of the beach experienced an accretion of the profile elevation. This section of the beach (P3) was previously eroded by past winter energetic events (Figure 8), removing most of the sand available above the cobble layer. During storm Barra, the dissipation of wave energy on the offshore bar led to sediment resuspension and therefore transport towards the beach (Voulgaris & Collins, 2000).

The west to central zone of the beach acts as a transitional area where the beach morphology evolves from an elevation of its profile towards onshore bars migrations to minor changes. In this area, the subtidal bar was closer to the shore, allowing more energy to reach the beach, therefore driving slight onshore bar migrations. Those migrations initiated in November were resumed during Barra.

Profiles that displayed minor to no change were the most dynamic between November and pre-Barra surveys. Here, the beach has been subjected to winter energetic conditions leading to some already modified pre-Barra beach profiles. In November, even though the conditions were much less energetic than during storm Barra, the profiles show onshore migration of the bars, congruent with previous observations (Biausque et al., 2023). This highlights the importance of beach shape/state prior to any extreme event and the sequence in which events occur within the winter season (Dissanayake, Brown, & Karunarathna, 2015).

In addition, the direction of wave energy (Figure 6) potentially controlling sediment transport showed an east-southeast (ESE) orientation in the western and central areas of Dundrum Bay. During Storm Barra, the residual energy (Figure 5) reached closer to the shoreline (after primary dissipation by the offshore bar) and, combined with the ESE orientation of the wave energy direction, drove sediment transport towards the western end of the bay (P3 and P4). This contributed to the morphological changes observed (Figure 10). P8 to P10 were located in the morphological transition zone, which corresponded to the area with the greatest variability in wave energy direction. This suggests that successive changes in wave and wave-induced sediment transport direction during the storm period led to limited residual morphological changes along these profiles.

The tidal inlet also played a key role in the dissipation of the waves and the response to P12 and P13 areas to storm Barra. Profiles located on each side of the inlet presented a higher number of bars and a longer cross-shore extent. Moreover, the beach at this location exhibited a dissipative profile (with a gentler slope) therefore allowing an efficient progressive dissipation of the wave energy within the intertidal area. Consequently, the bars were more mobile due to dominant cross-shore processes and migrated onshore as they were directly impacted by waves.

Consequently, the alongshore variability was the result of complex interactions between hydrodynamic forcing and local geology (e.g. inlet and headlands; Gallop et al., 2020), the pre-storm profile shape and the impact of previous events on the beach, the state of the MITB system (e.g., number of bars and amplitude) and the sediment composition of the beach (e.g., the presence of pebbles).

5 | CONCLUSIONS

This study investigated the morphological response of a Multiple Intertidal Barred (MITB) system located in Dundrum Bay, Co. Down (Northern Ireland) to an extreme event: storm Barra. The bay is divided into Murlough and Ballykinler beaches, which are located on the western and eastern sides of an active inlet, respectively. Results from pre- and post-storm topographical surveys displayed a strong alongshore variability in the morphological evolution of the profiles along the bay, with distinctly different responses at Murlough and Ballykinler beaches. The complex interactions between the local geology, pre-storm profile shape/impact of previous storms and the antecedent state of the MITB features influenced resulting morphological changes. Ballykinler beach, where the MITB system was already poorly developed before storm Barra, experienced linearisation and erosion of the profiles. In contrast, Murlough beach shows accretion in the westernmost profiles and minimal changes at the eastern end, highlighting the transitional nature of centre area.

Nearshore SWAN computations emphasised the crucial role of subtidal and intertidal sandbars in helping to dissipate wave energy during extreme events. The nearshore subtidal bar is particularly effective in protecting the upper beach and dune foot from erosion by dissipating most of the wave energy, especially at low-tide stages and under high to moderate hydrodynamic conditions (e.g., peak of storm Barra). At high tide, higher water levels and moderate energy conditions allowed some wave energy to bypass the subtidal bars. This residual energy was, however, subsequently dissipated by the intertidal MITB system within the intertidal area, thereby protecting the subaerial beach. Despite the high-energy waves generated by Storm Barra, the sandbars, under varying tidal stages, helped to mitigate the impact of the storm on the shoreline.

In conclusion, this work has highlighted the importance of nearshore MITB systems in attenuating the impact of extreme storm events at coasts. The work has important implications for other similar coastlines globally, particularly with reference to their response to high-energy storm events. Our findings also show the importance of wave forcing, water levels and complex coastal features in coastal resilience within a climate change and sea level rise context.

AUTHOR CONTRIBUTIONS

Melanie Biausque: Conceptualization; methodology (including methodological development); investigation (e.g., data collection); resources (provision of data, etc.); writing—initial draft; writing—reviewing and editing. **Emilia Guisado-Pintado:** Conceptualization; methodology (including methodological development); resources (provision of data, etc.); software (its provision and development); writing—initial draft; writing—reviewing and editing. **Derek W. T. Jackson:** Funding acquisition; supervision; writing—reviewing and editing. **J. Andrew G. Cooper:** Funding acquisition; supervision; writing—reviewing and editing. **Edoardo Grottoli:** Investigation (e.g., data collection); writing—reviewing and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Authors do not intend to share the data in a public repository.

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