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MORPHOLOGY AND HYDRODYNAMICS OF A MACROTIDAL RIDGE AND RUNNEL BEACH UNDER MODAL LOW WAVE CONDITIONS

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Abstract: Wave and current measurements were carried out over three days in the course of a week-long survey of the topography and bedforms of a macrotidal ridge and runnel beach, in Leffrinckoucke, northern France, during modal low wave energy (Hb < 0.25 m) conditions. The beach may be divided into three zones: a low-gradient (tanß = 0.008) lower beach dominated by longshore currents essentially driven by tides under the low wave energy conditions, and mid- and upper beach zones characterised by steep-faced ridges (tanß = 0.02-0.035) whose morphology and plane beds reflect both wave breaking processes and cross-shore current activity related to both tides and waves. Field observations show that wave behaviour near breaking is strongly affected by local depth variations over the ridge and runnel topography during the vertical tidal excursion. The runnels also play an important role in channelling swash bores and tide water alongshore. This gives rise to abundant current ripples and meso-scale bedforms in the runnels and the lower parts of the ridges. Short-term macro-scale changes involving overall ridge and runnel morphology are insignificant under the low wave energy conditions that prevailed during the experiment.

Key words: macrotidal beach, ridges and runnels, waves, currents.

MORPHOLOGIE ET HYDRODYNAMIQUE D'UNE PLAGE MACROTIDALE À BARRES ET À BÂCHES DANS DES CONDITIONS DE HOULE BASSE

Résumé : *Des mesures de la houle et des courants sur trois jours ont été effectuées au cours d'une étude d'une semaine portant sur la morphologie et les figures sédimentaires de la plage macrotidale à barres et bâches de Leffrinckoucke, dans le Nord de la France, dans des conditions modales de vagues de basse énergie (Hb < 0,25 m). La plage peut être divisée en trois zones : un bas de plage à faible gradient (tanß = 0,008) dominé par l'action des courants de marée à composante longitudinale dominante, une mi-plage et un haut-de-plage caractérisés par des barres à façades raides (tanß = 0,02-0,035) où domine l'action des vagues déferlantes et des courants transversaux liés à la marée et aux houles. Les observations montrent que le comportement des vagues au déferlement est fortement affecté par les variations de profondeur locale liées à la topographie des barres et des bâches lors de l'excursion verticale de la marée. Les bâches jouent aussi un rôle important de canalisation des écoulements d'eau de marée et de déferlement des vagues, ce qui favorise l'abondance de rides de courants et de figures sédimentaires de méso-échelle dans les bâches et les parties inférieures des barres. À court terme, les changements morphologiques affectant les barres et les bâches sont minimes dans les conditions de basse énergie de l'expérience menée.*

Mots clés : *plage macrotidale, barres et bâches, morphodynamique*

INTRODUCTION

Ridge and runnel beaches are a particular type of macrotidal beach found in northern France, Belgium, and along parts of the British Isles. They are characterised, as their name implies, by ridges or bars, alternating with runnels or troughs. These features dominate the intertidal zone of these beaches and their number may range from two to six (eg., King, 1972; Orford & Wright, 1978; Mulrennan, 1992; Levoy *et al.*, 1998; Sipka, 1998; Voulgaris *et al.*, 1998). Ridge and runnel beaches are, according to King (1972), associated with large tidal ranges and fetch-limited protected wave environments subject to episodic storms, and are characterised by essentially fine to medium sand. Little is known, however, of the hydrodynamics of this type of beach, although a recent set of studies (Voulgaris *et al.*, 1998; Levoy *et al.*, 1998; Sipka, 1998), carried out on the English Channel and North Sea coasts of France and Belgium throw some light on some of the hydrodynamic signatures of these beaches. These studies highlight, in addition to wave dominance of the hydrodynamics, the importance of tidal currents, especially on the lower beach circulation. The results reported here briefly examine the morphology and hydrodynamics of the macrotidal beach of Leffrinckoucke in northern France (figure 1). The brief hydrodynamic study is based on a three-day set of results obtained during low wave conditions, and is part of an ongoing programme of research on the ridge and runnel beaches of northern France, especially in view of determining the role of their complex topography in dune-beach sand exchanges.

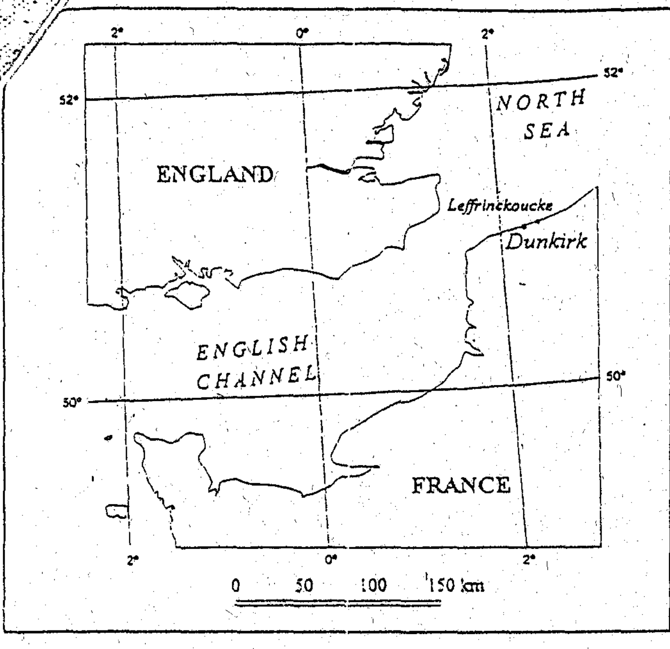

Figure 1: Location of Leffrinckoucke beach.
Figure 1 : Localisation de la plage de Leffrinckoucke.

EXPERIMENTAL SITE AND METHODS

The beach studied (figure 1) is situated 8 km east of the port of Dunkerque (Dunkirk), France. Backed by dunes, it is devoid of artificial structures such as groynes or breakwaters. Tides are semi-diurnal, and are characterised by a relatively large range that goes from 3.5 m during mean neap conditions to 5.6 m during mean spring conditions. Wave observations by Metéo France show that the dominant approach directions are from a north-northeast to northwest quadrant (> 70 %), the rest coming from west to west-southwest. Offshore wave periods recorded from a waverider bouy deployed by the Port Autonome de Dunkerque (Dunkirk) range from 3 to 6 s, typical of the fetch-limited environment. Offshore wave heights range from 0.25 to 1.5 m during modal conditions, and up to 3 m, during storms. The offshore zone consists of numerous tidal banks, the Flemish Banks, an elongate set of sand ridges whose dynamics are controlled essentially by strong longshore tidal currents with a northeasterly flood-dominant residual towards Belgium (Tessier, 1997). These nearshore banks considerably dissipate and refract the impinging waves. This commonly results in low modal breaker heights on the beach (H_b < 0.25 m), as our observations and those of other workers have shown (Corbau, 1995; Sipka, 1998).
The results reported here were obtained in the course of a week-long experiment from July 22 to July 30, 1997 (Julian days 203-211), during part of a spring-to-neap tidal cycle characterised by a tidal range that varied from 5.5 m at the start of the experiment to 3.85 m at the end. The 250 m-wide portion of beach studied is depicted in figure 2, together with instrument deployment locations and sediment sampling points. Several repeated high precision topographic surveys of the intertidal beach were carried out using a LEICA TC600 ® Electronic Total Station, whose errors are within ± 3 mm for distance and ± 0.0015° for direction. Surveys were carried out once a day between the foot of the dune and the low water mark at the time of each survey, and were related to a benchmark of the French National Geodesic Service (IGN 69). Daily profiles running through the central part of the beach and digital elevation models were generated from these data using terrain modelling software.
An S4ADW Inter-Ocean ® self-recording electromagnetic current meter with a built-in pressure sensor was deployed on the edge of a low-relief ridge on the lower beach (figure 2) during five semi-diurnal tidal cycles (22-24th July, 1997: Julian days 203-205). The instrument was fixed 40 cm above the beach surface on a stainless steel frame whose mountings were buried in the sand and was exposed at low tide. The results from this deployment are completed by a record covering half a semi-diurnal tidal cycle during an earlier deployment (April 24, 1997: Julian day 112) on a mid-beach ridge in the study zone (figure 2). The current meter recorded flow velocities and tide and wave-induced pressure at a burst duration of nine minutes every 15 minutes and at a sampling frequency of 2 Hz. The recorded data were processed by Inter Ocean Systems wave and current software packages supplied with the S4ADW current meter. They provided tabular and graphic displays of Fourier-transformed raw data. Results included burst-averaged significant wave height, peak period, water levels, mean horizontal longshore and shore-normal current components and angles of waves and steady currents. Instantaneous flow velocities in runnels on the beach were measured with two small hand-held General Oceanics ® digital, bi-directional impeller flowmeters.

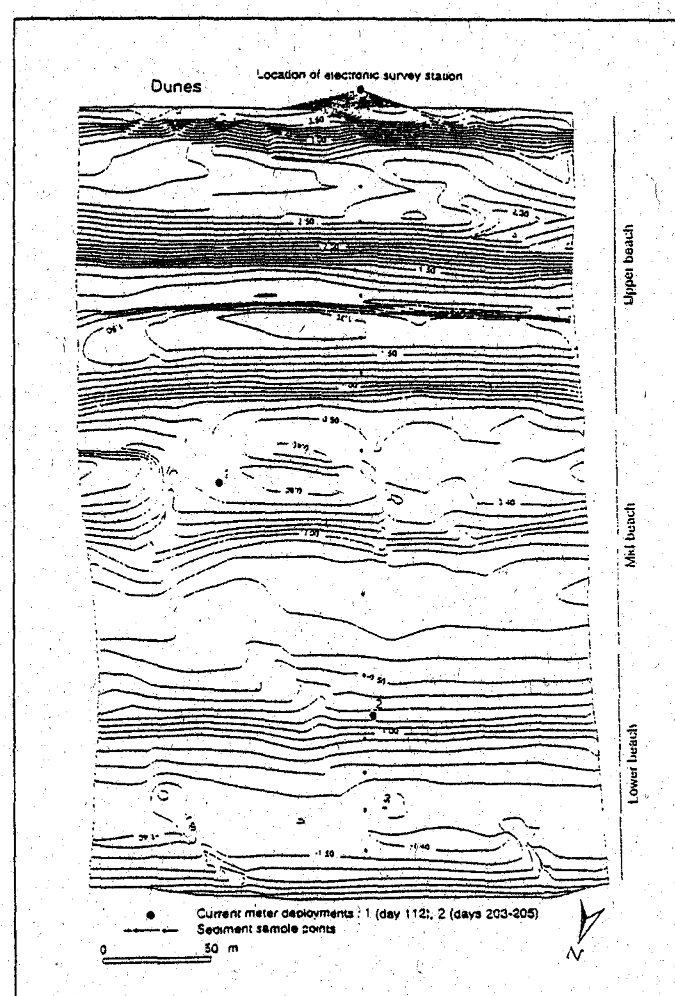

Figure 2: Contour map of the studied portion of beach, showing current meter locations during two brief deployments, grain size sampling points, and the three beach zones.
Figure 2 : Carte topographique du secteur de plage étudié, montrant la localisation du courantomètre lors des deux brefs déploiements, les points d'échantillonnage granulométrique, et les trois zones de plage.

Although no current and water level measurements were carried out in the migrating swash zone, field observations were carried out everyday on wave breaking characteristics and swash behaviour. Meso- and micro-scale bedforms were also observed and their variations mapped everyday on the contour maps generated from the previous day survey. Sediment samples were collected at various intervals along a shore-normal transect that ran through the central part of the beach (figure 2).

RESULTS

Morphology

Leffrinckoucke beach exhibits classic ridge and runnel morphology (figure 3) that our observations over the past three years have shown to be a quasi-permanent feature of beaches in the extreme north of France. Up to six sets of ridges and runnels were present during the experiment. We have divided the beach profile into three zones (figure 2), following other workers on macrotidal beaches (Wright *et al.*, 1982; Masselink & Hegge, 1995; Voulgaris *et al.*, 1998). Ridge and runnel topography is most pronounced on the upper beach and becomes more subdued on the lower beach. Widths of both ridges and runnels also increase seaward, from around 25 m at the upper and mid-beach zones to 50 to 75 m on the lower beach. The overall intertidal beach gradient averages 0.65° ($\tan\beta$ = 0.01). However, the lower beach exhibits a much smaller gradient ($\tan\beta$ = 0.008). Ridge crests and runnel bottoms similarly exhibit small gradients ($\tan\beta$ = 0.005 - 0.007) and their elevations decrease seaward. The steepest gradients ($\tan\beta$ = 0.02 - 0.035) occur on the seaward and landward faces of the ridges.

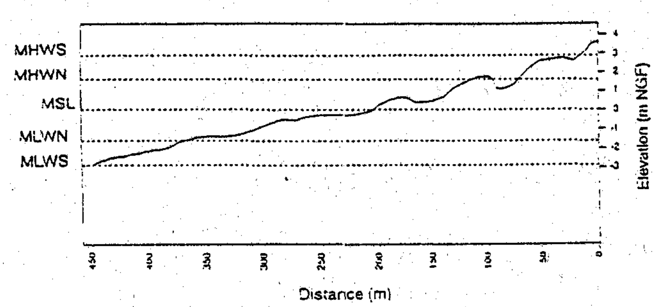

Figure 3: Typical profile of the central portion of the studied beach sector showing ridge and runnel topography and vertical tidal excursion limits.
Figure 3 : Profil type de la partie centrale de la plage montrant la topographie de barres et de bâches, et les limites d'excursion verticale de la marée.

Comparisons of seven daily profiles during our short study period showed hardly any change, as would be expected from the low wave energy conditions that prevailed during the study. The field observations on beach topography and examination of the contour maps generated by fine-resolution digital terrain modelling also showed little change. Computation of the global volumetric changes from the successive contour maps showed that bed level variations from day to day over the week-long study period never exceeded 0.01 m.

Sediments and bedforms

Leffrinckoucke beach shows a homogeneous, very well to well sorted (f = 0.22 to 0.45) fine sand (f = 1.83 to 2.0) with very little cross-shore variation. The sand tends to be slightly coarser and less well sorted on the upper beach. The ridges and runnels are associated with a wide variety of bedforms that are especially well developed in the runnels where wave and current ripples are particularly abundant. The ridge crests commonly exhibit flat beds or low-relief upper beach antidunes as defined by Reineck & Singh (1980). Further downslope, simple wave-formed ripples gradually appear on the ridges. These evolve further downslope towards more complex linguoid ripples as the ridge merges into the next runnel. The runnels exhibit a wide variety of micro- and meso-scale bedforms ranging from complex current ripples to channel antidunes, sand waves, scour pits and chutes and pools. The extreme lower beach lacks clearly defined bedforms other than washed out megaripples associated with fine sand rich in surficial suspension-sized (1-10 % < 50 mμ) sediments and particulate organic matter.

Hydrodynamics

Waves and wave breaking processes

Waves were small throughout the study period and show small significant heights, Hs < 0.25 m, and, with the exception of a couple of bursts, peak periods not exceeding 6 s (figure 4a), although slightly more energetic conditions prevailed at the start and at the end of the short deployment period. These conditions are quite typical of this fetch-limited environment and may be described as part of the modal beach wave climate in this area. Weather data over the deployment period supplied by Météo France show that winds were light (< 6 m/s) land and sea breezes, except on day 205 when slightly stronger (5-11 m/s) synoptic northwesterly winds prevailed. During the first two semi-diurnal tidal cycles, significant wave heights increased with increase in local water depth (figure 4b) due to tidal rise, as the tidal excursion led to migration of the swash and surf zones over the current meter. This trend, observed in records from other current meter deployments carried out since (not reported here), however disappeared from the third cycle onwards, with short phases of higher waves occurring with a clear lag relative to high water. Apart from the start and end of the deployment period, significant wave heights were in fact very low (0.05 to 0.1 m) and very close to the threshold of measurement by the current meter so that the fluctuations recorded may not be meaningful in terms of relationships between water depths and wave heights. The relationship between greater water depths and higher waves at the start of the deployment may be explained in terms of lesser frictional dissipation of higher incident waves at spring high water over the subtidal zone and the lower beach, while the last cycle of measurements corresponded to a slight increase in wave heights offshore as wind speed increased. Throughout the deployment, the wave incidence ranged from 320 to 360° to shore-normal, i.e., from north-northwest to north.

Although the wave records show relatively minor changes in significant wave heights in the course of the vertical tidal excursion, field observations of wave shoaling and swash processes, which are not detected by the type of instrument we deployed, show marked changes in wave characteristics during the semi-diurnal tidal cycle. These are related to changes in local water depth over the beach topography as the vertical tidal excursion leads to rapid migration of the wave breaker zone. On the lower beach, the very gentle slope (tanß = 0.008) associated with the subdued ridge and runnel morphology results in wave shoaling and spilling breakers. The breaker regime differs markedly on the mid- and upper beach zones. Wave breaking in these zones occurs on, and appears to be controlled by, the ridges. As the tidal excursion leads to migration of the breaker line during rising tide, the relatively sharp increase in slope (tanß = 0.02-0.035) as waves attain the faces of the mid- and upper beach ridges results in a gradual change in the wave breaking from spilling to plunging. Once the ridge crest is flooded, wave shoaling and swash processes affect the flat ridge surface and the next upslope runnel, while the breaker zone migrates rapidly upslope to the next ridge, starting a new cycle of spilling to plunging breakers. A similar control by bars on wave breaker migration was described by Hardisty & Laver (1989), who showed that there was very little breaking in the troughs between bars. Rapid upward excursion of the wave breaker front controlled by the rising tide in these mid- and upper beach zones strongly reduces or may even preclude backwash processes. Such backwash processes are also rather weak during the falling tide phase in these zones and only become important on the lower beach where ridge width is more important and ridge elevation more subdued. Shoaling processes also increase progressively during falling tides, while wave breaking similarly occurs mainly over the ridges. The turbulent energy of the plunging waves on the ridge crests leads to the formation of flat beds or of ephemeral upper beach antidunes.

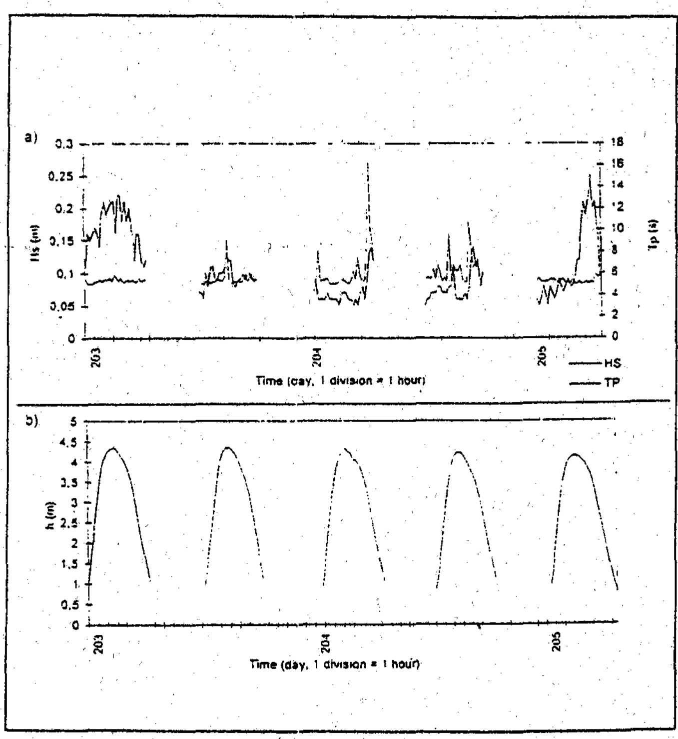

Figure 4: Significant wave height (Hs) and peak period (Tp) over five semi-diurnal tidal cycles on the lower beach (a), and local water depth (h), depicted in (b) for reasons of scale.

Figure 4 : Hauteur significative (Hs) et périodes pics (Tp) des vagues pour cinq cycles de marée semi-diurne sur le bas de plage (a), et la profondeur locale d'eau (h) montrée en (b) pour des raisons d'échelle.

Currents

The lower beach circulation during the rising tide involved dominantly unidirectional longshore currents towards Belgium (figure 5). Although spectral analyses have not been carried out to separate wave and tidal components, we attribute these longshore currents essentially to the flood tide, except at the very end of the deployment when wave height increased (figure 4). Before this, waves were very low and their incidence close to normal. The interpretation of tidal control on the current structure before the current peak observed at the end of the deployment is reinforced by the close correspondence between the rapid increase in longshore current velocity and the increase in water depth with rising tide (figure 5). However, the net north-northwesterly wave approach direction implies that waves acted in the same direction as the flood tide, and in opposition to the ebb tide. The results we obtained on currents varied very little from one semi-diurnal tidal cycle to the next except towards the end of the record where no current reversal occurred. The record shows that the maximum current speed generally occurred during the flood before high water. Similar tidally driven longshore currents have been identified recently by Voulgaris *et al.* (1998) in a study of a ridge and runnel beach with similar wave and tidal conditions, situated in Belgium, only 20 km east of our Leffrinckoucke experimental site. These authors similarly noted maximum current velocities before high water, and have tentatively attributed this behaviour to bed friction causing the longshore currents to lead the tidal elevation shoreward. Flood current velocities on Leffrinckoucke beach were higher than those of the ebb, attaining a maximum of close to 0.5 m/s. The flood also lasted longer than the ebb whose peak velocities hardly exceeded 0.15 m/s. The mean longshore current velocity increased rapidly during the flood, peaked just before high water, before steadily diminishing towards the end of the flood phase and during the ebb (figure 5). Except for the last semi-diurnal cycle, the current reversed in direction just 1 to 1.5 hours before low water. Its velocity then increased a little, attaining a maximum before low water. The current then reversed again while its velocity increased with the next flood. This behaviour is typical of that of a progressive wave characterised by strong flood-dominated asymmetry, but altered by stationarity effects, and corresponds to that of the deformed progressive wave propagating towards Belgium (Tessier, 1997). Peak velocities were not attained at high and low water as would be expected from a purely progressive wave. The relationships between current structure and tidal phase described above disappear at the very end of the deployment when both longshore and cross-shore currents peaked significantly (figure 5), in response to wave height increase (figure 4), the waves propagating in the same direction as the longshore current towards Belgium.

Apart from the marked current velocity increase on day 205, the mean cross-shore velocities were much lower than those of the longshore component, hardly exceeding 0.3 m/s during the flood and 0.2 m/s during the ebb (figure 5). The mean cross-shore current was dominantly directed onshore and also increased rapidly in velocity during the flood, attaining a maximum just before high water. It then reversed in direction, decreasing slowly during the ebb. The velocity stayed close to 0.05 m/s during low water and then increased rapidly during the flood (figure 5). Throughout the recordings, both mean longshore and cross-shore currents evinced a minor velocity plateau at high water that corresponded to current reversal. Towards the end of the deployment on day 205, the marked increase in cross-shore current velocity, which, like the longshore current, peaked at over 0.5 m/s (figure 5), reflects the increase in wave height and probably wind stress associated with the stronger onshore winds blowing over the shallow emerging lower beach near low water.

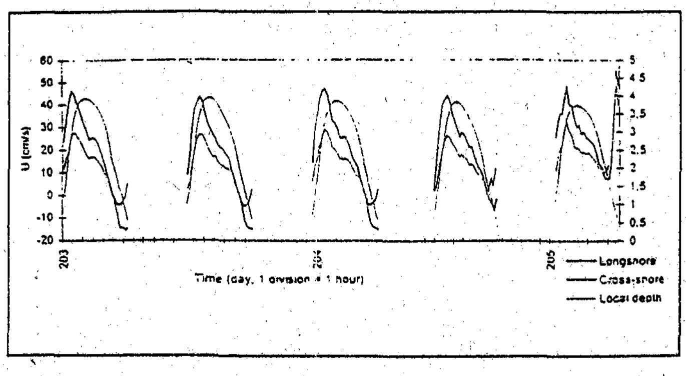

Figure 5: Mean longshore and cross-shore current components and local depth over five semi-diurnal tidal cycles on the lower beach. Positive and negative current (U) velocities represent, for the longshore component, respectively east-northeasterly flow (towards Belgium) and west-southwesterly flow (towards Dunkirk), and for the cross-shore component, respectively onshore and offshore flows.
Figure 5 : Le courant moyen longitudinal et transversal et la profondeur d'eau locale pour cinq cycles de marée semi-diurne sur le bas de plage. Les vitesses positives et négatives du courant moyen (U) représentent, pour la composante longitudinale, respectivement les directions vers l'est-nord-est (vers la Belgique) et l'ouest-sud-ouest (vers Dunkerque), et, pour la composante transversale, respectivement les directions vers la côte et vers le large.

Under low wave conditions, the currents measured during a tidal range of 4.7 m over a ridge on the mid-beach during the earlier instrument deployment (Julian day 112, figure 2) showed a somewhat different structure during the semi-diurnal cycle from that of the longer record on the lower beach. The short mid-beach record shows that while being of essentially similar strength to that recorded on the lower beach, the mean cross-shore current, which showed peak velocities of around 0.3 m/s just before high water, was slightly stronger throughout than the longshore current, except close to low water, when the latter was much stronger, and flowed towards Dunkirk (figure 6). This strengthening of the longshore current near low water may be due to topographic control in the mid-beach zone, as tide water became increasingly channelled by the runnel on the edge of which the current meter was deployed (figure 2).
The mean cross-shore and longshore currents on the mid-beach are presumably a mix of weaker tidal currents, relative to those on the lower beach (especially as regards the longshore component), and oscillatory wave currents. Both the mean longshore and cross-shore currents had very low velocities at about mid-tide. This current behaviour is typically that of a progressive tidal wave. Oscillations in cross-shore current strength in both offshore and onshore directions during this phase appeared to reflect wave dominance. As on the lower beach, the mean cross-shore current was dominated by onshore flows. The stronger mean onshore current may be attributed to waves and tides acting in the same direction. Apart from the mean currents recorded by the current meter during the period of tidal inundation, the intertidally emerging or inundating beach also showed important flows related to channelling of both tide water and swash bores.

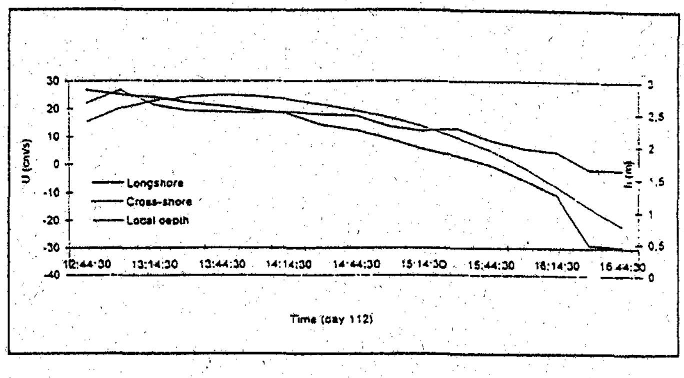

Figure 6: Mean longshore and cross-shore current components and local depth over a semi-diurnal tidal cycle on the mid-beach. Positive and negative current (U) velocities represent, respectively, for the longshore component, east-northeasterly flow (towards Belgium) and west-southwesterly flow (towards Dunkirk), and for the cross-shore component, respectively onshore and offshore flows.
Figure 6 : Le courant moyen longitudinal et transversal et la profondeur d'eau locale pour un cycle de marée semi-diurne sur la mi-plage. Les vitesses positives et négatives du courant moyen (U) représentent, pour la composante longitudinale, respectivement les directions vers l'est-nord-est (vers la Belgique) et l'ouest-sud-ouest (vers Dunkerque), et, pour la composante transversale, respectivement les directions vers la côte et vers le large.

Because of the rather pronounced ridge and runnel morphology of the mid- and upper beach zones (figure 3), during both rising and falling tides, the individual runnels serve to channel tide water and swash flows following wave breaking over the adjacent ridges, thus reducing backwash processes on these ridges. In parts of the intertidally exposed runnels, large instantaneous current speeds (1-2 m/s), measured by the flowmeters and associated with channelled turbulent flow of tide water and swash bores, were sometimes generated during both flood and ebb phases. Such channelled flows and large current speeds are responsible for the formation of ephemeral migrating high-flow velocity bedforms such as antidunes and chutes and pools.
On the whole, the abundance of bedforms and the shore-normal changes in bedform types reflect the changing hydrodynamic conditions during the tidal cycle. The abundance of complex current ripples, especially in the runnels, reflects, in particular, the importance of current activity on this beach.

DISCUSSION

The observations reported in this paper highlight a number of relationships between beach morphology and wave and current hydrodynamics under the low wave energy conditions of the brief experiment. Ridge and runnel beaches are considered as belonging to Group 2 beaches in the three-tiered hierarchy of wave-dominated macrotidal beach classification of Short (1991), who recognized wave dominance on the basis of wave processes and bedform development related to waves. Leffrinckoucke beach is a modally low-wave energy, macrotidal, sand beach, whose macro-scale morphology may be divided into three zones (figure 2): a lower beach dominated by tidal processes during modal wave conditions, and mid- and upper beach zones that reflect wave dominance even under low wave conditions.

The lower beach shows a clear trend towards what Short (1991) described as tidal flats, a beach type related to tidal dominance. Our current meter records show relatively strong and constant longshore tidal currents in this zone. Similar observations on this longshore tidal influence have been reported from macrotidal ridge and runnel beaches by Voulgaris *et al.* (1998), Levoy *et al.* (1998) and Sipka (1998), as well as for the lower beach and the subtidal zones of higher wave energy beaches not exhibiting the type of ridge and runnel morphology described here (eg., Wright *et al.*, 1982; Masselink & Hegge, 1995; Levoy *et al.*, accepted). The measured longshore current velocities on the lower beach in Leffrinckoucke are sufficiently strong (above 0.2 m/s for significant parts of the time the current meter is submerged) as to entrain the fine sand on the bed and to lead to the reworking and washing out of megaripples, resulting in a pitted lower beach surface on which suspension loads settle out. The general longshore sediment transport on this coast is to the northeast, towards Belgium, in response to both the longshore tidal current and longshore drift generated by waves from the northwest. The longshore tidal flows, especially over the lower foreshore, may be expected to strengthen the longshore wave- and wind-induced currents at times of larger waves, as has been reported from another ridge and runnel beach in northern France 100 km south of Leffrinckoucke (Levoy *et al.*, 1998; Sipka, 1998). The short current record on the mid-beach in Leffrinckoucke also shows that the longshore currents decrease in strength up the beach, presumably as a result of tidal energy dissipation over the pronounced ridge and runnel topography of the mid- and upper beach, except near low water, when channelling effects by the runnels may lead to increases in longshore current strength. Inversely, cross-shore currents driven by shoaling waves appear to increase in strength on the mid-beach.

Although the wave and current data presented in our paper are still limited, nor finely resolved, there is, even under the low wave energy conditions that prevailed during the study, strong feedback between wave dynamics and the morphology of the mid- and upper beach zones as to suggest wave dominance of the process domain. Similar wave control on processes of morphologic change in these zones has been described by Voulgaris *et al.* (1998), Levoy *et al.* (1998) and Sipka (1998). However, wave behaviour, defined in terms of shoaling and swash processes and breaker type, is strongly affected by changes in local water depth in the course of the vertical tidal excursion. The ridge and runnel morphology plays an important role in channelling, alongshore, flows of swash bores, so reducing backwash processes. Runnels also channel tide water, especially in the mid- and upper beach zones, particularly during neap tides, as local water depths decrease. This role may explain the absence of current reversals during the latter part of the current recordings (figure 5). The abundance of complex current ripples, especially in the runnels, reflects the importance of combined wave, tidal and topographically controlled bi-directional longshore and cross-shore current activity on this beach.

The short-term macro-scale changes of overall ridge and runnel morphology and volumetric variations during the short study period and the low wave energy conditions were insignificant. However, throughout the beach, the dominance of onshore currents in the mean cross-shore current component may be expected to favour, over the longer term, onshore ridge migration during fair-weather conditions, especially on the mid- and upper beach zones, where strong shoaling and swash processes are associated with minor backwash effects. Such ridge migration has been observed in both short- (Voulgaris *et al.*, 1998) and long-term (Mulrennan, 1992; Sipka, 1998) studies of ridge and runnel beaches. The longshore maintenance of the longitudinal ridge and runnel form may be enhanced by the significant mean longshore currents prevailing on this beach.

CONCLUSION

The brief survey of the morphology and hydrodynamics of Leffrinckoucke beach highlights a number of interesting aspects, concerning wave behaviour and tidal influence on this low energy macrotidal beach, that need to be refined by further experiments. While these beaches are part of the spectrum of wave-dominated beaches defined by Short (1991), they are affected by more or less long intervals of low wave energy and by relatively important tidal excursions related to the large tidal ranges acting across wide intertidal zones with marked shore-normal changes in bed gradient. These conditions favour marked shore-normal changes in wave behaviour near breaking during the vertical tidal excursion, as well as important tidal current activity and topographically controlled flows. The short-term macro-scale changes of overall ridge and runnel morphology and volumetric variations of Leffrinckoucke beach during the short study period and the low wave energy conditions were insignificant. On a longer-term basis, however, the dominantly onshore component of the cross-shore currents identified on this beach is expected to contribute to the long-term onshore migration of the ridges, while the longshore maintenance of these forms may be enhanced by the significant mean longshore current component prevailing on this beach.

There is a need for fine-scale studies of the hydrodynamics and near-bed sediment suspension and transport mechanisms associated with wave shoaling, breaking and swash processes, as well as with channelled runnel flows on this type of beach. Such studies should throw light on mechanisms and rates of ridge and runnel migration, and on the maintenance of these forms. They will also serve to elucidate the pattern of longshore sand transport due to the mean longshore currents and their role in maintaining the linear ridges and runnels.

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