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Morphodynamic response of a meso- to macro-tidal intermediate beach based on a long-term data set

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ABSTRACT

Four years of bi-monthly topographic surveys have been conducted on a 350 m stretch of the meso- to macro-tidal Truc Vert beach, France. Here we study the dynamics of both the inner bar and the upper part of the beach where a berm can develop in the presence of fair weather conditions. For the inner bar, the occurrences of the different states within the intermediate classification, following that of Wright and Short (Wright, L.D., Short, A.D. 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Marine Geology 56, 93–118), are presented and compared to other sites in both micro- and meso-tidal environments. The results show a similar frequency of occurrence of the Transverse Bar and Rip (TBR) state, while the more dissipative states, Rhythmic Bar and Beach (RBB) and Longshore Bar and Trough (LBT), are less regularly observed despite the high wave energy levels. The LBT and RBB states are also observed in the presence of fair weather conditions and the TBR state can persist during very energetic events. Similar results are also observed with the upper beach dynamics. Very energetic events are not necessarily associated with erosion while and low-energy events are not necessarily accompanied by accretion. The conditions given here indicate, that berm development occurs preferentially when the beach morphology exhibits a TBR or a LTT state. Apart from the control exerted by offshore wave conditions, the beach state and berm development patterns exhibited by Truc Vert beach are also discussed within the framework of possible morphological (morphodynamic) feedback and of the influence of the meso- to macrotidal range which modulates the type, intensity and duration of the wave processes operating on the cross-shore profile.

1. Introduction

Despite a long history of investigation of multiple bar beaches, prediction of beach morphology is still an issue. Generally, one of the first steps in beach morphological prediction is knowledge of all the different states a beach presents and their frequency of occurrence. The next step generally consists in the understanding of the dynamics of the beach; this means identifying the physical mechanisms involved in the modification of beach shape. Different approaches have been undertaken to answer the second question: intensive field experiments, among them Sandy Duck, Coast 3D and more recently ECORS-Truc Vert; numerical modelling (among others, Reniers et al., 2004; Garnier et al., 2006; Dronen and Deigaard, 2007; Smit et al., 2008); and, long-term observations (among others Van Enckevort and Ruessink, 2003a,b; Ranasinghe et al., 2004; Quartel et al., 2007). For this last approach, the emergence of video systems has played a key role (Holland et al., 1997; Smit et al., 2007). This method allows continuous beach morphology survey and thus a better analysis of short-term (daily) to long-term (seasonal) beach behaviour. Recently, many studies have been published on this method which has enabled significant progress in the knowledge of both intertidal and subtidal bar systems (Van Enckevort and Ruessink, 2003a, 2003b; Ranasinghe et al., 2004; Quartel et al., 2007, 2008 among others). In particular, the role of morphologic feedback (Wright et al., 1985; Ruessink and Terwindt, 2000; Plant et al., 2001; Quartel et al., 2008; Ortega-Sanchez et al., 2008) and possible coupling between the systems (Ruessink et al., 2007) have been investigated, as well as the influence of tide on the type, intensity and duration of the wave processes operating on the cross-shore profile (Masselink and Turner, 1999; Masselink et al., 2006; Reichmüth and Anthony, 2007; Price and Ruessink, 2008). Nevertheless, most of these studies concern micro- and meso-tidal environments and there are still knowledge gaps concerning meso-, macro-, and mega-tidal environments. The major reason for this is that the study of these environments is more recent (Voulgaris et al., 1998; Michel and Howa, 1999; Levoy et al., 2000; Kroon and Masselink, 2002; Masselink, 2004; Anthony et al., 2004, 2005; Reichmüth and

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Anthony, 2007; Castelle et al., 2007; Sedrati and Anthony, 2007; Masselink et al., 2008) and long-term observational datasets are still to be built.

In this paper, we present the first results of long-term topographic surveys acquired on a meso- to macro-tidal double-barred intermediate beach, Truc Vert beach (TVB). The data presented and discussed in this paper consist in 60 topographic surveys (each topographic survey comprising 15 cross-shore profiles) carried out between September 2003 and September 2007 through all the seasons and coupled to wave conditions. Different points are explored: first, the occurrence of the different beach states within the intermediate range of the beach classification proposed by Wright and Short (1984) will be discussed and compared to that of micro-tidal environments, in particular tidal influence on the intertidal morphology is discussed; secondly, the non-linear response of the intertidal morphology is discussed, as well as the role of morphologic feedback. Finally, we present seasonal accretion and erosion patterns of the beach.

2. Study area

Truc Vert beach is situated on the southern part of the French Atlantic coast (Fig. 1) and is typical of the relatively undisturbed coast extending 100 km between the Gironde Estuary (90 km to the north) and the Arcachon inlet (10 km to the south). This is a low sandy coast, almost N–S-orientated and bordered by high aeolian foredunes. The sediment consists primarily of a medium grained quartz sand with a median particle size around 350 µm (Lorin and Viguier, 1987). Recent studies showed that the particle size is not homogenous on Truc Vert beach: both shore-normal variation and alongshore variation were observed in median particle sizes (Gallagher et al., 2008). For this study, we only considered the median particle size and the settling velocity w_s of the Truc Vert beach median sand is about 0.050 m/s.

The beach experiences an annual mean spring tide range of 3.70 m. The wave climate is energetic with an annual mean significant wave height of 1.36 m and mean period around 8 s and strong seasonal dependence: waves being higher in winter than in summer (see Butel et al., 2002 for a complete wave classification on the Aquitanian coast). During storm conditions, offshore wave heights can reach up to 10 m. Nevertheless the subtidal bar system protects the intertidal beach from severe wave conditions. Inshore significant wave heights are generally less than 3 m, even during spring high tide.

Different studies have been undertaken at TVB since 1998: intensive field experiments (Michel and Howa, 1999; Senechal et al., 2004; Masselink et al., 2008), numerical modelling (Castelle et al., 2006) and long-term topographic surveys. Long-term data acquired on TVB consist of bi-monthly low-tide mark surveys (De Melo Apoluceno et al., 2002), satellite imagery (Lafon et al., 2002, 2004, 2005) and linear principal components analysis on a monthly to bi-monthly single measured cross-shore profile (Rihouey, 2004). The results of most of these studies have been synthesised in Castelle et al. (2007).

It has been shown that TVB exhibits complex three-dimensional and highly dynamic morphologies commonly involving two distinct sandbar systems. The inner bar can go through all the states within the intermediate classification (see Wright and Short, 1984; Masselink and Short, 1993) and usually exhibits a Transverse Bar and Rip

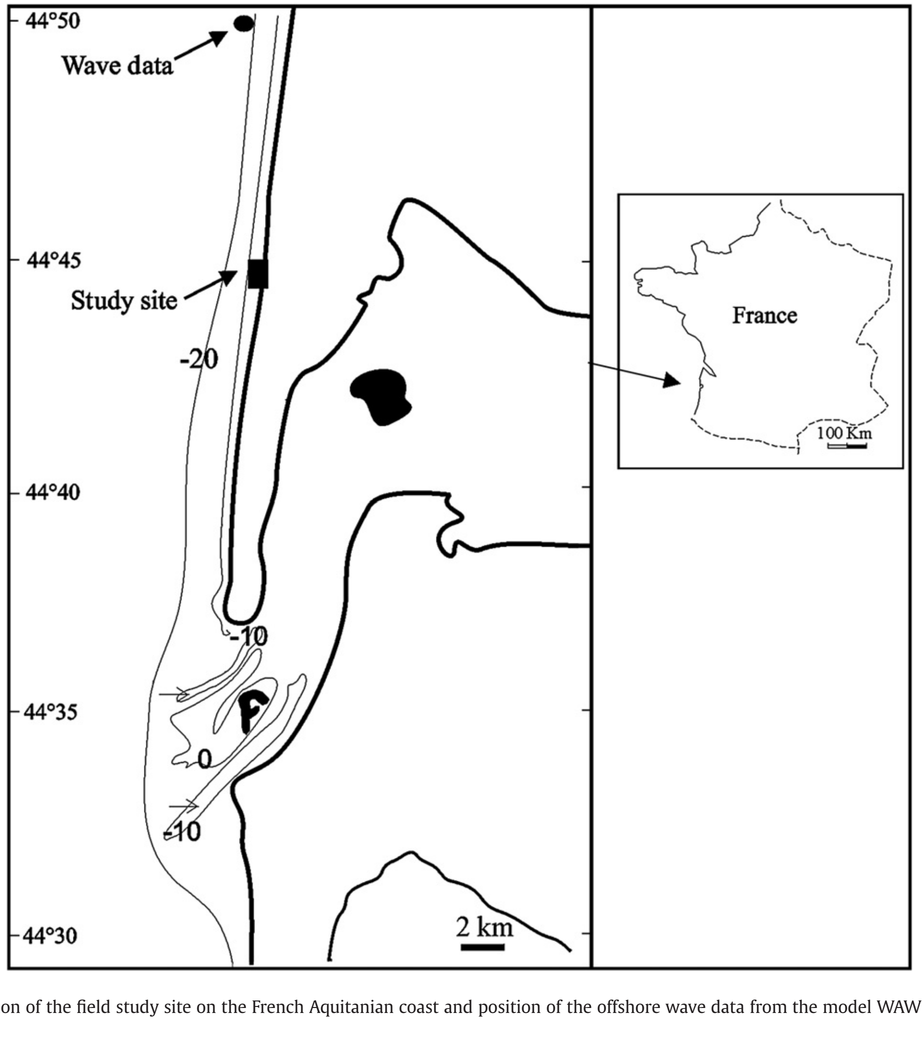

Fig. 1. Location of the field study site on the French Aquitanian coast and position of the offshore wave data from the model WAWEWATCH III.

morphology that also commonly becomes a Low Tide Terrace with a mean wavelength of 400 m after at least 10 days of fair weather conditions (De Melo Apoluceno, 2002; Castelle et al., 2007). The outer bar system exhibits long-term persistent crescentic patterns at a narrow range of wavelengths, the shape of which varies from symmetric to asymmetric (Castelle et al., 2007). A berm often forms on the upper part of the beach after fair weather conditions.

At this stage, even if each state has been observed at least once at TVB, there is no information on their percentages of occurrence. The present work addresses this knowledge gap and presents, for the first time results concerning a meso- to macro-tidal environment.

3. Materials and methods

3.1. Topographic surveys

Data have been acquired generally twice per month from September 2003 to January 2006 and then once per month from February 2006 to September 2007. Data were collected at low tide during spring tides. Topographic surveys were conducted using a DGPS (TRIMBLE 5700) with an accuracy of about 2.5 cm in the horizontal and 10 cm in the vertical (using an equipped ATV for topographic survey). At each low tide, 15 cross-shore lines were

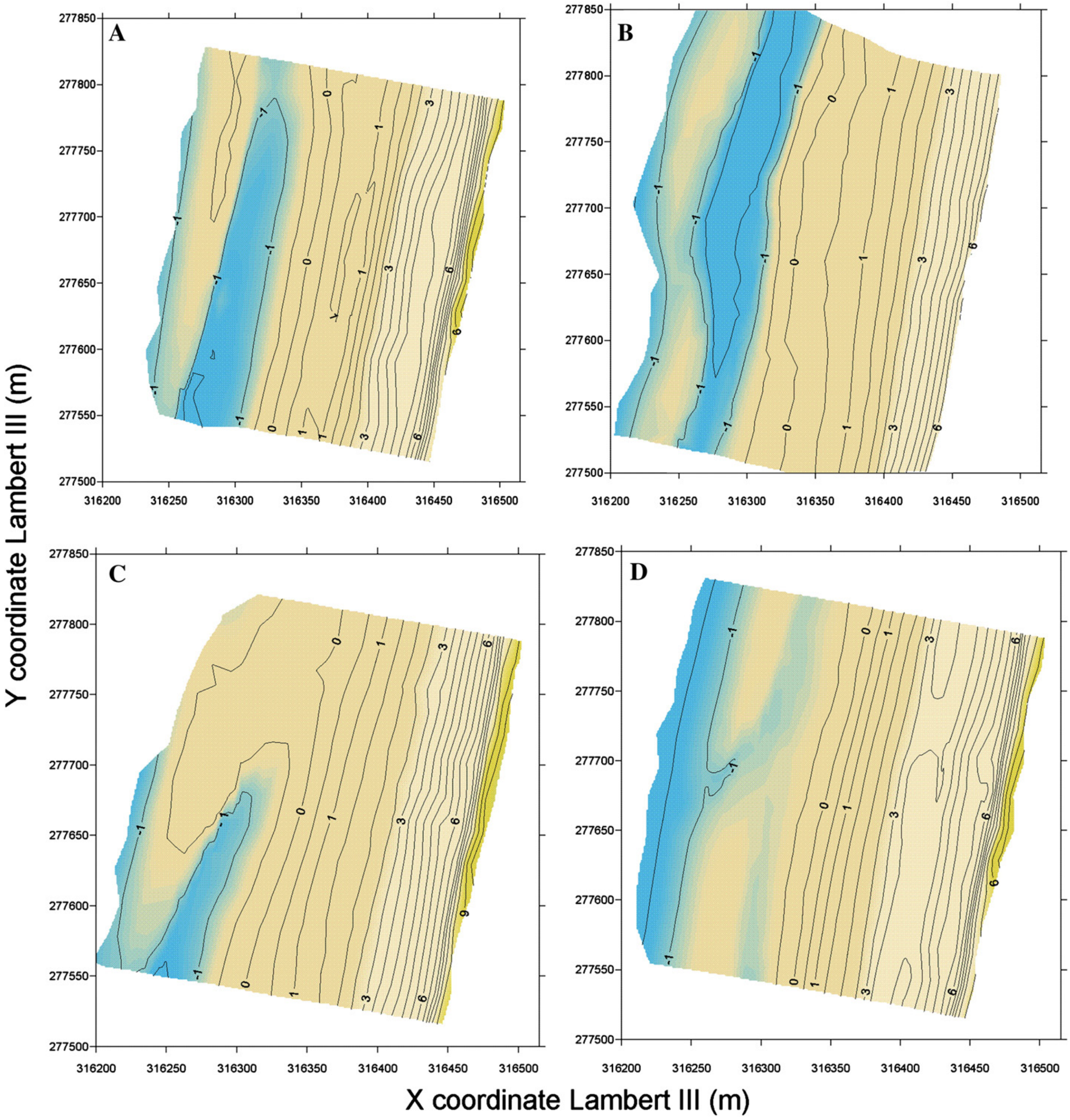

Fig. 2. Different beach states as observed at Truc Vert beach: (A) the longshore bar and trough, (B) the rhythmic bar and trough, (C) the transverse bar and rip and, (D) the low tide terrace.

Table 1

	Truc Vert occurrence	Truc Vert % occurrence	W (1987) % occurrence	LH (1990) % occurrence	R (2004) % occurrence
LTT	9	16	16	9	5
TBR	32	58	45	47	55
RBB	3 (5)	14	25	24	28
LBT	(6)	12	10	21	12

surveyed from the water line at low tide up to the aeolian foredune. The distance between each transect is about 25 m, so the total covered longshore length was about 350 m. The inner bar could not be completely covered systematically by the topographic surveys because of the water level being higher than the predicted tide levels due to high-energy wave conditions (storm surges and wave set-up). Most of the topographic surveys were coupled to low tide mark measurements using a GPS (GARMIN) and covering a longshore distance of about 3 km. The surveys were all referenced to benchmarks of the French National Geodesic Service (NGF-IGN 69) to allow inter-comparisons. The cross-shore transects were interpolated to create the topography of the beach with the low tide mark overplotted. Each topographic survey was then classified to a given beach state.

TVB has long been known from visual observations to be in the range of intermediate beach states. In the classification of Wright and Short (1984), intermediate beaches were further divided into four sub-states: the Longshore Bar and Trough (LBT) immediately below the high energy dissipative state, then the Rhythmic Bar and Beach (RBB), followed by the Transverse Bar and Rip (TBR) and finally the Low Tide Terrace (LTT) or ridge and runnel system (Wright and Short, 1984; Short, 1999). Of the 60 topographic suveys, only 5 could not be identified, due to water level being too high to allow access to the lower intertidal domain. Some 45 topographic surveys were clearly identified and 10 other topographic are supposed to be of the proposed states. The classification was less straightforward since it was based on observations of low tide marks and on annotations of the operator. In particular, the distinction between the RBB and the LBT beach type was all the more difficult because of the limited section of beach which was surveyed (350 m). Fig. 2 illustrates the different sub-states as they occur on TVB.

3.2. Hydrodynamic data

Hydrodynamic data were obtained from the French navy (SHOM) for the tide, and from the model WAVEWATCH III for the waves at location 45°00N and 1°25 W (TVB is situated at 44°74N and 1°24W, see Fig. 1). The wave data comprise significant wave height (H_s), peak period (T_p) and peak direction (D_p) with a 3-hour interval.

Wright et al. (1985) showed that beach morphology may be best related to wave conditions averaged over a few antecedent days, rather than the immediately preceding conditions. According to previous results (De Melo Apoluceno et al., 2002; Castelle et al., 2007) concerning the time response of the system on this beach (from one tidal cycle to several days), the wave conditions were considered up to 14 days before the topographic survey. Several parameters were then computed:

- The total energy flux, normalized by the energy flux computed by considering 14 consecutive days of mean annual conditions (following Butel et al., 2002) and termed the *R* parameter.
- The temporal distribution of the energy flux before the topographic survey. This should allow us to determine whether the response of the beach is due to an event or to "quasi-permanent" wave conditions.
- Offshore wave data were also used to compute the longshore component of the offshore wave energy flux P_{long} which can be approximated (Short, 1979; Komar, 1998; Ruesssink et al., 2000) by:

$$P_{\text{long}} = \frac{\rho g^2}{64\pi} H_s^2 T_p \sin\theta_0 \cos\theta_0 \qquad (1)$$

where ρ is water density, g the gravitational acceleration, H_s the offshore significant wave height, T_p the peak wave period and θ_0 the offshore wave angle to the shore. This value is positive if directed southward.

3.3. The Ω parameter

Wright et al. (1985, 1987) showed that time-varying beach state can be partially predicted in terms of the Ω parameter defined as:

$$\Omega = H_b / (w_s T) \qquad (2)$$

where H_b is breaker height, T is peak breaker period, and w_s is the mean fall velocity of the beach sand. In our study, T was supposed constant between the offshore point (see Section 3.1) and the surf zone. During storm conditions (offshore $H_s > 3$ m), H_b was fixed to 3 m.

Following Wright et al. (1985, 1987), a weighted mean value of Ω, computed from 3-hourly values for the several days preceding the day for which prediction is sought:

$$\overline{\Omega} = \left[\sum_{j=1}^{D} 10^{-j/\Phi}\right]^{-1} \sum_{j=1}^{D} \left(\Omega_j 10^{-j/\Phi}\right) \qquad (3)$$

where $j=1$ on the day just preceding the beach state observations and $j=D$ on D days prior to observation. The parameter Φ depends on

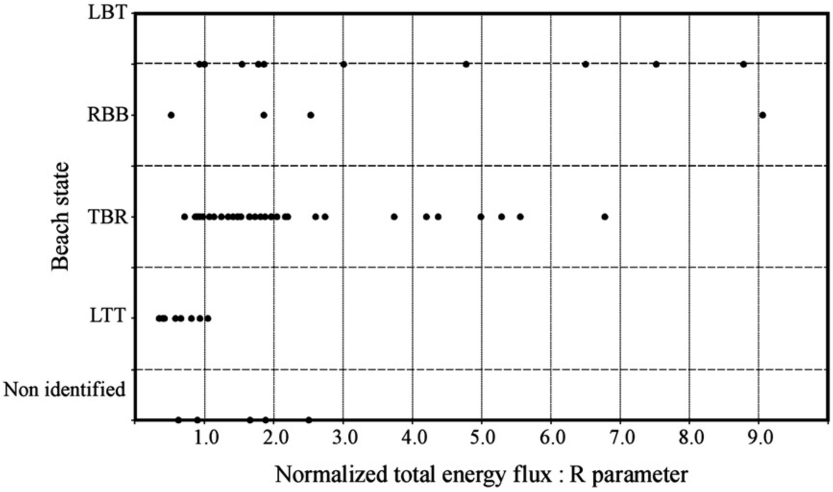

Fig. 3. Intermediate beach states versus energy flux ratio observed at Truc Vert beach.

Table 2

Beach state	Truc Vert $\overline{\Omega}$	Truc Vert standard deviation $\overline{\Omega}$	Wright et al. (1987) $\overline{\Omega}$	Wright et al. (1987) standard deviation $\overline{\Omega}$
LTT	2.35	0.49	2.69	0.61
TBR	2.83	0.68	3.26	0.72
RBB	3.73	0.59	3.63	0.79
LBT	3.73	0.70	4.72	1.26

the rate of memory decay. At Φ days prior to observation, the weighting factor decreases to 10%. For the dynamics of Truc Vert beach the values of $\Phi = 10$ days and $D = 30$ were used.

4. Frequency of occurrence of beach states

The number of occurrences and percentages of occurrence of each beach state are shown in Table 1. The percentages of occurrence of the various beach states reported by Wright et al. (1987) (1842 days of visual field observations at Narrabeen beach, Sydney, Australia, referred as W (1987) in Table 1), by Lippmann and Holman (1990) (523 days of visually classified ARGUS time-exposure images at Duck, NC, USA, referred as LH (1990) in Table 1) after combination in the same classification done by Ranasinghe et al. (2004), and Ranasinghe et al. (2004) (52 day-timex images, Palm beach, Sydney, Australia, referred as R (2004) in Table 1) are also shown in Table 1 for comparison.

The most frequently occurring beach state at Truc Vert beach is the TBR state (58%) with the LTT, the RBB and the LBT states distant a second, third and fourth, respectively, with only 16%, 14% and 12% of occurrence. As in micro-tidal environments, the TBR state is the most frequently occurring beach state. The value compares very well with the observations of Wright et al. (1987) at Narrabeen Beach, Sydney, those of Lippmann and Holman (1990) at Duck, NC, and those of Ranasinghe et al. (2004) at Palm Beach, Sydney. Nevertheless we observe an important discrepancy concerning the more dissipative states: the RBB and LBT states are less represented at TVB than in the micro-tidal environments.

Fig. 3 represents the beach state as a function of the energy flux ratio R as presented in the previous section. An energy flux ratio of 1 corresponds to 14 consecutive days with significant wave height $H_s = 1.36$ m and mean period $T = 8$ s. The LTT state is clearly associated with low wave energy levels and is observed only for a value of the R parameter below 1. This value is coherent with the mean wave

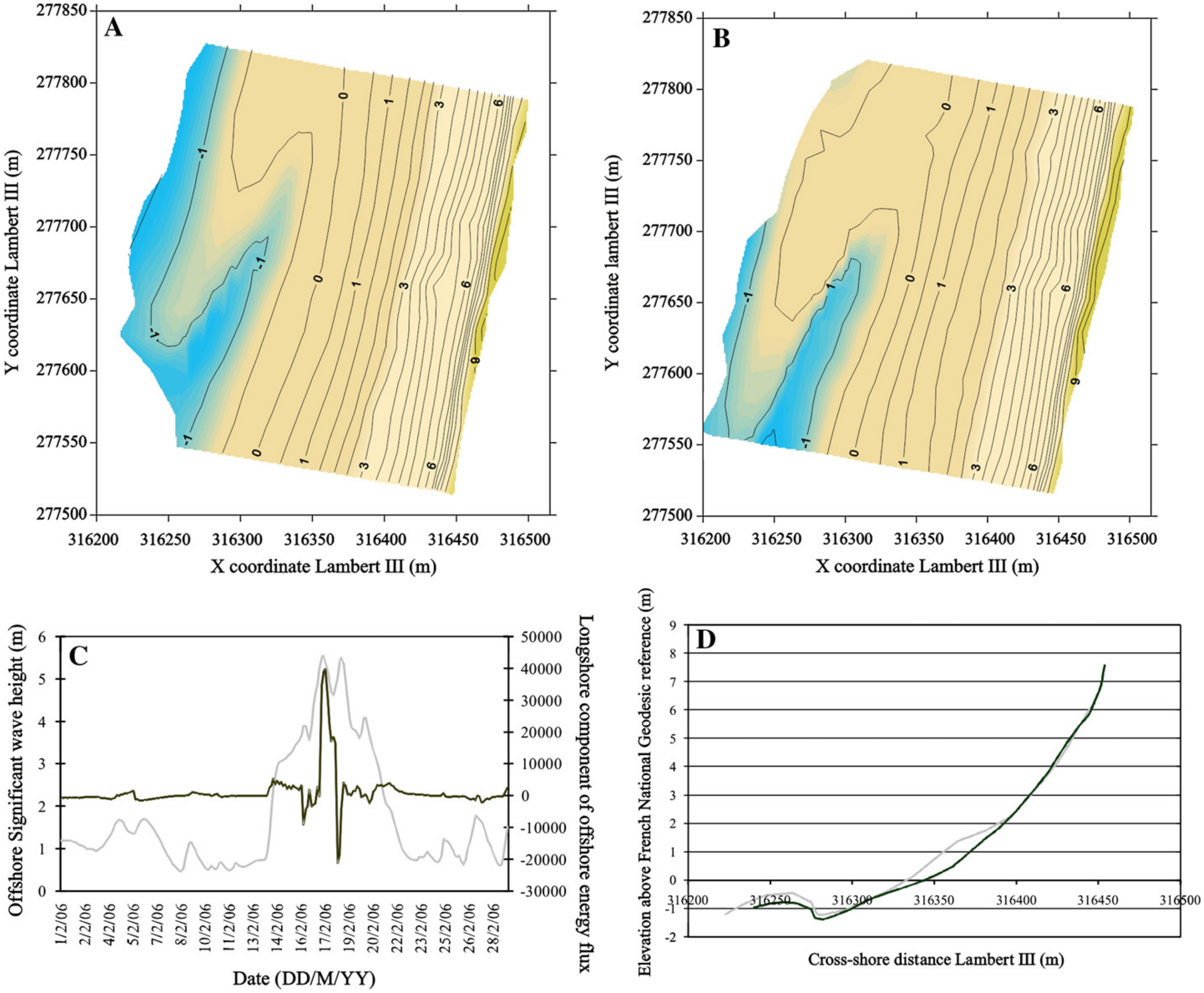

Fig. 4. Winter 2006 (a) initial topography showing TBR state. (b) Final topography showing the same TBR state migrating southward. (c) Offshore wave conditions between the two surveys: significant wave height (grey line), longshore component of offshore wave energy flux (black line). (d) Cross-shore profiles: initial (black) and final (grey).

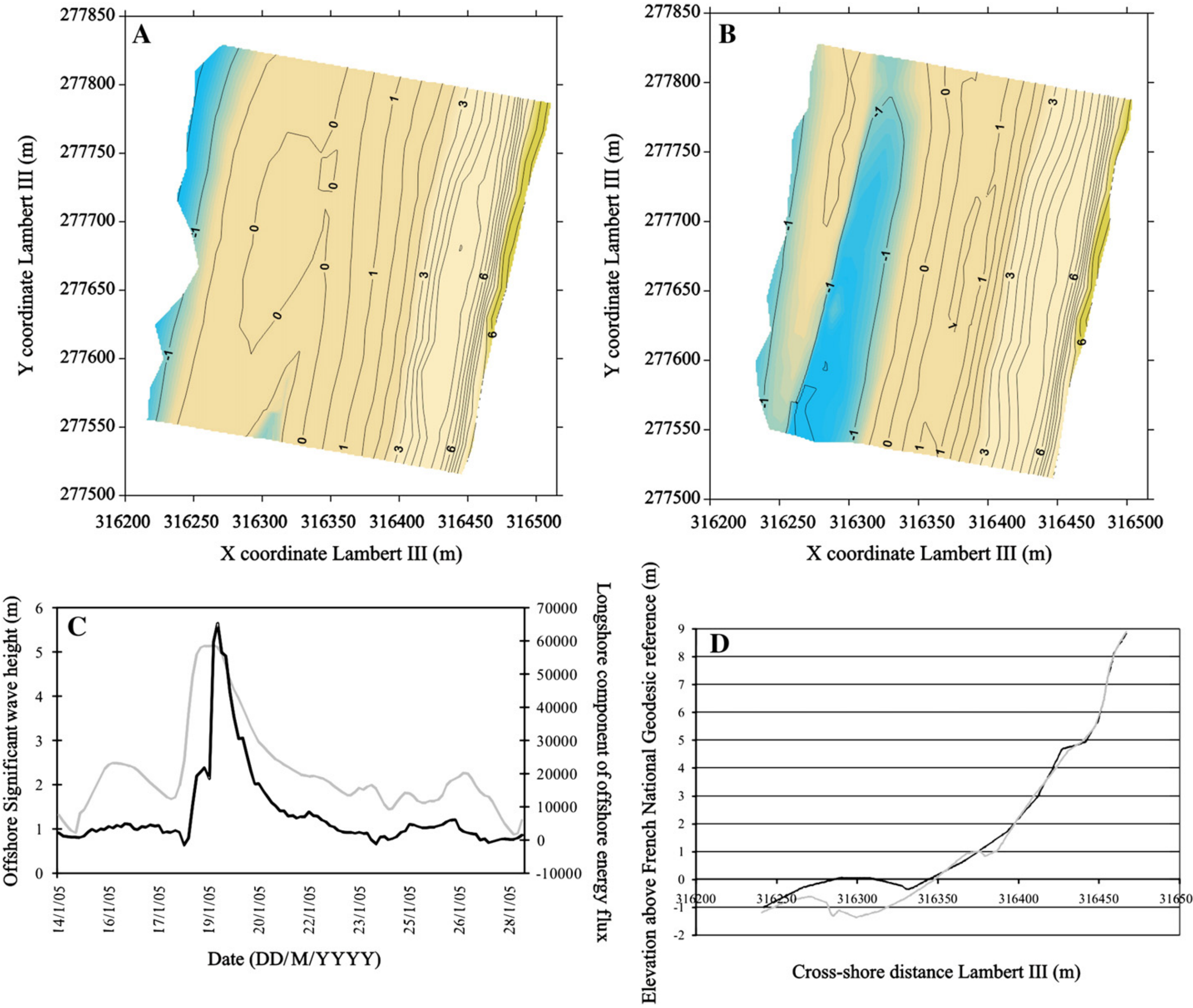

Fig. 5. Winter 2005 (A) initial topography showing TBR state. (B) Final topography showing the same TBR state migrating southward. (C) Offshore wave conditions between the two surveys: significant wave height (grey line), longshore component of offshore wave energy flux (black line). (D) Cross-shore profiles: initial (black) and final (grey).

conditions associated with the LTT state reported by Ranasinghe et al. (2004). LBT and RBB states, although characterised by a wide range of *R*, are associated with the highest *R* parameter consistent with previous work (Lippmann and Holman, 1990; Ranasinghe et al., 2004) which reported that these beach states were associated with higher levels of wave energy. This is also coherent with conceptual models (Wright and Short, 1984; Brander, 1999; Castelle et al., 2007) showing that high wave events result in rapid up-state transitions of beach state. Nevertheless, RBB and LBT can also be observed despite low values of the *R* parameter associated with low energy (H_s<1.5 m) short waves (mean peak periods are below 9 s). These situations are generally observed after an energetic event associated with both high values of *R* parameter and up-state transitions. The TBR state is also associated with a wide range of the *R* parameter; even if most of the time the TBR state was associated with an *R* parameter between 1 and 2, occurrences of this state were also observed in the presence of an *R* parameter of up to 7. During the whole observation period reported by Ranasinghe et al. (2004), the offshore significant wave height rarely exceeded 4 m and never exceeded 5 m. At TVB, several events with offshore significant wave heights higher than 5 m were observed and some of them were associated with a persistent TBR state (Fig. 2). These data reveal that the TBR system observed in Truc Vert beach can persist during more energetic events than reported from Palm beach by Ranasinghe et al. (2004). The reason for this will be discussed in the last section.

Table 2 indicates the central tendencies of the mean weighted mean value of Ω corresponding to each of the 4 beach states. The values found by Wright et al. (1987) are also indicated in Table 2 for comparison. The values of the means of omega for Truc Vert beach are very similar to the one observed by Wright et al. (1987) for Narrabeen beach. As observed by Wright et al. (1987), the means of *Ω* differ significantly between states. Increase in $\overline{\Omega}$ drives a beach/surf-zone system to more dissipative states. The values for the LBT and for the RBB are very close and should not be compared to each other because of the limited observations of these states and the difficulty in distinguishing these two states from each other.

5. Inner bar response to storm events

Two storm events will be presented in this part: the first event concerns winter 2006 with a persistent TBR state, and the second is winter 2005 with up-state transition.

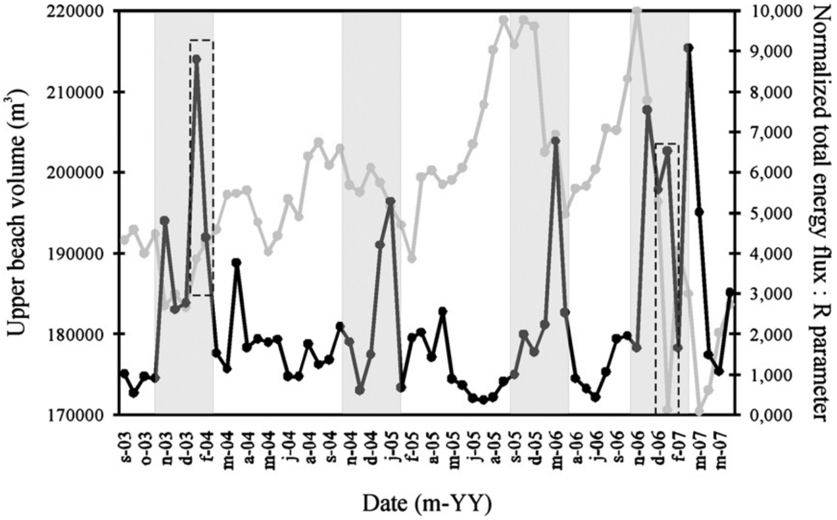

Fig. 6. Upper beach volume (grey) and normalized offshore wave energy flux (black) during the 4-year survey. Filled grey rectangles indicate winter period. Black rectangles show selected events.

5.1. Persistent TBR state during winter 2006 storm

Fig. 4 shows both the beach evolution and the wave conditions during the event in winter 2006. Between February 15th and 20th the beach was exposed to a severe storm with significant wave heights greater than 3 m and reaching 5.5 m at the peak of the storm (Fig. 4C). The tidal range during this period varied between 2.2 m and 3.3 m with a mean value of 2.9 m. After this period, the beach was exposed to mild weather conditions with significant wave heights generally below 1.5 m (Fig. 4C). On January 31st, a well-developed TBR state was clearly observed in the lower intertidal domain (Fig. 4A). The rip channel was well developed, orientated southward and relatively deep (more than 1 m), consistent with the wave climate at this period which is generally north-west (Butel et al., 2002). The upper part of the intertidal domain was relatively linear with an average beach slope of about 0.04. One month later (Fig. 4B), on March 1st, we observed the same TBR system migrated southward at an average rate of 3 m/s. Fig. 4D depicts beach profiles extracted from the topographic survey before (black line) and after (grey line) the storm event. We clearly observe the formation of the berm associated with accretion of the upper intertidal domain (Fig. 6).

The migration rate is consistent with previous observations (Lafon et al., 2005) but much smaller than those observed by Ruesssink et al. (2000) at Egmond aan Zee Beach for similar waves. Indeed, we observe during the storm event that the longshore component of the offshore wave energy flux was relatively high, up to 40, 000 (Fig. 3C). Ruesssink et al. (2000) measured longshore migration rates of up to 150 m/day under conditions of P_{long} about 45, 000, suggesting that the longshore migration rate at Truc Vert beach may have been about 150 m/day during the storm. This is not coherent with the overall migration of the bar: only 50 m southward, although positive longshore drift was dominant during most of the period, and was of higher intensity. Masselink and Hegge (1995) showed that if the orientation of the morphology mismatches the wave angle, an increase in wave height and breaking intensity will tend to decrease or even reverse the current circulation in the trough. In our case, this means that longshore drift in the surf zone may have been of less intensity when a negative longshore component of the offshore wave energy prevailed.

Berm construction and persistent TBR states are very interesting for two reasons: first, they show that a well developed TBR system can persist during long and intense storm event, and secondly they demonstrate the short time response of the upper beach, thus suggesting that the upper part of the beach was probably accreting during the short period of fair weather following the storm (6 days). Indeed, investigations in the same area (Masselink et al., 2008) reported the development and rapid growth (more than 1 m in a few days) of a berm during fair weather conditions characterized by H_s of 1–2 m, and the rapid destruction of the berm in the presence of high energy waves. These results are coherent with the observed values.

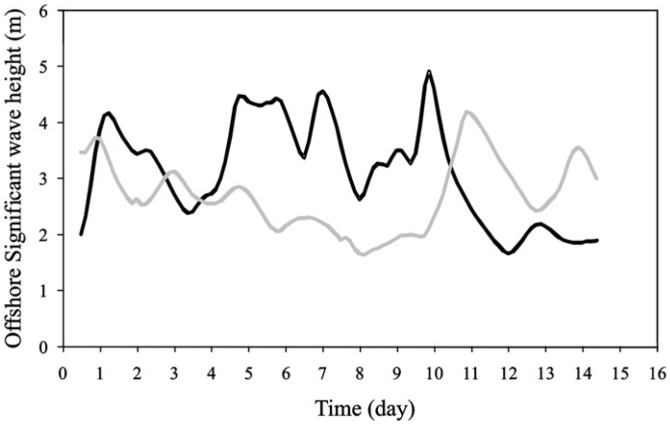

Fig. 7. Offshore significant wave heights during event December 2003–January 2004 (black line) and December 2006–January 2007 (grey line).

5.2. Up-state transition during the winter 2005 storm

Fig. 5 shows the event of winter 2005 that was quite similar in terms of wave energy levels to the previous one but of a shorter duration. Between January 18th and 20th the beach was exposed to a severe storm with significant wave heights greater than 3 m and reaching 5.2 m at the peak of the storm (Fig. 5C). The tidal range during this period was smaller than during the winter 2006 event with a mean value of 1.8 m. After this period, the beach was exposed to much lower energy conditions with significant wave height generally below 2 m (Fig. 5C). On January 12th, we clearly observe a well developed inner bar (Fig. 5A), corresponding to a TBR state with a rip less developed and a bar crest located closer shore than in the previous case, and suggesting a slip-face bar morphology following Masselink et al. (2006) (Fig. 5D, black line). The upper part is also linear with an average slope of about 0.04 as in the previous case. On

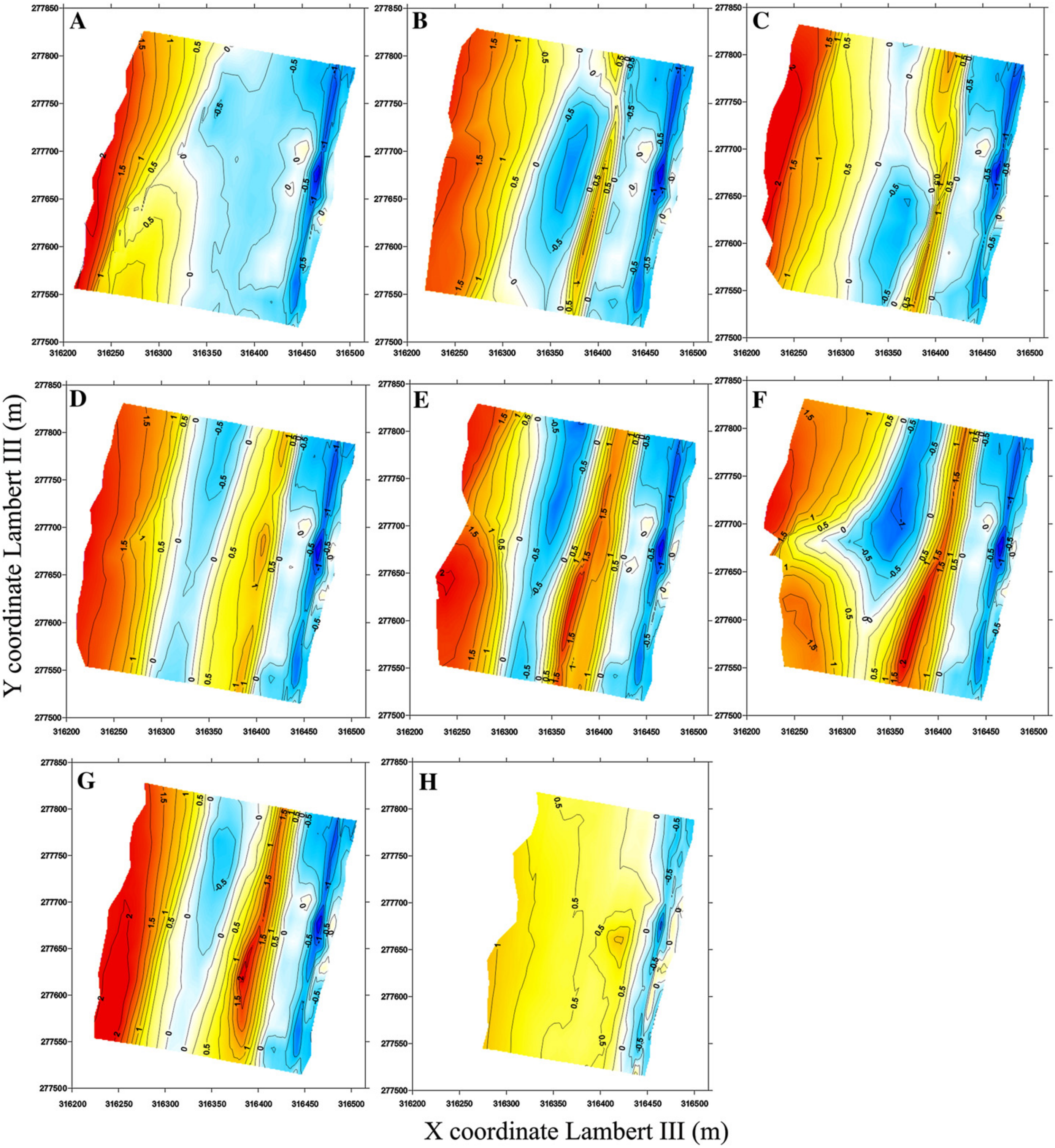

Fig. 8. Berm construction/destruction sequence: (A) May 23th, (B) June 23th, (C) July 22nd, (D) August 22nd (E) September 5th, (F) September 19th, (G) October 4th, (H) December 2nd.

January 28th, we clearly see that the inner-bar shape has been completely modified (Fig. 5B and D). The inner bar seemed to be completely disconnected from the upper intertidal area, suggesting a LBT state. A deep longshore trough was probably dug out by the persistent strong longshore drift during the storm, consistent with the wave forcing (Fig. 5C). These observations are in agreement with those proposed by Masselink et al. (2006). The authors observed that energetic waves (H_s>3 m) and high water levels (>2 m) resulted in reduced bar relief and offshore bar migration.

6. Upper intertidal beach dynamics

Wave-dominated beaches, following the ‘bar-berm’ model, generally exhibit a steep beach face and berm in the presence of low-energy swells during the summer periods and a flat profile in the presence of high-energy swells during winter (Aubrey, 1979). The formation of the berm is generally associated with an accretion phase whereas destruction of the berm is generally associated with an eroding phase. To measure this accretion/erosion cycle, quantification

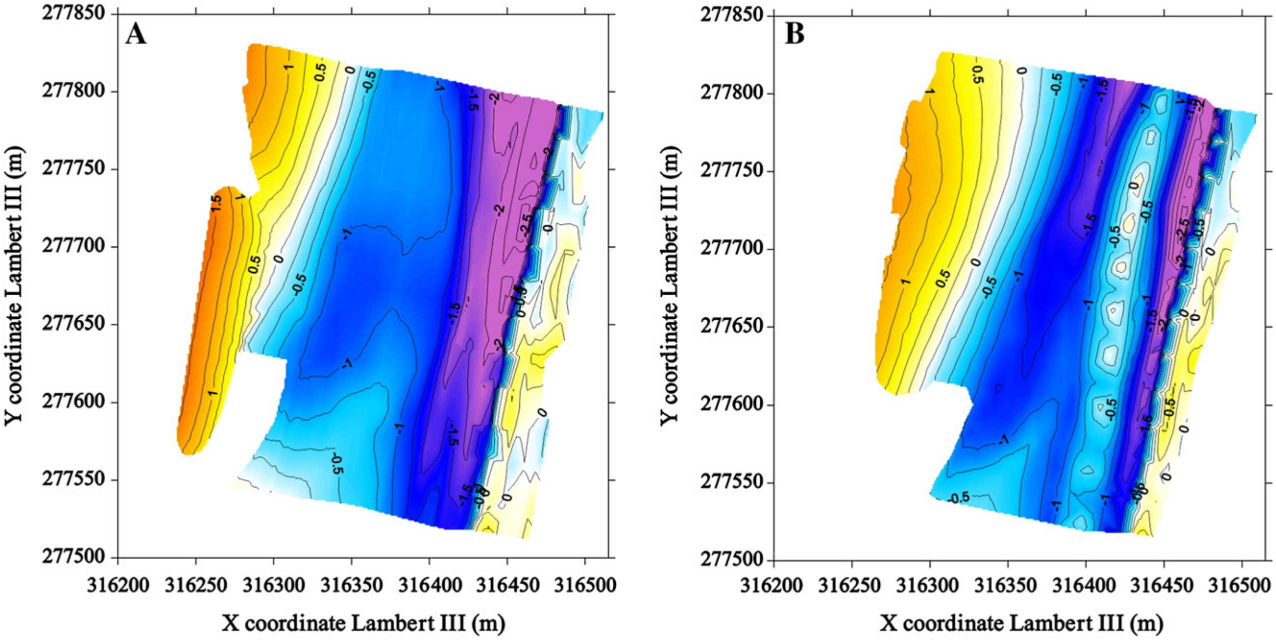

Fig. 9. Berm construction (A) April 3rd, no berm is visible, a TBR is developing in the lower beach domain, (B) May 4th, a berm is formed and the TBR is becoming increasingly developed in the lower beach domain.

of beach volume is essential (Allen, 1981). In this section, we will focus on the evolution of the upper intertidal beach. This area is not affected by inner bar dynamics but only by the berm dynamics and, thus, is indicative of this accretion/erosion behaviour.

6.1. Seasonal accretion and erosion patterns

Fig. 6 illustrates both the evolution of the *R* parameter (black line), as defined in Section 3.2 and the upper beach volume (grey line). This figure clearly highlights the seasonal variability of wave conditions, due to waves being generated by W–E-tracking subpolar deep low pressure systems over the North Atlantic Ocean. During winter periods, the *R* parameter is generally greater than 2, with maxima around 9, whereas during summer periods, the *R* parameter is generally below 1. Fig. 6 also shows that the winter of 2006/2007 was particularly energetic with 5 periods with the *R* parameter greater than 5, whereas in previous years, only one event had an *R* parameter greater than 5 during winter periods.

Fig. 6 also shows the alternation of periods of erosion and accretion at different time scales: a probably very long period of overall accretion until winter 2006/2007 when Truc Vert exhibited its lowest values of upper beach value since 2003; a seasonal pattern (grey rectangles, winter period generally associated with erosion), consistent with recent observations on a micro-tidal sandy beach (Quartel et al., 2008), and suggesting 'bar-berm' behaviour; and a final, much shorter period suggesting an important 'storm–post-storm' component that has been evoked in the previous section (see Fig. 4D).

However, periods of erosion and accretion are not necessarily correlated with periods of higher and lower energy as is generally the case for wave-dominated beaches (e.g. Wright et al., 1985; Dubois, 1998). For example, two periods are very significant: December 2003–January 2004 and December 2006–January 2007 (black rectangles). At the beginning of these two periods, the beach volume was about the same but it did not change in the same way. During the first period, the R parameter reached a value close to 9, indicating a very energetic period associated with three consecutive events with significant wave heights around 4.3 m (Fig. 7, black line) and respective mean tidal ranges of 3 m, 2.75 m and 2.25 m for the three events. At the same time, the beach volume slightly increased. During the second period, the *R* parameter reached a value close to 6.5 associated with two consecutive events with significant wave heights less than 4 m (Fig. 7, grey line) and respective mean tidal ranges of 3.1 m and 3.6 m for these two events. The beach volume decreased drastically, reaching its lowest value of the entire considered period. These observations are in agreement with recent observations by Quartel et al. (2008).

6.2. The 'bar-berm' component

The 'bar-berm' model clearly dominates the dynamics of the upper intertidal beach: periods of accretion being associated with low-energy conditions and construction of a berm, and erosion periods being associated with berm destruction as illustrated in Fig. 8. Fig. 8 shows a sequence of berm construction and destruction during summer–autumn 2005 when the upper beach volume increased drastically before decreasing very rapidly: each figure represents the difference between measured beach topographies and an idealized "reconstructed" planar beach.

Fig. 8A shows the situation as observed at the end of May, 2005. The beach exhibits a TBR state in its lower part and no berm on the upper part. One month later (Fig. 8B), we see the formation of a berm on the upper part; the beach exhibits a LTT state in its lower part. Offshore wave heights did not exceed 1.3 m during the whole period, and were associated with peak periods of around 8–9 s. The height of the berm is relatively high, about 1.5 m, in agreement with earlier observations in the same area by Masselink et al. (2008). The berm persists and grows during 2.5 months: Fig. 8C, D and E, respectively, illustrate situations at the end of July, the end of August and the beginning of September. During this period, significant wave heights did not exceed 2 m and consisted generally in wind waves (peak periods did not exceed 7–8 s).

After this period of growth, we observe a modification of the shape of the berm (Fig. 8F), probably due to the triggering of a rip in the lower intertidal domain. This is consistent with waves observed during this period: offshore significant wave heights reached up to 2.9 m with a normal incidence and with periods around 9 s. After this energetic period, fair weather conditions were observed with wave heights around 1 m and wave periods up to 12 s. Two weeks later

(Fig. 8G), the berm is still persistent despite very energetic conditions during the day before the topographic survey: wave heights reached up to 2.6 m with peak periods around 13.5 s and tidal range was about 3.3 m. These observations are very interesting since they indicate that a berm can persist during energetic events whereas previous observations indicated that the berm was rapidly destroyed in the presence of a high energetic event (>2 m) (Masselink et al., 2008).

Fig. 8H clearly illustrates the destruction of the berm. Unfortunately, this last topographic survey was carried out 2 months after the previous one, so it is quite hard to clearly identify the hydrodynamic conditions which led to the destruction of the berm. The month before this survey was particularly energetic, with several events of long and energetic swell (significant wave heights reached up to 3.5 m and peak periods reached 14 s). This construction/destruction sequence of the berm associated with an accretion/erosion sequence was also observed during the summers of 2004 and 2006.

6.3. The 'storm–post-storm' component

The 'storm–post-storm' component is also important in this data set. Indeed, Fig. 6 suggests that the beach did not recover between two successive storm events during winter 2007. The rapid succession of very energetic event during winter 2006–2007 led the beach to its lower volume since 2003.

As shown previously, fair weather conditions are required for berm construction but this is not the only factor. Indeed, Fig. 9 shows the situations (difference between measured and "idealized" planar beach) on April 3rd (Fig. 9A) and on May 4th (Fig. 9B). We clearly see that on April 3rd, the middle and upper parts of the intertidal beach are very low due to the previous storms. A TBR is developing in the lower intertidal domain (not observed on the previous survey). This situation is observed after two weeks of fair weather conditions: the wave climate was characterized by a long (11 s) and low-energy swell (<1.8 m). Previous observations (Fig. 4D and Masselink et al., 2008) showed that similar conditions allowed rapid construction (in a few days) of a berm, which is not the case in this situation. On the other hand, one month later, on May 4th, the upper beach was characterised by the formation of a berm with a height up to 2 m. Wave conditions were the same as previously.

7. Discussion

The foregoing results clearly show that on a meso- to macro-tidal beach subject to high wave energy, such as TVB, a well developed berm, generally associated with the low wave energy, at the reflective end of the spectrum of beach states, can persist under high wave energy conditions, especially in association with the Transvers Bar and Rip (TBR) state. The possible reasons for this are discussed with reference to offshore wave conditions, the influence of tidal range, and the possibility of morphodynamic feedback, based on the long-term dataset.

7.1. Offshore wave conditions

Concerning offshore wave conditions, as mentioned in Section 2, the subtidal bar system protects the intertidal beach from severe wave conditions. Inshore significant wave heights are generally less than 3 m, even during spring high tide. Nevertheless, storm waves also generate large set-up and intertidal systems are generally fully immersed during the whole tidal cycle in presence of very high energetic wave events (offshore significant wave height >3.0 m). Using offshore wave conditions allows us, in a way, to take into account this.

The upper intertidal beach is clearly mainly driven on the basis of a 'bar-berm' model: berms generally develop in summer due to the seasonal pattern of the wave climate in this area (Fig. 8) but can also develop very rapidly in a few days in presence of fair weather conditions (Fig. 4B). Berm construction is generally associated with an accretion period (Fig. 6). This is in agreement with recent observations in the same area (Masselink et al., 2008), but also with observations on micro-tidal sandy beach (Quartel et al., 2008). It has been shown that a berm can persist during an energetic (H_s>2.5 m) event associated with long swell (T_p = 13.5 s) and high water levels (Fig. 8). This is not consistent with the recent results of Masselink et al. (2008) who showed a rapid destruction of the berm in the presence of energetic waves (>2 m). Evidence has also been provided on the notion of time relaxing after a storm. Fig. 6 suggests that the beach did not recover between two successive storm events during winter 2007, leading to a significant erosion of the entire upper beach.

Concerning the lower intertidal domain, it has been shown that offshore conditions mainly drive the dynamics of the LTT state. Indeed, the LTT are observed only under conditions associated with an *R* parameter of about 1 which corresponds to 14 consecutive days with a significant wave height of about 1.36 m and a period of about 8 s (Fig. 3). In contrast, the other states are not mainly driven by offshore conditions: the LBT/RBB states have been observed even in the presence of low energy conditions following a morphological reset.

7.2. Tidal influence

Another phenomenon to be considered in this study is the tide. In this area, tidal ranges vary between 1.0 m on neap tides and more than 4 m on spring tides. It has been shown recently that morphological response can also be controlled by the tidal water levels on the beach, because, together with the offshore wave energy level and the beach morphology, they determine the type, intensity and duration of the wave processes operating on the cross-shore profile (Masselink and Turner, 1999; Masselink et al., 2006; Reichmüth and Anthony, 2007; Price and Ruessink, 2008).

Tidal influence contributes to the persistence of the LBT and RBB states in presence of fair weather conditions: this may occur because high water levels and the tidal translation effect lower the duration of action of waves at any point on the cross-shore profile, thus curtailing the propensity for onshore sediment transport and state transitions towards the low-energy end of the spectrum. Almar et al. (2008) reported from data based on video observations, that berm reconstruction after a storm event was not possible because waves were too small and associated wave periods too short to induce onshore sediment transport. In the present study, persistent LBT and RBB states under fair weather conditions are systematically associated with three parameters: a previous up-state transition, low energy short waves, and a mean tidal range of about 2.5 m.

The possible influence of the tide can also been underlined in the dynamics of the TBR system. Indeed, it has been shown that the TBR can be persistent under very energetic events associated with *R* up to 7 (Fig. 3). Fig. 4 also indicates that the migration rates observed at Truc Vert beach are smaller than those observed by Ruesssink et al. (2000) at Egmond aan Zee Beach for similar waves. During the considered period, mean tidal range at Truc Vert was about 2.9 m and only about 1.5 m at Egmond aan Zee, thus surf zone processes may operate over a shorter time at Truc Vert Beach. This amount of time increases with decreasing relative tide range (Masselink, 1993; Kroon and Masselink, 2002). This hypothesis is strengthened by observations made during winter 2005 when up-state transition was observed (Fig. 5). This occurred despite slightly lower offshore conditions (Fig. 4) but lower tidal ranges (mean range of about 1.8 m, whereas during the persistence of the TBR state, mean range was about 2.9 m).

7.3. Morphodynamic feedback

There is a need for further analysis in order to explain the dynamics of the inner bar and the berm. In particular, it would be interesting to consider the dynamics of the subtidal bar because of possible morphodynamic feedback between the outer and inner bars. Morphological feedback was defined by Plant et al. (2001) as “a component of the morphologic response that depends on the morphology itself”. In particular, observations by Ruessink and Terwindt (2000) on the behaviour of nearshore bars on the time-scale of years showed that the outer bar plays the trigger role in the development of the bar system and that the decay of the outer bar may cause an inner bar to start moving net offshore over the medium time-scale. Recently, Ruessink et al. (2007) investigated the coupled and non-coupled behaviour of three-dimensional morphological patterns in a double sandbar system. They showed, using wavelet analysis, that the outer bar geometry and the distance between the inner and outer bars are critical parameters governing the morphological evolution of the composite double sandbar system. Such coupling has been observed by Castelle et al. (2007) at TVB. More recently, Castelle et al. (in press) showed that morphological coupling may be much more important to understanding and predicting the evolution of double sandbar systems than previously envisaged.

In particular, possible morphological feedback should be considered in the dynamics of the inner bar during the two storms (winter 2006: Fig. 4D and winter 2005: Fig. 5D). Quartel et al. (2007) recently showed that the trough width previous to a storm event seems to be an additional factor in inducing beach morphological reset. They suggest that this can be explained by assuming a positive relation between the width and the depth of a trough. The mean flow may be undertow-dominated during high energy conditions when the trough is narrow and shallow, leading to beach erosion. This is coherent with the observations during winter 2006, when a deep and well-developed trough was associated with a persistent TBR state (Fig. 4D) and winter 2005, when a narrow trough was associated with an up-state transition (Fig. 5D).

Concerning berm dynamics, it is shown that the construction of a berm not only depends on wave conditions but also on the morphology of the lower intertidal domain (Wright et al., 1985; Quartel et al., 2008; Ortega-Sanchez et al., 2008) where wave dissipation by breaking may be important. Figs. 4B and 9B clearly show that a berm can be rapidly constructed when a TBR (or LTT) system is present in the lower intertidal domain whereas it is not necessarily constructed when the lower intertidal beach exhibits more dissipative states (LBT, RBB) as shown in Fig. 9A. This is consistent with recent observations presented by Ortega-Sanchez et al. (2008) who suggested that for low to moderate wave energy situations it is necessary to know both the previous beachface morphology and the previous wave climate.

In the same way, similar observations highlight the erosion of the upper beach (Fig. 6, black rectangles) in the course of two energetic events. Prior to the first event, the beach exhibited a well developed TBR system in its lower part. This will enhance wave energy dissipation by breaking processes and protect the upper part of the beach from storm wave action, whereas prior to the second event the beach did not exhibit such a well-developed TBR.

Finally, this study has been conducted on a restricted area: about 350 m longshore, relative to the mean wavelength of the inner bar which is around 350 m. Recent (Quartel et al., 2008) and older studies (among others, Ruesssink et al., 2000; Van Enckevort and Ruessink, 2003b) have documented alongshore variations and changes in beach morphology. Further investigations including both a larger area of investigation and subtidal bars should be undertaken to improve our knowledge in beach morphodynamics. A video system (CamEra technology – NIWA) has been deployed in April 2007 and should allow significant progress in the understanding of the dynamics of meso- to macro-tidal open beaches.

8. Conclusions

This study, based on a long-term data-set of topographic surveys, has allowed us to establish the occurrences of the different beach states within the intermediate range for a meso- to macro-tidal beach. In particular, there is a good agreement in the TBR state frequency with frequencies reported from micro- and meso-tidal environments, the TBR state being the most representative with 58% of occurrence. The study also highlights differences, notably, the fact that the more dissipative states were less represented at Truc Vert beach despite high energy wave conditions. It has also been shown that the ‘bar-berm’ model is dominant in the dynamics of the upper beach, the berm being constructed under low energy conditions (<2 m). Nevertheless, this study also clearly underlines possible morphological feedbacks in inner bar dynamics and berm dynamics, while also highlighting the influence of the tide. In particular, it has been shown that a berm can grow rapidly in the presence of a TBR state but not in that of the RBB/LBT states. Possible morphological feedback has also been observed both in the response of TBR to storm conditions and construction of the berm after a storm. It has been shown that the tidal range may also contribute to the beach response. TBR dynamics appear to be influenced by the tidal range: neap-tides conditions would both favour growth and destruction of TBR systems. This study clearly indicates that it is important to consider long-term data to better understand the dynamics of meso- to macro-tidal beaches because of the tide being a key parameter considering the duration of wave action on the profile. It also clearly shows, in agreement with theoretical approaches (Castelle et al., in press), that berm dynamics and inner bar dynamics should not be studied in isolation.

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