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Review

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Morphodynamics of wave-dominated beaches

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Abstract

Wave-dominated sandy beaches are highly valued by societies and are amongst the world's most energetic and dynamic environments. On wave-dominated beaches with unlimited sand supply and limited influence of tide and geology, beach change has long been conceptualised in the morphodynamic framework of Wright and Short (1984). Such framework describes the occurrence of beach types based on wave conditions and sediment characteristics across the complete reflective–dissipative spectrum. Building on theoretical work, field/laboratory measurements and monitoring programmes, the physical mechanisms underpinning this morphodynamic framework have been progressively unravelled. Cross-shore morphological changes are primarily controlled by equilibrium and beach memory principles with below (above) average wave conditions driving down-state (up-state) transitions associated with onshore (offshore) sediment transport. Such cross-shore behaviour mostly reflects the imbalance between the onshore-directed sediment transport driven by wave nonlinearities and the offshore-directed sediment transport driven by the undertow. Self-organised morphological instabilities resulting from different positive feedback mechanisms are primarily responsible for alongshore morphological variability and the generation of rhythmic morphological features, such as crescentic bars, rip channels and beach cusps. Critically, wave climate and changes in wave regimes are key in driving the coupled cross-shore and longshore behaviour that ultimately explains modal beach state and frequency-response characteristics of beach morphological time series.

Impact statement

Sandy beach morphology exhibits a large variability in space and time. Closely associated with such morphological variability are changes in the surf zone processes, such as type of wave breaking, wave energy gradients, strength and character of nearshore currents and modes of sediment transport. The beach model morphodynamic framework of Wright and Short (1984) captures this mutual feedback between morphological and hydrodynamic variabilities, and describes the occurrence of beach types across the complete reflective–dissipative spectrum. In this review, we provide this framework with a stronger physical underpinning by drawing on the results of several decades of coastal research, whilst also highlighting existing gaps in our knowledge and providing future perspectives. This review will provide physical coastal researchers with an enhanced morphodynamic framework within which to place their beach research and interpret their results, as well as providing them with suggestions for future research. However, sandy beaches are not only of interest and of relevance to physical coastal researchers, because beach morphodynamics directly affects, amongst others, beach ecology, pollutant dispersal in the surf zone and beach hazards. Anyone involved with these processes, either from a scientific or management point of view, will benefit from the enhanced beach model morphodynamic framework presented in this review.

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Introduction

Wave-dominated sandy beaches occur on all continents (Luijendijk et al. 2018) and are amongst the world's most energetic and dynamic environments. They are highly valued by society as they attract many visitors and contribute significantly to local, regional or even national economies (Houston 2018; Garola et al. 2022). They also represent natural forms of coastal protection against flooding; therefore, beach nourishment is increasingly seen as a sustainable means of coastal adaptation to climate change (de Schipper et al. 2020). Although historically referred to as ecological deserts, it is now recognised that sandy beaches support a diverse beach fauna (McLachlan et al. 2018) and that surf zones are nursing grounds for many fish species (Ciotti et al. 2013). Beaches can also be dangerous environments for beach users (West 2005), especially when rip currents are present (Brighton et al. 2013), and there is a direct link between the type of beach and the beach hazard level (Scott et al. 2011). Finally, beaches interact strongly with sandy dune systems, as dune development and beach–dune sediment exchange are closely related to beach state and surf zone processes (Walker et al. 2017; Cohn et al. 2019).

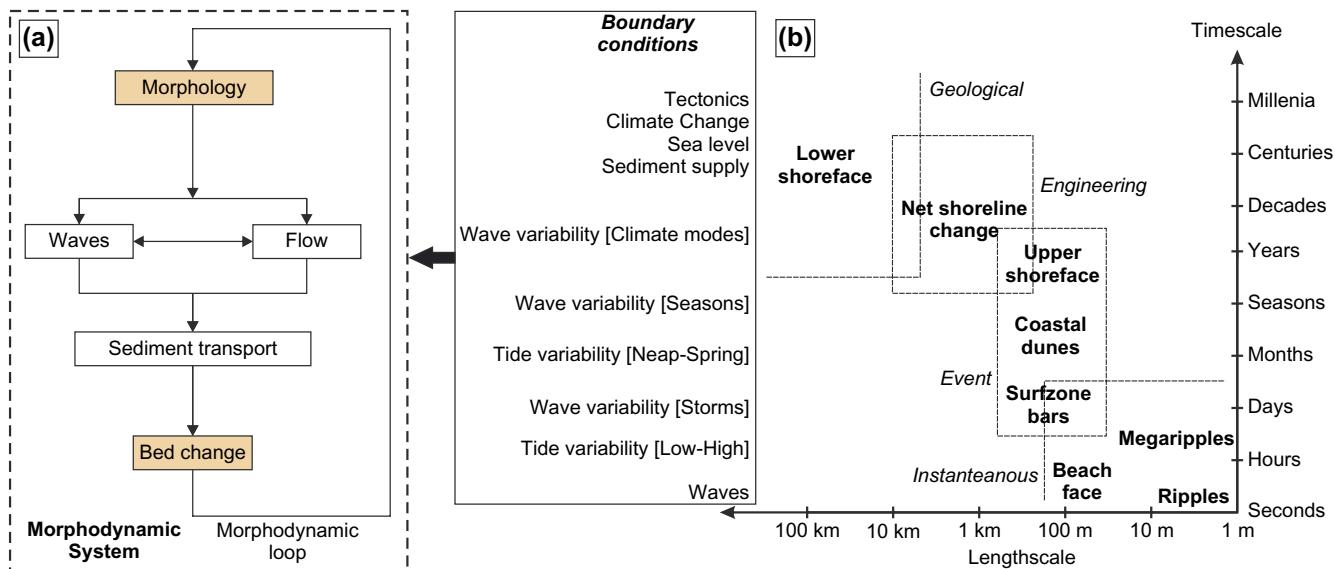


Figure 1. (a) Schematics of the coupled beach morphodynamic system and (b) time–space diagram of the primary modes of sandy beach variability modified after Cowell et al. (1995).

Beach morphodynamics refers to the mutual interactions between beach morphology and hydrodynamic processes (including wave, tide and wave-driven currents) involving the motion of sediment (Figure 1a). On any given beach, *temporal* changes in morphology can be forced by variability in the hydrodynamic conditions operating on a range of timescales (see Figure 1b; Cowell et al. 1995), including over individual waves (Blenkinsopp et al. 2011), tidal cycles (Almeida et al. 2015), storms (Harley et al. 2017) and seasons (Masselink and Pattiataratchi 2001). Over even longer periods, the integrated result of alternating storm sequences and recovery periods can give rise to multiannual changes in beach morphology (Dodet et al. 2018; Vos et al. 2019) linked with climate modes of atmospheric variability. Along any stretch of coastline, *spatial* changes in beach morphology are related to along-coast variability in the hydrodynamic conditions, mostly wave exposure, but also geographic variation in sediment characteristics, geological framework and tidal regime (Jackson et al. 2005; Scott et al. 2011; Aleman et al. 2015). Spatial and temporal variability in beach morphology has long been considered within the morphodynamic framework of Wright and Thom (1977), which underpins this review and is suitable to address changes typically on the timescales from day to years across hundreds to thousands of metres of coastline.

The last decades have been characterised by major advances in the understanding and modelling capacity of sandy beach dynamics, building on theoretical work (Ribas et al. 2015), intensive field experiments (Senechal et al. 2011), laboratory experiments (Ruessink et al. 2016) and monitoring programmes (Turner et al. 2016; Ludka et al. 2019). Such advances, which have provided new and quantitative insight into the underlying mechanisms underpinning the empirical morphodynamic framework of Wright and Thom (1977), are included in this review of the morphodynamics of wave-dominated sandy beaches. It is acknowledged that beach morphology and processes are also affected by tides and geological factors, human interventions including coastal structures and beach nourishment, and that beaches can also be composed of gravel or even cobble-sized sediments, but our emphasis is on how ocean waves affect the morphological behaviour of natural

sandy beaches. The ‘Nearshore processes’ section provides a brief overview of the key nearshore processes that shape sandy beaches. The ‘Static beach state classification’ section focuses on the spatial variability in beach morphology by describing static beach state classification models. The ‘Beach morphodynamics’ section discusses the underlying processes driving cross-shore and alongshore beach behaviour and, in turn, beach state changes. The ‘Conclusions and future perspectives’ section concludes this review and offers some future perspectives.

Nearshore processes

In the nearshore region, depth-induced gravity wave breaking is the primary driver of nearshore currents, sediment transport and morphological changes (Figure 2). From deep to intermediate water, waves start to ‘feel’ the bottom at water depth $h < L/2$, where L is the wavelength, and undergo the following changes (Dean and Dalrymple 1991): (1) wave shape becomes asymmetric by developing horizontal and vertical asymmetries (from linear to nonlinear wave theory); (2) onshore mass transport becomes non-zero and (3) waves shoal (increase in height) and refract with decreasing water depth, and can diffract and reflect in the presence of abrupt seabed changes or obstacles. These processes continue until, critically, depth-induced breaking occurs when the ratio of wave height to local water depth reaches the breaker index value γ (c. 0.8), which depends on many factors (e.g., beach slope, breaker type, offshore wave steepness and wind direction; Battjes 1974; Smith and Kraus 1990; Rattanapitikon and Shibaya 2000; Sous et al. 2021), before waves run up the beach face in the swash zone (Figure 2). Of note, incident gravity waves exhibit prominent groups that are associated with long ocean waves (Munk 1949), known as infragravity waves (Bertin et al. 2018), with frequencies below those of the gravity short waves (generally $<0.04\text{--}0.05\text{ Hz}$). On gently sloping beaches under storm conditions, infragravity waves can dominate the inner surf zone (and swash) energy spectra (e.g., Guza and Thornton 1982; Raubenheimer and Guza 1996; Ruessink 1998; Roelvink et al. 2009).

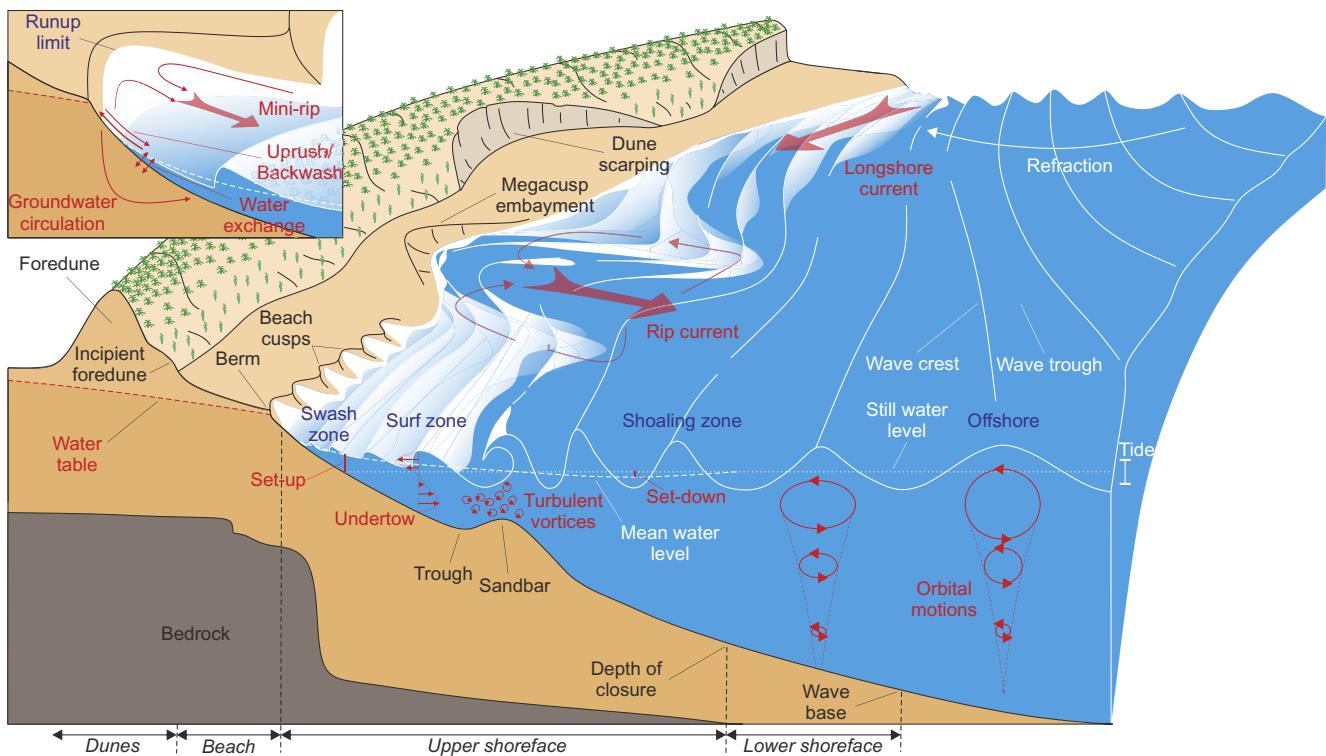


Figure 2. Schematics of the primary hydrodynamic and sediment transport processes occurring on wave-dominated beaches and the primary morphological and hydrodynamics compartments.

Energy loss through depth-induced gravity wave breaking results in a reduction of the wave momentum flux, or radiation stress (Longuet-Higgins and Stewart 1964), which drives the nearshore circulation system (Svendsen 2006) consisting of set-up, undertow, longshore currents and rip currents (Figure 2). In short, (1) wave set-up is the increase in mean water level due to wave breaking (Bowen et al. 1968); (2) undertow is a seaward-directed mean current compensating the near-surface net onshore mass flux due to both the organised wave motion and breaking wave roller, with its largest values close to the bottom and (3) rip currents are narrow and seaward-directed jets flowing through the surf zone. On open sandy beaches, the two most common types of rip current are (see the review of Castelle et al. 2016): (1) flash rips on alongshore-uniform beaches associated with surf zone eddies, which are transient in both time and space (Johnson and Pattiaratchi 2006; Feddersen 2014) and (2) channel rips flowing through the incised channels between sand bars (Figure 1), which are fixed in location and driven by alongshore variation in breaking wave energy dissipation due to alongshore variability in water depth (Bowen 1969; Haller et al. 2002; Bruneau et al. 2011).

Bed-load and suspended-load transport modes typically co-exist on sandy beaches (e.g., Komar 1978; Bailyard and Inman 1981) with, under high bed shear stresses (e.g., swash zone), sheet flow transport occurring where large quantities of sand are transported in a mixed sand-water layer moving very close to the bed (Masselink and Hughes 1998; Lanckriet and Puleo 2015). Critical to beach morphological response is cross-shore sediment transport. At any point along a beach profile, the net sediment transport is the result of the imbalance between the onshore-directed sediment transport driven by wave nonlinearity (skewed and asymmetric near-bed orbital velocities) and the offshore-directed sediment transport driven by the undertow, with infragravity waves also advecting the suspended

sand either onshore or offshore (Osborne and Greenwood 1992; Ruessink et al. 1998; Smith and Mocke 2002) depending on the local ratio of gravity and infragravity wave heights (de Bakker et al. 2016). During storms, intense wave breaking drives strong undertows that transport sediment seaward, resulting in offshore sandbar migration and beach erosion (e.g., Sallenger et al. 1985; Roelvink and Stive 1989; Gallagher et al. 1998). During weakly to nonbreaking, yet sufficiently energetic, wave conditions, the near-bed wave nonlinearity-driven bedload transport results in slow onshore sandbar migration concurrent with the accretion of the beach and berm formation (e.g., Trowbridge and Young 1989; Gallagher et al. 1998). The time evolution of the respective contributions of wave nonlinearity and undertow to the net cross-shore sediment transport (Thornton et al. 1996; Hoefel and Elgar 2003), which control beach response, is therefore intrinsically linked with incident wave climate variability (Figure 1b).

All wave-dominated beaches and surf zones are subjected to the same fundamental physical wave processes, but surf zone hydrodynamics differ significantly between steep and gentle beaches (Huntley and Bowen 1985). The difference in surf zone characteristics can be quantified by simple nondimensional parameters (Anthony 1998), such as the surf scaling parameter (ε_b)

$$\varepsilon_b = 2\pi^2 \frac{H_b}{g T^2 \tan^2 \beta}, \quad (1)$$

where H_b , T and $\tan \beta$ are significant breaking wave height, wave period and beach slope, respectively. The surf scaling parameter can be used to discriminate between reflective wave conditions with surging breakers and standing wave motion ($\varepsilon_b < 2$), and dissipative conditions with spilling breakers ($\varepsilon_b > 20$); intermediate conditions with plunging breakers occur in between.

Static beach state classification

Systematic field observations of beach morphological change commenced in the 1950s and, complimented by concurrent wave flume experiments, revealed the highly dynamic nature of beaches. These early studies, summarised by Komar (1976), highlighted the important control of wave conditions. Simple parameterisations of wave conditions (height, energy and steepness), sometimes involving sediment properties, were proposed as onshore/offshore transport thresholds (e.g., Gourlay 1968; Dean 1973). Wave conditions vary over a range of timescales, and beach morphology is expected to vary accordingly (Figure 1), giving rise to the notion of cyclic and seasonal beach response (Nordstrom 1980). This understanding resulted in a dichotomised profile characterisation of storm versus post-storm (and winter versus summer, bar versus berm and swell versus sea), and an essential component of the process of transitioning between these two polarised profile configurations is cross-shore bar migration. Furthermore, it became recognised that the transition between ‘barred’ and ‘non-barred’ beach profiles is characterised by Markovian inheritance (Sonu and van Beek 1971), whereby any resulting beach profile depends on a preceding profile, and that such transitions generally involve the development of three-dimensional bar features, referred to as ‘rhythmic topography’ (Sonu 1973).

By exploiting the natural laboratory of the southeast coast of New South Wales with its wide range of wave conditions and beaches, Australian coastal researchers were the first to link the variability in beach morphology to surf zone hydrodynamics. Short (1979) proposed a beach model based on several years of daily observations on Narrabeen Beach, Sydney, that covered the full reflective–dissipative domain, recognising erosional and accretionary beach state transitions. Wright et al. (1979) developed a similar model based on field measurements of waves and currents on different New South Wales beaches, also covering the full reflective–dissipative spectrum. The Short (1979) model was thus based on the *temporal* changes on a single beach forced by variations in the wave conditions, whereas the approach of Wright et al. (1979) leveraged the *spatial* variability in environmental conditions (mainly waves and sediments). The models were consolidated in a beach model consisting of six distinctive beach states, including the reflective and dissipative end members, and four intermediate beach states (Wright and Short 1984; see Figure 3). Reflective beaches are characterised by a steep beach face and often the presence of a beach step and beach cusps, whereas dissipative beaches have a low-gradient and subdued (multiple) linear bar morphology. The intermediate beach types are all characterised by rhythmic nearshore bar morphology. The real innovation of the Australian beach model was to link the occurrence of different beach types to the dimensionless fall velocity Ω originally proposed by Gourlay (1968) to separate onshore and offshore sediment transport based on flume experiments

$$\Omega = \frac{H_b}{w_s T}, \quad (2)$$

where w_s is the sediment fall velocity of the beach sediment. The different beach types and their associated values are: reflective (R , $\Omega < 1$); low tide terrace (LTT, $\Omega = 2$); transverse bar–rip (TBR, $\Omega = 3$); rhythmic bar and beach (RBB, $\Omega = 4$); longshore bar–trough (LBT, $\Omega = 5$) and dissipative (D , $\Omega > 6$; Figure 3).

The Australian beach model has been widely used as a basis for further research, and objective classification of beach morphology using video data broadly confirmed the Australian beach types and

also enabled the identification of residence times and beach state transitions (Lippmann and Holman 1990; Ranasinghe et al. 2004). The distinctive hydrodynamic process signatures that characterise the different beach types in terms of the importance of incident waves, infragravity waves and mean flows identified by Wright and Short (1984) was also further explored (Aagaard et al. 2013; Hughes et al. 2014; Figure 3).

Researchers also recognised shortcomings in the model. The role of tides in beach morphodynamics was addressed by Wright et al. (1982, 1987), and Masselink and Short (1993) introduced an additional dimensionless parameter, the relative tide range RTR, representing the ratio between the mean spring tide range and breaking wave height, to quantify the tidal importance in shaping beach morphology. On beaches with multiple bars, bar dynamics were found to be coupled with the outer bar morphology modulating the wave energy reaching the inner bar system(s) (Senechal et al. 2009), resulting in the formulation of multibar models (Short and Aagaard 1993; Castelle et al. 2007). Gravel beaches have a value for $\Omega < 1$ even under the most energetic wave conditions; however, distinctive gravel beach types exist that do not readily match the description of the reflective beach type, including pure gravel beaches, mixed sand–gravel beaches and composite gravel beaches (Jennings and Shulmeister 2002). Application of the beach model, originally developed based on observations on exposed sandy beaches, to low-energy settings proved problematic, most likely due to the presence of absolute energy thresholds to generate certain morphologies (bars and rips). It either led to the identification of unique beach types (Hegge et al. 1996) or it was found that following high-energy events, the beach morphology can become arrested over extended periods of low-wave conditions (Goodfellow and Stephenson 2005; Ojeda et al. 2011). The existence of wave energy thresholds also proved to be a critical factor in the classification of UK beaches; Scott et al. (2011) found that a wave energy flux P of 3 kW m^{-1} was found to differentiate between intermediate beaches with ($P > 3 \text{ kW m}^{-1}$) and without ($P < 3 \text{ kW m}^{-1}$) three-dimensional bar/rip morphology. Geology is generally identified as the most important factor that is missing from the beach model, and it has been argued that for embayed beaches, geological factors are more important determinants of beach morphology than contemporary dynamics (Jackson et al. 2005; Loureiro et al. 2013). Gallop et al. (2020) argue that geologically controlled beaches are a distinct beach type, having unique morphodynamics, and McCarroll et al. (2016) proposed a new headland-protected beach type that is resistant to upstate transition.

The Australian beach model is mainly a static predictive model, but of equal interest is the dynamic beach behaviour, especially the transitions between the different beach types. Such transitions are fundamentally driven by a disequilibrium between the surf zone hydrodynamics and the beach morphology, addressed in the ‘Cross-shore behaviour’ section.

Beach morphodynamics

In the coupled morphodynamic system (Figure 1a), hydrodynamic processes respond instantaneously to morphological change (Wright and Thom 1977). However, morphological change requires the redistribution of sediment, with sediment taking a finite time to move, resulting in a lag in the morphological response to hydrodynamic forcing and a disequilibrium between incident wave conditions and beach morphology (Wright et al. 1985). In

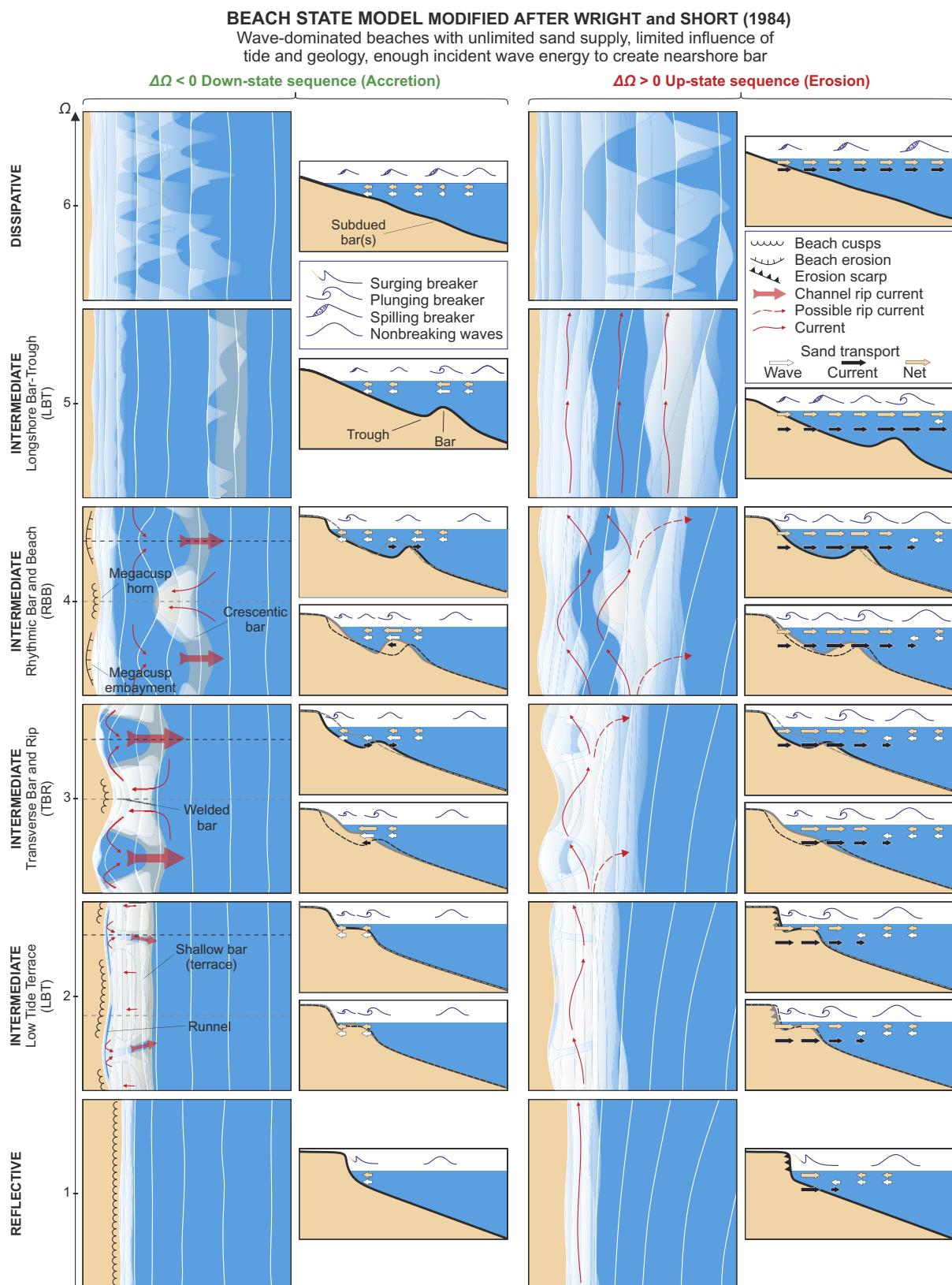


Figure 3. Beach state model modified after Wright and Short (1984) with (left-hand panels) accretive downstate sequences and (right-hand panels) erosive upstate sequences. The arrows represent indicative sediment transport magnitude and direction with relative contributions of waves and currents.

addition, morphodynamic processes exhibit positive and negative feedback mechanisms driving the development or decay of rhythmic patterns in the sand ('morphodynamic instabilities'), including sand ripples, beach cusps, transverse bars, crescentic sandbars and capes (Seminara 1998). These concepts of equilibrium beach response and morphodynamic instabilities are key to cross-shore and longshore beach behaviour (see the 'Cross-shore behaviour' and 'Alongshore behaviour' sections), and can explain the empirical beach state models described in the 'Static beach state classification' section, including their dynamic transitions (see the 'Coupled cross-shore and alongshore behaviour and natural complexity' section).

Cross-shore behaviour

A fundamental aspect of cross-shore beach profile behaviour is that sediment transport and morphological changes are governed by wave *process gradients*. In other words, the hydrodynamic driving forces vary in the cross-shore direction (Figure 2), and the resulting gradients in net sediment transport drive morphological change, including the formation, migration and decay of berm and bar features through feedback mechanisms. Process-based beach profile models have shown fair skill in predicting the underwater beach profile evolution at different sites on timescales from hours to years during both moderate and storm conditions (e.g., Thornton et al. 1996; Hoefel and Elgar 2003; Ruessink et al. 2007; Roelvink et al. 2009; Dubarbier et al. 2015). However, these models still require rigorous site-specific calibration. In addition, wave phase-averaged models, which disregard swash sediment transport processes, fail to reproduce the upper beach evolution and berm development. More computationally expensive gravity or infragravity wave phase-resolving models (Roelvink et al. 2009; Briganti et al. 2016) are more appropriate to simulate morphological changes along this section of the beach profile.

Even under steady wave forcing, given the lag in morphological response to hydrodynamic forcing, it takes time for a beach system to reach equilibrium (Grasso et al. 2009). However, given that the typical timescales associated with changes in incident wave conditions, compounded by tidal variations in the water level, are shorter than the timescales associated with morphological changes, the beach never attains equilibrium. The direction and rate of morphological change (e.g., erosion vs. accretion) of a given morphological state indicator A (e.g., shoreline position and beach state) towards a time-varying equilibrium condition D_{eq} (with D , e.g., incident wave energy, Ω) can thus be predicted in terms of the instantaneous wave thrust F (e.g., wave power or some other wave-based parameter) available to move the sediment, and the dynamic disequilibrium $\Delta D = D - D_{eq}$. Equilibrium models are generally of the form

$$\frac{dA}{dt} = k^{+/-} F \Delta D, \quad (3)$$

with $k^{+/-}$ a model-free response rate parameter that has different values for accretion ($\Delta D < 0$) and erosion ($\Delta D > 0$) events. Such equilibrium response was first introduced conceptually by Wright and Short (1984) to describe the beach state transition (with A the beach state and $F = D = \Omega$; see Figure 4). Such equilibrium approach was subsequently implemented in simple numerical models (e.g., Miller and Dean 2004; Davidson and Turner 2009; Davidson et al. 2010) for different morphological descriptors A , such as sandbar cross-shore position (Plant et al. 1999), beach profiles (Larson and Kraus 1989), sediment grain size (Prodger

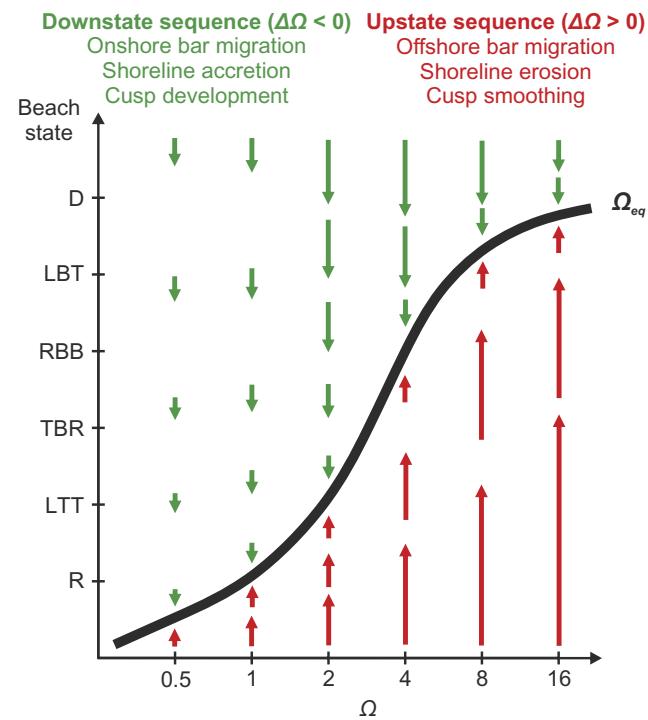


Figure 4. Conceptual diagram illustrating the relationships between change in beach state (and bar migration, shoreline change and cusp development) and morphodynamic disequilibrium and incident wave thrust, with arrow length proportional to the rate of change. Modified after Wright and Short (1984).

et al. 2016), three-dimensional beach morphology (Stokes et al. 2015), coastal embayment rotation (Turki et al. 2013) and, mostly, shoreline S response from the timescales of hours (storm) to decades at cross-shore transport dominated sites (e.g., Yates et al. 2009; Davidson et al. 2013; Lemos et al. 2018; Jaramillo et al. 2020; D'Anna et al. 2021). In the ShoreFor model (Davidson et al. 2013), the disequilibrium condition is based on the weighted average of Ω over the past 2Φ days, attributing to Φ the role of beach 'memory'. Model-free parameters including Φ can be estimated based on a weighted mean dimensionless fall velocity accounting for the seasonality in incident wave conditions (Splinter et al. 2014), resulting in a large inter-site variability of response modes. These contrasting beach responses are qualitatively illustrated in Figure 5, which shows four representative coastal sites with different wave climates (Figure 5a–c) and shoreline response time series: (1) strong seasonal and interannual timescales (large Φ) in southwest France (Figure 5d,f); (2) storm timescale (low Φ) in the Mediterranean Sea (Figure 5e,g); (3) (semi-)annual timescale in the Caribbean Sea (Figure 5h,j) and (4) low-amplitude seasonal timescale in the Bight of Benin (Figure 5i,k).

Alongshore behaviour

In contrast with cross-shore behaviour, alongshore behaviour on open sandy beaches is characterised by *no process gradients* as offshore wave conditions are mostly uniform alongshore. Despite this (initial) alongshore uniformity in wave forcing, the nearshore region often exhibits a wide range of coherent patterns in the sand, such as beach cusps (tens of metres; Guza and Inman 1975; Coco et al. 1999), megacusps (hundreds of metres; Short 1999; Thornton et al. 2007; Castelle et al. 2015) and three-dimensional surf zone

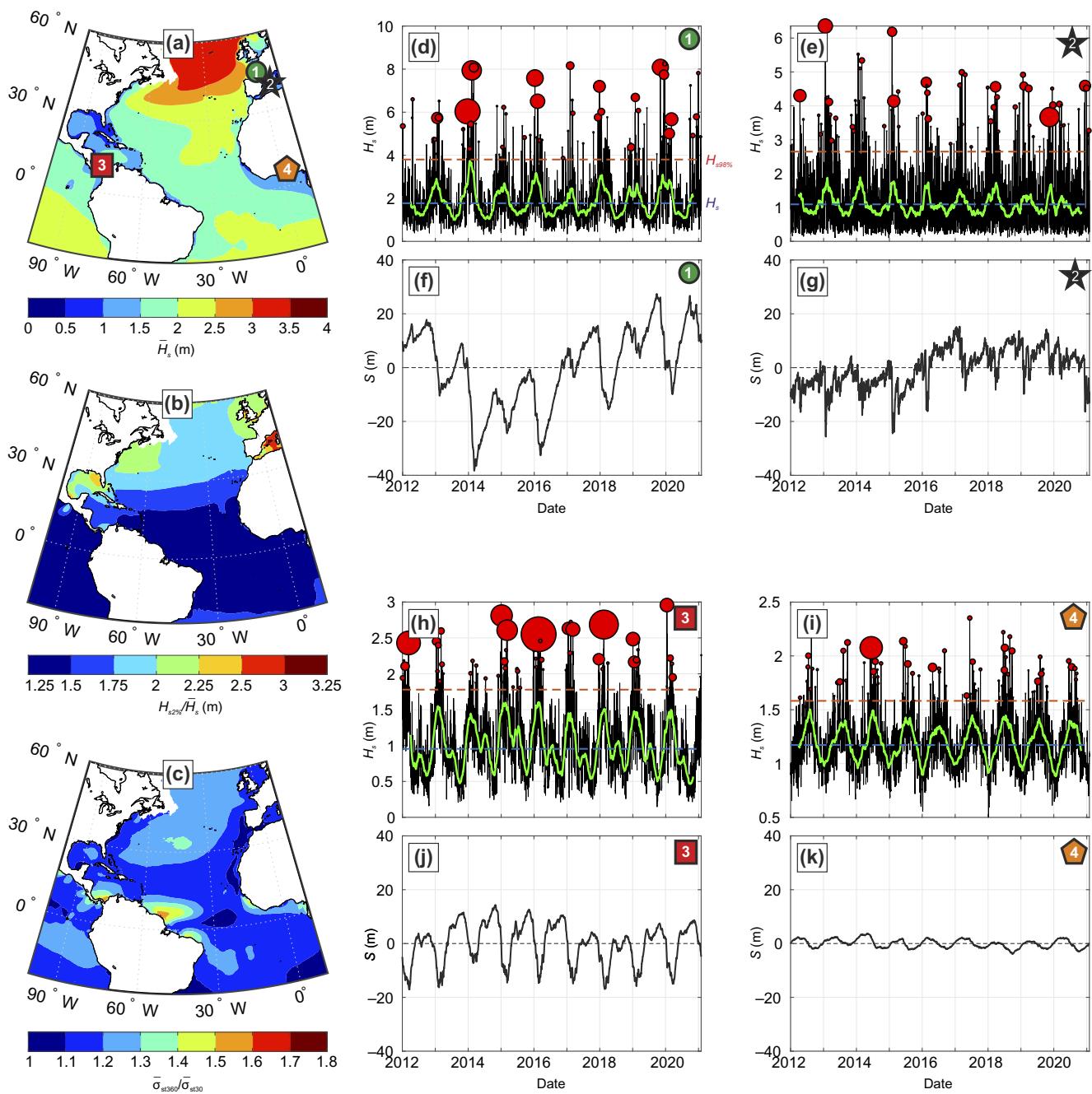


Figure 5. Illustration of the range of timescales and amplitude of beach response, here looking at shoreline position S . Left-hand panels: spatial distribution of (a) mean significant wave height \bar{H}_s , (b) $H_{s95\%}/\bar{H}_s$ where $H_{s95\%}$ is the 0.95 quantile and (c) $\bar{\sigma}_{H/T360}/\bar{\sigma}_{H/T30}$ where $\bar{\sigma}_{H/T30}$ ($\bar{\sigma}_{H/T360}$) is the average standard deviation of H_s/T_p at the monthly (yearly) timescale. Right-hand panels: time series of (d,e,h,i) H_s (black), its 2-month moving averaged (thick green) and storms (bubbles) with bubble size proportional to storm duration according to Masselink et al. (2014), with the largest bubble in (h) corresponding to a 27.25-day cluster, and (f,g,j,k) of shoreline position deviation around the mean S modelled with an adaptation of the ShoreFor model. The locations of the four sites are shown in (a). A first-pass calibration was performed for sites (d,f) and (i,k), and arbitrary parameters were used at (e,g) and (h,j).

bars (tens to thousands of metres; Short 1999; van Enckevort et al. 2004), as shown in Figure 3. The formation of these rhythmic features was initially ascribed to a forcing template in the hydrodynamics (Bowen and Inman 1971; Guza and Inman 1975; Holman and Bowen 1982), namely standing edge waves, which are along-shore periodic infragravity waves trapped close to the shoreline by refraction and reflection (Guza and Davis 1974). Similarly, cross-shore standing infragravity waves have been considered responsible for multiple nearshore parallel bars (Bowen 1980).

Such ‘forcing template’ theories for generating rhythmic patterns on beaches have been superseded by new explanations involving interactions between fluid flow, sediment transport and evolving morphology that create positive feedback mechanisms and lead to spontaneous pattern self-organisation (see the review of Coco and Murray 2007). Flow over a mobile bed, through associated sediment fluxes, can reshape the bed. If the changes in the shape of the bed reinforce the patterns of flow and sediment fluxes that lead to the shape change (positive feedback),

finite-amplitude bed features ('morphodynamic instabilities') can rapidly emerge where no coherent flow or sediment structures previously existed. Morphodynamic instabilities, which have been successfully modelled through linear or nonlinear stability analyses (e.g., Deigaard et al. 1999; Falqués et al. 2000; Calvete et al. 2005; Falqués et al. 2008; Castelle and Ruessink 2011) typically take the form of an alongshore sequence of horns (shoals) and bays (cross-shore troughs), alternating shoreward and seaward of a shore-parallel line (van Enckevort et al. 2004). They can form through different feedback mechanisms. For example, crescentic bars, finger bars and beach cusps develop through bed-surf (Falqués et al. 2000), bed-flow (Ribas and Kroon 2007) and beach-swash (Werner and Fink 1993) interactions, respectively. Under time-invariant wave forcing, these instabilities self-organise into alongshore-uniform features through merging and splitting (Garnier et al. 2006).

Coupled cross-shore and alongshore behaviour and natural complexity

The development of morphodynamic instabilities has been mostly observed during down-state (accretive) sequences (see the 'Static beach state classification' section), corresponding to a positive disequilibrium ($\Delta D < 0$; see the 'Cross-shore behaviour' section) characterised by general onshore sediment transport. From an initially alongshore-uniform offshore sandbar (e.g., LBT state), surf zone morphodynamic instabilities can develop through positive feedback between wave-driven rip-cell circulation and the evolving seabed (bed-surf interaction; Falqués et al. 2000). Dubarbieux et al. (2017) performed the first numerical experiment of a full down-state sequence from LBT to LTT. They showed that initially (LBT–RBB–TBR transition), onshore sediment transport driven by wave nonlinearities is critical to the overall rapid onshore sandbar migration (large positive disequilibrium), with concurrent positive feedback mechanisms through bed-surf interaction (alongshore morphodynamic instabilities). During such transition, instability wave length typically decreases through mergings (Garnier et al. 2010) as rip spacing decreases with decreasing sandbar distance to the shore (Calvete et al. 2005). Subsequently (TBR–LTT transition), gravitational downslope sediment transport acts as a damping term inhibiting further channel growth enforced by rip flow circulation, which, together with the slow onshore sandbar migration (small positive disequilibrium), results in the complete bar welding to the beach and rip channel infilling (negative feedback mechanism), resulting in a relatively alongshore uniform LTT state. In contrast, beach cusps experience positive feedback (bed-swash interaction; Coco et al. 1999, Coco et al. 2004) throughout the downstate sequence as evidenced by the increasingly cusped LTT beach face (Figure 3). Up-state (erosive) transitions characterised by general offshore sediment transport are less understood. The rapid decay of these morphodynamic instabilities has been observed during storms together with offshore bar migration (Wright and Short 1984; Almar et al. 2010). However, under storm conditions with long peak period and shore-normal incidence, morphodynamic instabilities can be maintained and beach megacusp embayments can even erode back to the dune system causing severe localised dune scarping without any up-state sequence (Castelle et al. 2015). More recently, morphodynamic instability decay has been observed and modelled under moderate energy obliquely incident waves (Price and Ruessink 2011; Garnier et al. 2013), coinciding with dominant offshore sediment transport, large longshore sediment fluxes, beach erosion and seaward sandbar migration (Price and

Ruessink 2011; Walstra et al. 2012), highlighting the key role of the angle of incidence in up-state sequences (Figure 3).

As acknowledged by Coco and Murray (2007), self-organisation hypotheses can be compatible with some template theory concepts. A salient example is morphological coupling whereby offshore bathymetric variability (e.g., outer sandbar and inner shelf ridges), which enforces alongshore variable incident wave conditions, can control the alongshore variability of bar patterns (Castelle et al. 2010; Price et al. 2014; Coco et al. 2020; Nnafie et al. 2021). Surf zone morphodynamic instabilities are also often mirrored at the shoreline with the presence of megacusp embayments, with megacusp embayments facing rip channels incising the bars (Figure 2). Hydrodynamic templates (edge waves; Guza and Davis 1974) were also found to trigger surf zone morphodynamic instabilities and to affect their fully developed characteristics (Reniers et al. 2004). Thus, the role of hydrodynamic templates in generating rhythmic morphology must not be completely excluded.

Conclusions and future perspectives

Using the morphodynamics approach (cf. Figure 1; Wright and Thom 1977) as the underpinning framework, this review provides a synthesis of how ocean waves affect the morphological behaviour of wave-dominated beaches over short-to-medium timescales (days to years). Based primarily on research conducted on relatively energetic ($H_s > 0.25 – 0.5$ m) and small tidal (mean spring tide range < 3 m) beaches with abundant sand, the 'Australian beach model' (cf. Figure 3; Wright and Short 1984) describes the occurrence of beach types across the full reflective-dissipative spectrum based solely on wave conditions and sediment characteristics. The model has been widely tested and applied, and remains a useful physical framework to consider sandy beach morphological characteristics and surf zone hydrodynamics, with significant applications to other fields of research (e.g., beach ecology, surf zone hazards and pollutant dispersal). Transitions between different beach types are driven by temporal changes in the wave forcing conditions, and the wave climate is key in explaining the frequency-response characteristics of beach morphological time series (e.g., beach type, shoreline position and beach volume; cf. Figure 5). Cross-shore morphological changes are primarily controlled by equilibrium principles with below (above) average wave conditions driving down-state (up-state) transitions associated with net onshore (offshore) sediment transport (cf. Figure 5; Davidson et al. 2013). Morphodynamic feedback processes resulting in self-organising behaviour are primarily responsible for alongshore morphological variability and the generation of rhythmic shoreline features, such as crescentic bars, rip channels and beach cusps (Coco and Murray 2007).

Previous beach research has mainly focused on the relatively easily accessible subaerial beach and the shallow subtidal region, with data obtained using conventional surveys and video imagery. Such data sets are generally not collected at the temporal scale (<10 years) and resolution (monthly) commensurate with beach morphodynamics, which can change from day to day (e.g., during storms; Almar et al. 2010) and can display decadal variability due to hemispheric-scale fluctuations in the wave climate (e.g., Masselink et al. 2014; Barnard et al. 2017; Dodet et al. 2018). Global satellite data sets going back to the 1980s are beginning to be analysed to explore hemispheric-scale climate forcing of beach change (Vos et al. 2022), and the availability of high-resolution geostationary satellite data also opens new perspectives by

increasing data frequency and reducing satellite-derived product uncertainties. The development of advanced nonlinear depth-inversion methods from LiDAR scanners (Martins et al. 2017), X-Band radar or even conventional video monitoring systems (Rutten et al. 2017) should enable including changes in the subtidal zone where data are lacking, particularly under energetic wave conditions.

It is increasingly realised that sediment exchange between the upper and lower parts of the shoreface, and also across the depth of closure (cf. Figure 2), can play a key role in the nearshore sediment budget and, thus, beach morphology (Harley et al. 2022). These sediment exchanges are difficult to quantify as the associated bed-level changes are comparable to the detection limit. Furthermore, in situ sediment flux measurements require large numbers of state-of-the-art acoustic instruments (e.g., Zedel et al. 2021) deployed for long periods of time to provide robust information from which to derive a sediment budget. Information gathered with sediment tracers might provide complimentary data (Pearson et al. 2021), especially if co-collected with hydrodynamic data and complemented by numerical modelling.

Complex process-based models, which typically couple hydrodynamics, waves, sediment transport and morphology through mass and momentum conservation laws (Lesser et al. 2004), are skilful on short temporal (O [days]) and spatial scales (O [100 m]). However, presently these models are not able to adequately simulate the swash–surf– shoaling morphodynamics continuum, and their strongly nonlinear nature results in an inescapable build-up of errors in longer-term simulations. Further progress must be made in the 3D description of nearshore currents, cross-shore sediment transport and beach recovery processes (e.g., Hoefel and Elgar 2003; Uchiyama et al. 2010). Computationally cheap hybrid models, which are based on general principles (e.g., behavioural laws and semi-empirical rules) and a selection of the dominant driving processes (e.g., cross-shore transport through equilibrium-based response), can lead to more reliable long-term evolution simulations with many recent skilful shoreline applications (Vitousek et al. 2017; Robinet et al. 2018; Antolínez et al. 2019). These models rely on free parameters that show a variability on timescales of years linked with wave climate variability which needs further investigation (Ibaceta et al. 2020). Sea-level-rise beach response is generally implemented using basic rules (Bruun 1962). New rules-based shoreface translation frameworks, including, for example, dune encroachment or barrier rollback (McCarroll et al. 2021), must be implemented. Given the uncertainties in the shoreline drivers (e.g., wave climate and sea-level rise) and in shoreline model formulation (e.g., model-free parameters), a (probabilistic) ensemble approach based on such hybrid models must be developed (Montaño et al. 2020; D'Anna et al. 2021) to address the future of beaches in the frame of climate change (Voudoukas et al. 2020; Cooper et al. 2020). Coastal scientists, managers and engineers will thus need to embrace uncertainties and build on improved beach change models to develop coastal management strategies (e.g., beach nourishment, nature-based solutions and well-designed coastal structures) to optimise coastal resilience.

The challenges presented by measuring (and modelling) the highly dynamic beach environments, occasionally exposed to wave conditions in excess of 5 m, require large research efforts, including long-term monitoring programmes (Turner et al. 2016), intense field campaigns (Senegal et al. 2011) and mining of remotely sensed data (Vos et al. 2019). Such projects, which ideally involve multidisciplinary research teams with expertise in field research, remote sensing, big-data and numerical modelling, will improve

our understanding and capacity to predict the future of sandy beaches, trajectory shifts and coastal hazards in an increasingly stormy world.

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