Earth-Science Reviews 210 (2020) 103358

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

Review Article

Multiple intertidal bars on beaches: A review

M. Biausque[a,*], E. Grottoli[a], D.W.T. Jackson[a,b], J.A.G. Cooper[a,b]

[a] School of Geography & Environmental Sciences, Ulster University, Cromore Road, Coleraine, Northern Ireland, UK
[b] Discipline of Geology, University of KwaZulu-Natal, Durban, South Africa

ARTICLE INFO

Keywords:
Ridge and runnel
Multiple sandbars
Intertidal systems
Morphodynamics
Surf zone

ABSTRACT

Ridge and runnel features were originally described by King and Williams (1949) from observations at Blackpool beach (U.K.) and laboratory experiments. They were characterised as intertidal, shore-parallel sandbars (ridges), commonly 2–6 bars in total, and disconnected from each other by troughs (runnels). The nomenclature 'ridge and runnel' was, however, also used by Hayes (1967) to describe multiple-barred beaches but referring to subtidal bars. The more specific term 'Multiple Inter-Tidal Bars' (MITB) was subsequently adopted for intertidal beaches exhibiting successive shore-parallel sandbars. To date, a detailed understanding of the formation of MITB has remained elusive and their precise definition is still unclear. It has been suggested that MITB features are the result of both swash and surf zone processes acting on the intertidal beach profile. These processes are involved in the formation, the long-term persistence, and behaviour of MITB.

Despite the long-term persistence of MITB systems they are dynamic at short timescales. Ridge crest positions are regularly modified over each tidal cycle by successive surf and swash processes. At seasonal scales, ridges may undergo erosion and cross-shore migration under high energy conditions (winter) while ridges are well developed during summers. Via a meta-analysis of 93 separate published works at 67 sites globally, we define MITB, characterise their morphodynamics and assess their global distribution. Our study shows that the distribution of MITB is a function of thresholds in beach slope (< 0.02), tidal range (3–10 m), and wave period (3–8 s). They are developed at sites with sufficient sediment supply, limited wind and wave fetch, meso- to macrotidal (> 3 m) and on low gradient (wide) intertidal beach slopes.

1. Introduction

Intertidal bar systems comprise shore-parallel features characterised by at least one intertidal bar crest and shoreward depression, or trough (Masselink et al., 2006). The number of bars observed between the mean low and high-water spring tide levels can vary from 1 up to 20 along the cross-shore profile. A classification of intertidal bar systems based on tidal range and beach slope parameters (and/or beach width) enables identification of different morphological environments including swash bars, sand waves and ridges and runnels (e.g. Short, 1991; Masselink et al., 2006). Intertidal barred beaches are ubiquitous globally yet are surprisingly less-studied than the subtidal environment. They (including subtidal bars), however, play an important role as natural buffers against wave energy under high energetic conditions and are important natural habitats (e.g. Dissanayake et al., 2015). Examining their morphodynamics at different timescales is therefore the first step toward a better understanding of coastal processes, especially in the context of climate change and sea-level rise.

'Ridge and runnel' beach morphologies are still poorly studied and understood environments, leading to controversial hypotheses, and opposing conclusions regarding their genesis and morphodynamics. Initially described in 1949 by King and Williams, the 'ridges and runnel' nomenclature was originally proposed to characterise a succession of two or more intertidal shore-parallel sandbars. In 1967 Hayes, followed by Hayes and Boothroyd (1969), however, used the same nomenclature to describe multiple-barred environments, including subtidal-barred features in North America. The use of the same name to characterise morphologies that differ in terms of genetic and physical processes helped (and still does) create confusion in the literature, leading to a misunderstanding of mechanisms involved in ridge and runnel genesis and their morphological evolution.

In this global study, we examine existing hypotheses and discussions/results from various metadata from 67 previously studied sites to concisely identify and define intertidal ridge and runnel features. Secondly, we review their observations and models of their short- to long-term morphodynamics. Finally, we identify key morphological parameters and hydrodynamic settings associated with ridge and runnel occurrence and elucidate their global distribution.

---

* Corresponding author.
E-mail address: m.biausque@ulster.ac.uk (M. Biausque).

https://doi.org/10.1016/j.earscirev.2020.103358
Received 19 May 2020; Received in revised form 31 July 2020; Accepted 7 September 2020

2. Nomenclature: a debate

2.1. From the past: the “British School” vs. the “North American School”

Originally, two schools of thought described and defined ridge and runnel systems: the ‘British School’, exemplified by King and Williams (1949), introduced a definition based on genetics and physical processes, and the “North American School”, (Hayes, 1967; Hayes and Boothroyd, 1969), proposed a morphological-based definition.

Ridge and runnels were first described from regular observations carried out at Blackpool (U.K.) between 1943 and 1949 (King and Williams, 1949). They applied the term “ridge and runnel” to intertidal bars, parallel to the shore, usually 2–6 in number, composed of fine to medium sand and built on low gradient beaches under macrotidal conditions and limited fetch (wind waves), in the presence of a sufficient sediment supply. They also noted that cross-shore channels formed along ridges, at falling tide, to drain the excess water from runnels. During rising tide waves break on ridges and water initially penetrates into runnels through the drainage channels. According to King and Williams' definition (1949), high tidal ranges and low-angle beach slopes are fundamental controls on ridge and runnel formation. Therefore, ridges and runnels are well-developed around semi-enclosed epicontinental seas (or inland seas) as The English Channel, the Irish Sea or the North Sea (e.g. Wright, 1976; Sipka and Anthony, 1999; Navas et al., 2001; Houwelingen et al., 2006; Reichmüth and Anthony, 2007; Héquette et al., 2009; Pye and Blott, 2016) and usually close to estuaries (Houwelingen et al., 2006).

Hayes (1967), and then Hayes and Boothroyd (1969), characterised ridge and runnels as morphologies associated with onshore sandbar migration. In this view ridge and runnels are the result of nearshore adjustments of an excess of sediment under different wave climates. In this context, the presence of ridges is related to post-storm, low-energy conditions, while runnels are revealed by the landward slope of the ridge and the old storm-eroded beach profile. According to the “North American school” the formation of ridges and runnels occurs via onshore bar migration driven by wave-climate changes, observed along swell-dominated tidal and non-tidal coasts.

The main differences between the two definitions were discussed in numerous papers (e.g. Orford and Wright, 1978; Orme and Orme, 1988; Short, 1991; Dawson, 2002; Stépanian, 2002; Houwelingen, 2005). Here, we are concerned only with multiple intertidal bar systems as conceived by the “British school”.

2.2. Toward a universal nomenclature: Multiple Inter-Tidal Bars

Orford and Wright (1978) argued that the term “ridge and runnel” should only be applied to geomorphologies corresponding to King and Williams' (1949) definition. Similarly, Mulrennan (1992) concluded that only structures following this definition qualify as “true” ridge and runnel topography. Indeed studies following the American definition include tidal to non-tidal environments (e.g. Davis, 1972; Dabrio, 1982), subtidal bars (e.g. Moore et al., 2003) and three-dimensional single swash bars (Table 1). Dawson (2002) elucidated the differences between ridge and runnels and swash bars in term of stability, shape and number of bars, hydrodynamic conditions (waves, tide) and genesis (Table 1).

Despite widespread acceptance of Orford and Wright's arguments that the term applies only to intertidal bars, the “American school” definition is still commonly employed. In a statistical analysis of 93 studies from 1949 to 2020 (Appendix and Fig. 1B), only 66% of the studies that use the nomenclature “ridge and runnel” actually refer to “ridge and runnel” systems sensu King and Williams (1949) (Fig. 1panels 8 and 9). The remaining 34% cover a variety of 3D bar morphologies, including single swash bars (Owens and Frobel, 1977; Garnier et al., 2007; Song et al., 2019, Figs. 1, 6), double-barred beaches with one inner and one subtidal bar (Pedreros et al., 1996; Michel and Howa, 1999, Figs. 1, 5; De Melo Apoluceno et al., 2002; Lafon et al., 2002), offshore bars (Moore et al., 2003),mud ridges (Whitehouse et al., 2000, Figs. 1, 7; Williams et al., 2008; Carling et al., 2009) and even sandbars in lakes (e.g. Lake Michigan, Davis, 1972). Studies describing intertidal sand waves (Mccave and Geiser, 1979; Hale and McCann, 1982; Moore et al., 2003; Yamada et al., 2007; Zonneveld et al., 2014) are also included in the 34% (“False RR”).

Even though sand waves are intertidal sandy bars parallel to the shore and morphologically comparable to ridges and runnels, they differ in terms of their shape (symmetrical vs. asymmetrical), number of bars (up to 20 bars for sand waves) and the slope of the intertidal beach (lower angle for sand wave morphologies). Furthermore, sand waves occur under low energy waves and in tidal ranges from micro- (Greenwood and Davidson-Arnott, 1979), meso- (Hale and McCann, 1982), to macrotidal (Short, 1991). Low slope topography and weak energy conditions are key forcing parameters leading to sand wave development while uncertainties still remain concerning tidal setting (Masselink et al., 2006). In a general morphodynamic classification of beaches, Short (1991) regarded sand waves as transitional features in tidal flat environments and distinct from ridges and runnels (Fig. 2).

The term “ridge and runnel” remains ambiguous and some authors have used alternative names to avoid confusion (e.g. Kroon and Masselink, 2002; Anthony et al., 2005; Masselink et al., 2006; Scott et al., 2011; Crapoulet et al. 2016). A statistical analysis of 93 studies (Appendix) shows that there are *five* different names commonly used in the literature to refer to “ridges and runnels”, including studies following the American definition (Fig. 1). The most common (74%) is “Ridges and runnels” but this can include different morphologies (see above), while the least-used (2%) is ‘Low-amplitude ridge’ (Wijnberg and Kroon, 2002; Masselink et al., 2006, Figs. 1, 3; Sassa and Watabe, 2009). “Intertidal bars” and “Intertidal bar-trough” are terms used largely by French authors working on sites in the North of France (Sedrati and Anthony, 2006; Anthony et al., 2007; Reichmüth and Anthony, 2007, Figs. 1, 1; Oblinger and Anthony, 2008; Maspataud et al., 2009, Figs. 1, 2; Cartier and Héquette, 2013), while “multiple intertidal bars” is more specific to U.K. authors (Kroon and Masselink, 2002; Masselink, 2004; Houwelingen et al., 2006, Van Houwelingen et al., 2008, Figs. 1, 4; Miles et al., 2019).

King and Williams' (1949) study proposed a definition based on site-specific observations based on a single transect measured on Blackpool beach (England). According to Masselink and Anthony (2001), even if their findings were confirmed by observations along the Lincolnshire coast (King and Barnes, 1964; King, 1972) they are mainly specific to these coasts, local reflecting hydrodynamic and topographic conditions, and are not necessarily representative of all ridge and runnel morphologies. Mulrennan (1992) showed that ridge and runnel morphologies can also be well developed under mesotidal conditions, suggesting that the tidal parameter must be less influential. Consequently, Masselink and Turner (1999), followed by Dawson et al. (2002), proposed that the intertidal profile width, which depends on the tidal range and the beach slope, was a more definitive parameter than a macrotidal range.

The term “ridge and runnel” remained ambiguous and Kroon and Masselink (2002) applied the term “Multiple Inter-Tidal bars” to a clearly defined succession of bars located in the intertidal beach area (Fig. 3) morphologically analogous to King and Williams' (1949) definition of ridge and runnel. Multiple intertidal bars were defined as relatively stationary topographies formed under tidal range conditions higher than 3 m. Therefore, meso- to macrotidal conditions are required to generate an intertidal area wide enough to allow the creation of multiple bar and trough systems. Scott et al. (2011) summarised MITB characteristics as incorporating: gentle slope (0.5–1.5°), intertidal beach width around 300–800 m, 3–6 sandbars located along the intertidal beach zone, parallel to the shore and interrupted by cross-shore drainage channels and other morphological irregularities as bifurcations or terminations (Fig. 1, panels 1–4, 8 and 9; Houwelingen et al.,

Table 1
Table comparing ridge and runnel and swash bar studies (based on Dawson (2002)).

Study	Classification	Wave climate	Beach slope	H_s (m)	T_p (s)	Sediment size	Width of intertidal zone (m)	Tidal range
King and Williams (1949)	Ridge and Runnel	Low energy	0.007	–	–	Medium to fine sand	1220	Macrotidal
Hale and McCann (1982)	Ridge and Runnel	Low energy	0.003	3.0 (max)	7.0 (max)	Medium to fine sand	1220	Mesotidal
Mulrennan (1992)	Ridge and Runnel	Restricted fetch	0.013	0.65	4	Medium to fine sand	240–1000	Mesotidal
Voulgaris et al. (1998)	Ridge and Runnel	Short fetch	0.012	0.5–1.0	4–12	Medium to fine sand	200–500	Macrotidal
Dawson (2002) – Linden Beach	Ridge and Runnel	Short fetch	0.004	0.1–0.5	3–4	Medium to fine sand	300–500	Microtidal
Davis (1972)								
Lake Michigan	Swash bar	Short waves	0.01	0.24	3.2	–	–	Microtidal
Massachusetts coast	Swash bar	Short waves	0.02	0.43	7.0	–	–	Mesotidal
Owens and Frobel (1977)								
West site	Swash bar	Limited fetch	0.003	0.58	–	Well sorted sand	–	Microtidal
East site	Swash bar	Limited fetch	0.001	0.83	–	–	–	Microtidal
Dabrio and Polo (1981)	Swash bar	Low energy	–	0.01–0.02	3–3.5	Medium sand	–	Microtidal
Dabrio (1982)								
Mazarron	Swash bar	Low energy	–	0.2–0.6	3–3.5	Medium sand	–	Microtidal
Gulf of Cadiz	Swash bar	Medium-Low energy	–	0.5–1.0	4–7	Medium to coarse sand	–	Mesotidal
Michel and Howa (1999)	Swash bar	–	–	1.45–6.0	12	–	–	Mesotidal

2006), low amplitude ridges not exceeding 1 m and low energy wave climate ($0.4 < H_s < 1$ m and $5 < T_p < 6.5$ s). Moreover, a sufficient sediment supply is normally necessary such as nearby ebb-delta estuaries. The role of sediment supply has however been poorly investigated (Crapoulet et al., 2016) and the hypotheses that imply dynamic equilibrium (e.g. Saye et al. 2005; Houwelingen et al., 2006; Dissanayake et al., 2015; Miles et al., 2019) do not consider the need for adequate sediment supply. This important aspect requires further investigation, especially in longer-term studies. The term MITB is considered preferable to "Ridge and Runnel" and has therefore been adopted throughout the rest of this paper.

3. The Genesis of MITB: hypotheses

MITB systems are permanent (to semi-permanent) intertidal morphologies and to date, their formation has never been directly observed in the field, nor effectively modelled. Therefore, their genesis is still subject to discussion. The competing hypotheses are summarised below.

3.1. Convergence model (breakpoint bars)

King and Williams (1949) proposed the convergence model for

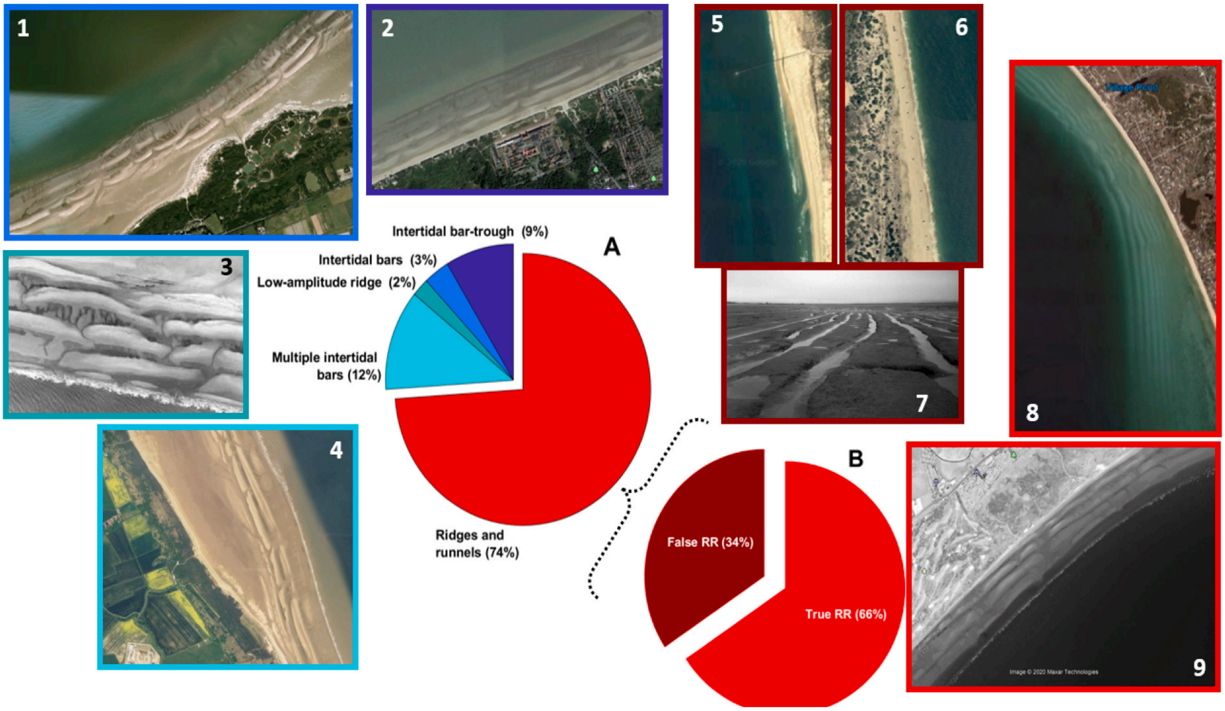

Fig. 1. Statistics based on 93 studies (Appendix 1): different names used in the literature to describe ridge and runnel systems (A) and use of the term RR in the literature to describe real RR system ("True RR") vs. non RR system ("False RR") (B).

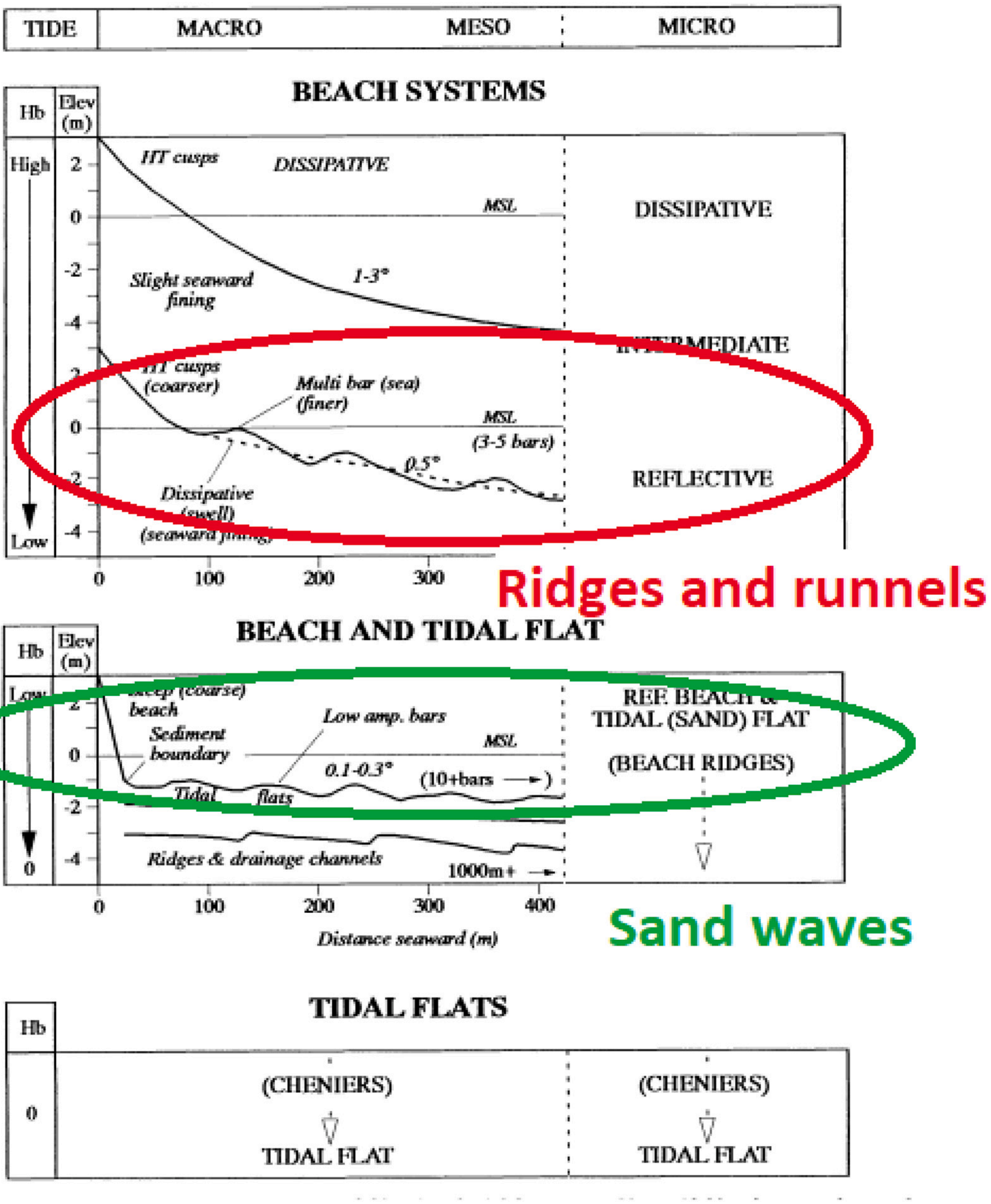

Fig. 2. Beach systems classification from Short, 1991 (modified) showing differences between sand waves and ridges and runnels.

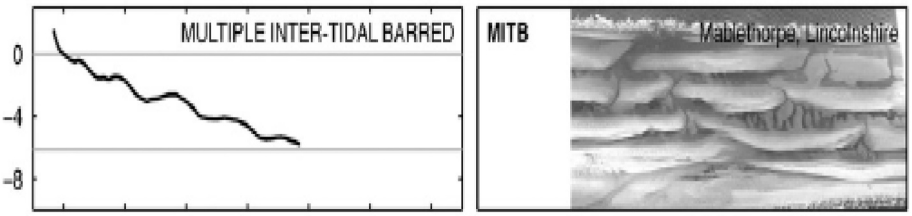

Fig. 3. Profile and corresponding aerial photograph of a multiple intertidal barred beach in England, from Scott et al., 2011 (modified).

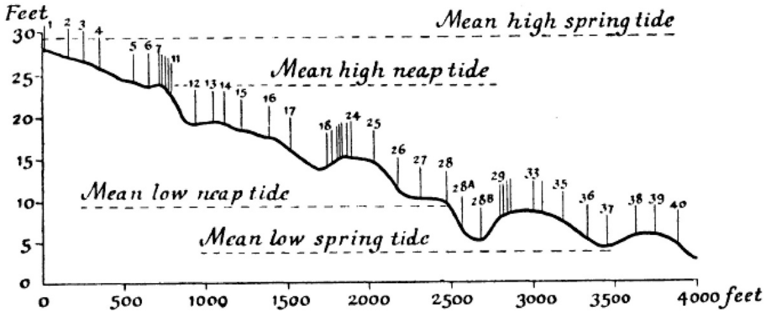

Fig. 4. Beach profile at Blackpool beach, from King and Williams (1949) showing the position of ridges and runnels compared to mean water levels.

formation of multiple intertidal bar morphologies. According to this hypothesis, the bars are formed around a convergence point defined as a breakpoint where sediment transported seaward meets the sediment carried toward the shore. Therefore, the sediment transported from both directions converges at the breakpoint, implying a decrease of the net sediment transport and an accumulation/deposition of this sediment, leading to the formation of a ridge.

A laboratory experiment, conducted by King and Williams (1949) using a wave tank, showed, however, flattening to complete erosion of a bar formed at the breakpoint, during falling water level periods (falling tides). Those observations were used to refute the convergence model as a suitable hypothesis for MITB formation (Dawson (2002)).

3.2. Swash-bar formation model

Although breakpoint bars were destroyed during falling tides, King and Williams (1949) also noted that bars which formed at high-tide by swash processes (swash-bars) survived. Consequently, they proposed an alternative model wherein ridges were swash-bars that ‘survived’ water level changes and was favoured by several other authors (e.g. King, 1972; Kroon and Masselink, 2002; Houwelingen, 2005). This model views MITB as the result of waves building a swash-bar at low tide, to create an equilibrium gradient or a naturally flatter beach. With rising tide, the ridge is progressively submerged and swash processes shifted landward; another swash-bar can then be subsequently built (Dawson (2002)). In advocating this model, King (1972) argued that as MITB are formed by swash mechanisms, those processes should be more efficient during particular water levels (i.e. those corresponding to the longest periods of stationary levels: mean spring and neap tide levels). The concept was supported by long-term observations recorded at Blackpool beach (England) where ridge positions coincided with relatively stationary water levels (Fig. 4). Field data showing a smooth seaward slope of the ridges and an increase in height in the seaward direction, supported the swash-bar formation hypothesis.

King and Williams (1949) and King's (1972) conclusions were, however, mostly based on site-specific observations and an incomplete model. Indeed, studies on MITBs mainly conducted around northern Europe (e.g. Wright, 1976; Mulrennan, 1992; Masselink and Anthony, 2001; Houwelingen et al., 2006; Masselink et al., 2006; Reichmüth and Anthony, 2008; Vaucher et al., 2018; Brand et al., 2020) reported ridges distributed across the entire intertidal beach profile and not just localised at mean spring and neap tide levels. Dawson (2002) suggested that it is unlikely, even in macrotidal environments, that the tide could stay stationary for a suitable time to build ridges and therefore the swash-bar model does not adequately explain MITB genesis. Moreover, Kroon and Masselink (2002) argued that King and Williams' (1949) experiment was inconclusive, as no attempt was made to model swash-bars in the intertidal beach area and thus, the impact of falling water levels on intertidal bars was not explored. They referred to results from Masselink and Anthony (2001) which suggested that the largest ridges in MITB systems seem to be positioned around the mid-tide level, a non-stationary swash zone, apparently refuting the notion of swash processes as the only parameters involved in MITB genesis, and therefore the swash-bar hypothesis as a general model.

3.3. Long wave processes

Simmonds et al. (1995, 1997) simulated the genesis of MITB morphologies, using the model described by Kirby et al. (1981), based on transport processes resulting from long wave mechanisms associated with incoming wave groups. They showed that the “potential for erosion” resulting from a monochromatic long wave envelope matched the scale of multiple intertidal morphologies on Nieuwpoort beach (Belgium coast). They also found sediment convergence patterns due to long wave processes to be well-correlated with ridge locations and spacing, and consequently argued that both intertidal features and long wave length-scales are similar. They therefore argued that standing long waves played a key role in the genesis of MITB morphologies within the intertidal zone of macrotidal, dissipative beaches.

Moreover, they also concluded that MITB and node-antinode spacing of stationary long waves were both related to the intertidal beach slope. Therefore, they asserted that it is more likely that long waves are responsible for multiple intertidal bar formations and argued that the swash-bar hypothesis (see above) should be rejected. Nevertheless, no actual field measurements or observations were reported in their study and the hypothesis does not include possible feedbacks between hydrodynamic processes and the evolving topography. Additionally, recurring changes in water levels along tidal cycles may affect the position of nodes and antinodes along the profile. Consequently, the “long waves hypothesis” has not been widely adopted in the literature.

3.4. Combined swash and surf zone processes

Carter (1988) suggested that both swash and surf processes were involved in the genesis of MITB features. He argued that bar formation might be initiated in the surf zone, depending on water levels and then maintained by swash mechanisms (Stépanian, 2002). Masselink and Anthony (2001) investigated the position of intertidal bars along the beach profile, at three different study sites in France and England, to examine the role of swash and surf processes in MITB genesis. They found that ridges were positioned across the entire intertidal zone and that the highest ridges were commonly localised around the mid-tide level. Those results supported the hypothesis of surf zone processes as main parameters that initiate the construction of MITB. Indeed,

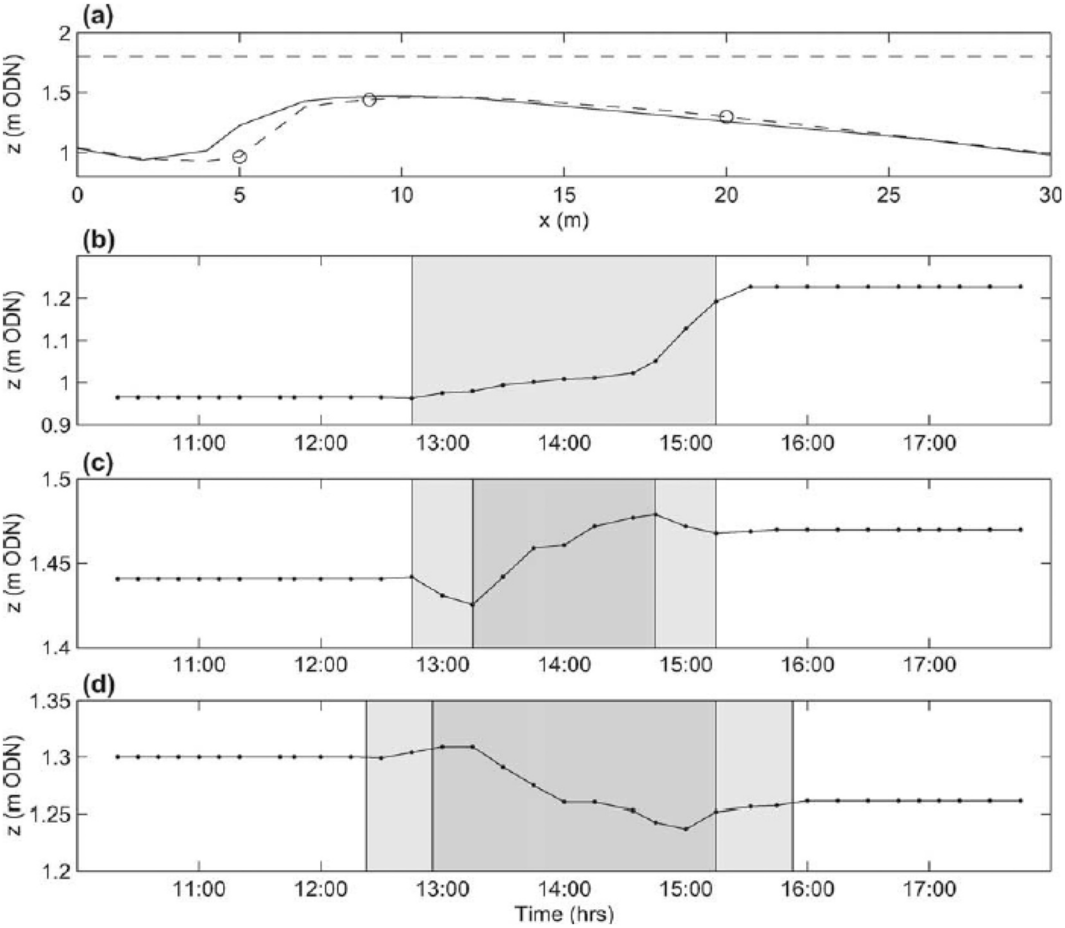

Fig. 5. From Kroon and Masselink, 2002: "(a) Beach profiles of bar 3 measured on the morning (dashed line) and evening (solid line) on 9 August. Horizontal dashed line indicates the high tide water level. Open circles indicate locations for which bed level changes are shown in figures below. (b) Changes in bed elevation measured during tidal cycle at x = 5 m. Shading indicates the time when wave and swash action took place on the bar crest. (c) Changes in bed elevation measured during tidal cycle at x = 9 m. Light and heavy shading indicates the time when swash and surf zone bores were operating at x = 9 m, respectively. (d) Changes in bed elevation measured during tidal cycle at x = 20 m. Light and heavy shading indicates the time when swash and surf zone bores were operating at x = 20 m, respectively".

energetic conditions acting during neap and mid-high tide periods help maintain mid-tide level under stationary surf zone conditions, a requirement in building intertidal bars. Furthermore, bars seemed to survive decreasing (to low) energy conditions as a result of an equilibrium between fast tidal translation rates and a longer time period required for the bar to adapt its morphology to hydrodynamic conditions (Masselink and Anthony, 2001).

Kroon and Masselink (2002) conducted a field experiment at Theddlethorpe beach, North Lincolnshire coast, in England. They positioned, instruments and rods along a cross-shore profile and measured the elevation above the surface of the rods at rising and falling tide every 15 min. They related every measured elevation point with hydrodynamic processes acting at the time, to quantify the relative importance of swash and surf mechanisms in time and space. When an onshore ridge was controlled by swash processes, the seaward ridges were commonly affected by breaking wave and surf zone mechanisms. This study showed that, every ridge in the MITB system undergoes swash, surf zone and shoaling wave processes during the neap to spring tidal cycle, leading to opposite sediment transport, and therefore to their stabilisation (Fig. 5).

Following those observations, Masselink (2004) proposed a numerical model to simulate MITB formation, evolution and stabilisation. A sediment transport shape function (e.g. Russell and Huntley, 1999; Mariño-Tapia et al., 2002) was used to model cross-shore sediment transport which included morphodynamic feedbacks. According to this model and congruent with field observations, ridges are built and enhanced under low wave conditions and flattened under high energy conditions (i.e. storms). Formation of ridges is visible when a sediment convergence is created due to the wave asymmetry and the bed return flow, inducing a dominant onshore sediment transport in the surf zone and insignificant transport outside the surf zone. Masselink concluded that two main requirements essential in producing multiple intertidal bars were: 1. low energy conditions in the surf zone, driving onshore sediment transport; and 2. the presence of separated cross-shore sediment transport cells. He suggested that self-organisation might also play a significant role in MITB genesis and maintenance.

In this model, MITB would be a combination between swash and breaker-bars, initiated and maintained as a result of surf and swash processes acting along the intertidal beach profile (e.g. Masselink and Anthony, 2001; Kroon and Masselink, 2002; Houwelingen et al., 2006). Additionally, strong longshore currents can take place within runnels, increasing the runnel's erosion and enhancing the ridges' amplitude

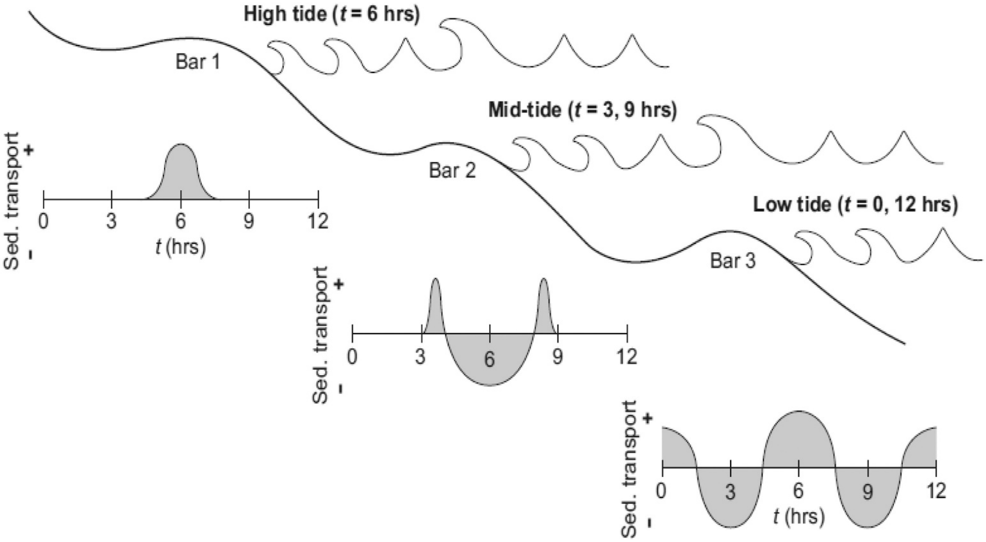

Fig. 6. From Masselink et al., 2006: "Variations in the cross-shore sediment transport rate and direction over a single tidal cycle for three different intertidal bar systems".

(Masselink and Anthony, 2001; Sipka and Anthony, 1999).

4. MITB morphodynamics

4.1. Short-term morphodynamics: role of tidal cycles

Short-scale morphodynamics of MITBs have been examined mainly through modelling (e.g. Voulgaris et al., 1996; Houwelingen, 2005) or field experiments with the purpose of investigating the driving processes involved over single tidal cycles and/or lunar tidal cycles, (e.g. Voulgaris et al., 1998; Levoy et al., 1998; Sipka and Anthony, 1999; Navas, 1999; Masselink and Anthony, 2001; Stépanian et al., 2001; Kroon and Masselink, 2002; Houwelingen et al., 2006; Sedrati and Anthony 2006; Cartier and Héquette, 2013).

Masselink and Anthony (2001) showed that intertidal bars in MITB systems were commonly distributed between the mean low water neap and the mean high-water neap tide levels. Additionally, the highest bars seem to be located around the mid-tide level where maximum tidal translation rates are observed, implying a key role for both lunar and single tidal cycles in altering MITB morphologies. The position of the water level along the beach profile, for a specific tidal cycle moment, divides the intertidal profile into different sediment transport cells, driven by different hydrodynamic mechanisms (Fig. 6). Over a single tidal cycle, changes in water levels induce a migration of the hydrodynamic processes across the profile, thereby changing cross-shore sediment transport rates and directions (Masselink et al., 2006). Additionally, when the ridges are underwater, surf processes predominate along the seaward slope and the crest, whilst the landward slope of the ridge is submitted to swash processes (Houwelingen, 2005).

The fact that MITB are found mainly in large tidal range environments, with rapid shifts in water levels implies long periods of non-exposure of ridges to hydrodynamic mechanisms (Reichmüth and Anthony, 2007). These tidally induced effects significantly impact relaxation periods, increasing the time needed for the ridges to adapt their morphologies to local wave conditions; morphological change rates are consequently related to the active period of surf and swash processes.

Over an entire tidal cycle, morphological changes are largely confined to the crests of ridges. Runnels are, however, affected by strong currents induced by the rising and falling tides. According to Voulgaris et al. (1996), interactions between waves and tidal currents at rising and falling tidal stages tend to enhance local wave heights. Strong currents are formed in runnels by the combination of tidal and groundwater discharge as well as swash bores (Sipka and Anthony, 1999; Reichmüth and Anthony, 2002). Current velocity and direction during a tidal cycle are driven by tide- and wave-generated currents over MITB features, with an increase in the dominance of wave-driven processes under high energy conditions (Houwelingen, 2005).

As described above for single tidal cycles, lunar tidal cycles (i.e. neap to spring tide) also influence the period during which swash and surf processes operate on ridges. Spring tides are associated with faster migration of the different processes. In contrast, the operational efficiency of each set of processes is focussed at specific locations along the profile (Kroon and Masselink, 2002). Brand et al. (2020) noted that whereas neap tides were dominated by cross-shore wave-induced currents, spring tides were dominated by alongshore tidal currents (Fig. 7).

Onshore migration of ridges over lunar tidal cycles is widely reported in the literature, with migration rates noted up to 1.6 m per tidal cycle (e.g. Parker, 1975; van den Berg, 1977; Voulgaris et al., 1998; Kroon and Masselink, 2002; Houwelingen, 2005; Reichmüth and Anthony, 2007). There is, however, significant cross-shore variability; middle and upper ridges seem to be more mobile than the lower ridges (e.g. King and WiIliams, 1949; Voulgaris et al., 1998) and over the lunar cycle. Kroon and Masselink (20002) argued that onshore migration of intertidal ridges is controlled by surf processes driving erosion of the seaward slope of ridges and deposition on the landward slope. MITB are thus very dynamic features over lunar cycles, and upper ridge(s) migration rates are related to wave energy conditions and tidal elevation.

Short-term migration of MITB are primarily related to surf zone processes over a lunar tidal cycle, the duration of stagnation periods allowing processes to operate on MITB features, and wave conditions. Winds also appear to significantly increase (or decrease) the strength and effects of tidal currents when oriented in the same direction (or

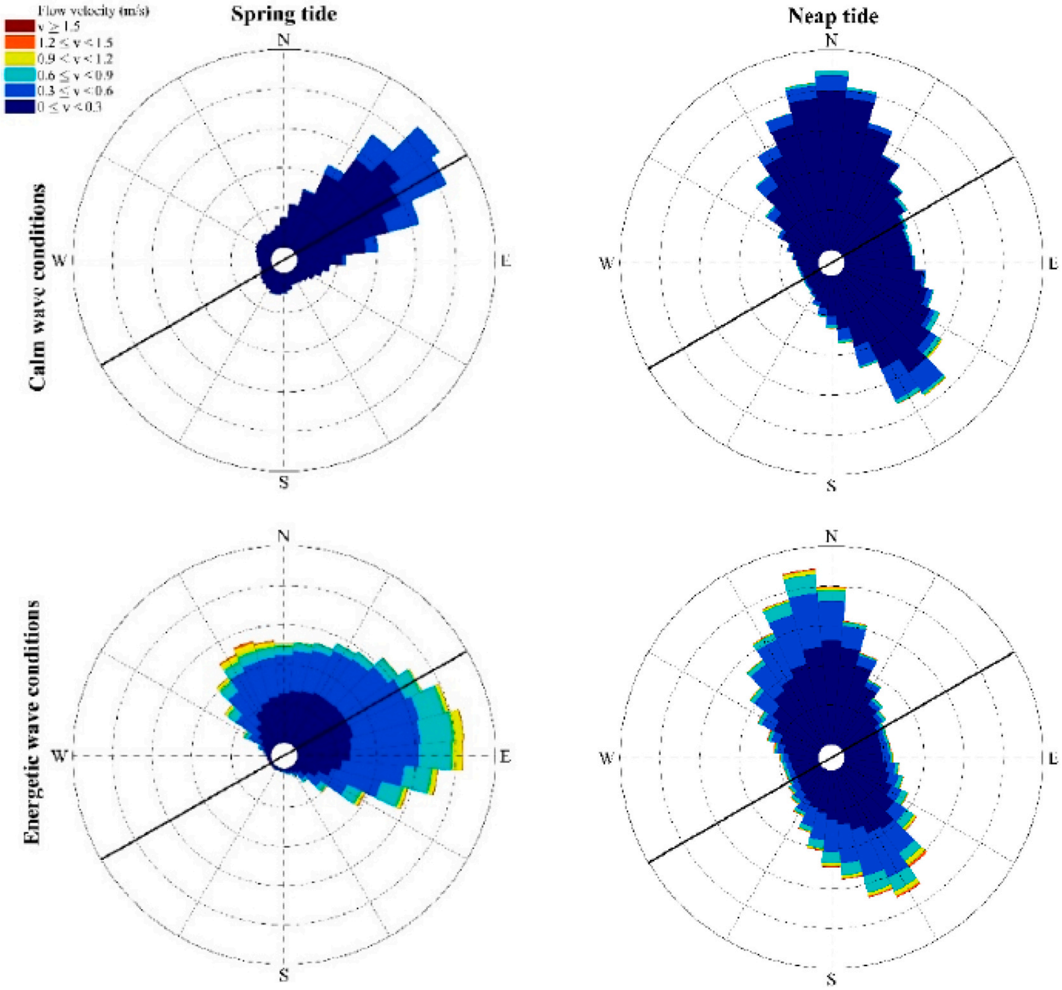

Fig. 7. From: Brand et al., 2020: Typical current roses for spring vs. neap tide (left vs. right panels) and calm vs strong waves. The solid black line shows the shoreline orientation.

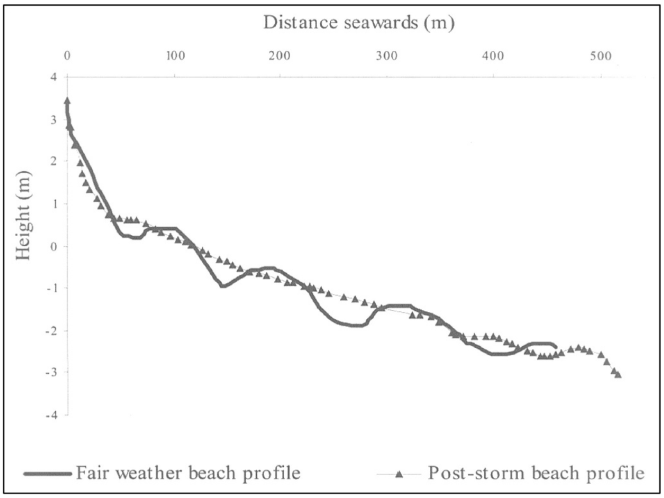

Fig. 8. Comparison of fair-weather and post-storm beach profiles at Dundrum beach, from: Navas et al. (2000).

opposite direction) (Héquette et al., 2005, 2008).

4.2. Seasonal morphodynamics

Some of the first field observations and descriptions from King and WiIliams (1949)and King (1972), showed significant morphological changes of ridges, driven by variations in hydrodynamic conditions. They concluded that high energy conditions (i.e. winter seasons) flatten the ridges and smooth the beach profile, while calmer conditions promote the development and accretion of ridges. In contrast with rapid winter ridge erosion, fair weather ridge-growth periods can last for weeks. However, rapid post-storm recovery could also take place under fair-weather conditions, rebuilding ridges in a few days. During summer seasons, the amplitude of ridges increases and onshore migration toward the upper beach has been reported (e.g. Reichmüth and Anthony, 2008; Maspataud et al., 2009). Indeed, Navas et al. (2001) argued that the most seaward intertidal bar plays a protective role on MITB dynamics under fair weather to moderate conditions, helping to dissipate incoming wave energy, inducing a potential sediment transport from the seaward slope of the ridge toward the crest. Moreover, as noted by Masselink (2004), onshore migration rates are site-specific and vary

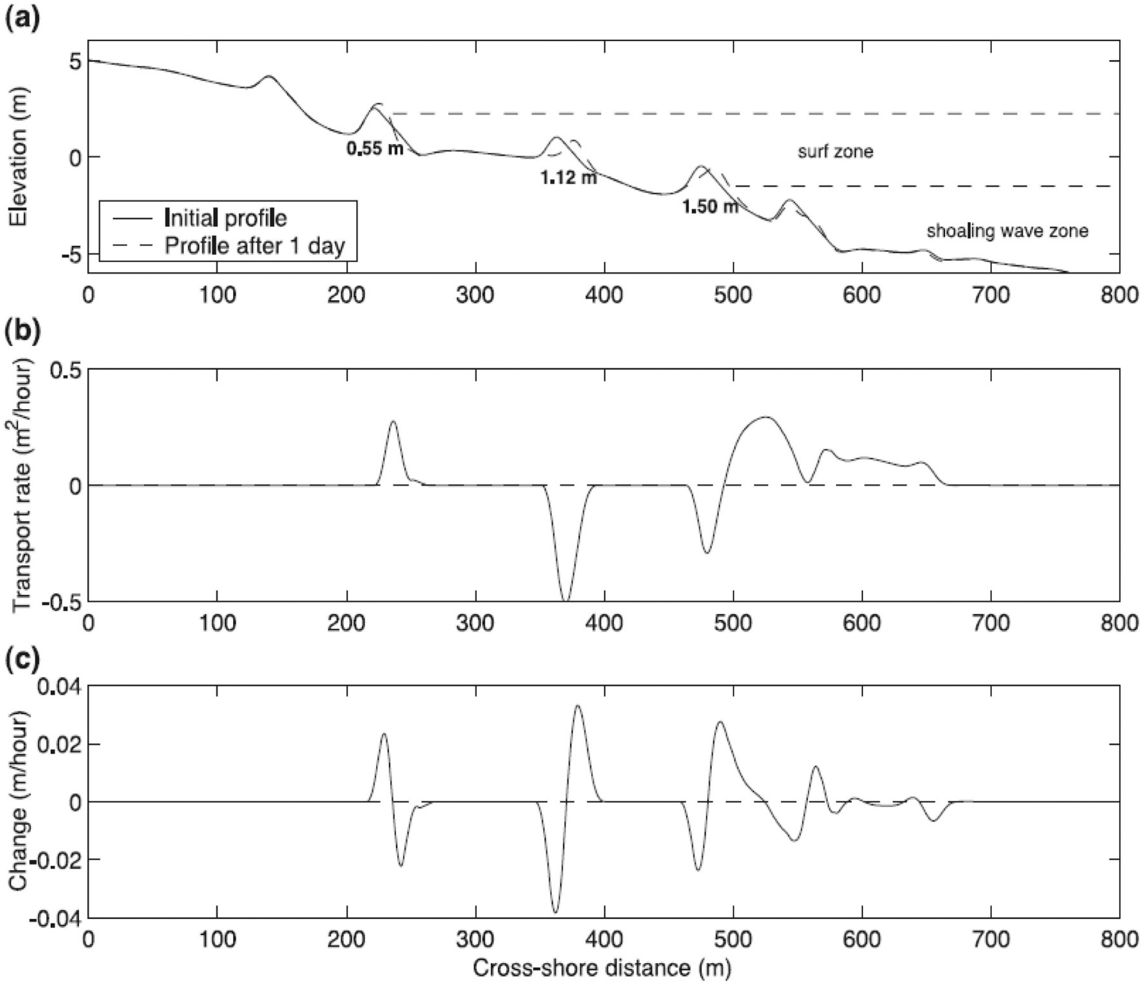

Fig. 9. "Simulated morphological response of a beach with 5 bars to constant wave forcing (H = 1.5 m) and stationary tide conditions. The model accounts for onshore sediment transport under low-wave conditions, bed-scale and beach-scale morphological feedback. (a) Initial beach morphology (solid line) and morphology after 1 day (dashed line). (b) Cross-shore variation in sediment transport rate and direction. (c) Cross-shore variation in morphological change. The bold numbers in (a) represent the breaker heights on the bars" from Masselink (2004).

from less than 1 m per month (Levoy et al., 1998; Sipka and Anthony, 1999) to 10 m per month (e.g. Mulrennan, 1992; Houwelingen et al., 2006).

King and Williams' (1949) observations of the flattening of ridges during winter and maximum development during summer is broadly supported (e.g. Wright, 1976; Mulrennan, 1992; Navas et al. 2001; Houwelingen, 2005; Masselink et al., 2006). In 2000, Navas et al. argued that ridges commonly succumb to flattening sequences under wave destructive actions during high energetic events smoothing ridges crests and filling runnels (Fig. 8). However, studies in the north of France have recorded stability of MITB features during storms (e.g. Anthony et al., 2005; Sedrati and Anthony, 2006; Reichmuth and Anthony, 2008; Maspataud et al., 2009). Flattening of ridges is, however, highly significant under high energy waves that are correlated with high water levels, i.e. spring tides (e.g. King, 1972; Sipka and Anthony, 1999; Reichmüth and Anthony, 2002). Indeed, morphological changes of ridges appear to be mainly driven by surf processes: energetic bore propagation, liberated by breaking waves on bars, tends to provoke onshore sediment transport from the crest of ridges toward runnels, and therefore, slow onshore ridge migration (Kroon and Masselink, 2002; Masselink et al., 2006; Ruiz de Alegria Arzaburu et al., 2007). Moreover, the storm chronology within the season (and within storm clusters) conditions MITB morphological response to winters, as higher significant changes are recorded when the most severe events occur early in the chronology (Dissanayake et al., 2015).

MITB seasonal behaviour is, therefore, controlled by both variations in wave energy (winter vs. summer), and water levels. Additionally, the potential mobility of ridges within seasons helps drive the variability in the upper beach and dune seasonal morphological response where a high mobility of bars generates a stronger response of the upper profile and the dune (Maspataud et al., 2009).

4.3. Long-term morphodynamics

Long-term morphodynamics of MITBs have been attributed to alongshore drainage channel migration and seasonal cross-shore migration of intertidal bars (e.g. King and Williams, 1949; Wright, 1976; Mulrennan, 1992; Ruiz de Alegria Arzaburu et al. 2007). Mulrennan (1992) concluded that the permanence of MITB morphology is related to both the storm characteristics (magnitude and frequency) and the

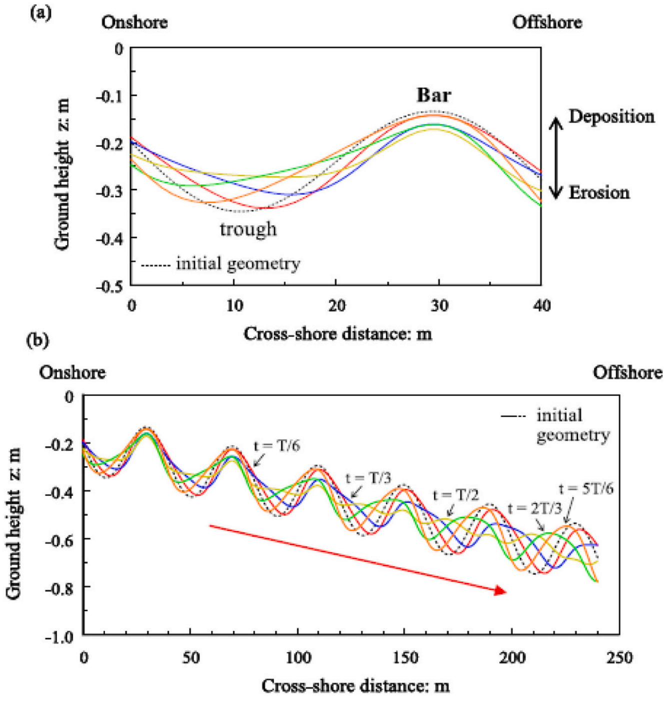

Fig. 10. Results from Sassa and Watabe (2009) showing analysis of the effects of suction dynamics, showing (a) the persistent nature of the bar and (b) the transformation of the bar behaviour in the offshore direction.

relaxation time of the ridges to respond to hydrodynamic conditions changes (Masselink and Anthony, 2001).

Long-term observations of MITBs are generally based on profile records (e.g. King, 1972), aerial photographs studies (e.g. Dawson (2002)) and more recently LIDAR surveys (e.g. Houwelingen et al., 2006; Miles et al., 2019) and video images (e.g. Ruiz de Alegria Arzaburu 2007). Numerical models have also been calibrated to investigate the long-term stability of MITBs. Masselink (2004) used a morphodynamic model to investigate the evolution of intertidal bars (Fig. 9). He argued that the permanence of MITB features is due firstly to the sheltered location of this type of morphology; the beach is, indeed, usually protected from extreme conditions by its location in a fetch-limited area. Also, the succession of sandbars acts as an effective buffer by dissipating the wave energy, even during stormy conditions, protecting the upper profile. The final argument of Masselink (2004) in favour of a stability in MITBs supports the relaxation time proposed by Mulrennan (1992). According to his study, the intertidal profile is only temporarily submitted to wave processes, depending on the water level over the tidal cycle. This period of wave influence on the profile is not long enough to allow the morphology to fully respond and reach an equilibrium with hydrodynamic conditions.

Another theoretical model proposed by Sassa and Watabe (2009) investigated the importance of geodynamic mechanisms in the persistent nature of MITBs. According to their study, a significant feedback exists between the effects resulting from suction processes and sediment transport, leading to a stability of ridge morphologies (Fig. 10).

In the literature, MITB features are, therefore commonly considered as long-term stationary structures (e.g. King, 1972; van den Berg, 1977; Orford and Wright, 1978; Masselink, 2004), even if individual bars undergo seasonal migrations (Houwelingen, 2005). Nevertheless, Miles et al. (2019) work based on LIDAR surveys recorded over a 17-year period, observed a net onshore migration of bars. This work highlights the importance of considering MITB as D systems and the lag in long-term datasets to characterise and analyse MITB behaviour.

5. Distribution of MITBs

5.1. Research on Multiple Intertidal Bar systems

Throughout this review, 67 scientific papers investigating MITB features (including only papers about “True RR” and sand wave morphologies) in over 12 different countries (Fig. 11) were analysed. Here, sand wave morphologies are included in the analysis; indeed, although not considered as “true” ridge and runnel systems sensu King and WIlliams (1949), sands waves are, however, multiple intertidal bar features. According to Fig. 11, MITB seem to have been sporadically studied from 1949 to the late 90's. The number of publications has, however, significantly increased since 2000, likely due to

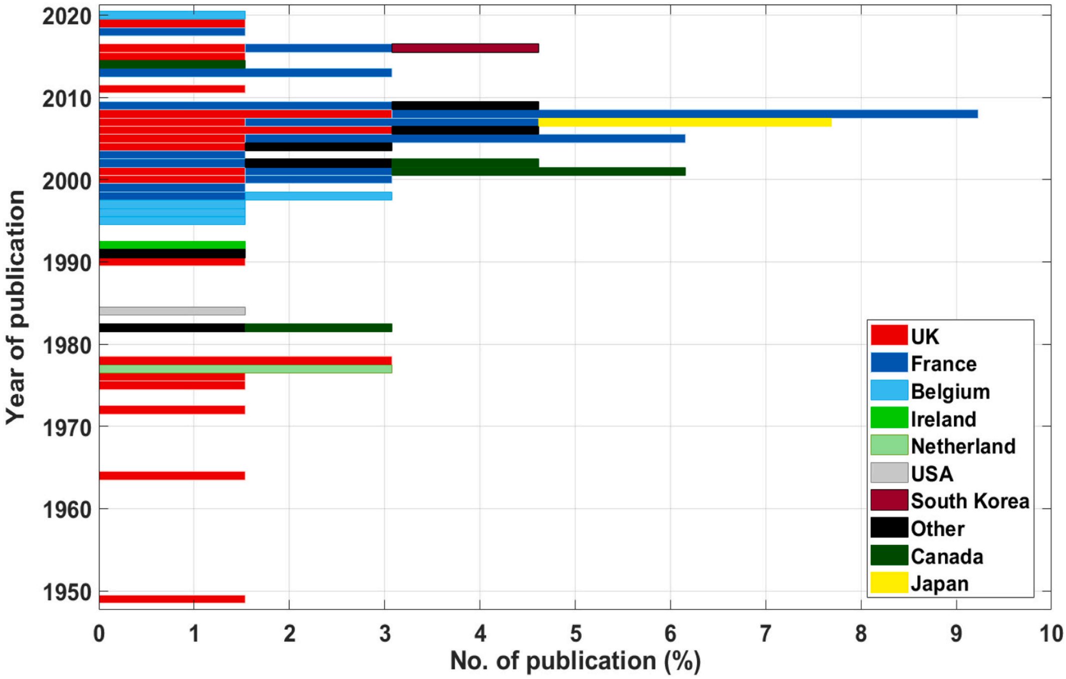

Fig. 11. MITB in the literature, based on 67 studies in total. ‘Other’ includes review papers and model-based analysis.

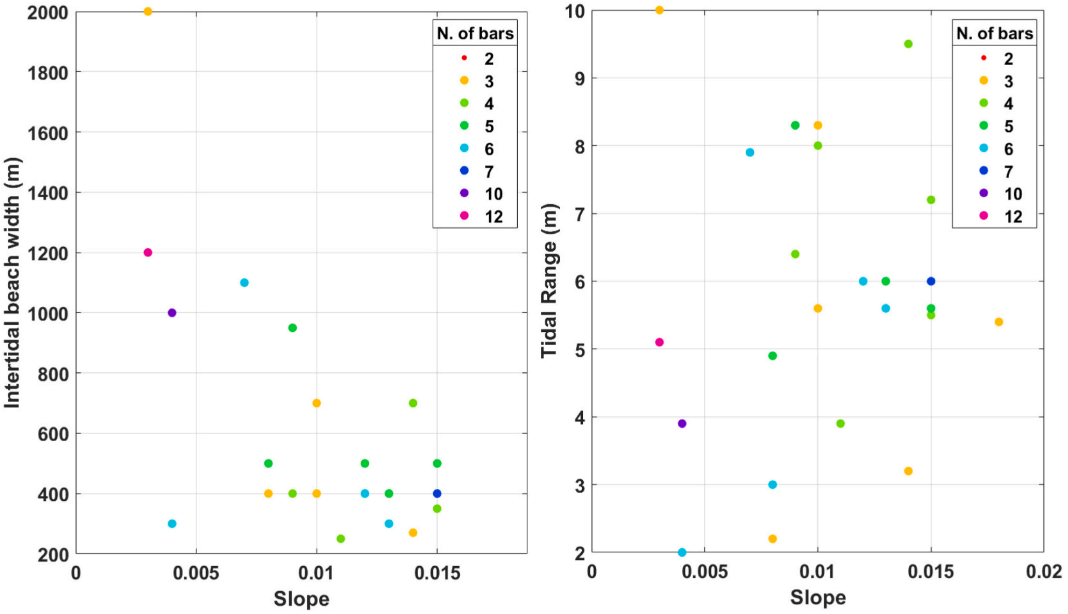

Fig. 12. Scatter plots presenting the number of intertidal bars related the slope and the intertidal beach width (left) or the tidal range (right).

improvements in field instrumentation and techniques, the development of numerical models and the increase of study sites beyond the U.K. (e.g. the north of France). In general, MITB research has been conducted mainly along the northern European coast (U.K., north of France, Belgium, and the Netherlands), along the English Channel, the Irish Sea, and the North Sea. A small number of other sites have been studied in the USA, Canada, and Asia.

5.2. Controls on MITB distribution and morphology

MITB are characterised by 2 up to 20 low-amplitude (< 1 m) shore-parallel sandbars located along the whole intertidal profile. MITB features may adjoin subtidal bar(s). Dawson et al. (2002) showed a link between number of bars, beach slope and intertidal beach width. According to their study, the number of bars increased with intertidal width and decreased beach slope. Fig. 12 presents scatter plots of the number of intertidal bars related to the beach slope and the intertidal width (left) or the tidal range (right), based on their 49 study sites (Appendix). Unfortunately, study site characteristics (beach width and tidal range, for instance) were not fully detailed for all 49 sites. The relation between the number of bars and the beach width or the tidal range is, however, not straightforward, but high numbers of bars (up to 10) are found on very low-angle beach slopes (< 0.005) and relatively wide intertidal beaches (> 1000 m).

The literature suggests that a low gradient beach, macro-tidal range and a short fetch are key parameters driving the formation of MITB. Thresholds reported in the 67 different studies collected are, however, usually site-specific. Figs. 13 and 14 investigate the potential relationship between the presence of MITB, the beach slope, tidal conditions, and local wave characteristics (significant wave height (H_s) and peak period (T_p)). On the upper plot of Fig. 13, there is no clear relationship between beach slope and significant wave height (H_s). However, the peak period (T_p) and slope together define a limit whether the presence of MITB features is observed or not. Indeed, a cluster of blue points representing the presence of MITB (Fig. 13, bottom plot) is clearly identifiable for a beach slope lower than 0.02 and a T_p between 2 and 8 s. Above those thresholds, no MITB morphologies are reported. To characterise wave conditions, the significant wave height is commonly the first (and usually only) parameter considered, while the wave period is often neglected. However, the peak wave period seems here be a more indicative proxy for short fetch conditions. This is also clear when comparing the relationship between the tidal range and wave conditions (Fig. 14). H_s does not show direct relation with the tidal range to explain the presence of multiple intertidal bars. In contrast, a line can be drawn separating the plot T_p/Tidal range in two distinct parts (Fig. 14, bottom plot): MITBs are observed for T_p between 2 and 8 s and a tidal range above 3 m.

Fig. 15 summarises the potential relationship of MITB features to beach slope, tidal range, and wave period. From this graph, thresholds can be identified for each forcing, and a distinct area can be defined by the presence of MITB morphologies. It appears that MITBs are well-developed in environments with a tidal range from 3 to 10 m, wave peak periods between 3 and 8 s and an intertidal beach slope less than 0.02. Moreover, multiple intertidal bars are sandbars composed of fine to medium sediment grain size.

In general, MITB are commonly located near river mouths and/or tidal inlets. The role of inlets in MITB morphodynamics has, however, so far not been explicitly examined and the potential relationship between those different, but possibly complementary environments, remains unknown. It seems, however, that a sufficient sediment supply is required for MITB formation and long-term stability.

Predicting the global occurrence or potential formation of MITB may be possible through the identification of thresholds in wave characteristics, tidal range, and intertidal beach slope presented above, and, in addition, a sufficient sediment supply (Fig. 16). Field observations will still be necessary to characterise local forcing, thereby restricting the identification of MITB features around the world without some field validation. Recent progress in wave modelling at different time and spatial scales (e.g. hindcast and forecast via models like WW3, ECMWF, *etc*…), and a better analysis of worldwide tidal range (Short, 1991; Masselink and Anthony, 2001; Flemming, 2012) are an important first step toward initial remote authentication of new MITB locations

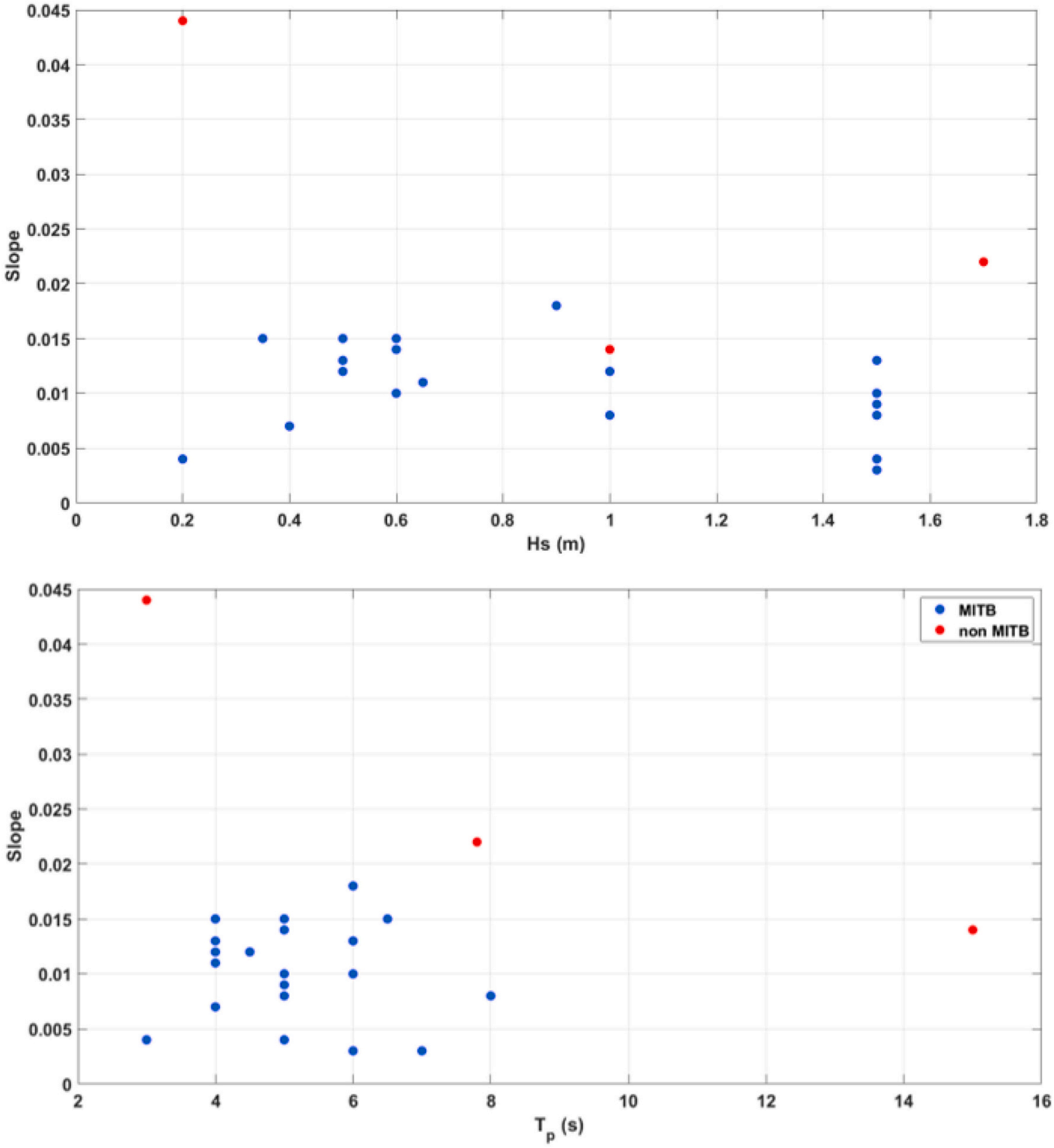

Fig. 13. Relationship between the presence (blue) or not (red) of MITB features, the beach slope and wave conditions (the significant wave height or H_s (top) and the peak period or T_p (bottom)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 16).Additionally, significant improvements in recent satellite image quality and resolution have promoted an increase in the development of new algorithms in coastal science (Ardhuin et al., 2017; Luijendijk et al., 2018; Almar et al., 2019; Vos et al., 2019; Bergsma and Almar, 2020). For instance, (Vos et al., 2020) recently proposed a new method to extract the beach slope from satellite images, introducing a new approach in remote-sensing coastal environment monitoring, which may have potential in remote identification of MITB features, with suitable data quality control.

6. Discussion

Masselink et al. (2006) proposed a conceptual diagram summarising the influence of non-local (offshore) forcing on local hydrodynamic processes (local wave conditions) leading to MITB morphodynamics. According to their diagram, offshore forcing including offshore bathymetry, wave, tide, and sea levels drive the interactions between nearshore waves and bars resulting in MITB features. Sediment transport within MITB morphologies are directly influenced by hydrodynamic processes and therefore, to local forcing. Indeed, surf zone and swash mechanisms, induced by nearshore waves conditions, are the main processes involved in morphological changes of MITB features. Moreover, the water level (tide and sea level) plays a role in the location and duration of each mechanism activity (surf or swash) over a tidal cycle. The type, intensity, and duration of hydrodynamic processes drive sediment transport rates and thus, bar morphology (shape, position, width, and height). At that juncture, a feedback (positive or negative) may be observed between the bar morphology and the local forcing. This diagram, however, fails to note sediment transport directions (alongshore or cross-shore, landward or seaward) nor does it present MITB morphodynamics over different timescales.

Based on the current review, the various processes, resulting in sediment transport and morphological response of MITB features to single tidal cycles, lunar tidal cycles (neap vs. spring tides), seasonal (winter

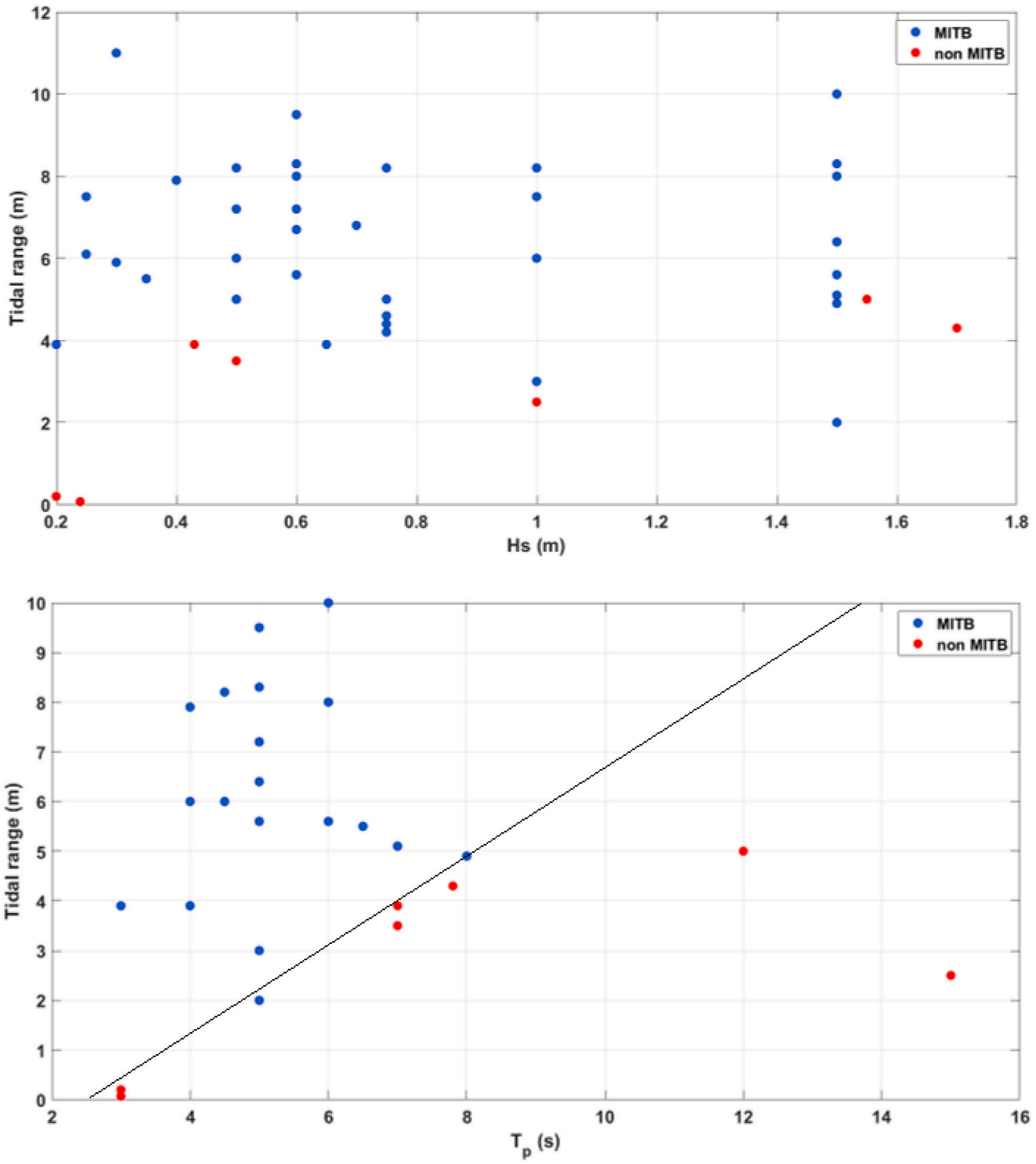

Fig. 14. :Relationship between the presence (blue) or not (red) of MITB features, the tidal range and wave conditions (the significant wave height or H_s (top) and the peak period or T_p (bottom)).

vs. summer periods) and long-term timescales is depicted in Fig. 17. Every timescale leads to a specific response of the system (cf. part 4). They are, however, all interlinked, and shorter timescales significantly influence the longer ones. Indeed, tidal cycles control the duration of surf and swash processes, which, in turn, play a key role in seasonal morphodynamics which then define long-term evolution of MITB morphologies. In this view, the apparent long-term stability of MITB features results from morphological adaptation of intertidal bars to hydrodynamic conditions, at shorter timescales, which could be described as a dynamic equilibrium.

The deductions presented in Fig. 17 highlight the dominant tendencies in MITB character and behaviour extracted from the metadata in the 67 different studies. MITB morphodynamics, however, are still poorly understood and questions relating to sediment circulation, bar genesis and bar/runnel/drainage channel coupling remain unanswered. Although cross-shore sediment transport and cross-shore bar migrations have been investigated, longshore transport and bar migration at different timescales and under varying sediment supply conditions are still poorly understood (Sedrati and Anthony, 2006; Héquette et al., 2008; Cartier and Héquette, 2013; Héquette et al., 2019). Therefore, the effect of variations in sediment supply on short-term changes to long-term dynamic equilibrium (described above)

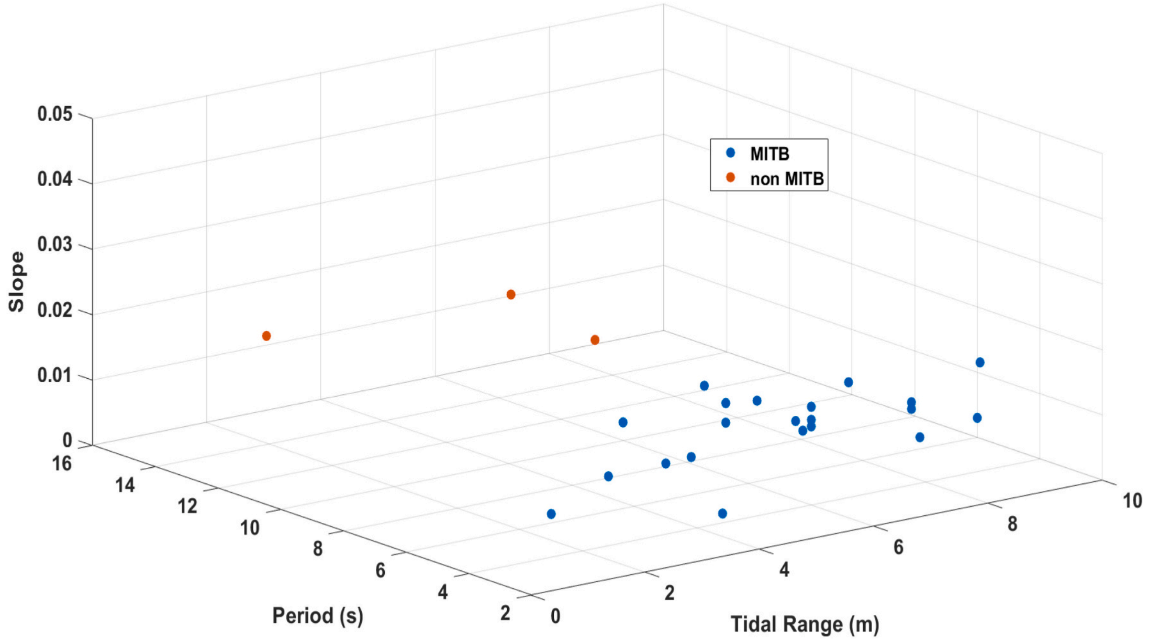

Fig. 15. Relation between the presence (blue) or not (red) of MITB features, the tidal range, the beach slope and the peak period (T_p). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

remains hypothetic. However, the long-term presence (and stability) of MITB features is commonly observed regardless of the trend in shoreline evolution (erosion, neutral or accretion) (e.g. Cooper and Navas 2004; Miles et al., 2019), questioning both the sources of sediment supply and the role of this sediment along with MITB genesis, stabilisation, and potential destabilisation.

The role of drainage channels and morphological cross-shore irregularities such as bifurcations are still poorly understood or studied, but they seem intrinsically linked with cross-shore sediment transport (cross-shore cells) and longshore bar migration. Each bar and its associated runnel and drainage channel (when observable) appears to create different cross-shore sediment transport cells. Uncertainties

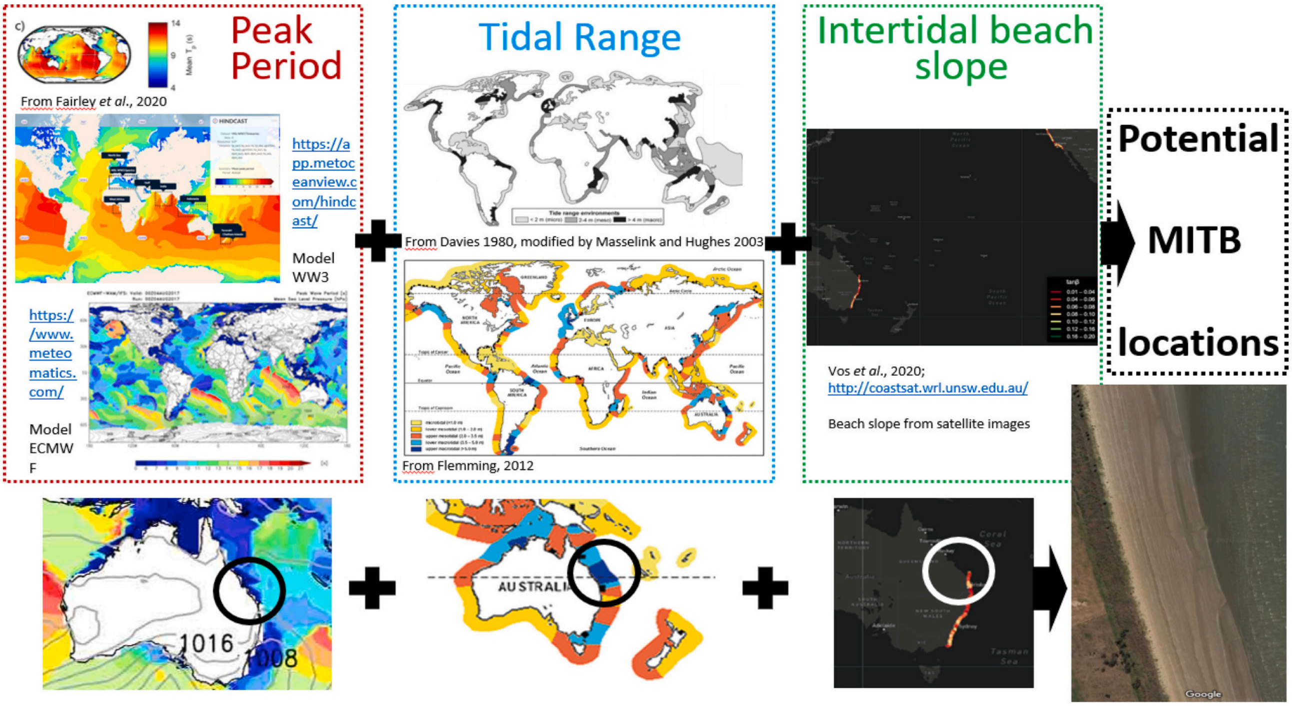

Fig. 16. Predict MITBs location around the world? Example of non-studied MITB located in Joskeleigh, Queensland, Australia: the site has presented itself using the maps above and Google Earth.

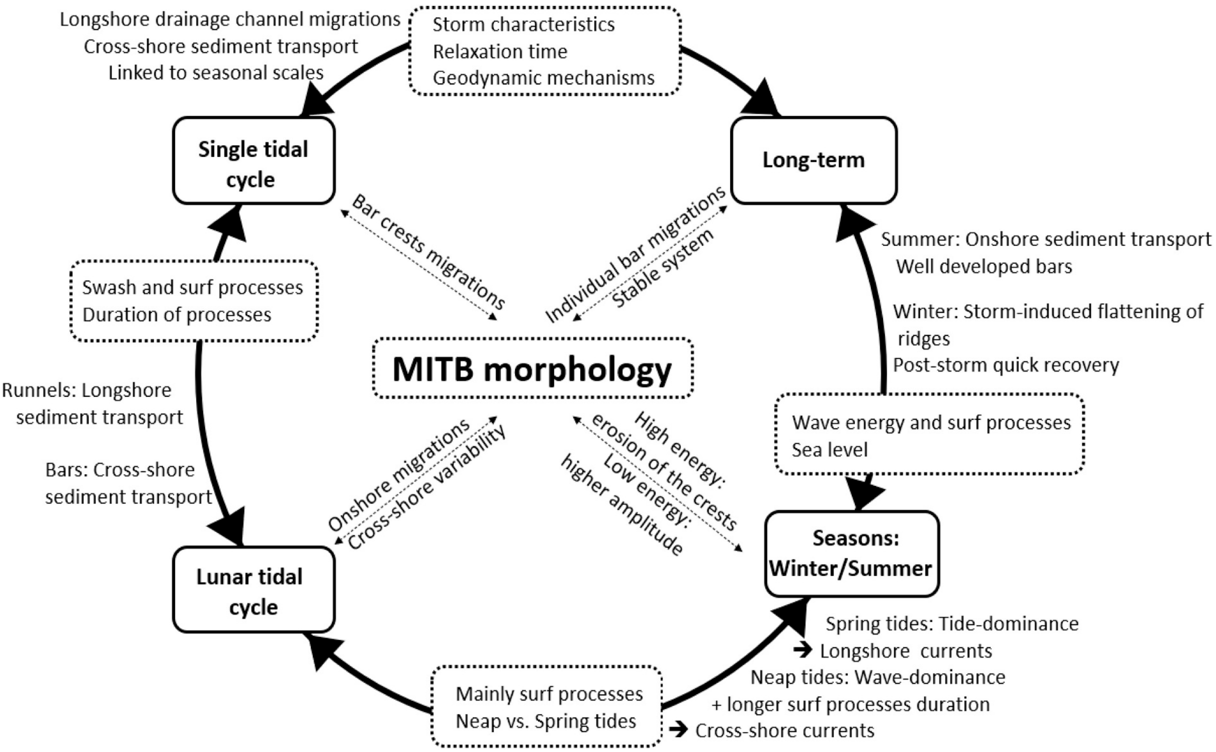

Fig. 17. Diagram summarising forcing, dominant processes, sediment transport and morphological changes acting over different timescales.

remain as to whether each system works independently or, if on the contrary, a coupling exists between the various intertidal bars (and runnels/channels). Moreover, even if some hypotheses concerning the genesis of MITB have been disproved while others prevail, the formative processes of multiple intertidal bars have not been fully demonstrated yet. More tidal-scale to long-term field data and observations will be necessary to complete our knowledge on MITB and inform future modelling efforts. Recent advances in instrumentation and data collection, especially repeat lidar surveys, hold much potential to quantify and explain MITB behaviour.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work is part of the MarPAMM project, funded by the European Union's INTERREG VA Programme with match funding from the Department of Agriculture, Environment and Rural Affairs in Northern Ireland and the Department of Housing, Planning and Local Government in Ireland (https://www.mpa-management.eu). Moreover, this paper is a contribution to NERC grant: NE/H024301/1. Finally, the authors would like to thank both referees G. Coco and N. Senechal for their contribution to this paper.

Appendix

Study	Year of publication	Location	Country	Name	Type
Hayes, 1967	1967	Texas	USA	RR	False
Hayes and Boothroyd, 1969	1969	Texas	USA	RR	False
Davis et al. (1972)	1972	Lake Michigan/Massachusetts bay	USA	RR	False
Owens and Frobel, 1977	1977	Magdalen Island, Guld of St Lawrence	Canada	RR	False
Mccave and Geiser (1979)	1978	The Wash	England	RR	False
Dabrio & Polo (1981)	1981	Puerto de Mazarron Beach	Spain	RR	False
Hale and McCann (1982)	1982	Craig Bay Vancouver Island	Canada	RR	False
Dabrio (1982)	1982	Huelva Province, along the Gulf of Cadiz	Spain	RR	False
Orme and Orme (1988)	1988	Ormond beach California	USA	RR	False
Pedreros et al. (1996)	1996	La Salie	France	RR	False
Michel and Howa (1999)	1999	La Salie	France	RR	False
Whitehouse et al. (2000)	2000	Seven Estuary	England	RR	False
Whitehouse et al. (2000)	2000	Marennes-Oléron	France	RR	False
Dawson & Davidson-Arnott	2001	Northumerland Strait (Linden Beach)	Canada	RR	False
Dawson (2002)	2001	Northumerland Strait (Linden Beach)	Canada	RR	False
Dawson et al. (2002)	2002	Northumerland Strait (Linden Beach)	Canada	RR	False
De Melo Apoluceno et al. (2002)	2002	Truc Vert beach	France	RR	False
Yamada & Kobayashi (2007)	2007	Okoshiki beach Ariake Bay	Japan	RR	False
Yamada et al. (2007)	2007	Okoshiki beach Ariake Bay	Japan	Multiple intertidal bars	False
Garnier et al. (2007)	2007	MODEL	Else	RR	False

Williams et al. (2008)	2008	Seven Estuary	England	RR	False
Carling et al. (2009)	2009	Seven Estuary	England	RR	False
Figlus (2010)	2010	Thesis	Else	RR	False
Figlus et al. (2010)	2010	Lab experiment	Else	RR	False
Figlus et al. (2012a)	2012	Lab experiment	Else	RR	False
Figlus et al. (2012b)	2012	Lab experiment	Else	RR	False
Lafon et al. (2002)	2002	Truc Vert beach	France	RR	False
Zonneveld et al. (2014)	2014	Craig Bay Vancouver Island	Canada	RR	False
Chandrasekar et al. (2014)	2014	Vembar to Kallar coast	India	RR	False
Figlus et al. (2015)	2015	Lab experiment	Else	RR	False
Morio et al. (2016)	2016	Bétahon beach	France	RR	False
Song et al. (2019)	2019	South Bethany beach, Delaware	USA	RR	False
King and Williams (1949)	1949	Blackpool	England	RR	True
King and Barnes (1964)	1964	Skegness South	England	RR	True
King (1972)	1972	Skegness South	England	RR	True
Parker (1975)	1975	Southwest Lancashire	England	RR	True
Wright (1976)	1976	Ainsdale	England	RR	True
van den Berg (1977)	1977	Schouwen	Netherland	RR	True
Doeglas (1955)	1955	Zandvoort	Netherland	RR	True
Orford and Wright (1978)	1978	Dundrum Bay Murlough beach	Northern Ireland	RR	True
Moore et al. (1984)	1984	Sapelo Island Georgia	USA	RR	True
Vincent et al. (1990)	1990	Holkham beach	England	RR	True
Short (1991)	1991	REVIEW	Else	RR	True
Mulrennan (1992)	1992	Portmarnock	Ireland	RR	True
Voulgaris et al. (1996)	1996	Nieuwpoort	Belgium	RR	True
Simmonds et al. (1995)	1995	Nieuwpoort	Belgium	RR	True
Simmonds et al. (1997)	1997	Nieuwpoort	Belgium	RR	True
Levoy et al. (1998)	1998	Merlimont	France	RR	True
Voulgaris et al. (1998)	1998	Nieuwpoort	Belgium	RR	True
Sipka and Anthony (1999)	1999	Leffrinkoucke	France	RR	True
Battiau-Queney et al. (2001)	2000	Merlimont	France	RR	True
Navas et al. (2001)	2001	Dundrum Bay Murlough beach	Northern Ireland	RR	True
Masselink and Anthony (2001)	2001	Blackpool	England	RR	True
Stépanian et al. (2001)	2001	Omaha beach Normandie	France	RR	True
Buscombe (2002)	2002	Blackpool	England		True
Chauhan (2000)	2000	Siloth	England	RR	True
Kroon and Masselink (2002)	2002	Theddlethorpe North Lincolnshire	England	Multiple intertidal bars	True
Reichmüth and Anthony (2002)	2002	Dunkirk	France	RR	True
Vanhee et al. (2002)	2002	Leffrinkoucke	France	RR	True
Wijnberg and Kroon (2002)	2002	REVIEW	Else	Low-amplitude ridge	True
Stépanian (2002)	2003	Omaha beach Normandie	France	RR	True
Masselink (2004)	2004	MODEL	Else	Multiple intertidal bars	True
Cooper & Navas (2004)	2004	Dundrum bay	Northern Ireland	RR	True
Anthony et al. (2005)	2005	Merlimont	France	RR	True
Reichmüth & Anthony (2002)	2002	Dunkirk	France	Multiple intertidal bars	True
Saye et al. (2005)	2005	Sefton Coast	England	RR	True
Sedrati & Anthony (2006)	2006	Wissant	France	Intertidal bar-trough	True
Houwelingen et al., 2006	2006	Theddlethorpe North Lincolnshire Llangennith	England Wales	Multiple intertidal bars	True
Masselink et al. (2006)	2006	REVIEW	Else	Low-amplitude ridge	True
Anthony et al. (2007)	2007	Calais	France	Intertidal bar-trough	True
Reichmüth and Anthony (2007)	2007	Calais	France	Intertidal bars	True
Ruiz de Alegria Arzaburu et al. (2007)	2007	Cleveleys	England	Intertidal bars	True
Reichmüth et al., 2008	2008	Dunkirk	France	Multiple intertidal bars	True
Reichmüth and Anthony (2008)	2008	Leffrinkoucke	France	Multiple intertidal bars	True
Héquette et al. (2008)	2008	Dunkirk	France	RR	True
Van Houwelingen et al. (2008)	2008	Theddlethorpe North Lincolnshire	England	Multiple intertidal bars	True
Oblinger and Anthony (2008)	2008	Malo les bains Dunkirk	France	Intertidal bar-trough	True
Pye & Plot (2008)	2008	Sefton Coast	England	RR	True
Anthony et al. (2009)	2009	Leffrinkoucke	France	Intertidal bar-trough	True
Maspataud et al. (2009)	2009	Zuydcoote	France	Intertidal bar-trough	True
Sassa and Watabe (2009)	2009	MODEL	Else	Intertidal bars	True
Scott et al. (2011)	2011	REVIEW and classification	England	Multiple intertidal bars	True
Anthony (2013)	2013	Wissant	France	Intertidal bar-trough	True
Cartier and Héquette (2013)	2013	Wissant	France	Intertidal bar-trough	True
Dissanayake et al. (2015)	2015	Formby Point	England	RR	True
Crapoulet et al. (2016)	2016	Wissant	France	Intertidal bar-trough	True
Kim et al. (2016)	2016	Baeksajang Beach	South Korea	RR	True
Pye and Blott (2016)	2016	Sefton Coast	England	RR	True
Vaucher et al. (2018)	2018	Berck beach	France	RR	True
Miles et al. (2019)	2019	Fylde coast	England	Multiple intertidal bars	True

References

Almar, Rafael, Bergsma, Erwin W.J., Maisongrande, Philippe, de Almeida, Luis Pedro Melo, 2019. Wave-derived coastal bathymetry from satellite video imagery: a showcase with pleiades persistent mode. Remote Sens. Environ. 231 (septembre). https://doi.org/10.1016/j.rse.2019.111263. 111263.

Anthony, E.J., Levoy, F., Monfort, D., Degryse-Kulkarni, C., 2005. Short-term intertidal bar mobility on a ridge-and-runnel beach, Merlimont, northern France. Earth Surf. Process. Landf. 30 (1), 81–93. https://doi.org/10.1002/esp.1129.

Anthony, Edward J., Vanhée, Stéphane, Ruz, Marie-Hélène, 2007. Embryo dune development on a large, actively accreting macrotidal beach: Calais, North Sea Coast of France. Earth Surf. Process. Landf. 32 (4), 631–636. https://doi.org/10.1002/esp.1442.

Anthony, E.J., 2013. Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. Geomorphology 199, 8–21. https://doi.org/10.1016/j.geomorph.2007.12.013.

Anthony, Edward J., Ruz, Marie-Hélène, et al., Vanhée, Stéphane, 2009. Aeolian Sand Transport over Complex Intertidal Bar-Trough Beach Topography. Geomorphology 105 (1-2), 95–105. https://doi.org/10.1016/j.geomorph.2007.12.013.

Ardhuin, Fabrice, Aksenov, Yevgueny, Benetazzo, Alvise, Bertino, Laurent, Brandt, Peter, Caubet, Eric, Chapron, Bertrand, et al., 2017. Measuring Currents, Ice Drift, and Waves from Space: The Sea Surface KInematics Multiscale Monitoring (SKIM) Concept. Preprint. Remote Sensing/Current Field/Surface/All Geographic Regions. https://doi.org/10.5194/os-2017-65.

Battiau-Queney, Y., Fauchois, J., Deboudt, P., Lanoy-Ratel, P., 2001. Beach-dune systems in a macrotidal environment along the northern French coast (English Channel and southern North Sea). Journal of Coastal Research 3, 580–592.

Bergsma, Erwin W.J., Almar, Rafael, 2020. Coastal coverage of ESA' Sentinel 2 mission. Adv. Space Res. 65 (11), 2636–2644. https://doi.org/10.1016/j.asr.2020.03.001.

Buscombe, D.D., 2010. The short-term morphodynamic response of a ridge-and-runnel system on a macrotidal beach. University of Lancaster, Lancaster, UK. BSc-thesis, pp. 87.

Brand, Evelien, Montreuil, Anne-Lise, Houthuys, Rik, Chen, Margaret, 2020. Relating hydrodynamic forcing and topographic response for tide-dominated sandy beaches. J. Mar. Sci. Eng. 8 (3), 151. https://doi.org/10.3390/jmse8030151.

Carling, Paul, Williams, Jon, Croudace, Ian, Amos, Carl, 2009. Erratum: Carling, P.A., et al., Formation of Mud Ridge and Runnels in the Intertidal Zone of the Severn Estuary, UK. Continental Shelf Research (2009), Doi:10.1016/j.Csr.2008.12.009. Cont. Shelf Res. 29 (14), 1756. https://doi.org/10.1016/j.csr.2009.06.007.

Cartier, Adrien, Héquette, Arnaud, 2013. The Influence of intertidal bar-trough morphology on sediment transport on Macrotidal beaches, northern France. Z. Geomorphol. 57 (3), 325–347. https://doi.org/10.1127/0372-8854/2013/0105.

Carter, R.W.G., 2014. Coastal Environments. Academic Press, London, pp. 617.

Chandrasekar, N., Saravanan, S., Rajamanickam, M., Rajamanickam, G., V. (2014). The spatial variability of Ridge and runnel Beach morphology due to beach placer mining along the Vembar Kallar coast, India. 10; 1515/umcsgeo-2015-0003. Annales Universitatis Mariae Curie - Sklodowska Lublin-Polonia, VOL. LXIX, 2, sectio B.

Chauhan, P.P.S., 2000. Bedform association on a ridge and runnel foreshore: implications for the hydrography of a macrotidal estuarine beach. Journal of Coastal Research 1011–1021.

Cooper, J.A.G., Navas, F., 2004. Natural bathymetric change as a control on century-scale shoreline behavior. Geology 32 (6), 513–516.

Crapoulet, Adrien, Héquette, Arnaud, Marin, Denis, Levoy, Franck, Bretel, Patrice, 2016. variations in the response of the dune coast of northern France to major storms as a function of available beach sediment volume: response of dune coast to storm as a function of beach sediment volume. Earth Surf. Process. Landf. 42 (11), 1603–1622. https://doi.org/10.1002/esp.4098.

Dabrio, C.J., et al., Polo, M.D., 1981. Flow Regime and Bedforms in a Ridge and Runnel System, S. Spain. Sedimentary Geology 28 (2), 97–110. https://doi.org/10.1016/0037-0738(81)90059-2.

Dabrio, C.J., 1982. Sedimentary Structures Generated on the Foreshore by Migrating Ridge and Runnel Systems on Microtidal and Mesotidal Coasts of S. SPAIN. 11.

Davis, Richard A., 1972. Comparison of Ridge and Runnel Systems in Tidal and Non-Tidal Environments. 9.

Dawson, J.C., 2002. The Morphodynamics of an Intertidal Sand Bar System. Northumberland Strait, Nova Scotia, Canada.

Dawson, Jaime C., Davidson-Arnott, Robin G.D., Ollerhead, Jeff, 2002. Low-energy morphodynamics of a ridge and runnel system. J. Coast. Res. 36 (mars), 198–215. https://doi.org/10.2112/1551-5036-36.sp1.198.

De Melo Apoluceno, D., Howa, H., Dupuis, H., Oggian, G., 2002. Morphodynamics of ridge and runnel systems during summer. J. Coast. Res. 36 (mars), 222–230. https://doi.org/10.2112/1551-5036-36.sp1.222.

Dissanayake, P., Brown, J., Karunarathna, H., 2015. Impacts of storm chronology on the morphological changes of the Formby Beach and Dune System, UK. Nat. Hazards Earth Syst. Sci. 15 (7), 1533–1543. https://doi.org/10.5194/nhess-15-1533-2015.

Doeglas, D.J., 1955. The origin and destruction of beach ridges. Leidse Geologische mededelingen 20, 34–37.

Figlus, J., 2010. Coastal morphological evolution in the wet and dry zone. University of Delaware.

Flemming, Burghard W., 2012. Siliciclastic back-barrier tidal flats. In: Davis Jr.Richard A., Dalrymple, Robert W. (Eds.), Principles of Tidal Sedimentology. Springer Netherlands, Dordrecht, pp. 231–267. https://doi.org/10.1007/978-94-007-0123-6_10.

Garnier, Roland, Falqués, Albert, Calvete, Daniel, Caballeria, Miquel, 2007. Modelling ridge and runnel system development from an intertidal shore parallel bar. In: Coastal Engineering 2006. World Scientific Publishing Company, San Diego, California, USA, pp. 2679–2690. https://doi.org/10.1142/9789812709554_0226.

Greenwood, Brian, Davidson-Arnott, Robin G.D., 1979. Sedimentation and equilibrium in wave-formed bars: a review and case study. Can. J. Earth Sci. 16 (2), 312–332. https://doi.org/10.1139/e79-030.

Hale, P.B., McCann, S.B., 1982. Rhythmic topography in a mesotidal, low-wave-energy environment. SEPM J. Sediment. Res. 52. https://doi.org/10.1306/212F7F6D-2B24-11D7-8648000102C1865D.

Hayes, M.O., 1967. Hurricanes as geological agents: case study of hurricanes Carla 1961, and Cindy 1963. In: Bur. Econ. Geol., Rep. No. 61. Univ. Texas 54 pp.

Hayes, M.O., Boothroyd, I.C., 1969. Storms as modifying agents in the coastal environment. In: Eastern Section, S.E.P.M. Guidebook, May 9–11, pp. 245–265.

Héquette, A., Hemdane, Y., Anthony, E.J., 2005. Determination of sediment transport paths on a macrotidal shoreface: comparison of the "Gao and Collins" method with near-bed current measurements. In: 5th Int. Conf. Coastal Dyn., Barcelona, April 2005, Cd-rom, 11 pp.

Héquette, Arnaud, Hemdane, Yacine, Anthony, Edward J., 2008. Sediment transport under wave and current combined flows on a tide-dominated shoreface, Northern Coast of France. Mar. Geol. 249 (3–4), 226–242. https://doi.org/10.1016/j.margeo.2007.12.003.

Héquette, A., Ruz, M.H., Maspataud, A., Sipka, V., 2009. Effects of nearshore sand bank and associated channel on beach hydrodynamics: implications for beach and shoreline evolution. J. Coast. Res. 56, 6.

Héquette, Arnaud, Ruz, Marie-Hélène, Zemmour, Amar, Marin, Denis, Cartier, Adrien, Sipka, Vincent, 2019. Alongshore variability in coastal dune erosion and post-storm recovery, northern coast of France. J. Coast. Res. 88, 21.

Houwelingen, S.T., 2005. Spatial and Temporal Variability in the Ridge and Runnel Morphology along the North Lincolnshire Coast. Doctoral dissertation. Loughborough University.

Houwelingen, Selma, Masselink, Gerhard, Bullard, Joanna, 2006. Characteristics and dynamics of multiple intertidal bars, North Lincolnshire, England. Earth Surf. Process. Landf. 31 (4), 428–443. https://doi.org/10.1002/esp.1276.

King, C.A.M., 1972. Dynamics of beach accretion in South Lincolnshire, England. In: Coates, D.R. (Ed.), Coastal Geomorphology. Proceedings 3'd Annual.

King, C.A.M., Barnes, F.A., 1964. Changes in the configuration of the inter-tidal beach zone of part of the Lincolnshire coast since 1951. Z. Geomorphol. 8, 105–126.

King, C.A.M., WiIliams, W.E., 1949. The formation and movement of sand bars by wave action. Geogr. J. 113, 70–85.

Kim, Chan Woong, Young, Ho Shin, Keun, Bae Yu, et al., Hosahng, Rhew, 2016. Morphodynamic Behaviors of Macrotidal Ridge and Runnel Beaches during Winter: The Case of Baeksajang Beach, South Korea. Journal of Coastal Research (sp1) 75, 1362–1366. https://doi.org/10.2112/SI75-273.1.

Kirby, J.T., Dalrymple, R.A., Liu, P.L.F., 1981. Modificationof edge waves by barred-beach topography. Coast. Eng. 5, 35–49.

Kroon, Aart, Masselink, Gerhard, 2002. Morphodynamics of intertidal bar morphology on a macrotidal beach under low-energy wave conditions, North Lincolnshire, England. Mar. Geol. 190 (3–4), 591–608. https://doi.org/10.1016/S0025-3227(02)00475-9.

Lafon, Virginie, Dupuis, Hélène, Howa, Hélène, Froidefond, Jean-Marie, 2002. Determining ridge and runnel longshore migration rate using spot imagery. Oceanol. Acta 25 (3–4), 149–158. https://doi.org/10.1016/S0399-1784(02)01190-8.

Levoy, F., Anthony, E., Barusseau, J.-P., Howa, H., Tessier, B., 1998. Morphodynamics of a macrotidal ridge and runnel beach. C. R. Acad. Sci. 327, 811–818.

Luijendijk, Arjen, Hagenaars, Gerben, Ranasinghe, Roshanka, Baart, Fedor, Donchyts, Gennadii, Aarninkhof, Stefan, 2018. The state of the world's beaches. Sci. Rep. 8 (1). https://doi.org/10.1038/s41598-018-24630-6.

Mariño-Tapia, I., O'Hare, T.J., Russell, P.E., Davidson, M.A., Huntley, D.A., 2002. Onshore and offshore bar migration modelled with an energetics-type sediment transport model. In: Solving Coastal Conundrums. Thomas Telford Publishing.

Maspataud, A., Ruz, M.-H., Hequette, A., 2009. Spatial variability in post-storm beach recovery along a macrotidal barred beach, Southern North Sea. J. Coast. Res. 56, 5.

Masselink, Gerhard, 2004. Formation and evolution of multiple intertidal bars on macrotidal beaches: application of a morphodynamic model. Coast. Eng. 51 (8–9), 713–730. https://doi.org/10.1016/j.coastaleng.2004.07.005.

Masselink, Gerhard, Anthony, Edward J., 2001. Location and height of intertidal bars on macrotidal ridge and runnel beaches. Earth Surf. Process. Landf. 26 (7), 759–774. https://doi.org/10.1002/esp.220.

Masselink, G., Turner, I., 1999. The effects of tide in beach morphodynamics. In: Short, A.D. (Ed.), Handbook of Beach and Shoreface Morphodynamics. Wiley & Sons, Chichester, pp. 204–229.

Masselink, G., Kroon, A., Davidson-Arnott, R.G.D., 2006. Morphodynamics of intertidal bars in wave-dominated coastal settings – a review. Geomorphology 73 (1–2), 33–49. https://doi.org/10.1016/j.geomorph.2005.06.007.

Mccave, I.N., Geiser, A.C., 1979. Megaripples, ridges and runnels on intertidal flats of the Wash, England. Sedimentology 26 (3), 353–369. https://doi.org/10.1111/j.1365-3091.1979.tb00914.x.

Michel, D., Howa, H.L., 1999. Short-term morphodynamic response of a ridge and runnel system on a mesotidal sandy beach. J. Coast. Res. 11.

Miles, Andrew, Ilic, Suzana, Whyatt, Duncan, James, et Mike R., 2019. Characterizing beach intertidal bar systems using multi-annual LiDAR data. Earth Surf. Process. Landf. 44 (8), 1572–1583. https://doi.org/10.1002/esp.4594.

Morio, O., Sedrati, M., Goubert, E., Floc'h, F., Furgerot, L., Garlan, T., 2016. Morphodynamic of a sandy-muddy macrotidal estuarine beach under contrasted energy conditions (Vilaine estuary, France). Journal of Coastal Research SI75, 258–262.

Moore, J.H., Fritz, W.J., Futch, R.S., 1984. Occurrence of megaripples in a ridge and runnel system, Sapelo Island, Georgia: morphology and processes. Journal of Sedimentary Petrology 54, 615–625.

Moore, Laura J., Sullivan, Charlene, David, G. Aubrey, 2003. Interannual evolution of multiple longshore sand bars in a mesotidal environment, Truro, Massachusetts, USA. Mar. Geol. 196 (3–4), 127–144. https://doi.org/10.1016/S0025-3227(03)00028-8.

Mulrennan, M.E., 1992. Ridge and runnel beach morphodynamics: an example from the central east coast of Ireland. J. Coast. Res. 8, 906–918.

Navas, Fatima, 1999. Coastal Morphodynamics of Dundrum Bay, Co. Down, Northern Ireland. Doctoral dissertation. University of Ulster.

Navas, F., Cooper, Andrew J.A.G., Malvarez, G., Jackson, D.W.T., 2001. Theoretical approach to the investigation of ridge and runnel topography of a macrotidal beach: Dundrum Bay, Northern Ireland. J. Coast. Res. 12.

Oblinger, Arnaud, Anthony, Edward J., 2008. Wave attenuation and intertidal morphology of a multi-barred macrotidal beach behind a breakwater. Z. Geomorphol. 52 (3), 167–177. https://doi.org/10.1127/0372-8854/2008/0052S3-0167. Supplementary Issues.

Orford, Julian D., Wright, Peter, 1978. What's in a name? — descriptive or genetic implications of 'Ridge and Runnel' topography. Mar. Geol. 28 (1–2), M1–M8. https://doi.org/10.1016/0025-3227(78)90088-9.

Orme, Antony R., Orme, Amalie Jo, 1988. Ridge-and-Runnel enigma. Geogr. Rev. 78 (2), 169. https://doi.org/10.2307/214175.

Owens, E.H., Frobel, D.H., 1977. Ridge and Runnel Systems in the Magdalen Islands, Quebec. vol. 8.

Parker, W.R., 1975. Sediment mobility and erosion on a multibarred foreshore (Southwest Lancashire, U.K.). In: Hails, J.R., Carr, A. (Eds.), Nearshore Sediment Dynamics and Sedimentation. Wiley and Sons, London, pp. 151–179.

Pedreros, R., Howa, H.L., Michel, D., 1996. Application of grain size trend analysis for the determination of sediment transport pathways in intertidal areas. Mar. Geol. 135 (1–4), 35–49. https://doi.org/10.1016/S0025-3227(96)00042-4.

Pye, K., et al., Blott, S.J., 2008. Decadal-Scale Variation in Dune Erosion and Accretion Rates: An Investigation of the Significance of Changing Storm Tide Frequency and Magnitude on the Sefton Coast, UK. Geomorphology 102 (3-4), 652–666. https://doi.org/10.1002/esp.1561.

Pye, Kenneth, Blott, Simon J., 2016. Assessment of beach and dune erosion and accretion using LiDAR: impact of the stormy 2013–14 winter and longer term trends on the Sefton Coast, UK. Geomorphology 266 (août), 146–167 10.1016/j.geomorph.2016.05.011.

Reichmüth, Béatrice, Anthony, Edward J., 2002. The variability of ridge and Runnel Beach morphology: examples from Northern France. J. Coast. Res. 36 (mars), 612–621. https://doi.org/10.2112/1551-5036-36.sp1.612.

Reichmüth, Béatrice, Anthony, Edward J., 2007. Tidal influence on the intertidal bar morphology of two contrasting macrotidal beaches. Geomorphology 90 (1–2), 101–114. https://doi.org/10.1016/j.geomorph.2007.01.015.

Reichmüth, Béatrice, Anthony, Edward J., 2008. Seasonal-scale morphological and dynamic characteristics of multiple intertidal bars. Z. Geomorphol. 52 (3), 79–90. https://doi.org/10.1127/0372-8854/2008/0052S3-0079. Supplementary Issues.

Reichmüth, Béatrice, et al., Anthony, Edward J., 2008. Dynamics of Intertidal Drainage Channels on a Multi-Barred Macrotidal Beach. Earth Surface Processes and Landforms 33 (1), 142–151. https://doi.org/10.1002/esp.1561.

Ruiz de Alegria Arzaburu, A., Ilic, S., Gunawardena, Y., 2007. A study of intertidal bar dynamics using the Argus video system. In Coastal Sediments' 07, 1865–1876.

Russell, P.E., Huntley, D.A., 1999. A cross-shore transport "shape function" for high energy beaches. J. Coast. Res. 198–205.

Sassa, Shinji, Watabe, Yoichi, 2009. Persistent sand bars explained by geodynamic effects. Geophys. Res. Lett. 36 (1), L01404. https://doi.org/10.1029/2008GL036230.

Saye, S.E., van der Wal, D., K, Pye., et al., Blott, S.J., 2005. Beach–Dune Morphological Relationships and Erosion/Accretion: An Investigation at Five Sites in England and Wales Using LIDAR Data. Geomorphology 72 (1-4), 128–155. https://doi.org/10.1016/j.geomorph.2005.05.007.

Scott, Tim, Masselink, Gerhard, Russell, Paul, 2011. Morphodynamic characteristics and classification of beaches in England and Wales. Mar. Geol. 286 (1–4), 1–20. https://doi.org/10.1016/j.margeo.2011.04.004.

Sedrati, Mouncef, Anthony, Edward J., 2006. The role of longshore currents in intertidal bar mobility on a macrotidal beach under high energy wave conditions. In: Coastal Dynamics 2005. American Society of Civil Engineers, Barcelona, Spain, pp. 1–14. https://doi.org/10.1061/40855(214)73.

Short, A.D., 1991. Macro-meso tidal beach morphodynamics: an overview. J. Coast. Res. 7 (2), 21.

Simmonds, D., Voulgaris, D., Huntley, D., 1995. Dynamic processes on a ridge and runnel beach. In: Proceedings of Coastal Dynamics'95.

Simmonds, David J., O'Hare, Tim J., Huntley, David A., 1997. The influence of long waves on macrotidal beach morphology. In: Coastal Engineering 1996. Orlando, Florida, United States, American Society of Civil Engineers, pp. 3090–3103. https://doi.org/10.1061/9780784402429.239.

Sipka, Vincent, Anthony, Edward J., 1999. Morphology and hydrodynamics of a macrotidal ridge and runnel beach under modal low wave conditions. J. Rech. Océanogr. 7.

Song, Youn-Kyung, Figlus, Jens, Chardón-Maldonado, Patricia, Puleo, Jack A., 2019. Numerical simulation of ridge-runnel formation and migration on a steep MESO-tidal engineered beach. In: Coastal Sediments 2019. WORLD SCIENTIFIC, Tampa/St. Petersburg, Florida, USA, pp. 742–753. https://doi.org/10.1142/9789811204487_0066.

Stépanian, Alexis, 2002. Evolution morphodynamique d'une plage macrotidale à barres: Omaha beach (Normandie). Océan, Atmosphère. Université de Caen Français.tel-00003997.

Stépanian, Alexis, Vlaswinkel, Brigitte, Levoy, Franck, Larsonneur, Claude, 2001. Sediment transport on a macrotidal ridge and runnel beach during accretion conditions. In: Coastal Dynamics '01, 1017–27. American Society of Civil Engineers, Lund, Sweden. https://doi.org/10.1061/40566(260)104.

van den Berg, J.H., 1977. Morphodynamic development and preservation of physical sedimentary structures in two prograding recent ridge and runnel beaches along the Dutch coast. Geol. Mijnb. 56, 185–202.

Vanhée, Stéphane., Anthony, Edward J., et al., Marie-Hélène, Ruz, 2002. Aeolian Sand Transport on a Ridge and Runnel Beach: Preliminary Results from Leffrinckoucke Beach, Northern France. Journal of Coastal Research (mars) 36, 732–740. https://doi.org/10.2112/1551-5036-36.sp1.732.

Van Houwelingen, Selma, Masselink, Gerhard, Bullard, Joanna, 2008. Dynamics of multiple intertidal bars over semi-diurnal and lunar tidal cycles, North Lincolnshire, England. Earth Surf. Process. Landf. 33 (10), 1473–1490. https://doi.org/10.1002/esp.1616. Geomorphology Symposia Series, Binghampton, Allen&Unwin, London, 73-98.

Vaucher, Romain, Pittet, Bernard, Passot, Sophie, Grandjean, Philippe, Humbert, Thomas, Allemand, Pascal, 2018. Bedforms in a tidally modulated ridge and runnel shoreface (Berck-Plage; North France): implications for the geological record. Bull. Soc. Géol. France 189 (1), 5. https://doi.org/10.1051/bsgf/2018004.

Vincent, Christopher E., Kay, Robert C., Chenghui, Chen, Li, Li, et al., Jarvis, Jack, 1990. Morphology, sedimentary bedforms and sand transport across a ridge- and- runnel beach under the action of summer waves. Chinese Journal of Oceanology and Limnology 8(3), 197–212. https://doi.org/10.1007/BF02849659.

Vos, Kilian, Harley, Mitchell D., Splinter, Kristen D., Simmons, Joshua A., Turner, Ian L., 2019. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. Coast. Eng. 150, 160–174. https://doi.org/10.1016/j.coastaleng.2019.04.004. août.

Vos, Kilian, Harley, Mitchell Dean, Splinter, Kristen, Walker, Andrew, Turner, Ian L., 2020. Beach slopes from satellite-derived shorelines. Preprint. Oceanography. https://doi.org/10.1002/essoar.10502903.1.

Voulgaris, G., Mason, T., Collins, M.B., 1996. An energetics approach for suspended sand transport on macrotidal ridge and runnel beaches. In: Proceedings of 25th International Confeence on Coastal Engineering. ASCE, pp. 3948–3961.

Voulgaris, G., Simmonds, D., Michel, D., Howa, H., Collins, M.B., Huntley, D.A., 1998. Measuring and modelling sediment transport on a macrotidal ridge and runnel beach: an intercomparison. J. Coast. Res. 14, 315–330.

Whitehouse, R.J.S., Bassoullet, P., Dyer, K.R., Mitchener, H.J., Roberts, W., 2000. The infuence of bedforms on flow and sediment transport over intertidal mudflats. Cont. Shelf Res. 26.

Wijnberg, K.M., Kroon, A., 2002. Barred beaches. Geomorphology 48, 103–120.

Williams, Jon J., Carling, Paul A., Amos, Carl L., Thompson, et Charlie, 2008. Field investigation of ridge–runnel dynamics on an intertidal mudflat. Estuar. Coast. Shelf Sci. 79 (2), 213–229. https://doi.org/10.1016/j.ecss.2008.04.001.

Wright, Peter, 1976. A cine-camera technique for process measurement on a ridge and runnel beach. Sedimentology 23 (5), 705–712. https://doi.org/10.1111/j.1365-3091.1976.tb00103.x.

Yamada, F., Kobayashi, N., et al., 2007. Intertidal Multiple Sand Bars in a Low-Energy Environment. Journal of Waterway, Port, Coastal, and Ocean Engineering 133 (5), 343–351. https://doi.org/10.1061/(ASCE)0733-950X(2007)133:5(343).

Yamada, F., Uehara, K., Hokamura, T., Yamabe, T., 2007. Morphology and seasonal evolutions of intertidal multiple sand bars in low wave environment. J. Coast. Res. 50, 8.

Zonneveld, John-Paul, Gingras, Murray K., Hodgson, Cheryl A., McHugh, Luke P., Myers, Reed A., Schoengut, Jesse A., Wetthuhn, Bryce, 2014. Biotic segregation in an upper mesotidal dissipative ridge and runnel succession, West Salish Sea, Vancouver Island, British Columbia. In: Hembree, Daniel I., Platt, Brian F., Smith, Jon J. (Eds.), Experimental Approaches to Understanding Fossil Organisms. Topics in Geobiology 41. Springer Netherlands, Dordrecht, pp. 169–194. https://doi.org/10.1007/978-94-017-8721-5_8.