THE INFLUENCE OF NEARSHORE SAND BANKS ON COASTAL HYDRODYNAMICS AND SEDIMENT TRANSPORT, NORTHERN COAST OF FRANCE

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Abstract

Tidal sand banks are common along the coast of the eastern English Channel and southern North Sea where they form linear shore-parallel or slightly oblique sand bodies in a wide range of water depths, from shallow coastal areas to depths of several tens of meters. Analyses of bathymetry changes revealed different behaviors in nearshore bank evolution that led to contrasting shoreline change along the coast. These analyses showed that at a time-scale of several decades, sand banks undergo significant morphological changes and commonly experience longshore as well as onshore migration. The longshore migration of the banks can be explained by the action of shore-parallel tidal currents, while their landward movement is attributed to storm waves that are responsible for onshore sediment motion across the bank crests. Wave propagation and sediment transport modeling and in situ hydrodynamic measurements show that nearshore sand banks strongly influence circulation and sediment transport in the coastal zone, and control wave energy distribution along the coast. Our observations clearly show that nearshore sand banks can have very different effects on coastal hydrodynamics and sediment dynamics, depending on the depth, orientation and distance of the bank to the coast. The changing position of sand banks consequently results in progressive modifications of wave refraction, circulation and sediment transport in the coastal zone.

Key words: Tidal sand banks, sediment transport, coastal hydrodynamics, shoreline evolution, macrotidal.

1. Introduction

Tide-dominated shorefaces may exhibit important deposits of fine sand to gravel, especially where tide-controlled bedload partings and convergences operate (Harris *et al*., 1995), as in the southern North Sea and the eastern English Channel (Grochowski *et al*., 1993; Anthony, 2002). These sediments are generally reworked into a diverse suite of bedforms and elongate tidal banks (Dyer and Huntley, 1999). Examples abound in the southern North Sea (Trentesaux *et al*., 1999; van de Meene and van Rijn, 2000; Héquette and Aernouts, 2010) and in the East China Sea (Liu *et al*., 2007). Such tidal banks may be active or relict. The latter are generally shown to be associated with drowned shoreline environments, but such tidal bank fields may be enriched by newly formed banks, or may migrate in response to modern hydrodynamics and attendant sand transport gradients (Kenyon et al., 1981; Dyer and Huntley, 1999). Although it is widely recognized that these shallow nearshore sand bodies can have important effects on coastal hydrodynamics and associated sediment transport (MacDonald and O'Connor, 1996; Thomas *et al*., 2011), only a few studies have been conducted on their influence on the exchange of sand between the nearshore zone and adjacent coast (e.g., Shaw *et al*., 2008), which strongly controls shoreline evolution. In this contribution, we present a series of investigations carried out at several sites along the macrotidal coast of northern

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France to study the morphodynamics of nearshore banks and assess their possible effects on coastal dynamics at different time scales.

2. Study area

Sand banks are particularly widespread in the eastern English Channel and the southern North Sea where they form linear shore-parallel or slightly oblique sand bodies about 10 to 30 km long and 1 to 3 km wide (Fig. 1). They generally occur as groups of banks in a wide range of water depths, from shallow coastal areas near beaches, estuaries and headlands (Tessier *et al.*, 1999; Aernouts and Héquette, 2006) to depths of several tens of meters (Anthony, 2002). These banks represent massive sediment bodies, ranging from 10 to 25 m in height above the surrounding seafloor (Beck *et al.*, 1991; Trentesaux *et al.*, 1999), in which large quantities of sediment are stored. The nearshore zone and the sand banks are generally characterized by medium to fine, poorly to very well sorted siliciclastic sands, especially at depths of 5-10 m, and by medium to coarse sands at greater depths (Augris *et al.*, 1990; Anthony and Héquette, 2007).

Although several theories have been proposed to explain the formation and maintenance of sand banks, it is generally agreed that they were created during the postglacial sea-level rise, but they may have been subsequently modified by changing currents and waves, eventually becoming moribund (or inactive) due to rising sea-level (Dyer and Huntley, 1999). In the eastern English Channel, sand banks are essentially relict Holocene sediment bodies, which became stranded as sea-level rose rapidly during the initial phase of the Holocene transgression, and are overlain by modern sand waves that migrate actively under the present current regime (Beck *et al.*, 1991; Reynaud et al., 2003). In the southern North Sea however, the nearshore sand banks are much more mobile and are actively migrating onshore and/or longshore (Tessier *et al.*, 1999; Héquette and Aernouts, 2010).

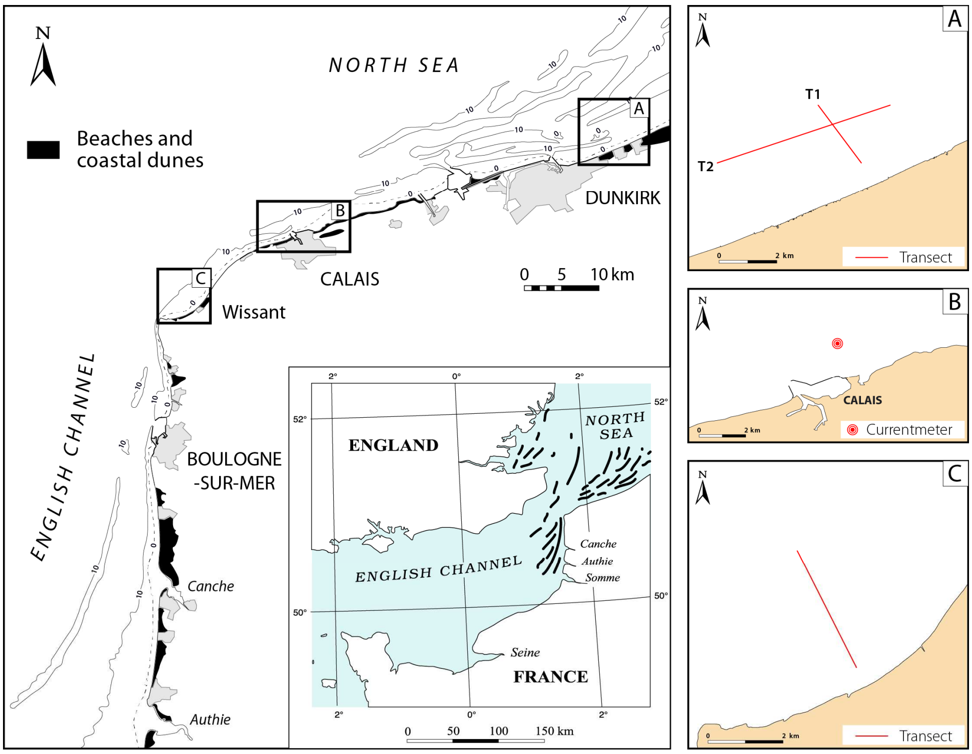

Figure 1. Location of the major nearshore sand banks in the eastern English Channel and southwestern North Sea

The sand bank environment of the southern North Sea is exposed to short-fetch, relatively low-energy waves punctuated by storm activity. The offshore wave regime is dominated by waves from southwest to west, originating from the English Channel, followed by waves from the northeast to north, generated in the North Sea. Most waves have periods and significant heights of less than 5 s and 1.5 m, respectively, but may episodically exceed heights of 4 m during major storms (Ruz *et al*., 2009). Wave heights are much lower at the coast, however, due to significant refraction and shoaling over the sand banks, both in the eastern Channel and southern North Sea (Héquette *et al*., 2009). The tidal regime in the region is semi-diurnal and macrotidal, the tidal range increasing from the North Sea to the English Channel, with a mean spring tidal range of more than 5 m at Dunkirk to approximately 6.9 m at Wissant (Fig. 1). Due to the large tidal amplitude, tidal currents are strong along the northern coast of France, reaching maximum near-surface speeds of 1.5 m s^{-1} during flood tide and 1.35 m s^{-1} during ebb in the narrow interbank channels (Augris *et al*., 1990). Tidal currents are alternating in the coastal zone, flowing almost parallel to the coastline. Along the North Sea coast, flood currents are oriented towards the east-northeast and ebb currents towards the west-southwest, whilst along the Channel coast the ebb and flood are directed southward and northward respectively. Measurements in various sectors of the coastal zone show that the speeds of flood currents exceed those of the ebb, resulting in a flood-dominated asymmetry responsible for a net regional sediment transport to the north in the coastal zone of the English Channel and to the east-northeast along the North Sea coast (Héquette *et al*., 2008). In detail, however, sediment transport patterns are complicated by the presence of the sand banks which locally modify bottom circulation and result in opposite transport directions on both sides of the banks (Gao *et al*., 1994).

The coast of northern France largely consists of 300 to 600 m wide multi-barred beaches and coastal dunes that are interrupted by urban areas and harbors (Fig. 1). Beach and dune erosion is common along the coast, with shoreline retreat rates up to several meters per year at several locations during the second half of the 20th century (Vasseur and Héquette, 2000; Aernouts and Héquette, 2006). Several stretches of coastlines are relatively stable, however, while the shoreline has also been advancing seaward at some locations during the last decades (Chaverot *et al*., 2008; Héquette and Aernouts, 2010).

3. Methods

The morphological evolution of sand banks and adjoining seafloor was studied using hydrographic field sheets from the French Hydrographic Service (*Service Hydrographique et Océanographique de la Marine*, SHOM) spanning from the early 20th century to the beginning of the 21st century, allowing the mapping of bathymetry changes down to depths of approximately -25 m. These data were also used for calculating changes in sediment volume across the nearshore zone, including volume change of sand banks. The spectral wave model SWAN (Booij *et al*., 1999) was used for simulating wave propagation over the present day and previous bathymetries in order to evaluate the effects of changing seabed morphology on wave refraction and on the pattern of wave energy distribution at the coast. The model was run for several wave conditions representative of the wave regime of the region, using a 50 m grid cell spacing. Simulations were carried out for waves from the west, which correspond to the dominant wave direction, and waves from the northeast, coming from the North Sea, representing the second major wave direction in the study area. The SWAN model was used for simulating the propagation of high-energy deep-water waves (H_s: 4.7 m, T: 8 s) corresponding to a one-year return period (Héquette and Aernouts, 2010), as well as more frequent moderate-energy waves (H_s: 2 m, T: 6 s).

In addition to this work that was aimed at evaluating the potential effects of sand bank movements on the adjacent coast, hydrodynamic measurements were carried out on or in the vicinity of nearshore sand banks and on adjacent beaches using electromagnetic wave-current meter in order to assess the influence of these shallow sand bodies on coastal hydrodynamics. The instruments were programmed to measure wave parameters at a frequency of 2 Hz for 540 consecutive seconds (9 minutes burst record duration), every 15 minutes. Spectral analyses of the raw data yielded values of significant wave height (H_s), period and direction. The current meters also recorded velocity components during 1 minute every 15 minutes, providing values of mean flow speed and direction. In the example shown in this paper, the instrument was located 0.65 m above the bed, so the mean current components correspond to time-averaged near-bottom flows. The use of the SEDTRANS96 sediment transport model for wave-current combined flows (Li and Amos, 2001) allowed us to estimate the magnitude and direction of sediment transport in the nearshore/shoreface zone for the observed wave and current conditions. Total time-averaged sediment transport rate per unit width of bed (kg m^{-1} s^{-1}) was calculated using Engelund and Hansen (1967) sediment transport equation for non-cohesive bed, modified by Li and Amos (2001) for continental shelf conditions.

4. Results

4.1. *Morphological evolution of the sand banks*

Analyses of nearshore sand bank evolution were carried out at different locations along the coast of northern France. East of Dunkirk, a shallow sand bank (Hills Bank), up to more than 15 m thick, extends over a distance of about 9 km along the coast. The crest of the bank may be exposed at spring low tides, forming a shoal at a distance of about 1400 m from a beach and dune shoreline that underwent variable phases of erosion and accretion during the last decades (Maspataud *et al.*, 2011). The bank is separated from the beach by a 10 to 15 m deep channel, sub-parallel to the coastline. Comparison of bathymetry data collected in 1911; 1962 and 2000 revealed significant changes in nearshore morphology, including changes in bank morphology and bank displacement. The bank experienced a landward migration ranging from 300 to 500 m between 1911 and 1962, and from approximately 70 to 150 m between 1962 and 2000 (Fig. 2A), which corresponds to rates of 6 to 10 m yr^{-1} and 2 to 4 m yr^{-1} respectively. This onshore movement of the bank is likely due to the action of incident waves responsible for an onshore sand transport over the shallow crest of the bank. The landward displacement of the bank resulted in a shoreward shift of the channel located between the bank and the shore and in a decrease in channel depth. The bank was also affected by a longshore migration to the northeast of more than 1000 m between 1911 and 2000, which can be explained by the action of strong northeast-directed longshore tidal currents that can be reinforced by wind forcing.

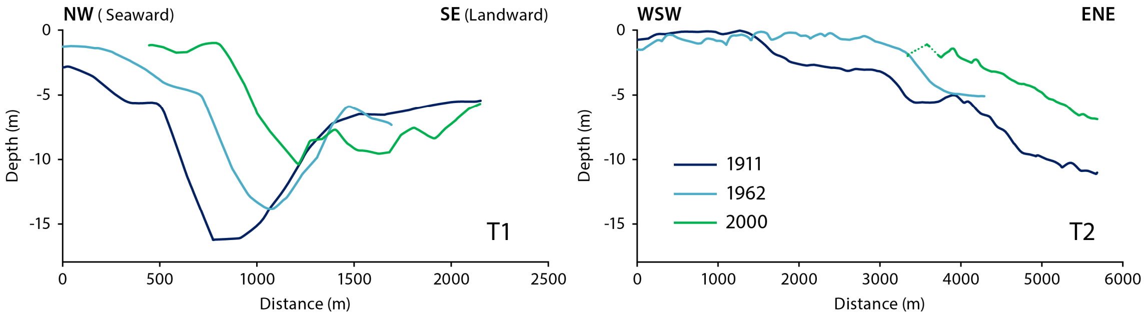

Figure 2. Changes in bathymetry between 1911 and 2000 along shore-perpendicular (T1) and longshore (T2) profiles across the Hills Bank, east of Dunkirk (see Fig. 1 for location). Depths are relative to Hydrographic Datum.

In Wissant Bay (Fig. 1), a banner-bank called *Banc à la Ligne* extends obliquely across the bay from a rocky headland, forming a 3.5 km long and 500 m wide linear sand body. The bank is approximately 10 m thick and stretches out seaward to a distance of about 2 km from the shore. The bank is relatively shallow, as its crest lies at about 5 m below Hydrographic Datum (which roughly corresponds to the lowest astronomical tide), and can thus be responsible for significant wave energy dissipation. The *Banc à la Ligne* experienced a complex evolution during the 20th century. Comparison of bathymetry charts revealed that the length of the bank increased towards the northeast and underwent vertical accretion in the same direction, presumably due to the dominant northeast-directed tidal currents. Although some sediment deposition took place near the distal end the bank, significant erosion also occurred on both the seaward and landward sides of the bank. Overall, the bank mostly underwent erosion between 1911 and 2002. In addition to the bank, extensive areas of the bay were affected by seabed erosion, notably near the shore where seafloor erosion reached more than 4 m in places. This resulted in a significant sediment loss across the bay, estimated at approximately 1.2 x 10^6 m^3 for the 20th century. Associated with this sediment deficit, most of the coast of the Bay of Wissant has been eroding during the second half of the 20th century, the shoreline having retreated by more than 250 m in the middle of the bay since 1949 (Aernouts and Héquette, 2006).

Onshore bank migration was also observed, notably east of Calais (Fig. 1) where a prominent nearshore sand bank, called *Ridens de la Rade*, eventually welded to the shore in only a few decades. This shore-attached bank favored the formation of a wide sand flat that constitutes a deflation surface for wind-blown sand that are transported to the upper beach where active dune development takes place (Anthony *et al.*, 2006). As a result, extensive shoreline progradation occurred along this coastal sector, locally exceeding 300 m during the second part of the 20th century (Héquette and Aernouts, 2010).

4.2. *Impacts of sand bank and nearshore bathymetry changes on wave propagation*

Simulation of wave propagation using the SWAN wave model shows that the observed changes in nearshore bathymetry, which are largely due to changes in sand bank location and morphology, may be responsible for significant variations in wave propagation that lead to major changes in the longshore distribution of wave heights. East of Calais, for example, onshore bank migration resulted in a decrease of wave energy in the nearshore zone through time, leading to more dissipative conditions that were increasingly favorable to shoreward sand transport by waves (Héquette and Aernouts, 2010), partly explaining the progradation of the shoreline in that area during the last decades.

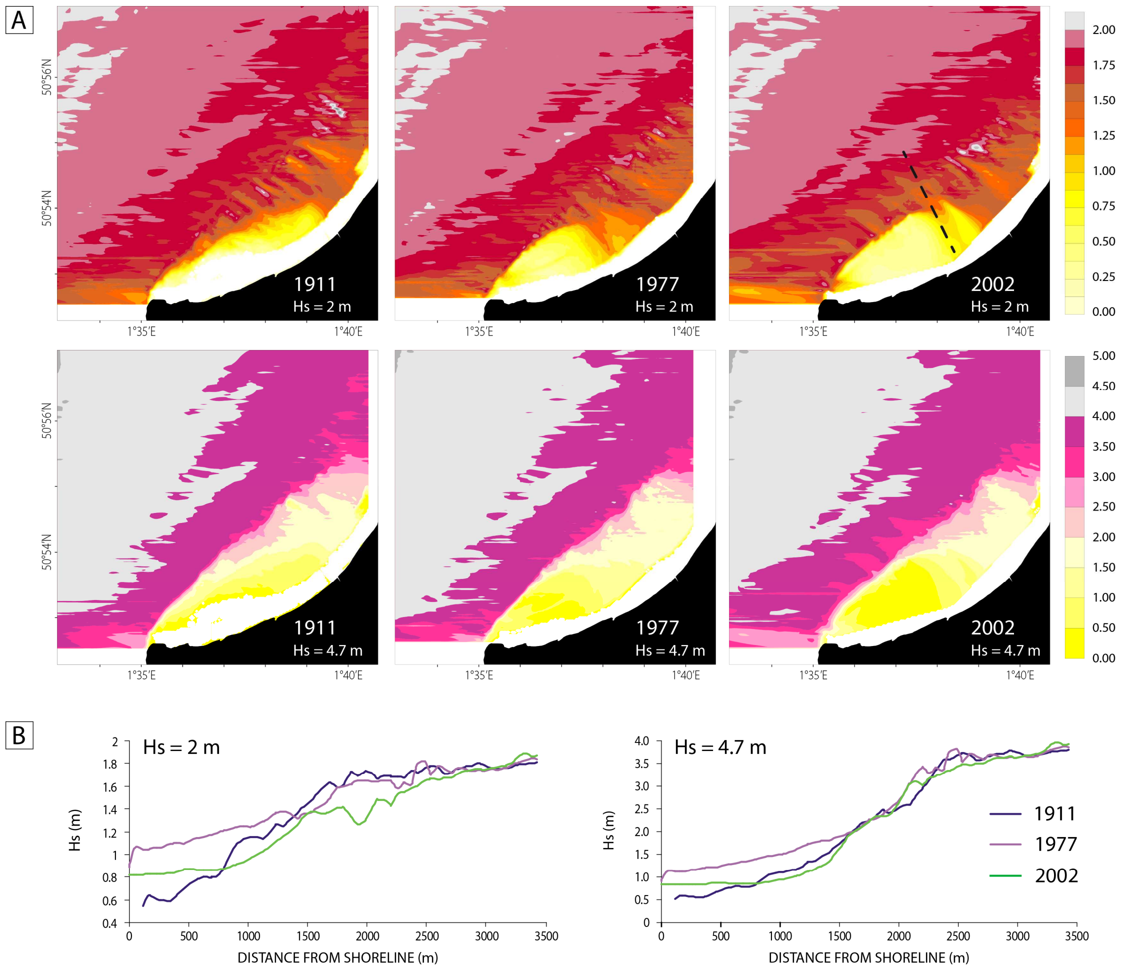

Figure 3. Simulation of changes in significant wave height (H_s) for westerly waves propagating over 1911, 1977 and 2002 bathymetries in Wissant Bay using SWAN model. Lower diagrams (B) show the variations in H_s along a shore-perpendicular transect (shown on upper right diagram) as waves propagate towards the coast over the different bathymetries.

Offshore of Wissant (Fig. 1), modeling of wave propagation also shows a decrease in wave height towards the coast, but the reduction in wave height is different over the bathymetries obtained in 1911, 1977 and 2002. Modeling of waves propagating from the west, which corresponds to the dominant wave approach direction in that area, shows higher wave heights at the shoreline in the central part of the bay in 1977 and 2002 compared with 1911 (Fig. 3A), this being likely due to the decrease in size of the banner-bank extending across the bay (*Banc à la Ligne*) and to nearshore seabed erosion, resulting in less wave energy dissipation. This increase in wave height at the coast is obvious on Figure 3B showing changes in wave height along a shore-normal transect for both moderate (H_s: 2 m) and higher energy waves (H_s: 4.7 m), the increase being particularly pronounced over the 1977 bathymetry. It is noteworthy that wave modeling suggests that wave height at the coast significantly decreased between 1977 and 2002 (Fig. 3B), while during the same time period shoreline retreat in the central part of the bay decreased from 6 m yr^{-1} before 1977 to about 4 m yr^{-1} after 1977 (Aernouts and Héquette, 2006).

4.3. *Influence of nearshore sand banks on coastal circulation and sediment transport*

Wave and current measurements were carried out at several sites between nearshore sand banks and the coast in order to evaluate the effects of these sediment bodies on coastal hydrodynamics and sediment transport. In the example presented here, directional wave and current data were obtained using an InterOcean S4 electromagnetic current meter deployed during 6 days in about 6 m water depth offshore of Calais (Fig. 4C). The instrument was moored near the toe of the landward flank of a 1.4 km wide nearshore sand bank (*Ridens de la Rade*) extending over almost 13 km along the coast. The depth of the bank crest varies alongshore, decreasing from about 5 m below Hydrographic Datum west of Calais to +1 m east of Calais where the bank is attached to the shore.

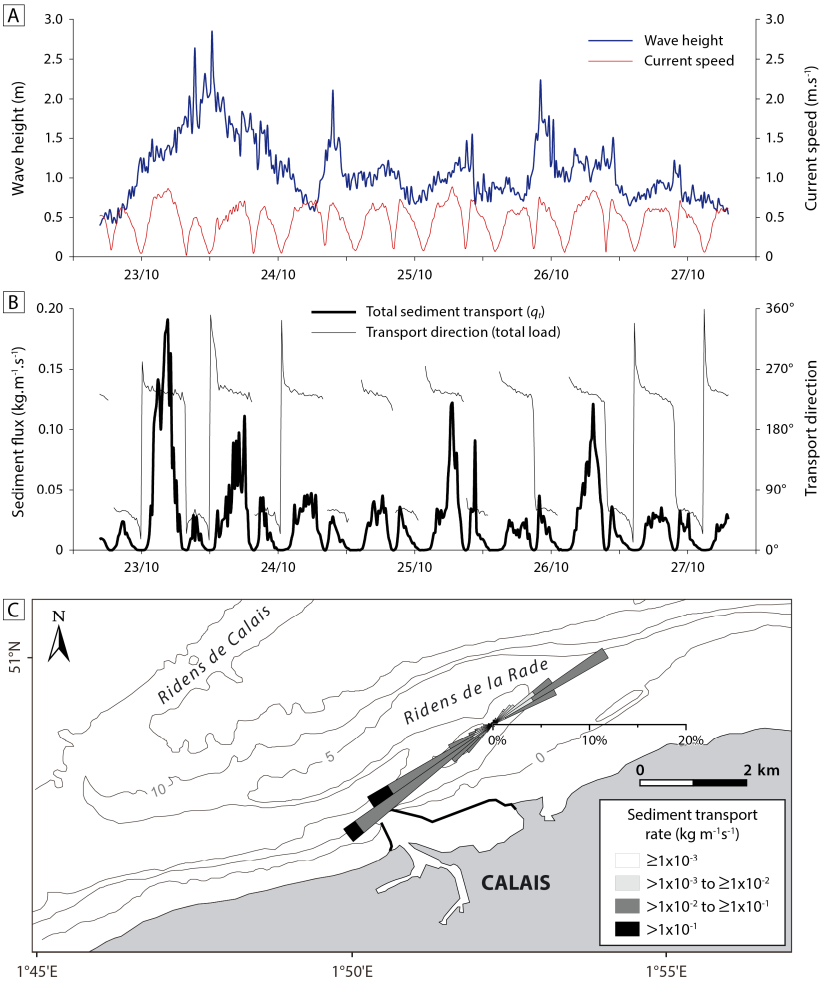

Figure 4. Hydrodynamic measurements in October 2003 offshore of Calais and estimates of sediment transport based on SEDTRANS96 model (modified from Héquette *et al*., 2008). Depths are relative to Hydrographic Datum. Rose diagram on Fig. 4C is centered on the location of the current meter.

Hydrodynamic measurements revealed large fluctuations in current velocity, with peaks occurring at a semi-diurnal frequency (Fig. 4A), which is typical of the tide-induced circulation prevailing in the coastal zone of the region. Flow velocity exceeded 0.6 m s^{-1} during all but one tide during the field experiment, with flood currents setting alongshore to the northeast and ebb currents to the southwest. Although near-bed currents are essentially tidally-driven, our measurements showed that wind action can significantly affect circulation over the shoreface. During the first two days of the experiment, northeasterly winds with speeds up to 13 m s^{-1} considerably reinforced southwesterly flowing ebb currents which reached a speed of 0.9 m s^{-1} on 23 October (Fig. 4A). Conversely, flood currents, flowing in the opposite direction, were strongly reduced, hardly exceeding 0.5 m s^{-1} on the same day. Lower intensity wind events occurred during the rest of the experiment, reducing or reinforcing nearshore currents depending on wind direction relative to currents. Winds were also responsible for substantial surface agitation with significant wave heights of 2 m or more on several occasions and even exceeding 2.5 m on 23 October (Fig. 4A).

Estimations of sediment transport rates using SEDTRANS96 numerical model (for a representative seabed grain-size of 0.37 mm) demonstrate that sand transport does not solely depend on a single forcing factor such as current velocity or wave height, but is a response to the combined influence of waves and currents. Figure 4B clearly shows that total sediment flux varies with mean current speed, sediment transport being negligible when current speeds are minimal while increasing when flow velocity magnitude increases. The results of sediment transport modelling also show that the higher sediment fluxes take place when tide- and wind-induced currents are associated with wave orbital currents that cause significant sediment remobilization due to enhanced shear tress. According to the model, the maximum sediment transport rate that almost reached 0.2 kg m-^{1} s^{-1} occurred during the northeasterly wind event of 23 October which was characterized by high amplitude waves (4B). The peak in sediment transport did not take place when waves were at their maximum height, however, but when more moderate waves were combined with relatively strong mean currents. Such combination of moderate wave heights and high mean current speeds is observable for each peak in sediment transport, highlighting the fact that even if waves are responsible for a significant increase in bed stress and sand resuspension, the magnitude of sediment transport strongly depends on the strength of the mean flow.

Numerical modeling of sediment transport also showed that sediment was essentially transported alongshore (Figs. 4B & 4C), even during high wave energy conditions that result in enhanced onshore-directed bed stress due to the action of shore-normal wave oscillatory motions. Our results suggest that wave orbital currents were not strong enough to overwhelm longshore tidal currents that were flowing at speeds of several tens of centimeters per second for periods of several hours during each tide, thus favoring shore-parallel rather than shore-normal transport. Because cross-shore transport appears insignificant, onshore sediment supply from the shoreface to the adjacent beaches seems minor at such depths, at least for the conditions observed during this experiment. More significant onshore transport may possibly occur during low-frequency storm events characterized by high onshore-directed orbital velocities, but these conditions are by definition restricted to very limited periods of time. The presence of numerous sand banks offshore, which cause significant wave energy dissipation, is probably an additional factor limiting the action of waves in the nearshore zone that appears to be strongly dominated by longshore tidal flows. The supply of nearshore sediments to beaches may therefore be limited to shallower water depths where wave orbital currents become more efficient in driving sediment onshore as tidal flow velocity magnitude decreases and wave asymmetry increases shoreward.

5. Discussion and conclusion

Analyses of bathymetry changes revealed different behaviors in nearshore bank evolution that led to contrasting shoreline change along the coast. These analyses showed that at a time-scale of several decades, sand banks underwent significant morphological changes and commonly experienced longshore as well as onshore migration. A large body of literature has been dedicated to the origin and evolution of linear sand banks, usually emphasizing the role of tidal currents in their formation and morphological maintenance (Kenyon *et al*., 1981; Collins et al., 1995; Dyer and Huntley, 1999). Although the elongation and longshore migration of the nearshore sand banks of the southern North Sea and Dover Strait can certainly be attributed to tidal currents, their landward movement is very likely due to the action of storm waves that can be responsible for onshore sediment motion across the bank crests. When waves reach these nearshore banks, their direction is always close to shore-perpendicular, regardless of the offshore wave direction, because of significant wave refraction over the offshore sand banks. The decrease of water depth over the shallow bank crests induces the shoaling of incident waves, and eventually their breaking during storms, which should lead to an increase in wave asymmetry resulting in onshore-directed orbital velocities that are favourable to shoreward sediment transport (Aagaard *et al*., 2004).

Even if all nearshore banks are presumably affected by onshore-directed wave-induced transport during high energy events, the fate of the sediments transported landward across the banks likely varies depending on the depth of the bank and its distance from the shoreline. Historical data show that shore-attached sand banks may represent major sediment sources for the adjacent beaches, as east of Calais where sediment has been transported onshore, contributing to the development of the sand flat and aeolian dunes on the upper beach (Anthony et al., 2006). Simulation of wave propagation using the SWAN wave model suggests that the onshore movement of this sand bank during the 20th century resulted in a decrease of wave energy in the nearshore zone, leading to more dissipative conditions through time which would be favorable to shoreward sediment transport by waves (Héquette and Aernouts, 2010).

When sand banks are not attached to the shore, they are separated from the coast by a channel that may constitute a major barrier limiting onshore sediment transport. East of Dunkirk, for example, the presence of a relatively deep channel (>10 m) between the Hills Bank and the coast (Fig. 2) probably favors longshore rather than cross-shore transport. Such an interpretation is based on the existence of relatively high-velocity tidal flows in the channel, comparatively to wave orbital currents that are reduced due to the dissipation of wave energy over the bank, especially at low tide (Héquette et al., 2009). Therefore, most of the sand that can be driven landward by onshore-directed wave oscillatory flows across the bank is probably transported alongshore in the channel, in response to shore-parallel tidal currents, and can hardly be transported onshore to the beach, which may explain the apparent sediment deficit and coastal dune erosion observed behind the bank (Maspataud *et a*l., 2011). Numerical modeling of sediment transport carried out at several locations on the shoreface off the coast of northern France, which indicates that transport directions are essentially alongshore (Héquette et al., 2008), is additional evidence supporting this interpretation. Eastward of the Hills Bank, however, the shoreline has experienced progradation for several decades associated with aeolian dune development on the upper beach (Maspataud et al., 2011). Sand can more likely be transported onshore by waves over the low gradient nearshore slope eastward of the bank, potentially resulting in a higher sediment supply to the beach. As shown in several studies, gently sloping dissipative shoreface profiles increase onshore-directed transport and are commonly associated with coastal dune development (Aagaard et al., 2004; Cooper and Navas, 2004). Based on shoreline change analysis and sediment budget, it appears that onshore transport especially occurs at the downdrift terminus of banks where more gentle shoreface slopes favor shoreward sediment transport by onshore-directed asymmetrical wave oscillatory flows that can overwhelm shore-parallel tidal currents in shallow water depths.

Nearshore sand banks do not only influence nearshore circulation and sediment transport, but also strongly control wave energy distribution along the coast, as wave propagation modeling shows. Because the shape and location of sand banks change through time, the resulting patterns of wave energy distribution also vary along the coast. In Wissant Bay, for instance, the changes in bank morphology and crest elevation that occurred during the 20th century resulted in modifications of wave refraction patterns (Fig. 3) that were important enough to cause significant changes in the spatial distribution of coastal erosion and accumulation along the shore of this bay.

Our observations clearly show that nearshore sand banks can have very different effects on coastal hydrodynamics and sediment dynamics, depending on the depth, orientation and distance of the bank to the coast. The changing position of sand banks consequently results in progressive modifications of wave refraction, circulation and sediment transport in the coastal zone. The results of our investigations suggest that the migration of sand banks may possibly correspond to a continuum of nearshore bank evolution, the welding of sand banks to the coast representing the last stage of the continuum. Through the different stages of bank evolution, the coast would undergo various phases of erosion and accretion due to the sheltering effect of the bank, followed by periods of sediment deficit caused by the close proximity to the beach of bank-associated channel, and would eventually experience progradation once the bank becomes attached to the shore, providing sand to the beach.

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