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Seasonal Evolution of Shoreface and Beach System Morphology in a Macrotidal Environment, Dunkerque Area, Northern France

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ABSTRACT

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Differential maps have been digitalized and compared from successive bathymetric and topographic surveys performed under different meteorological conditions from May 1992 to December 1994 in the shoreface-to-beach system of the 30 km long coastal area extending from Gravelines to the French-Belgian border in southernmost North Sea. The data, which concern a low-relief sandy coastal system exposed to a macrotidal regime with flood-driven eastward sediment transport, have been interpreted according to meteorological, hydrodynamical and aerodynamical characteristics.

A balanced sediment budget was observed, which contradicts previous data suggesting a progressive long-term erosional trend. This result indirectly underlines the key-role on the sedimentary budget of exceptional events such as severe storms. The two types of erosion identified comprise the action of frontal waves and the combined interaction of tidal currents and wind.

Five hydrodynamical cells have been recognized along the shoreface. The corresponding segmentation is attributed to the specific distribution of the wave energy along the coast due to the presence of submarine banks responsible for the deformation of the wave propagation.

The morphological changes of the beach depend on the tide and swell action responsible for the construction/migration/destruction of the ridge and runnel system.

ADDITIONAL INDEX WORDS: *Morphology, shoreline evolution, shoreface, beach, macrotidal regime, cell segmentation, cross- and long-shore transport, erosion, accretion.*

INTRODUCTION

Beach and nearshore morphology, and associated sedimentary processes, are predominantly influenced by tide, wind and wave regimes. Although the literature on macrotidal beaches has increased significantly during the recent years, only a small number of papers concerns the morphodynamics of macrotidal beaches relative to microtidal beaches (CARTER, 1988; SHORT, 1991; MASSELINK and HEGGE, 1995). Many workers have already investigated morphological and sedimentological changes of sandy coastal systems at both short- and long-term scales (CLARKE and ELIOT, 1983; ELIOT and CLARKE, 1986; DUBOIS 1988; BYRNES and HILAND, 1995). These changes have mostly a large seasonal component depending on weather conditions, but spatial variability along the systems is also frequently observed (KOMAR, 1976; DAVIS, 1985). Such a variability generally results from a complex interaction between environmental parameters and coastal morphology. The precise understanding of this interaction is necessary in case of coastal management problems.

After the severe damage caused by storms on February 1990, several northern coastal French cities, grouped in the "Syndicat Intercommunal of the Littoral Est dunkerquois" (S.I.L.E.), decided to fund a scientific program, the results of which could allow to chose the type of defensive measures best able to protect against erosion in the coastal area. The area includes the dune, the beach and the upper shoreface domain located between Dunkerque and the Belgian frontier (Figure 1). The research program comprised a multiple scale approach, including the estimation of long-term and short-term sedimentary budgets, field surveys related to waves and currents regime, the elaboration of a numerical wave refraction model and of an integrated mathematical model (BRYCHE *et al.*, 1993).

In order to study the morphological evolution of the shoreface and beach system and to understand its causes, topographic and bathymetric surveys have been performed from May 1992 to December 1994 along the coastal system east of Dunkerque. Differential maps were elaborated by the automatic comparison between two successive surveys and analysed according to meteorological and hydrodynamical conditions. This paper presents the main results of the study that allows an estimation of the sediment budget and a better understanding of the relationships between shoreface and beach responses to hydrodynamical processes.

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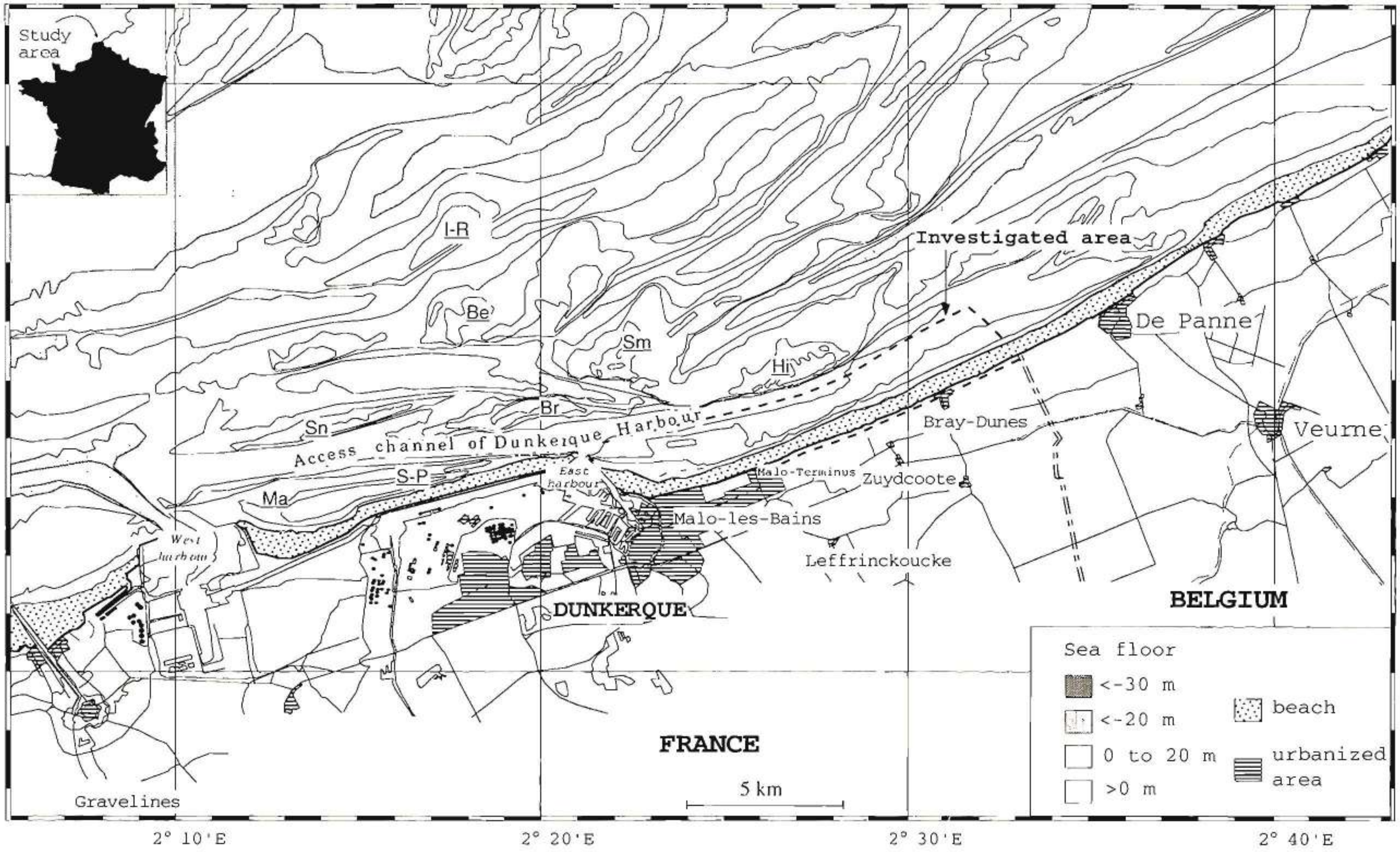

Figure 1. Study area. (*Be*) Breedt bank, (*Br*) Braek bank, (*Hi*) Hills bank, (*I-R*) In'Ratel bank, (*Ma*) Mardyck bank, (*Sm*) Smal bank, (*Sn*) Snouw bank, (*S-P*) Saint-Pol bank.

Table 1. *Characteristics of the survey (wind characteristics are given by the French National Meteorology, tide characteristics by the French Marine and Oceanographic Hydrographic Service).*

Date	Organisation in Charge	General Conditions	Winds: Origin and Speed	Tidal Regime	Seasonal Trends
April 92	EUROSENSE	FW	S < 10 m/s	Mean tide	Winter
October 92	L.N.H.	WW	NNE 17 m/s	Mean tide	Post summer
June 93	bathymetry: EUROSENSE Topography L.N.H.	FW	SSW < 10 m/s	Mean tide	Post winter
September 93	L.N.H.	FW	WSW < 12 m/s	Mean tide	Post summer
June 94	L.N.H.	WW	NW 17 m/s	Mean tide	Post winter
December 94	L.N.H.	WW	WSW 11-17 m/s	Spring tide	Winter

(L.N.H.: National Hydraulic Laboratory, FW: fair weather and WW: bad weather)

METHODS

Hydrodynamical conditions were measured by the National Hydraulic Laboratory of Electricité de France (L.N.H.) and include:

- offshore tidal currents measured using AANDERAA and SEREPS current meters;
- on the beach, tidal current were measured with SUBER current meters along three cross-sections ;
- offshore, a complete wave record (height and period) was obtained between November 1991 and June 1993 from a DATAWELL wave rider buoy.

Morphological changes affecting the shoreface and beach systems were investigated using very high resolution topographic and bathymetric surveys. The surveys were performed by the L.N.H. and the Belgian company EUROSENSE (Table 1).

The method developed by the L.N.H. consists in measuring from a small ship the depth (Z), the geographic position (X, Y) and the sea level (Figure 2). X, Y geographic coordinates are given by a short and medium range radiolocalisation system called AXYLE. Depth values are obtained at 4 Hz by using a bi-frequency (33 and 210 kHz) ultrasonic sounder (ATLAS KRUPP DESO 20). In order to correct the depth variation due to tides, a pressure sensor measured the sea level every five minutes. Data were collected during high tide along meter-distant lines normal to the shore. At low tide, beach topographic measurements were obtained using a geodimeter AGA 140 along profiles prolonging the bathymetric lines, so that bathymetric and topographic data overlapped on the lower foreshore to upper shoreface. The geodimeter is able to measure the horizontal and vertical angles and the oblique distance (X, Y and Z values).

A BEASAC (Belfotop Eurosense Acoustic Sounding Air Cushion platform) hydrographic system mounted on a hovercraft is used by EUROSENSE for monitoring the coastal morphology (EUROSENSE, 1988; see HOUTHUYS *et al.*, 1994 for detailed description of the method). The BEASAC system uses both Trisponder and Toran systems for positioning. Depths are measured using a DESO 20 echo sounder. The BEASAC is both manoeuvrable and very stable. It allows surveys to be made rapidly and accurately even in shallow areas that are inacessible to traditional survey vessels.

From April 1992 to December 1994, six surveys were performed (Table 1). The study area (Figure 1) extends from Dunkerque to the Belgian frontier about 12.5 km. It is about 1.5 km wide, including about 500 m of beach and about 1000 m of shoreface, *i.e.* from the seawall or the coastal dune to the access channel of Dunkerque harbour.

Topographic and bathymetric lines were shot with a spacing of 200 m. They are subperpendicular to the coastline. Data were digitized at the L.N.H in order to produce topobathymetric maps integrating tidal correction. To allow an accurate comparison between two surveys, an interpolation of z-value was calculated, based on PH method (Paraboloïde

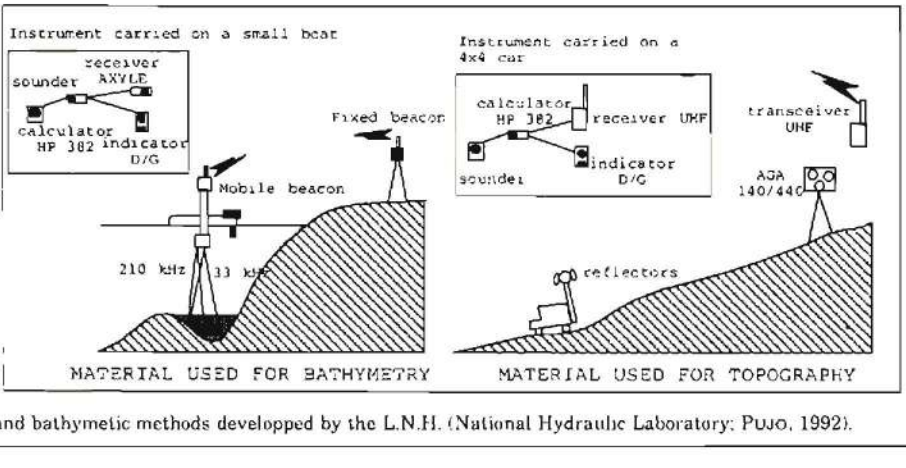

Figure 2. Topographic and bathymetic methods developped by the L.N.H. (National Hydraulic Laboratory; PUJO, 1992).

Hyperbolique), in order to obtain a regular grid (50×50 m) from the data set. To study sediment movements occuring between two successive surveys, every data point from the first grid surface was projected onto the second one and the z-values were subtracted. The z-value of the resultant map, called differential map, represents the difference of elevation between the two grids. Differential maps thus indicate changes in elevation between two successive periods and thus point out the sectors submitted to either erosion or accretion. In order to complete the differential map analysis, total volumes of eroded and deposited sediments over the whole study area were calculated.

Bed level changes higher than 0.2 m are supposed to be significant. However, values from 0 to -0.2 m are considered as expressing an erosional trend, and from 0 to $+0.2$ m, an accretional trend.

HYDROSEDIMENTARY CONTEXT

The study area has a WSW–ENE-oriented, 30-km-long, coastal domain located in the north of France between Dunkerque and the Belgian border, in the southern bight of the North Sea (Figure 1). It forms a low relief sandy coastal system with large and wide beaches and gently sloping shoreface.

Morphological and Sedimentological Characteristics

The French part of the southern North Sea consists of a shallow shelf sea with water depths generally not exceeding 40 m (Figure 1). The shoreface and offshore systems are characterized by the presence of numerous sand banks which belong to the Flemish banks complex (KENYON *et al.*, 1981). Within this group, the Dunkerque's Banks refer to the sand bodies called Mardyck, Saint Pol, Snouw, Braek, Breedt, Hills, Smal, In'Ratel and Buiten Ratel. These banks are 8 to 32 km long, 1.5 to 3 km wide and 15 m high. Their crest is located at least at -5 m below the mean sea level and may be exposed at low spring tide (*e.g.* the Hills and Smal banks). The banks display an asymmetry: the southern flanks, i.e. coastward, are generally steeper than the northern (*i.e.* seaward) flanks due to the net wave- and current- induced transport (LAHOUSSE *et al.*, 1993, TESSIER *et al.*, 1996). The banks are separated by 10 to 20 m deep sandy throughs or channels. The first channel separating the beach from the first bank alignment constitutes the access channel of Dunkerque harbour. The nearshore zone, located between the coast and the access channel, is characterized by a low slope (0.4° to 0.6°) to the east of Dunkerque and by a slightly steeper slope (1°) to the west.

The analysis of the shoreface surficial sediments between the coast and the first bank alignement (Figure 3) shows that their distribution is controlled by the bathymetry (VICAIRE, 1991; CORBAU, 1995). In the channels deeper than 10 m, the surficial sediments are mixed and consist of well-sorted fine-grained sand to poorly-sorted coarse-grained sand. The mean grain size value ranges from 125 μm to more than 600 μm. The coarser channel deposits occur locally in the nearshore zone between Zuydcoote and Bray-Dunes. In the shallower sectors of the banks and upper shoreface, the surficial sediments are well-sorted fine- to medium-grained sands with a mean grain size of 125 to 315 μm (VICAIRE, 1991; CORBAU, 1995).

The beach domain is different on each side of Dunkerque city (VICAIRE, 1991; LAHOUSSE *et al.*, 1993). To the west, from Calais to Dunkerque, the coastal dunes are small (width: 500 m and height: 15 m); beaches are up to 1200 m wide and made up of medium-sized sand (200 to 350 μm). By contrast, the dune complex is massive to the east of Dunkerque (width usually more than 1000 m) with heights up to 25 m. Beaches are about 300 to 600 m wide. The foreshore morphology is characterized by a multiple ridge and runnel system cut by ebb and rip channels (Figure 3). The length of an individual ridge is about 100 m, and its height does not exceed 1 m. Usually the ridges present a typical steeper flank oriented coastward reflecting their landward movement. The beach profile displays a concave shape with low slope. This pattern suggests a dissipative profile (MASSELINK and SHORT, 1993). Along the eastern shore of Dunkerque the beaches are composed of well-sorted fine to medium lithoclastic sand. The sand displays a medium grain size of 160 to 240 μm with a seaward fining trend.

OCEANOGRAPHIC AND CLIMATIC REGIMES

Tides

Tidal regime in the study area is semi-diurnal (HOUBOLT, 1968). The tidal range varies from 3.4 m during neap tides and 5.4 m during spring tides. The environment is predominantly macrotidal

In general the tidal currents are alternating (Figure 4A) and their direction follows the main channels direction. The flood is oriented to the NE or ENE and the ebb to the SW or WSW. The tidal currents are modified by the presence of the banks (BECK *et al.*, 1991). In the narrow interbank channels, the current velocities are relatively strong. For mean spring tide, the maximum subsurface velocity reaches 1.5 m/s during the flood time and 1.35 m/s during the ebb (VICAIRE, 1991). The flood directions are N065 to N090 and N225 to N270 for the ebb. The tidal velocities are low over the bank, the nearshore and where the channels are wider or cutting obliquely the banks. In the Zuydcoote interbank for example maximum tidal current velocities are 1 m/s in spring tide and 0.7 m/s in neap tide (MANCEL, 1992). The results of the tidal current measurements on the beach recorded by the L.N.H. exhibit alternating currents with dominant flood (Figure 4B). Current velocities decrease towards the east with maximum values at Dunkerque. The general flood current orientation is N060 and the ebb current N260.

The stronger tidal currents occur usually in front of Dunkerque (where the banks are concentrated), and the weaker to the east in front of Bray-Dunes. Because of the prevailing flood current, the net tidal induced transport along this coastal zone is directed to the northeast (S.H.O.M., 1968, 1988; VICAIRE, 1991).

Winds

The observations at Dunkerque between 1951–1960 and 1990–1994 show that the prevailing winds blow from NE and

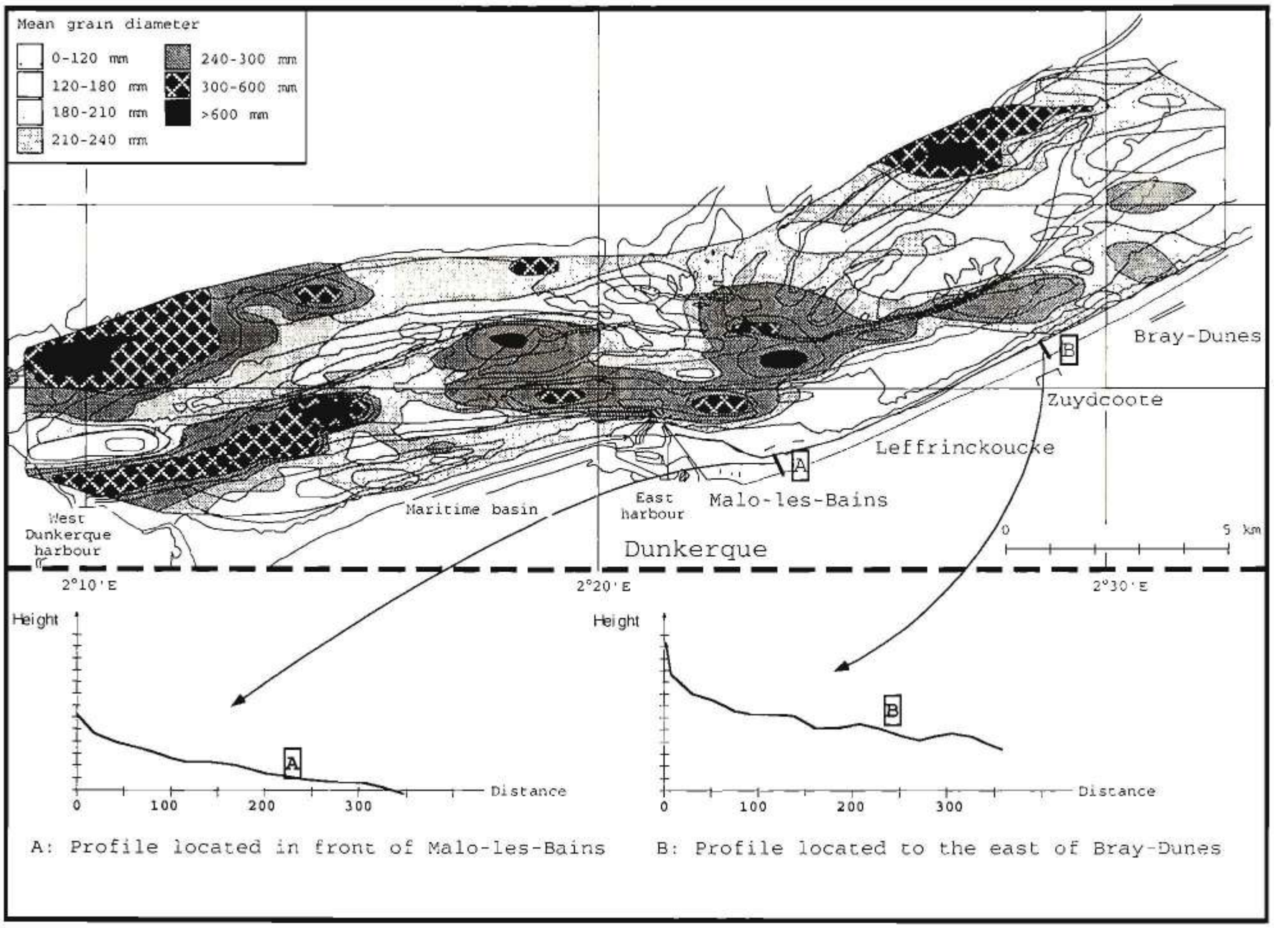

Figure 3. Morphological and sedimentological characteristics of the study area. The sediments were collected in September 1992 and the topographic profiles were made in October 1992.

from SW (Figure 5). Among frontal winds, NE and N winds, blow essentially during the spring, and NW winds during autumn and winter. The latter reach higher velocities (up to 22 m/s).

The winds affect the tidal currents. A flood or ebb tidal phase may be delayed or prevented due to the wind action. In the study area the spring flood current is possibly delayed by NE winds and the spring ebb current by SW winds. Wind may also induce an acceleration of one tidal currents (the flood or the ebb). Tidal velocities may be up to 25% higher than normal values at spring tide and up to 40% higher at neap tide (S.H.O.M., 1968).

Waves

In the offshore domain, the dominant directions of wave propagation are NNE (26%), N (16%), and SSW (10%) to WSW (16%) (Figure 6). The wave heights currently reach 1.5 m to 2.5 m, and attain 4 to 5.5 m for 10% of the waves. The wave periods are generally of 5 to 7 s (BONNEFILLE *et al.*, 1971; CLABAUT, 1991).

The wave parameters measured in front of Bray-Dunes (MANCEL, 1993) show that:

- the predominant wave direction is from W (54%),
- their significant height is often greater than 0.5 m (70%),
- the wave period is about 3 to 4 s,
- the annual maximum wave height is estimated to 2 m and the decennal wave height to 2.6 m.

At the coast, the wave direction is N (42%), NW (18%), NNW (14%) or WNW (12%). NNE waves are rare and NE wave do not occur. The wave refraction due to the presence of banks is largely responsible for the modification registered in the wave direction (CLIQUE, 1986; PELTIER and LE SAUX, 1992).

The Dunkerque coast can be considered as a mixed environment influenced by both strong tidal currents parallel to the coastline and moderate wave conditions (HAYES, 1979).

Human Influence

West of Dunkerque, the exposed zone is characterized by a wide industrial harbour zone. The western outer harbour of

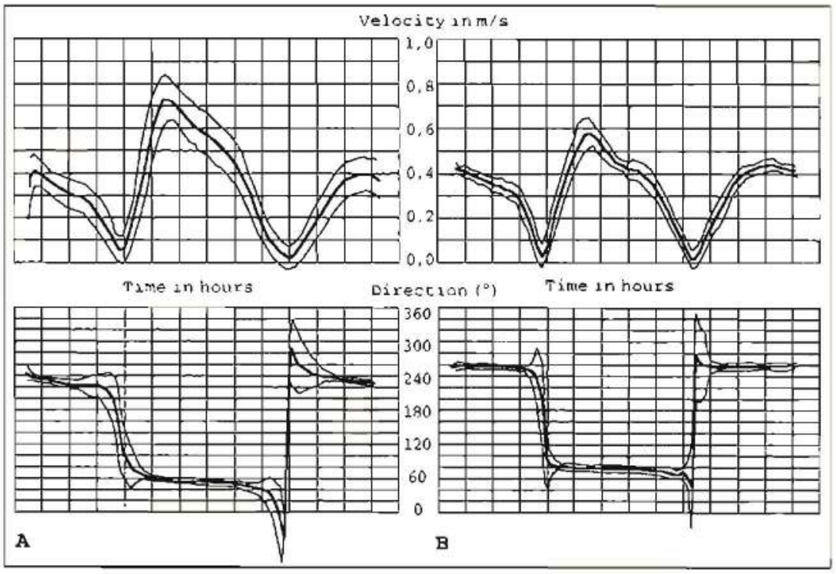

Figure 4. Tidal current characteristics—velocity and direction—for mean spring tide with tidal coefficient of 70 to 95 (MANCEL, 1992). (A) in the access channel of Dunkerque Harbour in front of Bray-Dunes and (B) on the beach of Malo-terminus.

Dunkerque was built between 1975 and 1978. Since the construction of this industrial complex the coastline has shifted more than 1000 m offshore (VICAIRE, 1991). East of Dunkerque, dune system has been progressively urbanized. The 1831 topographic map shows a continuous aeolian dune line from Malo-les-Bains to the Belgian frontier along a distance of 11.5 km. In 1987, the natural dune line is fragmented in three sectors separated by urbanized zones. The development of urban sectors is responsible for a decrease of 40% of the aeolian dune complex (CORBAU *et al.*, 1993). The natural morphology has been influenced by man-made coastal structures such as harbour jetties, seawalls and breakwaters. Three breakwaters are located in front of Malo-les-Bains close to the east of Dunkerque harbour. Two first breakwaters were built in 1978, which led to a beach nourishment of 250 000 m^3. In 1988 the last one was realized simultaneously with a beach nourishment of 160 000 m^3. These breakwaters have been set up at 1-m depth. At high tide they are submerged and at low tide they emerge. Finally, for the navigation needs, depth of the the access channel to the harbour is maintained by dredging. In 1986, 1987 and 1988 a volume of

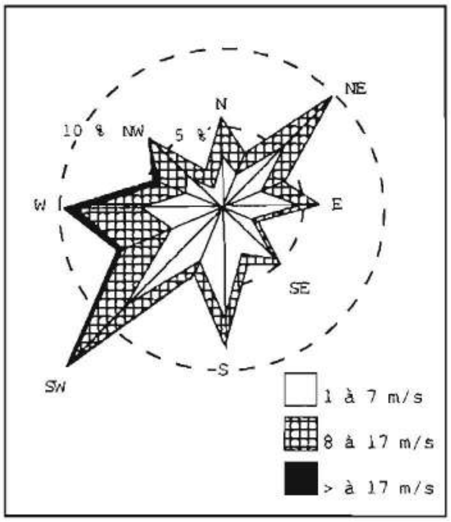

Figure 5 Wind directions and velocities at Dunkerque between 1951–1960 (after BONNEFILLE *et al.*, 1971).

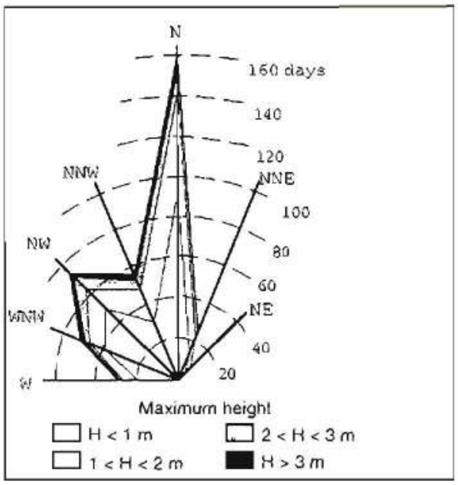

Figure 6. Wave height and directions at Dunkerque after 399 consecutive days of observation (after BONNEFILLE *et al.*, 1971).

315 000 m³/year *i.e.*, 1 800 000 t/year of dry material (mud and sand) was dredged.

MORPHOLOGICAL RESULTS

The morphological modifications of the beach and the shoreface expressed by the differential maps have been considered relative to the hydrodynamical and meteorological conditions that prevailed before the topographic and bathymetric survey. We have considered both influence of short-term meteorological events which are assumed to determine the major morphological changes in the high energy-dominated sandy coastal environments of the Dunkerque type, and the effects of normal summer to winter conditions.

The hydrodynamical and meteorological conditions which prevailed before and during the compared surveys, are of three mean types (Table 1): fair weather marked by moderate and increasing tidal range, heavy swell conditions associated with moderate and increasing tidal range, and both bad sea conditions and high tidal range during a winter period.

Three of the differential maps constructed are presented and discussed here: 1—June 1993–September 1993: fair weather, mean tide, situation in early fall, 2—September 1993–June 1994: bad weather, frontal wind, mean tide, situation after winter conditions and 3—June 1994–December 1994: bad weather, wind parallel to the coast, spring tide, winter situation.

Differential Map Comparing June 1993 and September 1993 Situations

The whole system has experienced a strong accretion (volume of sedimentation ≈ 5 000 000 m³, erosion volume ≈ 360 000 m³). The mean elevation value ranges from +0.2 to +0.4 m (Figure 7a). The distribution of accretion is not random. With respect to the average z-value variability, beach and shoreface domains can be divided in severals sectors. The shoreface displays a segmentation into fives sectors, from several hundred meters to a few kilometers wide, whereas the beach exhibits a different organization with two main sectors each of them extending over kilometers.

The five sectors (1–5, Figure 7A) identified on the shoreface display from west to east the following characteristics:

(1) From Harbour jetty to Malo-Terminus camping, high positive z-value changes (up to +1 m).
(2) From Malo-Terminus Camping to Zuydcoote Batterie, low positive z-value changes (< +0.2 m).
(3) From Zuydcoote Batterie to Maritime hospital, medium positive z-value changes, from +0.3 m to +0.4 m. Off this sector, high positive values up to +1 m and negative values up to -0.4 m occur locally.
(4) From Maritime hospital to Bray-Dunes, low positive z-value changes, from +0.1 m to +0.2 m.
(5) East of Bray-Dunes, low to high positive z-value changes, from +0.2 m to more than +1 m.

In each of these sectors the areas in accretion or erosion do not display any special pattern of spatial distribution.

On the beach, the two sectors comprise:

(a) From Tixier lock to Malo-Terminus Camping, positive z-value changes are low and locally alternate with low negative values.
(b) From Malo-Terminus lock to Bray-Dunes, z-values range from -0.4 m to +1 m. Further to the east high positive up to +1 m z-values are recorded.

In the first sector, the distribution of z-values is random, whereas to the east of Malo-Terminus Camping, it is organized in alignements subparallel to the coastline.

Differential Map Comparing September 1993 and June 1994 Situations

Erosion is greater than accretion although positive z-value changes, reaching +1 m, appear locally (Figure 7b). The erosion volume reaches 3 500 000 m³, and the accretion volume 1 950 000 m³. Z-value changes range from +1 m to less than −1 m. With respect to the morphological changes, the shoreface area can be divided into five main sectors which display almost the same limits as the sectors recognized on the previous differential map.

(1) From Harbour jetty to Malo-Terminus Camping, high negative z-value changes up to −1 m, especially close to the channel. Accretion up to +0.4 m occurs close to the jetty.
(2) From Malo-Terminus Camping to Zuydcoote Batterie, low positive z-value changes (+0.2 m).
(3) From Zuydcoote Batterie to the Maritime hospital, medium to high negative z-value changes up to −0.6 m; sectors in accretion occur in the distal part of the area.
(4) From Maritime hospital to Bray-Dunes, low positive z-value changes up to +0.4 m.
(5) East of Bray-Dunes, high negative z-value changes up to −0.8 m.

Z-value changes on the beach are predominantly negative. The distribution of the erosional and accretional sectors is similar than in the previous situation, *i.e.* random at the west of Malo-Terminus (sector 6) and characterized by bands parallel to the beach line at the east of Malo-Terminus (sector b).

Differential Map Comparing June 1994 and December 1994 Situations

Sectors in erosion are larger than on the former maps: the erosion reaches 4 000 000 m³ and the accretion 950 000 m³. Average z-values range from about +0.2 m to −0.4 m with local extreme values of +0.6 m and −1 m (Figure 7c). The most significant feature concerns the shoreface which has mainly experienced erosion whereas the beach has predominantly accreted.

The shoreface shows again a segmentation into five main sectors. However the segmentation is not as evident as for the previous situations, and the boundary between the sectors has moved some several 100 m westward.

(1) From Harbour jetty to the west of Malo-Terminus Camping, low to medium negative z-value, from −0.1 m to −0.4 m. Accretion up to +0.4 m occurs in front of Tixier lock.
(2) From Malo-Terminus Camping to the west of Zuydcoote Batterie, medium to high negative z-value changes, up to −0.6 m.

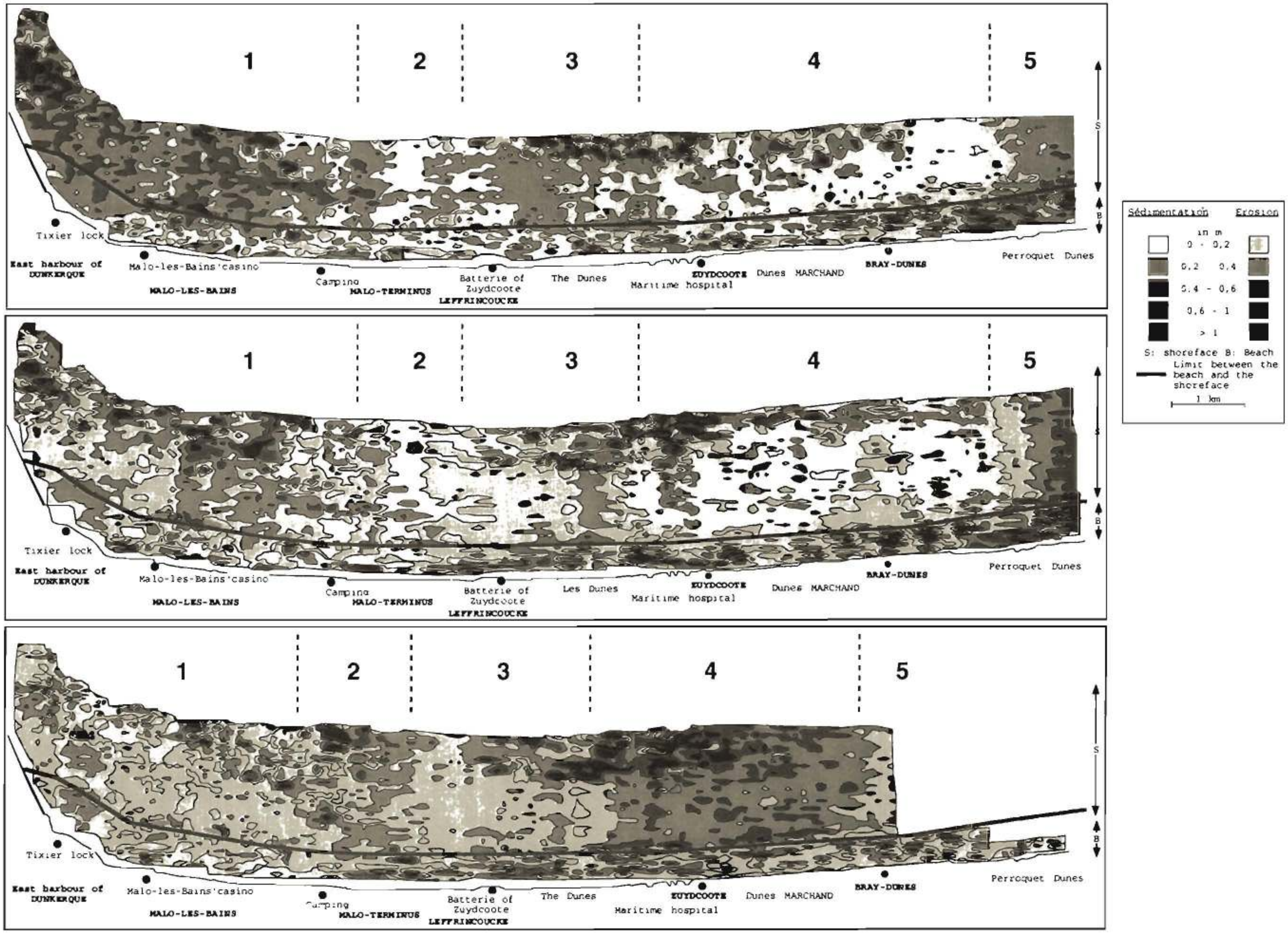

Figure 7. Differential map between June 1993 and September 1993. Figure 7b: Differential map between September 1993 and June 1994. Figure 7c: Differential map between June 1994 and December 1994.

(3) From Zuydcoote Batterie to the maritime hospital, low negative z-value changes (−0.2 m).
(4) From Maritime hospital to Bray-Dunes, high negative z-value changes, from −0.2 m to −1 m.
(5) In front and east of Bray-Dunes, low negative z-value changes (−0.2m).

On the beach, the accretion reaches +0.6 m to +1 m. Weak erosion occurs locally. Similarly to previous situations, the distribution of erosional and accretional sectors is random to the west of Malo-Terminus Camping (sector a), and consists of bands parallel to the shoreline to the east (sector b).

DISCUSSION

General Trends of the Short Term Morphological Evolution

From June 1993 to December 1994, the differential maps show that the z-values variations rarely exceeded ±1 m, pointing to the fact that the study area has not been affected by significant morphological changes. Moreover the comparison between the differential maps over the complete study period (*i.e.* April 1992 to December 1994) shows that the volumes of erosion and sedimentation are almost constant, with a slight positive budget.

This short-term sedimentary balance recognized on the eastern side of Dunkerque area appears to contradict previous data indicating that the general long-term evolution resulted in an erosional trend (BRIQUET, 1930; SOMMÉ, 1977; CLIQUE, 1986). The result obtained in our study is attributed to the low energy hydrodynamical and meteorological conditions that prevailed during the period of investigation. Such short-term morphodynamic equilibrium related to low to moderate wave energy conditions is common in terms of beach behaviour (*e.g.* WRIGHT *et al.*, 1982).

The discrepancy between the long-term, negative budget, and the short-term, positive budget emphasizes the importance of exceptional events such as severe storms. Coastal storms have often been considered as the main agent for sediment transportation, morphology modification and recent beach erosion (BRYANT, 1988). During severe storms, the coastline retreats due to beach erosion, whereas between such major meteorological events the beach is rebuilt and tends to shift seaward. Usually this erosion/accretion alternation has a seasonal component because storm frequency is seasonal in most world areas (DAVIS and FOX, 1972; DAVIS, 1985). However the accretion and destruction of beaches are not strictly a seasonal phenomenon since the evolution is controlled by the frequency and intensity of storms. The seasonal, and therefore the short-term erosion/accretion changes, usually balance each other. A disequilibrium in the sediment budget, and more especially an erosional tendancy, may occur when the short-term seasonal alternation is superimposed to a longer-term evolution that is characterized by a higher frequency of severe storms, which not necessarily take place during their usual season (KOMAR, 1976). Such desequilibrium with significant beach erosion seems to have occured in the end of the 1970's. As no severe storm occured during the study period, and because the wave regime had been quiet as an average, the coastal system did not experience noticeable morphological and sedimentological changes.

Shoreface Evolution

Segmentation Into Cells

According to the evolution expressed by the differential maps five sectors have been identified along the shoreface (Figure 8). These sectors, here called cells, are quite well individualized on each differential map but their boundaries may fluctuate laterally for several hundred meters.

During fair and bad weather (heavy swell) associated with mean tidal range the cells of "Malo-les-Bains" and "East Bray-Dunes" were characterized by high amplitude changes, *i.e.* by accretion during fair weather and by erosion during wavy weather, whereas the "Zuydcoote–Bray-Dunes" cell presented low amplitude changes. By contrast, during bad weather with spring tide conditions the higher erosion was observed along the "Zuydcoote–Bray-dunes" cell.

WRIGHT *et al.* (1991) described a zonation on storm-dominated shelves by both regional and local weather system. BRAY *et al.* (1995) have proposed a detailed classification of sediment transport boundaries according to the continuity of sediment transport and to the temporal stability of process interactions. These authors have identified two types of cells:
(a) cell with fixed boundaries experiencing a historical stability of 20 to 100 years.
(b) cell with transient partial boundaries with a stability period lower than 20 years.

The five cells identified on the differential maps along the shoreface East of Dunkerque should fit the second type since they display transient boundaries and short-period stability. The long-term regional evolution of the coastal system is inferred by the comparison of old maps of Dunkerque coastal area. Since 1750, the width of the beach east from the Dunkerque decreased while the beach located to the west has been moving seaward (CORBAU *et al.*, 1993). These two sectors can thus be considered as cells with fixed boundaries experiencing a long-term stability.

Several examples of studies about littoral cell segmentation (STAPOR, 1973; KROON, 1994; LARSON and KRAUS, 1994; LEVOY, 1994) show that the cells occurrence depends on different factors such as littoral drift following refraction, and wave and sea-bottom morphology interaction. STAPOR (1973) first noticed a littoral segmentation into longshore drift compartments due to natural causes in the region of Panama City, Florida. MAY and TANNER (1973) proposed the concept of residual longshore drift cells following refraction. STAPOR (1983) identified from sediment and compositional data along the northeast Florida coast six distinct coastal segments which most probably experienced minimal communication. This was confirmed by computer simulation of wave-generated currents. The major drift cells stayed at the same general locations under both fair weather and storm conditions. STAPOR (1983) proposed that the cellular nature of the northeast Florida coast drift system was caused by refraction resulting from the low-to-moderate wave energy and the specific offshore bathymetry of the region.

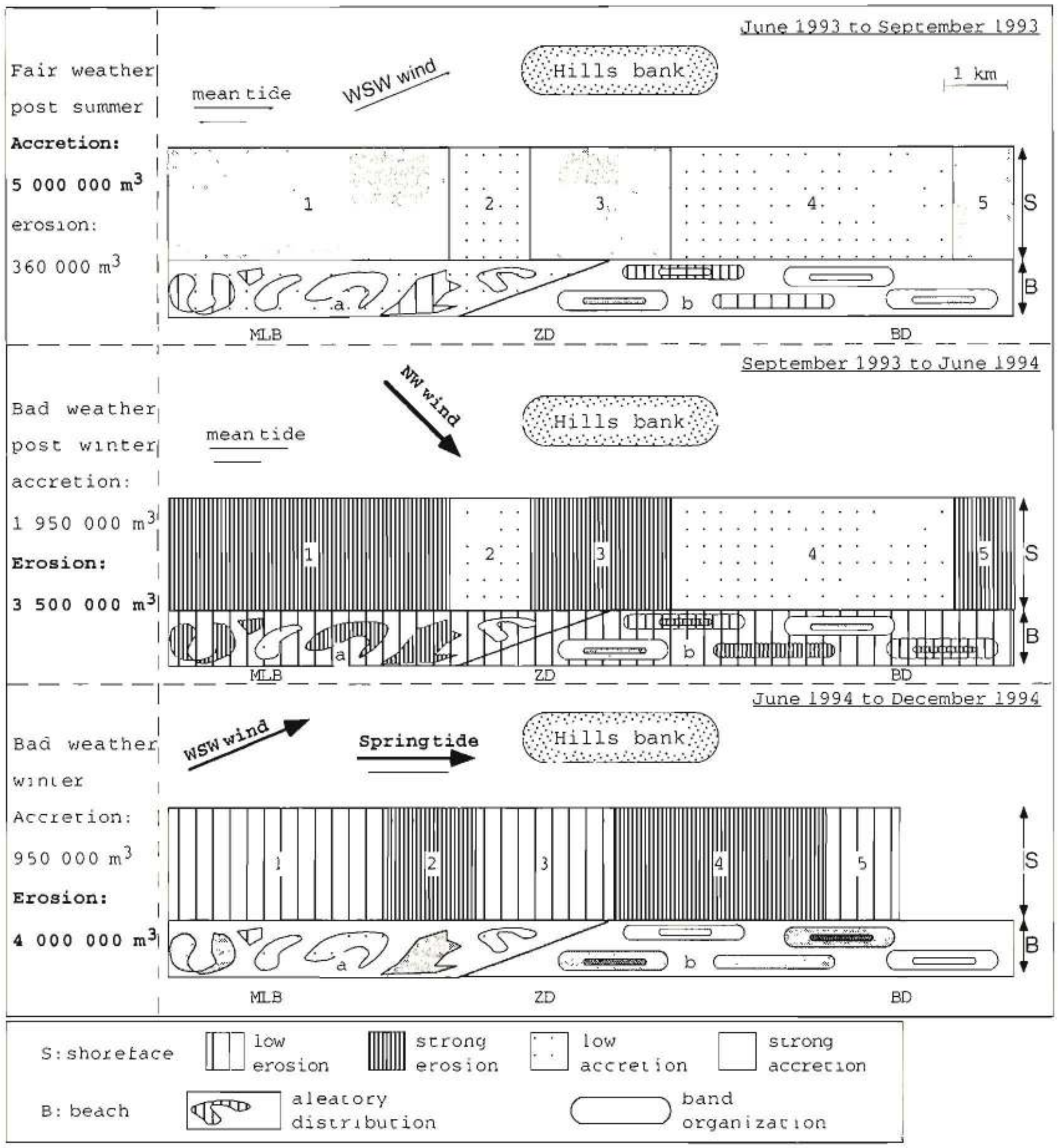

Figure 8. Major interpretations deduced from the differential maps (MLB) Malo-les-Bains, (ZD) Zuydcoote, (BD) Bray-Dunes, (S) Shoreface, (B) Beach.

Similarly, the cell segmentation of the East Dunkerque area can be interpreted as the result of wave and bottom interactions. The banks located off the area appear to be responsible for the deformation of wave propagation that generates a specific redistribution of wave energy along the coast. This fact has been simulated by the L.N.H. (PELTIER and LE SAUX, 1992) by using a wave refraction modelling (DHELLEMMES, 1989). For NNE-NNW incident waves, *i.e.* prevailing frontal waves, simulations display an alternation pattern of energy concentration and dissipation, which roughly fits the cell distribution. According to the wave refraction model, the morphological long-term (multi-annual) evolution of this shoreface appears to be characterized by the segmentation into the five cells cited above with two sectors displaying strong erosion. For WSW incident waves (*i.e.* shore parallel waves) the alternation disappears. This last simulation is consistent with field observations: during WSW winds and high tidal range, *i.e.* situation June 1994–Dec 1994 (Figure 7C) the cell boundaries were not clearly identified. These conditions seem to favour the sediment movement between the different cells.

Erosional Processes

The shoreface erosion observed during windy sea conditions is in agreement with the commonly cited seasonal pattern of evolution. Two modes of erosion have been deduced. From the differential map analysis the erosion developed either during N frontal wind conditions associated with mean tide (Sept 93–June 94) or during WSW wind conditions associated with spring tide (June 94–Dec 94).

First Mode. For a northern frontal wind, the predictive wave propagation model (PELTIER and LE SAUX, 1992) shows a wave concentration in two coastal sectors located in front of Malo-les-Bains and in front of Bray-Dunes. However erosion is significantly weaker in the second sector than in the first one. The harbour jetties of Dunkerque prevent the eastward longshore transport of sediment. A sediment deficit occurs close to the east of the harbour jetties, *i.e.* in the sector of Malo-les-Bains. This leads to significant erosion.

According to the wave propagation model, wave dissipation is predicted from Maritime hospital to Bray-Dunes. The Hills bank, located in front of Zuydcoote–Bray-Dunes, plays the role of a natural breakwater. The waves break over the crest, and thus their energy diminishes towards the shoreline. As a consequence the erosion due to wave is less efficient. A similar protection effect has been observed at Pacific Beach (Japan), where the nearshore bars protect the beach from erosion by acting as a submerged breakwater (TAKEDA and SUNAMURA, 1992).

Second Mode. The wave refraction model established for a WSW wind direction predicts an energy dissipation at the coast leading to a negligible erosion. Therefore we suppose that the strong erosion observed in front of Zuydcoote–Bray-Dunes sector is caused by the interaction of the spring tidal currents and the WSW wind. Sedimentological data seem to reinforce this interpretation (CORBAU, 1995). In the channel, the surficial sediments consist of fine to coarse-grained sand while the banks and the upper shoreface are exclusively composed of fine to medium-grained sand (see Figure 3). Considering this sedimentary distribution, we assume that the tidal currents constitute the dominant transport process in the channels and tend to converge toward the coast between Zuydcoote and Bray-Dunes where sediments are similar to those deposited on the channel. The WSW wind blows parallel to the flood tidal current which is consequently intensified. Thus during a spring tide stage associated with WSW wind, the flood current is therefore considered to be sufficently strong to induce measurable erosion.

To summarize, shoreface erosion occurs under two conditions: (1) during N frontal wind, and (2) during WSW wind associated with spring tidal currents.

Beach Evolution

Z-value changes are more uniform along the beach compared to the shoreface, with no clear differences in polarity and/or amplitude. The segmentation into five cells observed on the shoreface is not recognized on the beach domain. However the beach system can be divided into two main sectors: (1) east of Malo-Terminus, (2) west of this locality.

(1) East of Malo-Terminus, the distribution of the z-value is organized into bands parallel to the beach line. These bands reflect the ridge and runnel system that characterizes the local beach profile. The ridges are swash bars, which are built and migrate landward under the action of fair weather constructive waves. They are smoothed during storms (KING, 1972). Runnels are deepened by ebb tidal currents. The bands observed on the differential maps express these sediment movements, *i.e.*, the mechanisms responsible for the ridge system construction/migration/destruction.

The best organization is observed during the construction and migration of the ridges under fair weather conditions, or during the destruction of the ridges under storms. Ridge destruction was not observed as no severe storm occurred during the study period. Thus the differential maps characterizing fair weather conditions, *e.g.* the map established between June 1993 and September 1993, potentially displays the best band organization. However the best organization has been observed during the following winter (Figure 7c). During summer 1993, the waves were weaker and the sediment transport due to the wave action was probably slower than during winter period which was characterized by moderate wind and wave conditions inducing higher amplitude movements of the ridge and runnel system. This explains why the band organization is not clearly observed on the summer differential map.

(2) West of Malo-Terminus, bands have never been observed. The morphology of this beach is basically flat without pronounced ridges and runnels (Figure 3). This is attributed to the presence of breakwaters located on the lower foreshore which reduce the wave energy at the shoreline and provide a sheltered coastward area (KOMAR, 1976; HORIKAWA, 1988) within which a ridge and runnel system can not develop.

To summarize three main patterns of z-values evolution are deduced from the differential maps analysis:

(1) After a summer fair weather period with WSW winds and moderate tidal range (differential map from June 1993 to September 1993), the bands related to the ridge and runnel system are not well expressed. We therefore assume that these conditions favour the beach stability with limited processes of construction and migration of ridge and runnel.

(2) After a winter weather period with frontal wind (heavy swell) and medium tidal range (differential map from September 1993 to June 1994), the bands related to the ridge and runnel system are morphologically well expressed. The general negative budget related to this situation probably reflects the erosional trend that occurs during winter. However, the well developped bands show high amplitude movements of the ridge and runnel system induced by the action of frontal winds.

(3) After a wavy period marked by WSW winter winds and spring tides (differential map from June 1994 to December 1994), the "ridge and runnel" related bands are discernable but of reduced length and height. The differential map demonstrates that beach accretion is not necessarily related to the reconstruction of a given ridge after winter storms. The global accretion of the beach domain seems to have been favoured by tide dominated processes instead of constructive wave action. Moreover the shorter ridge bands probably reflect a deepening of runnel and rip channels under the action of strong ebb currents related to spring tides. In such a scheme the ridges have effectively been constructed under these wave conditions (WSW wave regime), but were subsequently shortened because of tide-induced conditions (spring tide). Low amplitude z-value changes reflect a low ridge mi-

gration rate, which is attributed to oblique incident waves superimposed to a relatively strong component parallel to the shore. This interpretation is consistent with observations made on the first differential map (June 1993–September 1993).

Relationships Between the Shoreface and Beach Evolution

The morphological cells identified from the differential map analysis along the shoreface show several variations depending on hydrodynamic and meteorological conditions. By contrast the beach domain can hardly be divided in two morphological cells and moreover shows sediment movement occasionally opposite to that affecting the shoreface system during the same period. This fact demonstrates the wide spatial and temporal variability of the sediment movements and the diversity of the processes acting along the coastal system.

This variability has both a longshore and a cross-shore component. The longshore component along the shoreface (*i.e.* segmentation into five cells) is attributed to the wave energy distribution along the coast. This distribution shows an alternating zonation of 1) energy concentration inducing erosion and 2) energy dissipation inducing accretion. Such a zonation is assumed to essentially depend on the banks located off the area that induce wave deformation.

The longshore component along the beach (*i.e.* segmentation into two cells) is assumed to be due essentially to human factors (breakwaters) that prevent the full development of natural ridge and runnel system.

The mechanisms and causes of the cross-shore transportion between the shoreface and the beach domains are still poorly understood but the onshore-offshore sediment exchanges extending beyond the surf zone account for both low frequency and large amplitude fluctuation in the volume of beach sand (ANTHONY, 1990; WRIGHT *et al.*, 1991). CLARKE and ELIOT (1988) think that long term, low frequency changes, largely result from an onshore-offshore exchange between the beachface and the inshore zone. Some assumptions on the mechanisms responsible for cross-shore sediment transport have been proposed by WRIGHT *et al.* (1991) who suggest a significant contributions by incident waves, long-period oscillations, medium flows and gravity. However the shoreface may act as a major sedimentary source for the beach domain. KOMAR (1976) explains that sediments may be occasionally eroded from unconsolided offshore sources on the continental shelf and drifted shoreward and onto the beach. The banks may also serve as sand sources. For example in 1645 the attachment of the Schürcken sandbank in the Dunkerque Malo-les-Bains area provided a sand supply to the beach (LAHOUSSE *et al.*, 1993). Presently the swell action maintains a coastward progression of subtidal sandbanks at an average rate of 1 to 5 m/y (CORBAU *et al.*, 1993), part of the removed material being probably transported eastward in the access channel under the action of the tidal current. Moreover this potential sand supply to the beach provided by the landward migration of the banks is artificially limited due to dredging for maintaining the channel depth necessary for the ship access to Dunkerque harbours. In the present study, a cross-shore transport has been observed: the shoreface erosion that occurred between June 1994 and December 1994 has probably favoured the sedimentary accretion on the beach.

An additional question arises from the differential map analysis: Why does not the cell segmentation of the shoreface exist on the beach?

We suppose that the short-term longshore component is more efficient than the short-term cross-shore component. Indeed the wave action increases landward as the tidal action decreases. If the segmentation was due to the wave and bottom interaction we should expect to observe the same segmentation on the beach. A beach profile survey made on the same area (CORBAU, 1995) displays a spatial and temporal variability of the beach evolution which is in accordance with the segmentation observed on the shoreface.

Another explanation for the absence of cell segmentation on the beach could consist in the interaction between human and natural factors. During low energy conditions, characterized by small sedimentary movements, it has been demonstrated that the harbour jetties and breakwaters deeply disturb the action of natural factors on the beach. As a result no clear segmentation is observed on the beach. In that conditions, during high energy conditions, natural factors become predominant and the beach would displays a segmentation into hydrosedimentary cells.

CONCLUSION

The study area is a low-relief sandy coastal system of about 30 km in length, with a WSW–ENE orientation, characterized by wide beaches and gently sloping shoreface the main morphological features of which consist of elongated banks and channels parallel to the coastline. West of Dunkerque the coast comprises a 15 km-long industrial and harbour zone, and to the east an alternation of natural and urbanized zones. The macrotidal and highly variable wind regime typifies this area as a mixed environment submitted to moderate energy waves and strong tidal currents parallel to the coast. The flood is dominant and determines a net eastward sediment transport.

Topographic and bathymetric surveys were performed by the National Laboratory of Electricité de France and by the EUROSENSE society from May 1992 to September 1996. Comparative differential maps were elaborated and examined in order to understand the sediment movements in this coastal area and to determine their causes, according to meteorological and hydrodynamical conditions. During the study period, these conditions were quiet to moderately active and no strong storm was observed. The differential maps allowed to investigate the effects of 1) moderate tide during fair weather condition, 2) moderate tide with moderate frontal wave (heavy swell) and 3) high tidal energy with moderate wind wave parallel to the coast.

The net sedimentary budget was a slightly positive. This general result stresses the role of major events, such as storms, to induce significant negative (erosional) budget. Two types of conditions favour erosional processes: (1) frontal waves and (2) combinations between strong tidal currents and wind blowing in the same direction reinforcing the tidal energy. This second mode appears to induce erosion of shoreface whereas beach experience accretion.

Sediment movements along the Dunkerque system define a cell segmentation: five distinct cells are differenciated on the shoreface domain at a time where the beach domain is divided in two main sectors. The potential mobility of these sectors points to the large space and time variability of sediment processes prevailing along the Dunkerque coast. The shoreface cell segmentation is assumed to result from frontal wave energy redistribution in interaction with bottom morphology, in particular that of the banks. Such longshore variability expressed by the five cells along the shoreface is thought to also affect the beach system. However sediment movements on the beach are strongly influenced by human factors and especially by the installment of breakwaters located in a local sector. Their influence is probably responsible for segmentation into two cells. Cross-shore movements deduced from the maps by comparison between shoreface and beach responses appear to be of relative low importance relative to longhshore transports, but additional hydrodynamical data is required to better test this interpretation. It seems that the present-day moderate conditions that commonly characterize the coastal system tend to favour a slow, long-term transfer of sediment from the shoreface to the beach.

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