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Short-term beach–dune sand budgets on the north sea coast of France: Sand supply from shoreface to dunes, and the role of wind and fetch

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Abstract

Three experimental plots, covering the transition from the upper beach to the dune, on the North Sea coast of France were monitored at various intervals over a period of 18–24 months via high resolution terrain surveys in order to determine inter-site sand budget variability, as well as patterns and processes involved in sand exchanges between the upper beach and dune. The wind regime consists of a fairly balanced mix of moderate (80% of winds are below 8 m/s) onshore, offshore and shore-parallel winds. Sustained dune accretion over several years depends on the periodic local onshore welding of shoreface tidal banks that have developed in the storm- and tide-dominated setting of the southern North Sea. The only site where this has occurred in the recent past is Calais, where bank welding has created a wide accreting upper beach sand flat. At this site, significant sand supply from the subtidal sand bank reservoir to the upper beach flat occurred only once over the 18-month survey following a major storm. The bulk of the sand deposited over this large flat is not directly integrated into the adjacent embryo dunes by onshore winds but is progressively reworked in situ into developing dunes or transported alongshore by the balanced wind regime, thus resulting in alongshore stretching of the embryo dune system. The Leffrinckoucke site near Belgium shows moderate beach–dune mobility and accretion, while the Wissant site exhibits significant upper beach bedform mobility controlled by strong longshore currents that result in large beach budget fluctuations with little net budget change, to the detriment of the adjacent dunes. Accretion at these two sites, which are representative of the rest of the North Sea coast of France, is presently constrained by the absence of a shore-attached sand bank supply reservoir, while upper beach–dune sand exchanges are further limited by the narrow wave-affected upper beach, the intertidal morphology of bars and troughs which segments the aeolian fetch, and the moderate wind energy conditions. The balanced wind regime limits net sand mobilisation in favour of either the beach or the dune, and may explain the relatively narrow longshore morphology of the dune ridges bounding this coast.

Keywords: Beach–dune exchanges; Aeolian sand transport; Fetch length; Winds; North Sea coast; Shoreface sand banks

1. Introduction

Beach–dune interfaces are characterised by sand exchanges that depend on a wide range of environmental parameters (Nickling and Davidson-Arnott, 1990;

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Bauer and Davidson-Arnott, 2002; Davidson-Arnott, 2005; Davidson-Arnott et al., 2005). Chief among these are sand availability and the wind conditions (speed and direction) necessary for transporting available sand. Intervening factors that may modulate sand transport by wind include the intrinsic properties of beach–dune interfaces such as microscale topography, vegetation cover, moisture content, and extrinsic factors such as surrounding morphology and storm wave impact on the upper beach and dune front. The complexity of these factors renders dune budget change predictions based on empirically formulated combinations barely reliable over very short timescales of minutes to hours (Sherman et al., 1998), and extremely tenuous when extrapolated to longer timescales (Davidson-Arnott and Law, 1996; Davidson-Arnott et al., 2005). One way of circumventing the problem of beach–dune sand budget estimates at timescales ranging from days to years is through instrumented field surveys and photographic and remote sensing techniques that enable regular monitoring of beach–dune topographic change (Psuty, 1988; Davidson-Arnott and Law, 1990; Arens, 1994; Davidson-Arnott and Law, 1996; Davidson-Arnott, 2005). Terrain modelling has been used over the past few years to generate dune budget changes over short (order of days) to medium (order of months to a few years) timescales. Examples include very high resolution ground surveys using total electronic stations (Arens, 1997; Andrews et al., 2002; Vanhée, 2002; Ruz and Meur-Ferec, 2004) and airborne LIDAR surveys (Woolard and Colby, 2002; Saye et al., 2005). Budgets generated in this way may not only be useful in quantifying potential sand gains or losses by dunes, but may also highlight processes and patterns of sand dispersal within dune and beach–dune systems. They may, additionally, be used to assess the efficiency of dune rehabilitation measures (Vanhée, 2002), and could thus be an essential tool in coastal dune management.

The aim of this paper is to synthesise data on upper beach–dune sand budgets from experimental plots at three sites on the North Sea coast of France (Fig. 1) exhibiting contrasting overall morphological situations, and surveyed from 1999 to 2001. The results provide a basis for a discussion of the local and regional controls involved in imparting inter-site variability in net budget trends and in influencing upper beach–dune sand exchanges at each site, notably marine sand supply and wind (fetch) conditions.

2. Study area

The North Sea coast of France from Cape Gris Nez to Belgium (Fig. 1) is characterised by 300–600 m wide intertidal bar-trough (ridge-and-runnel) beaches backed by aeolian dunes. This north-facing coast consists of transverse dunes forming a single linear ridge 100–1000 m wide and with a maximum inland height of

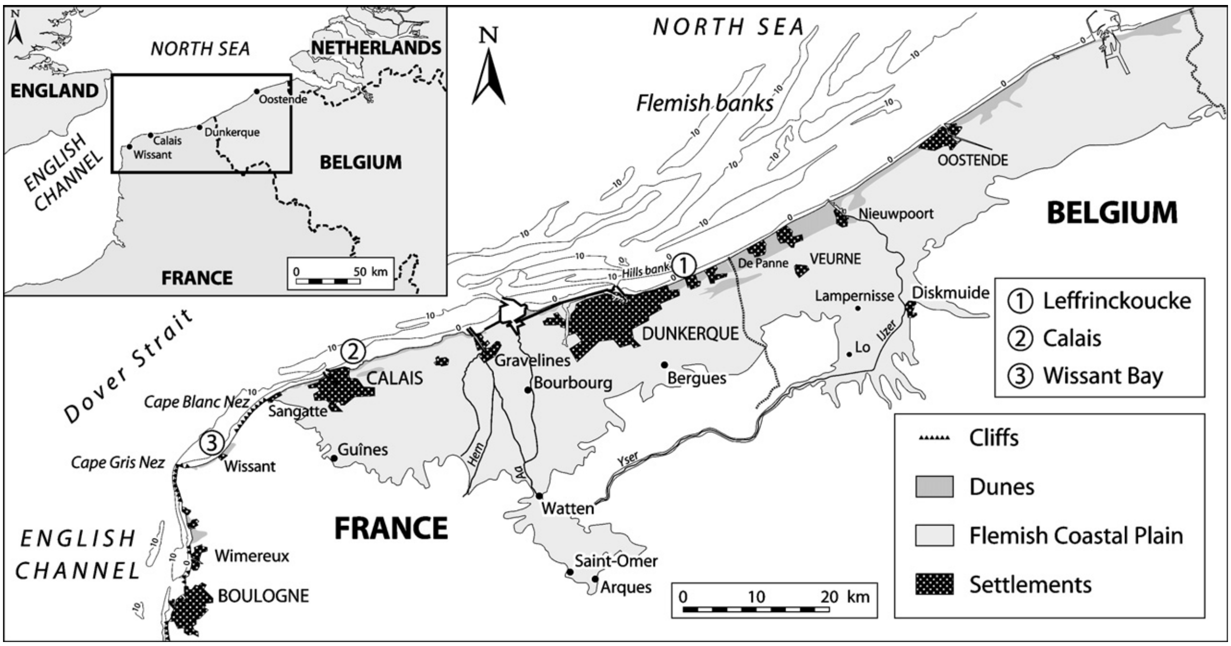

Fig. 1. The narrow linear dunes of the North Sea coast of France bounding the large Flemish Coastal Plain. The shoreface comprises abundant tidal sand ridges and banks. Dots with numbers refer to locations of survey sites.

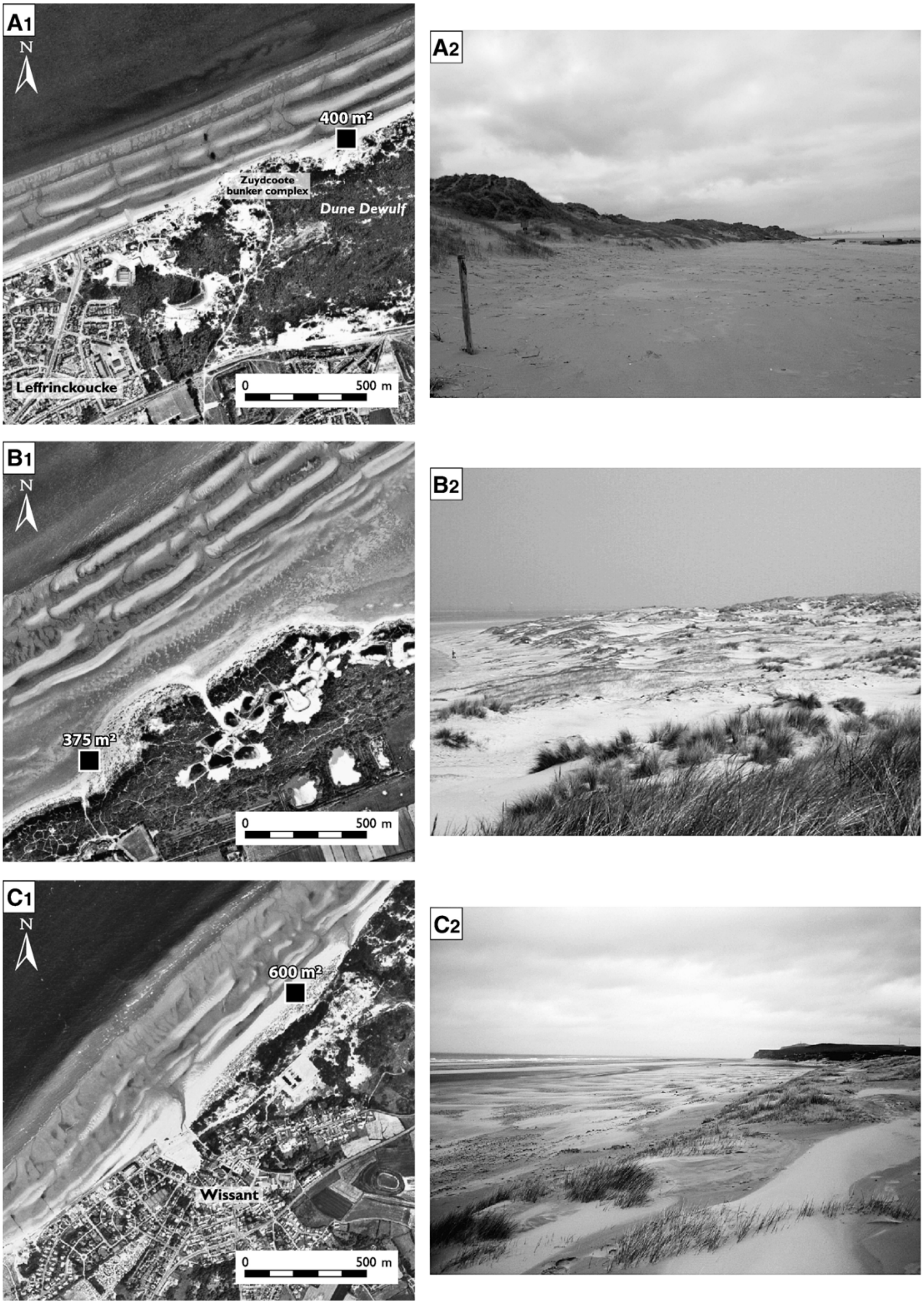

Fig. 2. Aerial and ground photographs of the three monitored sites. (A) Leffrinckoucke; (B) Calais; (C) Wissant. Note the marine bedforms on the upper beach in Wissant. Boxes with numbers indicate survey plot locations and sizes.

25 m. Two ridges of this type have developed, respectively between Cape Gris Nez and Cape Blanc Nez, and from Calais along the southern North Sea as far as the Netherlands (Fig. 1). In France, the dunes in this latter sector bound the sand-rich empoldered Flemish Coastal Plain, and have been massively transformed or obliterated by urban and port development. The dominant winds affecting this coast are from south to west–southwest (38–40%), north to northeast (19–22%), and southeast (12–14%). Offshore winds represented by the south to west–southwest and the southeast windows are, thus, largely dominant.

The abundant accumulation of fine sand on these coasts is the product of large-scale tide-dominated hydrodynamic circulations in the English Channel that have gradually sorted the heterogeneous sea-bed sediments that accumulated under past changing sea-level and land drainage conditions (Anthony, 2002). These deposits have been sourced solely by sand from the adjacent beds of the eastern English Channel and the North Sea, which exhibit numerous tidal ridges, relict and presently active sand banks, collectively named the Flemish banks (Fig. 1), as well as several wave- and tide-driven sand transport pathways, including coastal

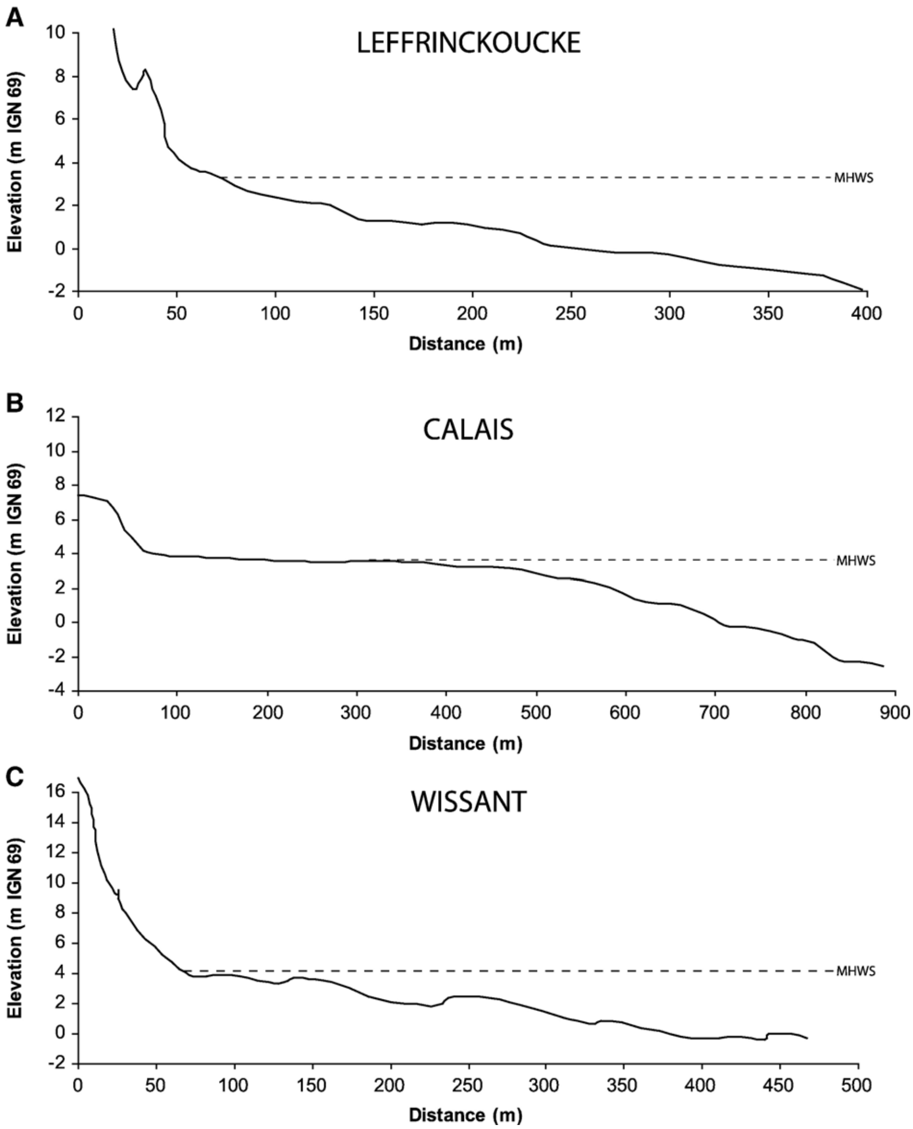

Fig. 3. Representative beach topographical profiles showing bar-trough morphology and the upper beach–dune contact. MHWS = mean high water spring tide level.

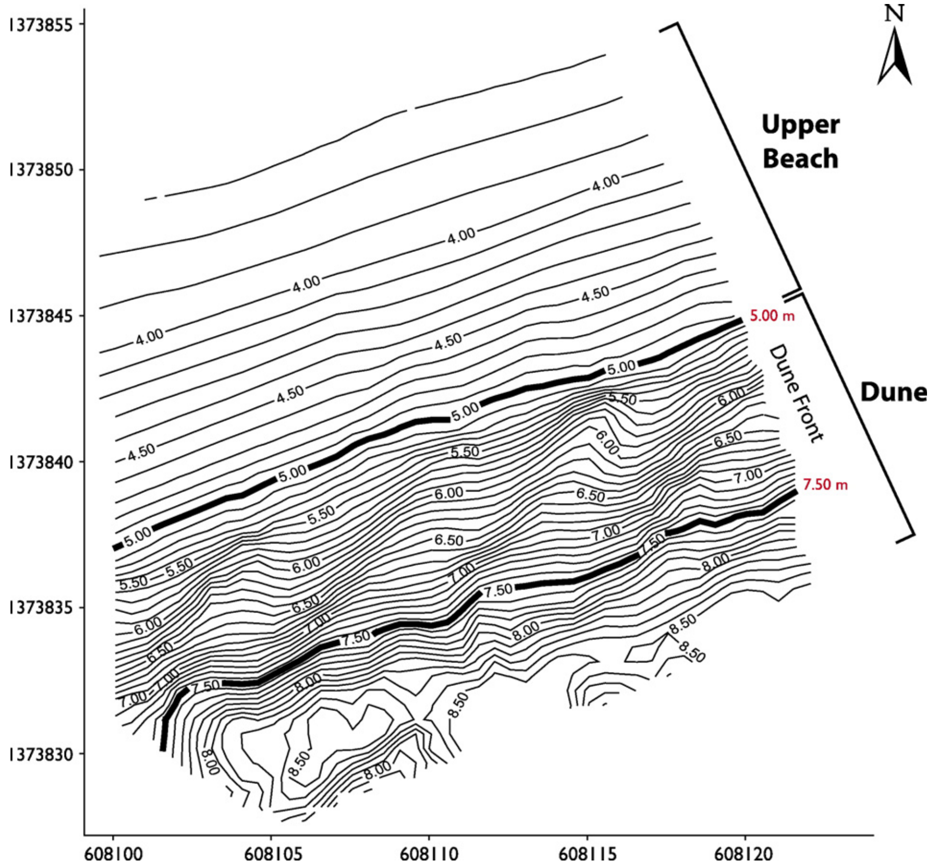

Fig. 4. Typical DEM segmentation of the survey plots between upper beach and dune.

pathways (Anthony, 2000, 2002). The coast is exposed to fetch-limited, relatively low-energy waves punctuated by storm activity, and experiences tidal ranges of 5–8 m at spring tides. Storms may force up to 1 m of surge above high-tide swash excursion levels. The combination of storm winds and waves and large tidal ranges also generates strong longshore currents that affect both the shoreface and the beaches of the southern North Sea (Anthony and Orford, 2002; Reichmüth, 2003; Sedrati and Anthony, 2005). A number of recent studies suggest gross stability of the beach–dune system (Clabaut et al., 2000; Vasseur and Héquette, 2000; Ruz et al., 2005), which presently functions under conditions of rather limited sand supply from the shoreface in spite of the abundant stocks of sand locked up in the shoreface tidal ridges and banks (Anthony and Héquette, 2005). Mild dune scarping in winter is often followed in spring and summer by limited embryo dune formation. Locally, however, sand banks progressively driven onshore by repeated storms become welded to the shore, resulting in significant accretion followed by aeolian dune development (Garlan, 1990), as in Calais (Fig. 1). Such onshore welding of shoreface banks is considered as the prime mode of shoreline sand supply (Anthony, 2000) and explains the rather irregular pattern of shoreline accretion of this mixed storm- and tide-dominated coast.

Three field sites were selected for this study (Fig. 2). The Leffrinckoucke site is located east of the highly urbanised area of Dunkerque (Dunkirk). The foredune ridge in this area (Fig. 2A) was seriously damaged at the beginning of the 20th century by urban development, and almost completely destroyed during World War II. In the 1980s, the 10–20 m high semi-vegetated foredune was affected by blowouts and by erosional scarps cut by storms. The dunes are presently in a state of medium scale (order of 10–20 years) stability, attributed in part to human intervention (Ruz et al., 2005). Active rehabilitation carried out in the early 1990s has resulted in mild accretion and incipient foredune development in places. The dune front still shows the effects of past erosion; various blockhouses built during World War II now lie on the beach. The beach exhibits a barred intertidal morphology comprising several sets of bars and troughs linked to a relatively narrow upper beach

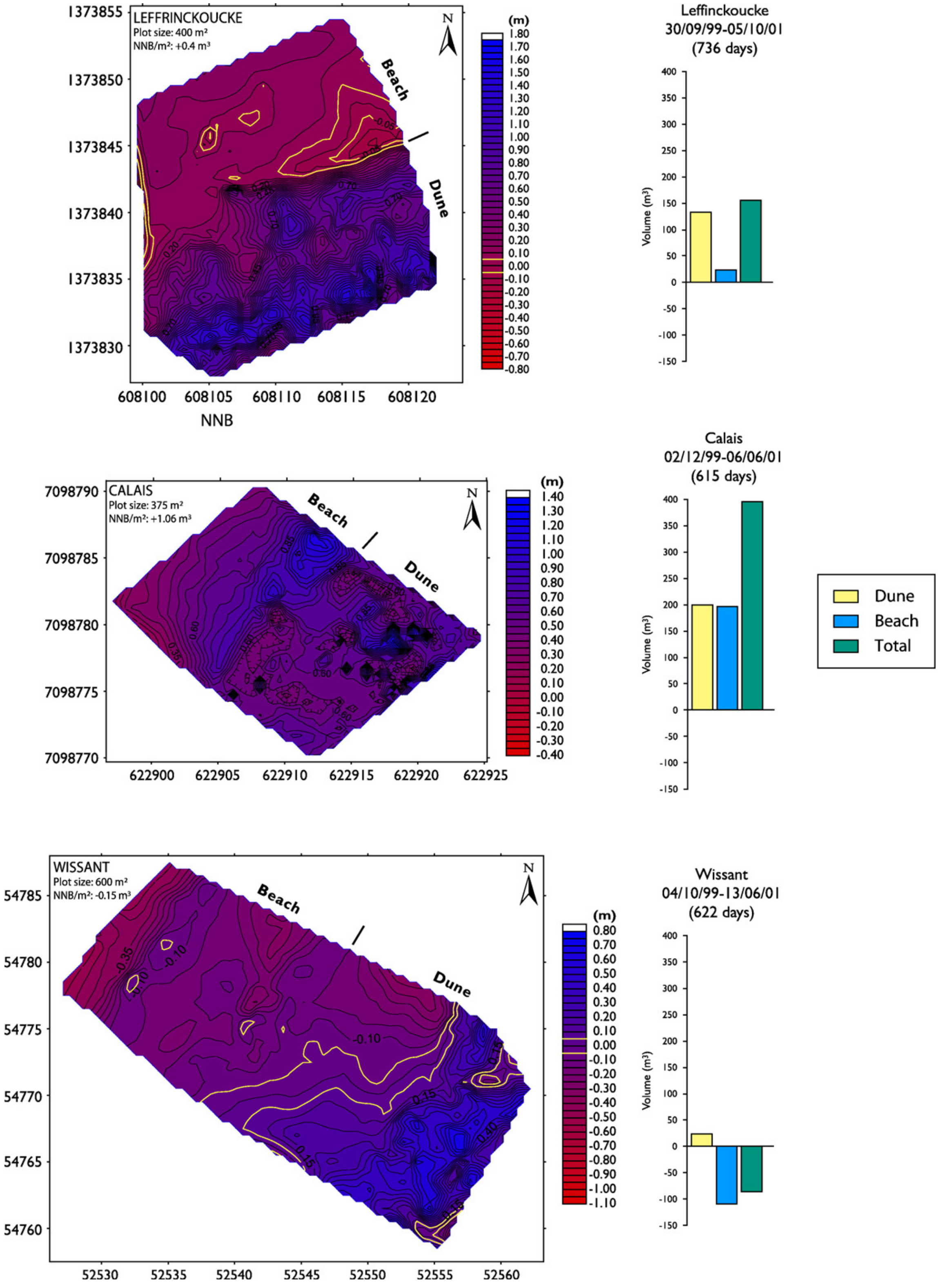

Fig. 5. Net DEM budget changes, and histograms of net budget changes for the three survey plots. NNB = normalised net budget, obtained by dividing survey plot size by budget volume change.

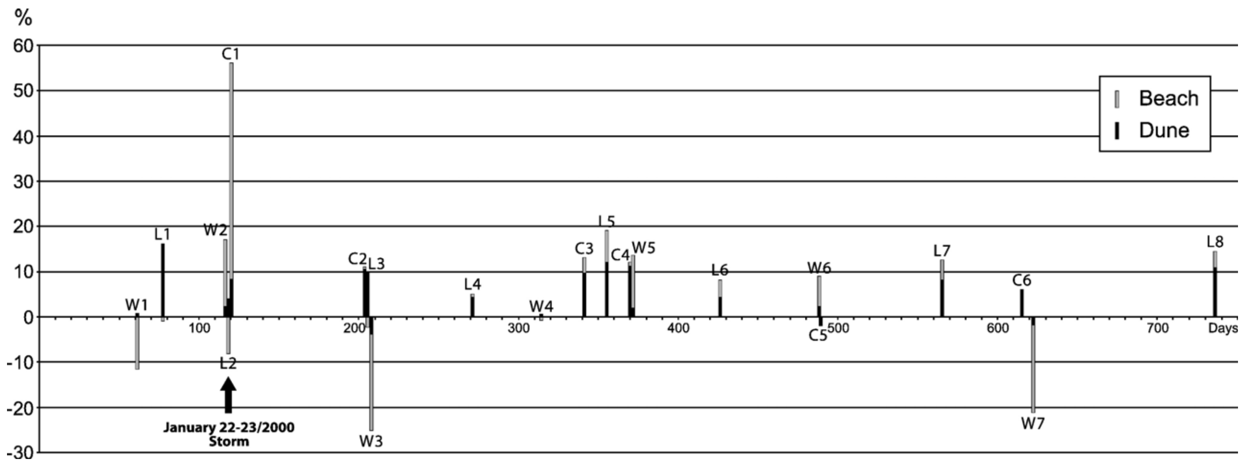

Fig. 6. Contributions of the upper beach and dune to budget mobility at each site, expressed, for each survey, as a percentage contribution to the cumulative (100%) budget change (+ and −) over the 2-year survey (30/09/99–05/10/01). Numbered letters refer to successive surveys at each site (L = Leffrinckoucke, C = Calais, W = Wissant), starting from the initial state 0 at each site. Note the significant contribution of beach change following the most important storm event over the survey period (surveys C1, L2, W2), and the strongly beach-dominated changes in Wissant.

zone adjoining a fairly steep dune front (Fig. 3). The beach in Leffrinckoucke is partly protected from storms by the most shoreward of the shoreface sand banks in this sector, the Hills bank, the crest of which is exposed at spring low tides.

The Calais site (Fig. 2B) is one of the rare actively accreting sectors of coast in the extreme north of France. Accretion has occurred through the active accumulation of longshore-coalescing embryo dunes that form a low-lying platform consisting of constantly reworked hummocks of sand colonised by a sparse cover of marram grass. The platform is linked seaward, via a gentle dune front, to a sand flat 300–500 m wide (Fig. 3) associated downslope with a classic bar-trough beach. The recent accretion in Calais has been attributed to the onshore migration, over the twentieth century, of a tidal sand bank that has welded onto the coast, leading to the accumulation of a shore-attached sand reservoir of 400,000 m^3 in nearly 80 years (Garlan, 1990) and in the formation of the large upper beach sand flat fronting the dunes. Much of this flat, located at about mean spring high tide level (Fig. 3), serves as a swash depocentre, especially during storms, and the rest of the time as a combined fetch, deflation and accretion surface for aeolian dune growth. Field observations over the last 5 years show that the innermost parts of the flat serve as a basement for embryo dune development.

Wissant Bay (Fig. 2C) forms a well-defined single longshore sediment transport cell between Capes Gris Nez and Blanc Nez. The southwestern and central parts of the Bay form an updrift erosional sector that feeds a downdrift sand sink in the northeast characterised by significant foredune growth and the active formation of embryo dunes. The updrift source zone is the most rapidly eroding sector of coast in France, with retreat of the dune front of over 100 m in the last 80 years. The reasons for the onset of dune erosion in this once stable area are still unclear. They seem to involve interactions between offshore sand bank development, longshore sand transport in the coastal corridor of which this bank is a part, and the activity of current gyres (Anthony and Dolique, 2001) related to the projecting headland of Cape Gris Nez. The aeolian dunes updrift have been retreating actively, releasing sand which is then transported alongshore by strong combined wave-, tide- and wind-induced currents along the intertidal and subtidal zones, and by shore-parallel aeolian transport in the upper beach and dune front sectors, towards the sink zone in the northeast. The surveys at this site were carried out in the transitional zone between the updrift source and the downdrift sink zones of the Wissant Bay sediment cell. As at Leffrinckoucke, the dunes are fronted by a narrow upper beach linked downslope to a barred intertidal beach (Fig. 3). Unlike the previous two sites, strong marine bedform development is commonly observed on the upper beach (Fig. 2C), which is also topographically lower than that of the other two sites, being well under the spring high tide level (Fig. 3).

The upper beach and dunes at the three sites are characterised by fine to medium, well to very well-sorted quartz sand (D_{50} = 0.17–0.31 mm). The sand tends to be slightly coarser and less well sorted on the upper beach. In Calais, wind winnowing of fine sand from the upper beach flat creates in places a surface sandy lag deposit rich in coarse sand-sized shelly debris.

3. Methods

Three plots were monitored, one in each site. The sizes of these plots are indicated in Fig. 2, and were a compromise between the following conditions: the necessity of covering the transition from the upper beach to the dune, high density sampling for maximum accuracy, and surveys at regular intervals. Beach–dune topography was surveyed using a very high resolution laser electronic station with errors within ±3 mm for distance and height and ±0.0015° for direction. Digital elevation models (DEMs) were generated from these surveys using standard terrain modelling software based on point interpolation techniques. Sampling using electronic stations is time-consuming but yields very accurate results when sampling density is high, a condition for reliable sediment budget calculations (Andrews et al., 2002). Given the number of surveys (6 in Calais between 02/12/99 and 06/06/01, 7 in Wissant between 04/10/99 and 13/06/01, and 8 in Leffrinckoucke between 30/09/99 and 05/10/01), each DEM grid database was generated from a dense cover of points spaced 2–4 m apart. An empirically derived error margin of 5 cm, covering both field measurement and interpolation, was applied to the raw data. The results reported in the following section include this error margin. For this set of experiments, the DEMs were segmented into the two main morphological units, dune and beach (Fig. 4), using the DEM contours of the initial survey marking the foot of the dune. The overall wind conditions that prevailed over the survey period were determined from MétéoFrance wind records from stations nearest to the study sites (Fig. 1): Dunkerque (8 km west of Leffrinckoucke), Calais (5 km west of the survey area) and Boulogne (25 km south of Wissant).

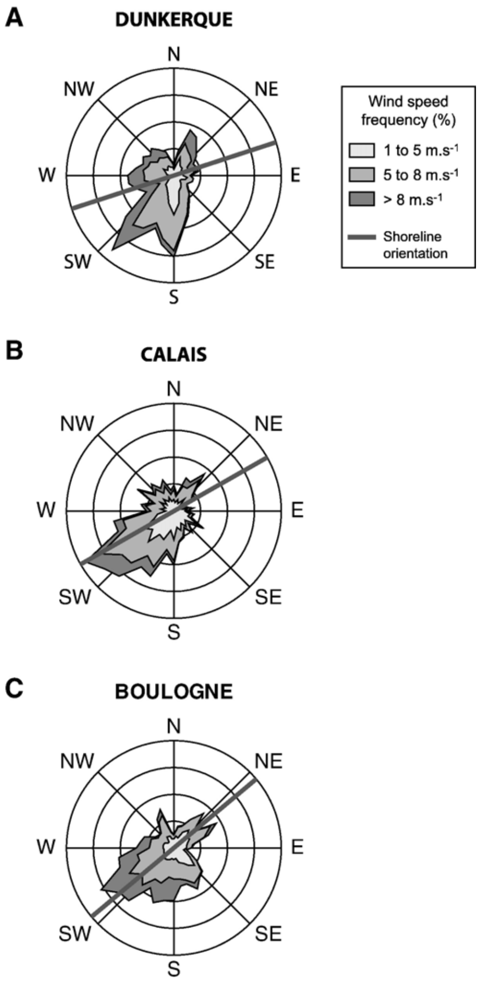

Fig. 7. Winds conditions for nearby weather stations over the 2-year survey period. Each circle represents two percent of the overall total over the survey period. NB: the shoreline orientation in the Boulogne data refers to that of the Wissant survey site.

4. Results

The overall data for the three sites are summarised in Fig. 5. Leffrinckoucke showed a net sand gain of 157 m^3, of which 85% was captured by the dune and 15% by the beach, while Calais experienced a total accretion of 400 m^3, of which 220 m^3 (55%) was accounted for by the upper beach. Wissant underwent a net sand loss of 90 m^3. The beach and dune showed opposite behaviour at this site, the former undergoing a net erosion of 110 m^3, while the latter registered a net gain of 21 m^3. Nearly 85% of the budget change was thus accounted for by the beach. In order to compare the sites, the net budget change at each site has been normalised by dividing survey plot size by the net budget change (Fig. 5). Although the Calais survey site was only slightly larger than half that of Wissant, and only 90% that of Leffrinckoucke (Fig. 2), it showed a much greater normalised net accretion of 1.06 m^3, compared to 0.4 m^3 in Leffrinckoucke and a net loss of 0.15 m^3 in Wissant.

A measure of the degree of morphological mobility is given by the cumulative gross change (gain and loss) over the successive surveys, relative to the net overall budget change. Although Wissant experienced the smallest net budget change, this site showed the greatest overall gross mobility, attaining nearly 1350 m^3 over the 7 successive surveys, largely dominated by the upper beach (84%). However, when considering such overall gross mobility, it must be noted that the larger size of the Wissant survey plot theoretically favours greater cumulative mobility. The 'normalised' mobility at this site attained 2.25 m^3. With a value of 270 m^3 for

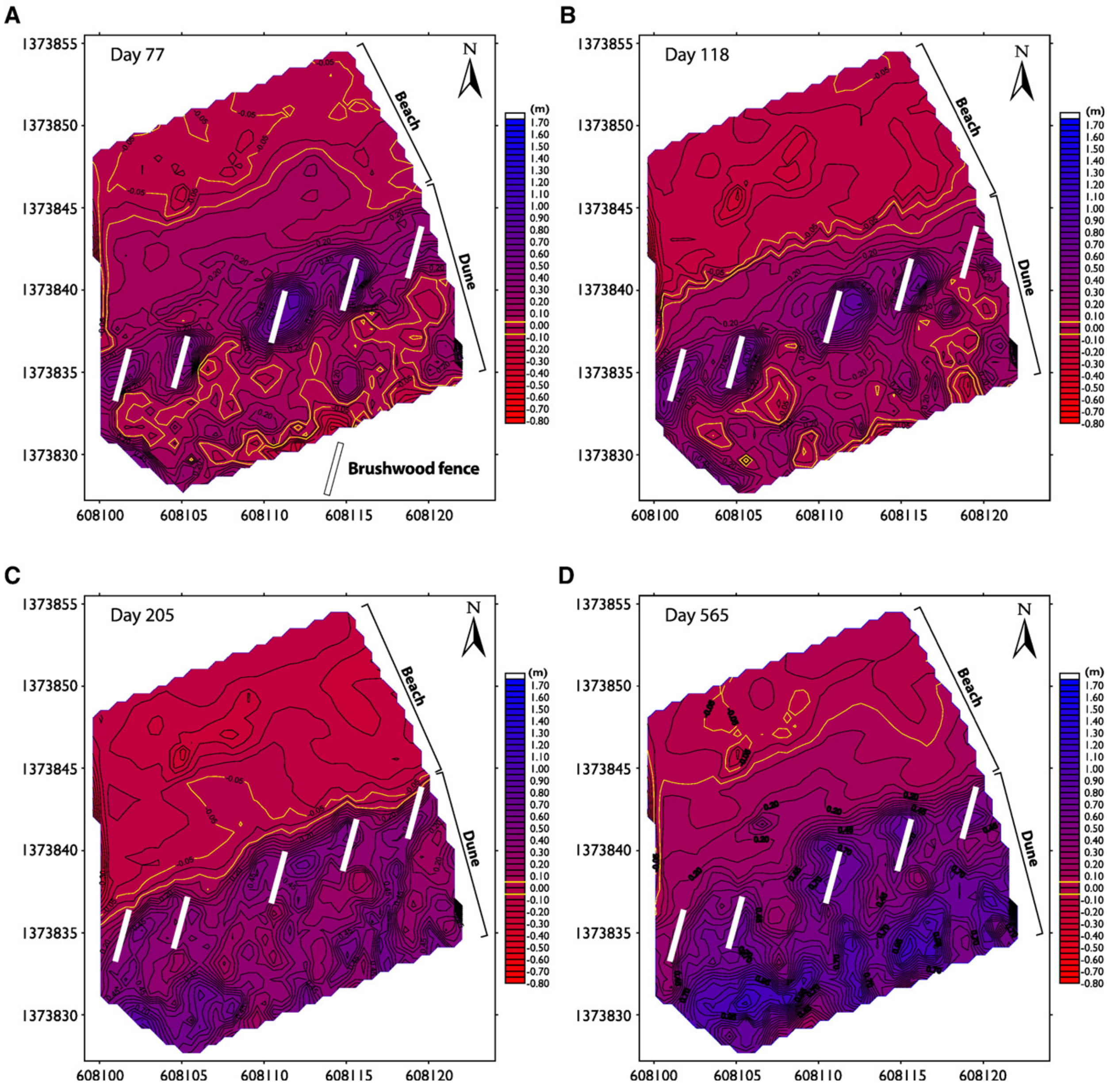

Fig. 8. DEMs of the Leffrinckoucke site, showing the rapid initial accretion of distinct hummocks induced by brushwood fences.

8 surveys, of which 70% was accounted for by the dune, Leffrinckoucke exhibited the least mobility (0.68 m^3). The gross mobility in Calais (450 m^3 for 6 surveys, thus yielding a 'normalised' mobility of 1.2 m^3) slightly exceeded the net sand budget change of +400 m^3, and was dominated by the beach (51%). The Calais site, smallest of the three survey plots, thus evinced 'efficient' budget mobility compared to the other two sites, especially Wissant, where the large upper beach mobility was accompanied by rather moderate net budget change. Budget differentials expressed as percentage contributions of each DEM survey to the overall net change for the upper beach and dune are shown in Fig. 6. The surveys show a concentration of budget change essentially within survey C1 (Fig. 6) in Calais, and budget change spread over the various surveys in Leffrinckoucke and especially Wissant (Fig. 6). The implications of these trends are discussed in the next section.

In Leffrinckoucke much of the initial accretion, in the form of distinct hummocks, involved the dune front followed by more generalised accretion affecting the dune surface and leading to the coalescence of the earlier hummocky topography. During the first three surveys, the beach showed a weakly negative budget, but picked up over the remaining surveys. Overall, significant accretion characterised the summer 2000 period (survey L5, Fig. 6). In Calais, the upper beach flat exhibited strong initial accretion, and then more or less stabilised afterwards, while the embryo dunes underwent progressive mild accretion (Fig. 6). Accretion in these two units occurred separately during the first five surveys as they were separated by a mild deflation corridor that was finally eliminated by coalescent accretion of both the upper beach and the embryo dunes. In Wissant, the overall trend is a highly fluctuating one throughout the survey period (Fig. 6). In Leffrinckoucke and Calais, a significant proportion of the overall beach change occurred in just under 30 h during the only significant storm event (22–23 January, 2000, peak wind speeds of 14 m/s) over the survey period, characterised by strong onshore winds (NE). This event led to an important upper beach deficit in Leffrinckoucke (survey L2 in Fig. 6), but to significant upper beach accretion in both Calais (survey C1, Fig. 6) and Wissant (survey W2, Fig. 6). In Calais, the upper beach accretion following this storm led to the emergence of hummocks of embryo dune over the inner parts of the upper beach flat. Thus, although the beach and dune budget changes at this site are treated as separate quantities, embryo dune development at this site was also generated in situ within the upper beach flat. The underlying mechanisms will be discussed later.

The wind conditions that prevailed over the survey period were typical of longer term conditions (Fig. 7), dominated by moderate velocities (5–8 m/s). A threshold of wind velocity above 8 m/s, considered as a reasonable limit above which significant aeolian transport may occur, given the humidity and roughness constraints in the study sites (humid upper beach, semi-vegetated hummocky dune topography), has been used in order to class wind orientation relative to the shoreline in each of the three sites using three categories: offshore, onshore and shore-parallel. Winds exceeding 8 m/s accounted for 22.5% of the regime in Dunkerque, 13.5% in Calais, and 21% in Boulogne. The weaker proportion of significant winds in Calais may be attributed to the more inland location of the weather station compared to the other two sites, distant by 60 km, but having practically the same proportion. Strong winds (>12 m/s), dominantly from southwest, were rather uncommon, ranging from 3.8% in Boulogne to 1.2% in Calais. When only the >8 m/s category is considered, offshore winds over the 2-year survey attained 7.7% in Dunkerque and Boulogne, and 5.7% in Calais. Onshore winds in this category were more frequent in Dunkerque (9.8%) but slightly less frequent in Calais (4%) and Boulogne (6.7%). Shore-parallel winds attained 4.2% in Calais, 5.1% in Dunkerque and 6.6% in Boulogne.

5. Discussion

5.1. The role of marine sand supply

The underlying fundamental control exerted on aeolian dune development on many coasts by sand supply from the shoreface has been emphasised recently (Aagaard et al., 2004; Anthony and Héquette, 2005). Large stretches of the dune coast bordering the North Sea in France appear to be in a state of medium scale (decades) stability. In a few areas, dunes show mild but chronic erosion. This suggests a presently limited potential for sand supply from the shoreface, notwithstanding the abundance of fine sand in this shoreface. Upper beach–dune accretion was much more important in Calais than at the other two sites (Fig. 5), the Calais area being the only portion of the North Sea coast where shoreface sand reservoir conditions are presently favourable to significant accretion. These sand supply conditions are not met in the Leffrinckoucke and Wissant areas, where potential foredune accretion is constrained. The upper beach–dune sand budget patterns shown by Leffrinckoucke and Calais are similar, in that their trends are dominated by net fluctuating accretion punctuated by the major storm event of 22–23 January 2000 (Fig. 6). In both sites, mild dune accretion occurred almost throughout the survey period, but the two sites differ in terms of upper beach accretion and subsequent dune development. The pattern in Wissant is much more variable, with a highly mobile upper beach subject to strong budget fluctuations.

A scrutiny of the beach–dune budget pattern in the Calais plot throws some light on the way sand is supplied from the shoreface to the upper beach, and hence the dunes. Although 55% of the net budget change recorded at this site was explained by the upper beach, nearly 48% of this overall change was accounted for by the single January 2000 storm event (survey C1 in Fig. 6). Field observations showed that this event led to significant aeolian mobilisation of sand across the upper beach flat at low tide, and to important swash deposition of sand at high tide, as the upper beach flat became flooded by the large spring tides combined with water level setup due to strong onshore winds. During the rest of the survey period, this sand flat exhibited little mobility. Notwithstanding the important accretion of the foreshore in the Calais site over the past decades, monthly surveys of the intertidal beach profile carried out in 1998–1999 (Reichmüth and Anthony, 2002) and from January 2001 to November 2002 (Reichmüth, 2003) show that the profile experiences weak but positive annual sand budget changes, of the order of 1–2% of the intertidal beach volume (ca. +35 to +70 m^3/m). Net time-integrated inputs of this type occur through onshore bar migration at rates of up to 90 m a month (Reichmüth, 2003), and should contribute to the gradual accretion of the upper beach, through high-tide incorporation of upward-migrating bars by swash attenuation over the large flat surface of this morphological unit. Such sand inputs do not explain the major budget change recorded by survey C1. Significant sand supply to the upper beach flat at this site is episodic, and due solely to major storms such as the storm that preceded the C1 survey, capable of driving large amounts of sand onto the upper beach flat from the shore-attached sub-tidal sand bank source. Storm winds also generate aeolian transport on the upper beach flat, but this aspect will be examined in the next section. The rest of the overall budget change in Calais was accounted for by mild accretion in the initial (embryo) dune sector (as defined by the beach–dune segmentation in the methods section, Fig. 4). However, the budgets show that the bulk of the sand gained by the upper beach flat, especially following survey C1 (Fig. 6), was not directly incorporated into the embryo dunes, thus suggesting that the development of the latter is not simply a function of sand supply from the upper beach flat.

At the Leffrinckoucke site, the upper beach budget fluctuated significantly but showed little net overall change, thus suggesting that sand accumulating on the upper beach is recycled to the dune, which registered a more substantial gain. Reichmüth and Anthony (2002) and Reichmüth (2003) have shown that the bar-trough systems of Leffrinckoucke beach are the most stable of the three beaches in the monitored sites. Volumetric changes from monthly profile surveys over the period 1996–2002 are weak (ca. +15 to +30 m^3/m of intertidal beach), but sufficient to explain the net dune budget gains at this site. Sand loss on the upper beach in Leffrinckoucke due to the January 2000 storm (survey L2, Fig. 6) was almost as great as the net gain recorded by the upper beach over the two-year survey period. This suggests that potential sand inputs to the beach from the shoreface may be offset by severe storms if such inputs are not incorporated into the dunes. Compared to the large upper beach flat in Calais which attenuates storm swash, the narrow upper beach in Leffrinckoucke cannot fulfil this buffer role against storms. In spite of the intensity of the January 2000 storm, mild dune accretion occurred following survey L2, probably as a result of efficient sand trapping over the survey period by sand fences (see below) implanted well above the storm surge level.

Overall, the Leffrinckoucke plot seems to reflect the general conditions at this site, which has fluctuated over the past century between mild erosion/accretion and relative stability (Clabaut et al., 2000; Vasseur and Héquette, 2000; Ruz et al., 2005); the pattern probably being controlled by the inshore arrival of sand driven by storms from the Hills Sandbank. More active sand supply from shoreface to beach is hindered by the constant dredging operations necessary to keep the port navigation channel of Dunkerque open to high-tonnage ships. Ruz et al. (2005) have emphasised the importance of human intervention in dune rehabilitation at this site. The first three DEMs at this site, which was initially part of a blow-out, show clearly defined hummocks of sand rapidly trapped by simple brushwood fences (Fig. 8). Thus, much of the initial accretion at this site essentially involved the dune front.

In Wissant, the upper beach fluctuations captured a significant amount of the overall budget change, and are largely responsible for the large cumulative budget mobility recorded at this site (over 10 times the net budget change). The monitored sector of coast is found in a sand transport corridor between updrift source and downdrift sink zones, and the mobility of the upper beach recorded by the DEMs matches beach profile mobility trends in this part of Wissant Bay (Reichmüth and Anthony, 2002; Sedrati and Anthony, 2005). Reichmüth and Anthony (2002) also showed that this part of Wissant beach underwent a net volumetric loss of over 10% between 1996 and 2000. A recent study of intertidal beach hydrodynamics in the surveyed sector has shown that under strong wind conditions coinciding with spring tides, even the upper beach is subject to significant wind-, wave- and tide-induced longshore currents that lead to active longshore bedform migration (Sedrati and Anthony, 2005). Such longshore marine transport has been very efficient in inducing gross, upper beach-dominated, cumulative budget changes (Fig. 6), to the detriment of the upper beach–dune budget. Strong bedform development on the upper beach in Wissant (Fig. 2C) results in significant daily beach profile mobility (Sedrati and Anthony, 2005). The upper beach surface, which lies well below mean high water spring tide level (Fig. 3), evinces strong moisture control (Ruz and Meur-Ferec, 2004), which, together with marine bedform development, would considerably limit sand mobilisation towards the dune in this sector. The upper beach budget fluctuations occurred apace with much milder changes in the neighbouring dune.

The differences between the three monitored sites on the north-facing North Sea coast of France thus depend primarily, over timescales of years, on the availability of marine sand, derived either directly from the shoreface or through the longshore sediment cell circulation.

5.2. Wind and fetch conditions

The overall aeolian dynamic regime of this North Sea coast operates within the framework of a relatively low frequency of strong (>12 m/s) onshore/offshore winds (1.2–3.8%), and of a relatively balanced wind regime, in which the proportion of 'counter-active' offshore winds in the significant wind category (>8 m/s) attains 34%, 41% and 36% respectively in Dunkerque, Calais and Boulogne. Overall, combined offshore and shore-parallel winds account for 57%, 71%, and 68% of winds >8 m/s, respectively in Dunkerque, Calais and Boulogne. The net effect of this wind regime is best reflected in the recent morphology and current development of embryo dunes in Calais, because of both the width and accretionary status of the upper beach flat. This sand flat clearly serves as a basement for seaward, and, especially longshore, embryo dune development. Redistribution of sand alongshore by shore-parallel winds, and from the poorly vegetated foredune platform towards the beach flat by oblique offshore winds suggests that dune sand is spread out and alongshore more or less unevenly rather than accumulating vertically or moving monotonously inland. The net sand gain recorded by the upper beach flat at this site suggests that this unit is developing, through both initial in situ storm-generated deposition and aeolian redistribution of sand, as a net depocentre accreting towards the limits of spring tidal flooding. This development thus results in enlargement of the area of embryo dune development. This can be seen from the hummocky embryo dune morphology depicted by the net DEM budget changes in the inner parts of the upper beach flat (Fig. 5). The absence of significant dune accretion following the important sand accumulation on the upper beach in survey C1 (Fig. 6) shows that sand deposited on the upper beach flat is largely sequestered by this unit rather than being directly integrated by onshore winds into the adjacent embryo dunes. Thus, the embryo dune sector in the survey plot is not the immediate sink for incoming shoreface sand in transit via the upper beach flat. The Calais site shows the least vegetated dunes, and visual observations over the last five years have shown that the vegetation cover has not become denser, and that the dunes in the surveyed sector undergo significant local reworking. These conditions may explain the low altitudinal level but significant spatial spread and development of the embryo dunes at this site, as they encroach on the adjacent sand flat (Fig. 2B). However, the direct development of parts of the upper beach flat into embryo dunes shows the much more intricately linked nature of these two units, compared to the other two sites, and the importance of the presence of a large upper beach flat to the spread of embryo dunes. Finally, it is worth noting that by protecting the developing embryo dunes from storm erosion, the broad sandflat reinforces the net accretionary status of the beach–dune system.

In both Leffrinckoucke and Wissant, the combined dominant offshore and shore-parallel winds would also potentially favour remobilisation of sand from dune to beach, and alongshore on the upper beach. However, although wind velocities tend to increase downwind from the dune front, high dune roughness inland in the well-vegetated dunes at these two sites imposes velocity reductions, while the uppermost beach trough acts as an efficient moist trapping surface for sand transported downslope (Vanhée, 2002; Vanhée et al., 2002). A significant transfer of sand from the dune to the beach would require much stronger offshore winds than those prevailing on this North Sea coast.

Although onshore winds in the significant category (>8 m/s) were important over the survey period (Dunkerque: 43%, Calais: 29%, Boulogne: 32%), the same constraints apply to sand transport from the beach to the dune in Leffrinckoucke and Wissant. The beach bar-trough morphology tends to segment the onshore fetch, considerably limiting aeolian sand transfers inland (Vanhée, 2002; Vanhée et al., 2002). Under these circumstances, the effective fetch for direct supply of blown sand to the dunes by onshore winds is limited to the width of the upper beach surface, which is 30–50 m wide in Leffrinckoucke and Wissant depending on wind approach from northeast to northwest. This would be considered as a moderately large fetch if steady-state transport conditions are achieved (Jackson and Cooper, 1999). However, apart from the relatively low net frequency of strong onshore winds, significant transport of sand from these narrow upper beach surfaces to the dunes is mitigated by the various upper beach factors evoked earlier, notably high moisture levels conditioned by inundation by the large tides, frequent shallow-water wave and current bedform development, and the occurrence, over the large upper beach sand flat in Calais, of patches of silt that accumulate during high tides and that dry out during exposure.

At all three sites, the dune front and upper beach exhibit significant longshore fetch distances for shore-parallel winds (23–32% of winds >8 m/s). This is confirmed by short-term experiments measuring both wind conditions and sand flux variations across and along the upper beach and dune front (Vanhée, 2002; Vanhée et al., 2002). Sand mobilised under these long fetch conditions may thus be redistributed alongshore over long distances, moving offshore (to be ultimately trapped in the humid beach troughs), or inland to feed the dunes, depending on wind orientation, which, on this coast may change rapidly (few minutes) from a purely northerly to a purely southerly direction. In the accreting Calais area, dune development tends to be 'stretched' alongshore by the combined action of offshore and shore-parallel winds, thus explaining the relatively mild net budget gain recorded by the surveyed embryo dune sector at this site, in spite of the important sand gain recorded by the upper beach flat following survey C1 (Fig. 6). Thus, the most active transport may not yield change in morphology. Overall, the relatively narrow shore-parallel dune morphology prevailing in all three study sites, and characteristic of this southern part of the North Sea, appears to reflect the long-term effects of the balanced wind regime.

6. Conclusions

Differences in net upper beach–dune sand budget patterns between the three monitored sites on the north-facing North Sea coast of France are, over timescales of years, primarily controlled by the availability of sand from the tide-and storm-dominated shoreface. Such marine sand supply depends on the local onshore welding of shoreface tidal banks that create a large upper beach fetch favourable to dune development. The only site where this has occurred in the recent past is Calais. Where these source and fetch conditions are not met (presently the case of the rest of the North Sea coast of France), upper-beach dune sand exchanges, such as those at the other monitored sites of Leffrinckoucke and Wissant, are further limited by the narrow wave-tide affected upper beach and the barred intertidal beach morphology immediately adjoining the dune front. This barred morphology, which comprises damp troughs, segments and thus limits both the aeolian fetch and sand transport, thus mitigating sand supply to the critical upper beach zone that sources the dunes. Two further constraints are the energetic intertidal beach hydrodynamic conditions, and the relatively moderate wind energy conditions affecting the North Sea coast of France. The longshore-dominated intertidal beach hydrodynamic circulations at Wissant favour marine bedform development and significant longshore sand mobilisation on the upper beach (entailing large cumulative budget fluctuations but minor net budget changes), to the detriment of the dunes. Wind conditions on this coast are further characterised by a fairly balanced regime of onshore, offshore and shore-parallel winds that tends to limit net sand mobilisation in favour of either the beach or the dune. This balanced wind regime would tend to favour longshore sand transport and may explain the relatively narrow morphology of the linear dune ridges characterising this coast.

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