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# Response of wave-dominated and mixed-energy barriers to storms

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ABSTRACT

Wave-dominated and mixed-energy barriers are extremely dynamic landforms, responding to processes operating over a spectrum of time scales, ranging from daily-to-monthly fluctuations related to storm and post-storm conditions, to century-to-millennium-scale evolution driven by relative sea-level change. Two types of storms are of particular relevance: warm-core tropical and cold-core extratropical cyclones. Both are responsible for generating very large waves, highly energetic surf zone dynamics and sediment transport, elevated inshore water levels, and extensive morphological responses. All cyclones are affected by climate change, which governs their frequency, intensity and tracks.

Barrier storm response is primarily governed by maximum storm runup and barrier morphology, as conceptualised in Abby Sallenger's Storm Impact Scale model (Sallenger, 2000). This model defines four storm-impact regimes and includes erosive as well as accretionary responses. On the *erosion* side, the swash regime drives bar and berm flattening; the collision regime is marked by dune scarping and beach lowering; the overwash regime leads to dune scouring and channel incision; and the inundation regime may result in barrier destruction. On the *deposition* side, storm berms and beach ridges may form and accrete in the swash and collision regimes; localised vertical beach and barrier accretion are associated with the collision and overwash regimes; and washover deposition takes place in the overwash and inundation regimes. Site-specific factors play a key role in moderating the morphological response and include storm characteristics (type, duration and track), longshore sediment supply, upwelling–downwelling currents, coastal setting and inner-shelf topography.

The response of a barrier to a tropical or extratropical cyclone can, however, not be considered in isolation and has to be appreciated in a longer temporal context involving morphological preconditioning due to antecedent wave and water-level conditions. Additionally, a simple process-response approach of the cause-and-effect type is inappropriate and a more complex conceptual framework, involving thresholds, feedbacks, resilience and vulnerability, will need to be adopted. A useful way to visualise and conceptualise more complex storm behaviours and the longer-term vulnerability of barriers is the 'resilience trajectory', which maps out the changes in barrier geometry (elevation and width) over various time scales, from weeks to years or even longer, and under varying forcing conditions, including changes in storminess and sea-level rise.

An increased understanding of barrier response to storms and sequences of storms is required to better quantify long-term barrier response to climate change. High-resolution and comprehensive decadal records of barrier response to storms are a prerequisite to achieve this ambition, linking site-specific coastal settings, hydrodynamic drivers and morphological responses, and allowing the recognition of recovery- and impact-dominated phases. The enhanced insights in barrier response to extreme events must then be incorporated into improved coastal response models to help predict the impacts of future climate change on wave-dominated and mixed-energy barriers around the world.

## 1. Introduction

Wave-dominated and mixed-energy barriers occur in a wide range of settings. Their distribution and types are governed by various environmental boundary conditions, including hydrodynamic forcing (wind, waves and tides), sediment characteristics (abundance and grain-size distribution), offshore bathymetry, tectonic setting and (relative) sea-level history (e.g., Roy et al., 1994; Fig. 1). Constructed out of loose material and located in energetic wave-influenced environments, barriers are extremely dynamic landforms. Their seaward and landward margins migrate significantly over a wide spectrum of time scales, ranging from wave- and tide-controlled hourly and daily fluctuations to century- or millennium-scale evolution driven by relative sea-level change.

Regardless of the time scale under consideration, storm-induced extreme wave and water-level conditions are key drivers of barrier dynamics. They are associated with the largest morphological responses and changes in shoreline position. Single storms can result in meters of

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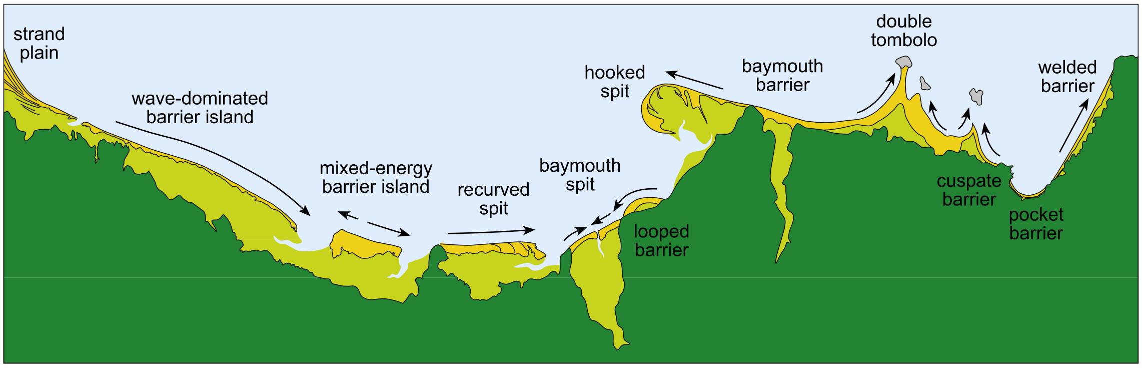

**Fig. 1.** Main barrier types. Attached forms include welded barriers, pocket barriers, cuspate barriers, double tombolos, baymouth barriers and various spits. Detached forms are mixed-energy and wave-dominated islands. Strand plains are characterised by a multiple-barrier planform in a progradational setting. Arrows denote littoral drift and light green shading represents submerged and low-lying back-barrier areas.
Source: Van Heteren (2014).

shoreline change within hours. A sequence of storms, for example during a winter season, may cause a seasonal, cumulative shoreline response (Komar, 1998). Over longer time scales, storminess-driven coastal change is marked by annual variability (e.g., caused by El Nino/La Nina), by decadal cycles associated with atmospheric teleconnections (e.g., North Atlantic Oscillation NAO), and by century-scale periodicity linked to climatic changes (e.g., Little Ice Age). Even in the long term, barrier erosion and retrogradation are far from gradual processes. Most barriers are characterised by periods of relative stability punctuated by short-lived change. The landward migration of transgressive barrier systems, although governed by rising sea level operating over centuries to millennia, is accomplished during individual storms and other, less energetic, wind-driven events.

Meteorologically, storms are easy to define by factors such as maximum sustained wind speed, lowest atmospheric pressure or largest pressure drop over a certain amount of time. Similarly, from a purely oceanographical point of view, storms can be defined as distinct events during which waves exceed a certain height and/or energy threshold for a certain amount of time (e.g., Lemm et al., 1999). Storm groups can then be defined as sequences of individual storms separated by maximum time intervals of non-storm conditions. However, a storm definition based on a wave-height threshold (e.g., maximum significant wave height $H_s$) is highly site-specific, and depends strongly on the modal wave conditions. For a sheltered barrier, $H_s = 2$ m might qualify as a storm (e.g., Houser and Greenwood, 2005), whereas for an exposed barrier, $H_s = 5$ m might be the lower limit. From a marine geological point of view, a more appropriate approach to defining storms, identifying storm thresholds and investigating storm statistics might be to consider hydrodynamic forcing (wave conditions and water level) in the context of coastal change. Such approach is more useful to coastal managers (e.g., Gervais et al., 2012). The EU-funded MICORE project (https://www.micore.eu/), which followed this approach, resulted in several site-specific storm definitions applicable to a number of coastal sites in Europe (e.g., Almeida et al., 2012; Armaroli et al., 2012; Del Río et al., 2012; Haerens et al., 2012; Trifonova et al., 2012). Clearly, there is a disconnect between the purely meteorological/oceanographical storm forcing and the ensuing coastal response, and they must be considered in concert when investigating coastal impacts of storms.

Two types of storms are of particular relevance to barriers: warm-core tropical and cold-core extratropical cyclones (Fig. 2); both are responsible for generating highly energetic wave conditions and elevated inshore water levels. Tropical cyclones (TC) are non-frontal low-pressure systems that develop over tropical or subtropical oceans. Depending on location, the highest-intensity TCs are referred to as 'hurricanes', 'typhoons', '(severe) tropical cyclones' or 'severe cyclonic storms'. Hurricanes are further subdivided into 5 categories on the basis of wind speed (Saffir–Simpson Hurricane Wind Scale), with Category 5 Hurricanes (maximum sustained wind speeds > 69 m $s^{-1}$) being the strongest. Since 1924, 13 of the 35 recorded Category 5 Hurricanes that made landfall in the USA did so at maximum strength. When looking at storm-generated waves, a distinction is made between locally generated wind waves and much longer swell waves formed by distant storms. As these swell waves travel, shorter waves are easily dissipated, with only long waves reaching the coast.

Extratropical or mid-latitude cyclones (ETC) are frontal systems that evolve along the polar front, which is defined as a semi-continuous boundary in the mid-latitudes that separates cold polar from warm subtropical air masses (Fig. 2). The more general terms 'depressions' and 'lows', sometimes with the adjective 'frontal' are commonly used. ETCs are generally associated with significantly less extreme wave and water-level conditions than TCs. Compare, for example the maximum storm surge of 3.5 m during the 1953 North Sea flood, associated with the region's most devastating storm of the twentieth century (Wolf and Flather, 2005), with surge values up to 8.5 m during Hurricane Katrina in 2005 (Fritz et al., 2007).

This paper will review progress made in the past two decades in our understanding of barrier response to extreme wave and water-level conditions caused by TCs and ETCs. An overview of short- and long-term influences as well as key hydrodynamic drivers determining storm-related barrier behaviour provides the framework needed to understand various types of destructive and constructive barrier response to individual storms. We build on Sallenger's (2000) impact scale of barrier response to hurricanes, placing beach change, dune erosion, overwash, breaching and destruction in a context of pre-storm conditioning and post-storm recovery. Understanding barrier response to storms requires fully integrated long-term monitoring series, laboratory experiments and numerical modelling of drivers and coastal change.

## 2. Long-term influences: sea-level change and storminess

Sea-level change is the key driver for longer-term barrier evolution and owing to global warming most barriers are affected by relative sea-level rise. The global rate of sea-level rise estimated from (satellite) altimetry data over the 15-year period from 1993 to 2008 is 3.5 mm $yr^{-1}$ (Nicholls and Cazenave, 2010), but according to most global sea-level data sets sea-level rise is accelerating (Church and White, 2011) and may approach rates experienced during the early and mid-Holocene periods (5–10 mm $yr^{-1}$; Woodroffe and Murray-Wallace, 2012) by the end of this century. According to the 5th Assessment Report (AR5) of the International Panel for Climate Change (IPCC), and depending on the emission scenario, global mean sea-level rise for 2081–2100 relative to 1986–2005 will likely be in the range of 0.26 to 0.82 m (http://www.ipcc.ch/; Summary for Policymakers). On the other hand, following their analysis of sea-level rise and its possible coastal impacts given

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